Comparing strategic deep tillage options on soil constraint removal and crop performance across two soil types in Western Australia

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Abstract
Over the past 10-years numerous strategic deep tillage methods have been developed for ameliorating sandplain soil constraints in WA. Degree of soil disturbance varies: deep ripping loosens soils with low topsoil impact; ripping with inclusion generates seams of incorporated topsoil; deep mixing incorporates topsoil and amendments to 0.3-0.4m; and inversion buries topsoil (and weed seeds) in layers at 0.15-0.4m. Replicated field experiments comparing 13 strategic deep tillage combinations, were established on deep sand (0.4-0.6 m) over clayey gravel (duplex sandy gravel) and deep yellow sand in 2016 and 2017, respectively. On duplex sandy gravel, treatments with deep ripping to 0.5m+ increased wheat yields by 39-49% in 2017, but combining ripping with mixing or inversion has had more sustained yield increases of 42-62% in barley for 2018. For the deep sand, which has limited capacity to store water, grain fill was compromised on mixed or inverted soils, with deeper ripping better matched to crop water supply in both 2017 and 2018. At this site a loss of tillers between 22 August and 12 November in 2018 reflected dry, hot conditions through September with greater losses for some of the deep mixed and inverted treatments which had higher yield potential that could not be met.

Key Words
Soil amelioration, strategic deep tillage, soil constraints, water repellence, subsoil compaction, grain yield

Introduction
Strategic deep tillage involves one-off or occasional tillage intervention to depths of 0.3m or more with aim of overcoming soil, and sometimes agronomic, constraints (Scanlan and Davies 2019). Large areas of the Western Australian (WA) wheatbelt are susceptible to soil constraints. It is estimated that 13.2M ha are susceptible to subsurface compaction, 12.6M ha have subsoil acidity, 9.9M ha are susceptible to topsoil water repellence and 6.2M ha have low soil water storage, less than 70 mm/m (van Gool 2016). Strategic deep tillage, often in combination with soil amendments such as lime, gypsum and clay-rich subsoil, can, in full or in part, overcome some of these constraints. The type of deep tillage practice employed determines its impact on soil conditions. Deep rippers remove hardpans in compacted subsoils often with minimal topsoil disturbance, though topsoil inclusion in slots can be achieved with addition of an opener behind the ripping tine which allows loose topsoil to flow into the subsurface layers (Davies et al. 2015; Blackwell et al. 2016). Rotary spaders and deep working offsets can deeply mix soils and, although the mixing is not thorough (Scanlan and Davies 2019; Ucgul et al. 2019), have proven useful to incorporate soil amendments and reduce topsoil water repellence. Mouldboard, square or modified deep working one-way disc ploughs can invert soils, burying repellent topsoil and associated weed seeds in a layer below a covering of subsoil brought to the surface (Scanlan and Davies 2019; Ucgul et al. 2019). While there has been considerable field research on individual strategic deep tillage methods (e.g. Davies et al. 2019; Blackwell et al. 2016) there have been few studies comparing multiple approaches over time.

Methods
The experiments are randomised complete block designs with 4 replications and were established in either 2016 on a duplex sandy gravel (Ferric Bleached-Orthic Tenosol) near Meckering or in 2017 on yellow deep sand (Yellow-Orthic Tenosol) near Goomalling (Table 1) in the central wheatbelt of WA. Plots were established within the growers' existing controlled traffic systems. Plots were 4-4.5m wide and 45m long and were located in the seeder wings, either side of the wheel tracks so the plots receive no compaction from large machinery. The area between the wheel tracks has been left as untreated. Sites were seeded and managed by the grower throughout the season, with a small plot header used for harvesting individual plots.

Table 1. Experimental site location, soil type, average annual (Avg. Ann.) and growing season (April-October) rainfall (2016-18) and soil properties.

Site *Soil type*	Rainfall (mm)		Topsoil Repellence Molarity of Ethanol Droplet Test	Average Soil pH in $CaCl_2$ (m depth)				Severe (>2.5MPa) compaction depth (m)	Soil fertility (0-0.1m)			
	Avg. Ann.	Growing season (Apr-Oct)		0-0.1	0.1-0.2	0.2-0.3	0.3-0.4		% OC	P	K	S
Meckering *Duplex sandy gravel*	388	323 ('16) 253 ('17) 291 ('18)	2.1 Severe	5.9	5.2	4.7	4.6	0.22-0.42	0.8	13	37	11
Goomalling *Deep sand*	365	181 ('17) 282 ('18)	1.5 Moderate	5.4	4.8	4.5	4.4	0.20-0.50+	1.0	16	67	4

Strategic deep tillage implements used included an Agrowplow deep ripper, a Heliripper very deep ripper, a Farmax rotary spader, an Alpler 5-furrow reversible mouldboard plough and a 4-disc trial scale one-way plough with 55cm discs. All of the tillage treatments were applied and rolled prior to seeding (Table 2). The Meckering site was sown on: 28 June 2016 to Scepter wheat at 100 kg/ha with 42 kg/ha N, 12 kg/ha P and 18 kg/ha K; 29 May 2017 to Scepter wheat at 75 kg/ha with 22.4 kg/ha N, 12 kg/ha P and 25 kg/ha K; 30 April 2018 to Bass barley at 80 kg/ha with 30 kg/ha N, 9.7 kg/ha P, and 12.9 kg/ha K. The Goomalling site was sown on: 13 June 2017 to Calingiri wheat at 70 kg/ha with 13.5 kg/ha P, 15 kg/ha K and 26 kg/ha N and in 2018 to Scepter wheat at 80 kg/ha on 19 May with 10.1 kg/ha P, 8.4 kg/ha K, and 27.2 kg/ha N.

Table 2. Strategic deep tillage treatment details, effective working depth, cost and application timing.

Deep Tillage Treatment	Abbreviation	Effective Working Depth (m)	One-off Cost ($/ha)	Treatment Application Timing	
				Meckering	Goomalling
1. Untreated control	CON	-	-	-	-
2. Deep ripping	DR	0.32-0.34	45	Apr-16	May-17
3. Deep rip with topsoil inclusion	DRI	0.34-0.36	50	Apr-16	May-17
4. Deep rip + rotary spading	DR+SP	0.33-0.35	150	Apr-16	May-17
5. Very deep ripping	VDR	0.65-0.68	90	Apr-16	May-17
6. V. deep rip with topsoil inclusion	VDRI	0.62-0.65	95	Apr-16	May-17
7. V. deep ripping + spading	VDR+SP	0.62-0.65	190	Apr-16	May-17
8. V. deep rip with inclusion + spade	VDRI+SP	0.62-0.65	195	Apr-16	May-17
9. One-way disc ploughing	OWP	0.30-0.35	50	Jun-16	Jun-17
10. V. deep rip + one-way plough	VDR+OWP	0.62-0.65	140	Jun-16	May/Jun-17
11. Mouldboard ploughing	MBP	0.34-0.36	120	Jun-16	Jun-17
12. Mouldboard plough + v. deep rip	MBP+VDR	0.62-0.65	200	Jun-16+Apr-17	Jun-17

Results

Both sites have severe compaction, defined as the point at which the soil penetration resistance exceeds 2.5MPa. This occurred at a depth of 0.22-0.42m at the Meckering site (Table 1) and below 0.2m at the Goomalling site (Table 1). All treatments reduced the soil strength of the top 0.28m of soil to a penetration resistance less than 2.0MPa (data not shown). The treatments with deep ripping, mouldboard ploughing and one-way ploughing reduced the penetration resistance below 2.5MPa to a depth of 0.32-0.35m while very deep ripping or delving increased the depth of loosened soil to 0.57m or more (data not shown).
Topsoil water repellence was reduced to very low or nil by those treatments that either mixed (rotary spader) or inverted (mouldboard or one-way plough) the soil surface (data not shown). Deep ripping on its own, irrespective of depth, did not reduce topsoil repellence, while deep ripping with topsoil inclusion was inconsistent across the sites and had either no or a small impacts on soil water repellence (data not shown).
At Meckering, wheat grain yields were increased by 26-49% over the control for the very deep ripping with and without topsoil inclusion, ripping with spading and one-way ploughing in the first season (2016, Table 3). Standard deep ripping, mouldboard ploughing and inversion tools (mouldboard and one-way ploughs) with very deep ripping did not increase grain yield. In these treatments, loose soil and unconsolidated seed beds reduced crop establishment sufficiently to negate likely yield benefits. Over the subsequent two seasons, 2017-18, the soil inversion with a mouldboard plough combined with very deep ripping treatment was the highest yielding, with a 39% (+1.49 t/ha) wheat yield increase in 2017 and 62% (+1.92 t/ha) barley yield increase in 2018 compared to the control (Table 3). At Meckering, those treatments which included

deep soil mixing (rotary spader) or soil inversion sustained large yield increases over the control while deep ripping with and without topsoil inclusion typically had limited response (Table 3). Shoot K concentrations for deep tillage treatments were 7-46% higher in 2016, 5-32% higher in 2017 and 32-116% higher in 2018 than the control (data not shown). After treatment cost (Table 2) and using seasonal grain prices the net financial return from the deep tillage treatments over the 3-seasons at Meckering was highest for mouldboard ploughing with very deep ripping ($777/ha benefit), followed by the various deep ripping with spading treatments ($624-730/ha benefit) and lowest for the 'shallower' deep ripping with or without topsoil inclusion ($115-281/ha benefit; data not shown).

Table 3. Impact of strategic deep tillage treatments applied in 2016 on head density, grain yield and yield change of cereal crops grown 2016-2018 on duplex sandy gravel at Meckering, WA. Head density and grain yield values significantly different (LSD 0.05) from the control are highlighted in bold.

	Wheat 2016				**Wheat 2017**				**Barley 2018**		
Strategic Deep Tillage Treatment	**Head No.**	**Grain Yield**	**Yield Change**		**Head No.**	**Grain Yield**	**Yield Change**		**Grain Yield**	**Yield Change**	
	#/m^2	t/ha	t/ha	%	#/m^2	t/ha	t/ha	%	t/ha	t/ha	%
CON	236	2.14	-	-	204	3.80	-	-	3.08	-	-
DR	224	2.47	0.33	15	241	3.99	0.19	5	3.22	0.14	4
DRI	220	**2.71**	0.57	26	223	4.09	0.29	8	3.55	0.47	15
DR+SP	237	**2.88**	0.74	34	**280**	**5.05**	1.25	33	**4.57**	1.49	48
VDR	250	**2.97**	0.83	39	225	4.34	0.54	14	3.68	0.60	20
VDRI	256	**2.97**	0.83	39	228	4.28	0.48	13	**4.00**	0.93	30
VDR+SP	249	**2.95**	0.81	38	**246**	**4.72**	0.92	24	**4.55**	1.47	48
VDRI+SP	249	**3.19**	1.05	49	**273**	**4.98**	1.18	31	**4.36**	1.28	42
OWP	235	**2.86**	0.72	34	**263**	**4.77**	0.97	26	3.56	0.48	16
VDR+OWP	216	2.40	0.26	12	233	4.15	0.35	9	**4.38**	1.30	42
MBP	269	2.37	0.23	11	**248**	**5.01**	1.21	32	**4.01**	0.94	30
MBP+VDR[a]	216	2.51	0.37	17	219	**5.29**	1.49	39	**5.00**	1.92	62
LSD (0.05)	*37*	*0.49*			*57*	*0.72*			*0.61*		

[a] Note very deep ripping (VDR) component of the mouldboard + very deep ripping (MBP+VDR) treatment at Meckering was not implemented until early 2017.

Table 4. Impact of strategic deep tillage treatments applied in 2017 on head density, grain yield and yield change of wheat crops grown 2017-2018 on deep yellow sand at Goomalling, WA. Tiller density and grain yield values significantly different (LSD 0.05) from the control are highlighted in bold.

Strategic Deep Tillage Treatment	**Wheat 2017**				**Wheat 2018**					
	Tiller No.	**Grain Yield**	**Yield Change**		**Tiller No. 22 Aug.**	**Tiller No. 12 Nov.**	**Change in Tiller No.**	**Grain Yield**	**Yield Change**	
	#/m^2	t/ha	t/ha	%	#/m^2	#/m^2	%	t/ha	t/ha	%
CON	49	0.80			264	221	-16	0.89		
DR	58	0.81	0.01	2	267	200	-25	1.04	0.15	17
DRI	39	0.86	0.06	8	270	220	-18	1.02	0.13	14
DR+SP	50	0.89	0.09	12	**289**	237	-18	**1.15**	0.26	29
VDR	59	**1.54**	0.74	93	266	227	-15	**1.58**	0.69	77
VDRI	55	**1.35**	0.55	69	**300**	**284**	-5	**1.50**	0.60	68
VDR+SP	62	**1.39**	0.59	74	**303**	**306**	1	**1.63**	0.74	83
VDR+OWP	**76**	**1.47**	0.67	84	**413**	**262**	-36	**1.40**	0.51	57
VDRI+SP	**80**	**1.47**	0.67	84	**346**	**297**	-14	**1.66**	0.77	83
OWP	59	0.92	0.12	15	**364**	**273**	-25	1.03	0.14	16
MBP	**65**	**1.24**	0.44	55	**360**	**301**	-16	**1.25**	0.35	40
MBP+VDR	**69**	**1.40**	0.60	76	**383**	**268**	-30	**1.32**	0.43	48
LSD (0.05)	*15*	*0.16*			*19*	*36*		*0.19*		

At Goomalling, wheat grain yields were considerably lower than the Meckering site with untreated control treatments only achieving 0.8 and 0.9 t/ha in 2017 and 2018, respectively (Table 4). In the first season, 2017, very deep ripping was the key factor in any treatment combination achieving a significant wheat grain yield increase. These increases ranged from 55-93%, but the highest yield was obtained with very deep ripping only which increased yield by 0.74 t/ha over the control (Table 4). In the second season a similar pattern was seen with treatments containing very deep ripping having the highest grain yields, with an increase of 48-83% over the control (Table 4). Higher tiller numbers counted in August for inversion and mixing treatments were indicative of higher yield potential but this was not realised through the dry September period (17mm was received for the month and none after 9 September compared to long term average of 28mm for the month), with these treatments losing a higher proportion of tillers when assessed in November (Table 4). Soil inversion with mouldboard plough increased grain yield 60%, generally lower than most treatments which included very deep ripping. The greatest net financial benefit for the 2017-18 seasons was for very deep ripping at $189/ha. Only the treatments with shallower deep ripping did not have a positive net return, indicating the need for deeper ripping at this site (data not shown).

Conclusion

This research compared new and more established strategic deep tillage approaches for ameliorating multiple soil constraints at several grower-managed sites with different soil-types. On the deep sand over gravel site at Meckering, removal of deeper compaction and improved root access to K and N at depth were critical drivers of increased productivity in the first year. More sustained yield responses in years two and three at Meckering were achieved with those treatments that had additional topsoil and subsoil modification with deep soil mixing (spader) or inversion (one-way or mouldboard) with K uptake continuing to be important. At Goomalling, on a deep yellow sand with limited capacity to store water, yield benefits came primarily from removal of deep compaction. At this site, deep soil mixing and soil inversion have shown potential benefit on crop establishment, weed control and yield over ripping alone, but for both 2017 and 2018 seasons there was insufficient plant available water during grain filling for this to be realised in higher grain production over the very deep ripping treatments. The findings demonstrate that strategic deep tillage can provide profitable grain yield benefits over multiple seasons but that the choice of tillage approach depends on the combination of soil constraints and the inherent yield potential of the soil, largely driven by its plant available water holding capacity.

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