Inert mineral mulches provide an additional grain yield on alkaline-sodic-saline soils of the eastern wheatbelt of Western Australia.

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Abstract
Poor water relations reduce crops grown on alkaline-sodic-saline soils in low rainfall environments of the eastern wheatbelt of Western Australia (<350mm, annual rainfall). The poor water relation is due to the high sodium content, which results in soil dispersion and low water infiltration, and the saline conditions associated with transient salinity, which result in osmotic stresses that reduce water availability. We investigated the impact on grain yield using novel soil amelioration systems, which include gypsum applied at a low rate ($G_{0.1}$, 0.1 t ha^{-1}), in-furrow compared to a high rate ($G_{3.0}$, 3.0 t ha^{-1}), gravel mulch (GM) (2–4 cm) thick applied to the soil surface and deep tillage using a Paraplow (PP) to 35 cm at three sites in the shires of Mullewa (Devils Creek), Merredin (Moorine Rock) and Esperance (Grass Patch) in 2022 and 2023. The GM treatment increased the average yield by 0.53 t ha^{-1} (0–1.24 t ha^{-1}) across all sites and years, representing a mean percent yield increase of 54% (0–164%). The $G_{0.1}$, $G_{3.0,}$ and PP treatment's main effects were insignificant. Physical constraints are not the greatest constraint in these soils so investment in deep ripping can be ruled out until chemical constraints are managed. The only site to respond to gypsum was sodic with low EC in the topsoil. Mulching, through inert mineral mulch, can provide yield stability during drier seasons.

Keywords: evaporation, gravel stone, gypsum, deep ripping

Introduction
Crop production on alkaline-sodic-saline soils in WA often fluctuates between excellent productivity in years with above-average rainfall and poor production in years with below-average rainfall. Poor soil-water relations are responsible for this. High sodicity and, pH result in clay dispersion, limiting water infiltration and resulting in high levels of soil evaporation and limited water storage. Clay dispersion has also resulted in the accumulation of cyclical salts within the soil profile, leading to transient salinity and high osmotic pressures that further limit water availability to crops in dry years (Barrett-Lennard et al. 2016). Ameliorating these soils requires improving water infiltration, reducing soil evaporation, leaching excess salts, and removing compacted layers. Recent research has shown crop yield benefits on alkaline-sodic-saline soils from gypsum applied in-furrow at low (0.05 – 0.10 t ha^{-1}) rates (Barrett-Lennard et al. 2021). Mineral mulches in the form of sand and gravel stone, when applied at a thickness of 2–4 cm, have been shown to reduce soil evaporation in glasshouse experiments and increase grain yields by as much as 2 t ha^{-1} at Ravensthorpe (Hall et al. 2022). Crop responses to deep tillage on these soils have been highly variable due to the risk of delving toxic subsoils to the surface. However, deep tillage systems that shatter dispersed and compacted clay layers have not been tested.

Our research aimed to assess the effectiveness of inert mineral mulch, combined with gypsum and deep ripping, for increasing grain yield on alkaline-sodic-saline soils in the low rainfall areas of WA's eastern wheatbelt. Specifically, we aimed to test the hypotheses: 1) Crop production on sodic soil can be enhanced using chemical (gypsum) and physical (gravel mulch, deep ripping with a Howard Paraplow slant tine ripper) ameliorants. 2) The effects of each ameliorant are additive or result in a positive interaction with respect to grain yield. 3) Gypsum in-furrow at low rates is as effective as broadcast gypsum at conventional rates. This paper aims to test these hypotheses using three small plot field trials.

Methods
Experimental design and management
We conducted three factorial and randomised complete block trials with three main treatments: ripping using a Paraplow (PP), application of inert surface mulch (GM), surface application of 3.0 t gypsum ha^{-1} ($G_{3.0}$) or in-furrow application of 0.1 t gypsum ha^{-1} ($G_{0.1}$). The sites were near Mullewa (Devils Creek) in the northeastern wheatbelt, Moorine Rock in the eastern central wheatbelt and Grass Patch in the southeastern on Calcic Calcarosols (Isbell, 2016). We replicated the treatments three times and conducted the experiments in 2022 and 2023. The plots were 2 m wide by 20 m long. We used the no-till farming system to seed crops between early April and early June and harvested the crops between October and December, depending on

the seasonal conditions. We controlled weeds using herbicide applications and applied basal fertiliser treatments (N, P, S, Cu and Zn) at seeding and N applications post-seeding when required.
At the Devils Creek site, an inert gravel mulch (GM) source was screened to a size of 10 to 20 mm. In contrast, ironstone gravel, containing a high percentage of gravel, was sourced from pushed stockpiles near the Moorine Rock and Grass Patch sites. Each site had the GM laid to an even depth of 2–4 cm using a skid-steer loader. We used a Paraplow (PP) to rip the soil profile to a depth of 35 cm and minimise bringing sodic sub-soil to the soil surface. We applied 3.0 t gypsum ha^{-1} to the soil surface ($G_{3.0}$) and banded 0.10 t gypsum ha^{-1} into the seeding furrow ($G_{0.1}$) at seeding. We applied the $G_{3.0}$ and GM and PP treatments in autumn 2022. The $G_{0.1}$ treatment was applied in-furrow in both years by splitting half with the seed and fertiliser to prevent machinery blockages. We applied the seed and fertiliser in the same furrow but at different depths. Devils Creek and Moorine Rock was sown to wheat both 2022 and 2023, at Grass Patch wheat and canola was sown in 2022 and 2023 respectively.

We calculated the potential yield of wheat using a water use efficiency (WUE) of 24 kg mm^{-1} ha^{-1} and soil evaporation of growing season rainfall (GSR) of 45 mm (Harries et al. 2022). The GSR was defined between April and September for the Devils Creek and Moorine Rock and between April and October for the Grass Patch. We assumed 70% of the soil water derived from January to 31 March rainfall was lost by soil evaporation, and there was no soil water leakage below the root zone or runoff from the experimental sites.

Soil measurements
We used a 50 cm soil auger/corer to collect soil samples to 50 cm in increments of 10 cm at five locations of the control plots in autumn or early winter. We then used 1:5 soil-to-solution ratio with DI water to measure pH (pH_W), electrical conductively ($EC_{1:5}$) and soluble carbonate, bicarbonate and total alkalinity, exchangeable cations with alcohol prewash to derive ESP, soil organic carbon (SOC), hot boron, particle size analyses (Rayment and Lyons 2010).

Statistical analysis
We used an analysis of variance in Genstat® version 22 to define significant ($P<0.05$) main and treatment effects. Significant difference among treatments was determined for each site and year using Duncan multiple comparison tests, where significant ($p < 0.05$) treatment differences are illustrated by different letters.

Results and Discussion

Rainfall
The seasonal conditions were significantly different, with the 2022 growing season rainfall ranging from 209–367 mm, with one of the longest and coolest season finishes on record (Table 1). In contrast, 2023 had lower growing season rainfall (111–176 mm) with a warm to hot finish. Potential yields were 4.3 t ha^{-1} at Devils Creek, 4.7 t ha^{-1} at Moorine Rock and 6.1 t ha^{-1} at Grass Patch in 2022 (Harries et al. 2022). In 2023, these values were 3.7 t ha^{-1} at Devils Creek, 2.6 t ha^{-1} at Moorine Rock and 1.8 t ha^{-1} (canola) at Grass Patch.

Table 1 Mullewa (Devils Creek, DC), Moorine Rock (MR) and Mount Madden East (Grass Patch, GP) monthly rainfall, annual rainfall (AR), growing season rainfall (GSR), fallow season rainfall in mm (FSR). Months of year represented in first row using respective first letter.

Site	Year	J	F	M	A	M	J	J	A	S	O	N	D	AR	GSR	FSR
DC	2022	3	6	57	22	25	21	53	89	27	5	1	9	317	237	66
	2023	27	0	88	2	20	37	16	26	10	2	0	0	230	112	115
MR	2022	0	13	25	14	20	30	30	82	33	28	9	0	284	209	38
	2023	15	1	84	6	21	30	21	25	22	2	0	0	227	125	100
GP	2022	2	17	20	94	25	30	48	66	46	58	15	7	427	367	38
	2023	1	2	43	19	20	44	15	42	23	13	0	0	223	176	47

Soil test results
The soil test values pH_W, EC and ESP in the 0–10 cm soil layer were 8.0, 0.17 dS m^{-1} and 0.4% at Devils Creek, 8.7, 3.2 dS m^{-1} and 7.8% at Moorine Rock and 7.6, 0.1 dS m^{-1}, 7.8% at Grass Patch, respectively (Table 2). The sand content of the 0–10 cm layer at the Grass Patch site (75%) was greater than that of the Moorine Rock site (55%). These soil test values in the 0–30 cm soil layer were 8.4, 0.13 dS m^{-1} and 0.6% at Devils Creek, 9.0, 2.7 dS m^{-1} and 10.7% at Moorine Rock and 8.8, 0.4 dS m^{-1}, 14.3% at Grass Patch, respectively.

Table 2. Soil chemical and physical properties within the soil profile include pHW, electrical conductivity (EC, d S m^{-1}), soil organic carbon (SOC, %), exchangeable sodium percentage (ESP, %), boron (B mg kg^{-1}), clay, silt sand (%), water-soluble CO_3, HCO_3 and total alkalinity (cmol kg^{-1}).

Site and depth (cm)	pH_W	EC (dS m^{-1})	SOC (%)	ESP (%)	B (mg kg^{-1})	Clay (%)	Silt (%)	Sand (%)	CO_3 (cmol kg^{-1})	HCO_3 (cmol kg^{-1})	Total alkalinity (cmol kg^{-1})
Devils Creek											
0–10	8.0	0.2	1.0	0	1	na	na	na	0.0	1.0	0.4
10–20	8.4	0.1	0.8	0	1	na	na	na	0.1	0.9	0.5
20–30	8.7	0.1	0.5	1	2	na	na	na	0.3	1.1	0.7
30–40	8.8	0.1	0.4	2	2	na	na	na	0.5	1.3	0.9
40–50	9.3	0.2	0.3	7	3	na	na	na	0.6	1.1	0.9
Moorine Rock											
0–10	8.7	3.2	1.6	8	16	19	25	55	0.0	0.8	0.4
10–20	9.0	2.7	1.0	11	37	24	25	51	0.2	0.6	0.4
20–30	9.2	2.1	0.4	13	49	29	20	51	0.3	0.6	0.5
30–40	9.3	2.0	0.3	17	57	33	33	34	0.5	0.7	0.6
40–50	9.3	1.9	0.2	22	66	32	21	47	0.6	0.8	0.7
Grass Patch											
0–10	7.6	0.1	0.8	7	2	19	6	75	0.0	0.8	0.4
10–20	9.1	0.4	0.5	17	12	39	5	56	0.3	1.8	1.1
20–30	9.6	0.6	0.3	22	18	30	11	59	0.7	2.6	1.7
30–40	9.7	0.7	0.2	26	20	32	7	62	1.0	1.9	1.4
40–50	9.7	0.8	0.2	30	24	34	3	62	1.1	1.7	1.4

Note: na = not available

Grain yield

The Gravel Mulch treatment (main effect) increased grain at Devils Creek by 20% in 2022 and 37% in 2023 at Moorine Rock by 98% in 2022 and 179% in 2023 compared to the nil gravel treatments (Table 2). The response was insignificant at Grass Patch in both years. The greater response at Moorine Rock was due to the site's soil test values in the 0–10 cm soil layer being more alkaline (pH_W=8.7, compared to 7.6–8.0), saline ($EC_{1:5}$=3.2 compared to 0.1–0.2 dS m^{-1}) and sodic (EPS = 8% compares to 0% at Devils Creek and 7% at Grass Patch).

Table 2. Effects of gypsum rates (0, 0.1, 3.0 t ha^{-1}), gravel mulch (GM) and Paraplow (PP) ripping to 30 cm on grain yields (t ha^{-1}) for crops grown at Devils Creek, Moorine Rock and Grass Patch, both treatment and main effects presented. Lowercase letters indicate a significant difference between means at $p < 0.05$ for each site and crop production year. We present the LSD values at $p < 0.05$.

	Devils Creek		Moorine Rock		Grass Patch	
Treatments	2022	2023	2022	2023	2022	2023
1. Control	2.09^{d}	2.70^{b}	1.23^{d}	0.22^{def}	4.90^{ab}	1.05^{b}
2. $G_{3.0}$	2.12^{d}	2.43^{bc}	1.21^{d}	0.27^{def}	4.99^{ab}	1.14^{ab}
3. $G_{0.1}$	2.23^{bcd}	2.63^{b}	1.08^{d}	0.32^{def}	4.97^{ab}	1.10^{ab}
4. PP	2.41^{abcd}	2.73^{b}	1.19^{cd}	0.20^{ef}	4.92^{ab}	1.21^{ab}
5. PP + $G_{3.0}$	2.14^{cd}	2.47^{bc}	0.91^{d}	0.08^{f}	5.08^{a}	1.15^{ab}
6. PP + $G_{0.1}$	2.20^{bcd}	2.32^{c}	1.06^{d}	0.15^{f}	4.90^{ab}	1.25^{ab}
7. GM	2.68^{a}	3.41^{a}	2.11^{ab}	0.58^{abc}	4.98^{ab}	1.07^{b}
8. GM + $G_{0.1}$	2.56^{abc}	3.67^{a}	2.41^{a}	0.72^{a}	4.94^{ab}	1.25^{a}
9. GM + $G_{3.0}$	2.52^{abcd}	3.50^{a}	2.37^{a}	0.66^{ab}	4.95^{ab}	1.18^{ab}
10. GM + PP	2.68^{a}	3.41^{a}	2.16^{ab}	0.38^{cde}	4.78^{b}	1.10^{ab}
11. GM + PP + $G_{3.0}$	2.60^{ab}	3.46^{a}	2.35^{a}	0.62^{abc}	4.83^{ab}	1.22^{ab}
12. GM + PP + $G_{0.1}$	2.79^{a}	2.70^{a}	1.70^{bc}	0.44^{bcd}	4.75^{b}	1.10^{ab}
LSD	0.38	0.28	0.49	0.21	0.25	0.15
GM average yield	2.64	3.50	2.11	0.58	4.66	1.15
Potential yield	4.27	2.40	4.66	2.58	6.15	1.70
Main effects						
GM	P=0.18	P=0.14	P=0.20	P=0.09	ns	ns
PP	ns	ns	ns	P=0.09	ns	ns
Gypsum	ns	ns	ns	ns	ns	P=0.02

Gypsum applied at 0.10 t ha^{-1} in-furrow and top-dressed at 3.0 t ha^{-1} had no yield benefit (non-significant gypsum main effect). Similarly, deep ripping using a Paraplow had no yield benefit at Devils Creek and Grass Patch (non-significant Paraplow main effect) and a decline in crop yield at Moorine Rock (-10–-47%, data not shown) due to reduced crop establishment when compared to no ripping treatment. The GM treated crop yields achieved 62% and 153% of rainfall limited yield potential at Devils Creek in 2022 and 2023 respectively. Equivalent values were 45% and 22% at Moorine Rock and 75 and 64% at Grass Patch. Hence, the GM treatment did not entirely remove the alkaline-sodic-saline constraint.

Gravel mulching increased grain yields at two of the three sites in years with rainfall extremes. The mechanism for the grain yield increase we believe is due to reduced soil evaporation resulting in increased transpiration. Hall et al. (2022) found that mineral mulches reduced soil evaporation by 50 to 75 % over a four month period. While measurements of evaporation were not taken from these field trials, the presence of increased soil moisture beneath the gravel mulch treatments was observed when compared to nil mulch. The lack of response to the gravel treatment at Grass Patch is not clear but could be due to the presence of sufficient sand in the topsoil to make the mulch treatment ineffective. Gypsum applied either in furrow at low rates or surface spread at high rates did not consistently increase grain yields. The only site to respond to gypsum was sodic with low EC in the topsoil which is to be expected. Deep ripping with the Paraplow did not increase grain yield in any year or site. This suggests that the physical limitations in these soils are secondary to their chemical limitations.

Current costing estimates for the gravel mulching technique are far greater than \$2000 ha^{-1}, providing access to the resource within one kilometre of the use site. The profitability of the gravel mulch will depend on the longevity of the treatment. Farmer observations suggest that improvements in crop yields can persist for 10 years.

Conclusion

With regards to the hypotheses we found that crop production on sodic soils (1) was increased by mineral mulches and to a lesser extent by gypsum but not by deep ripping even when using tynes that resulted in shattering without delving (2) did not show additive or synergistic responses in grain yield as a result of the treatments and (3) gypsum in-furrow at low rates was as ineffective as broadcast gypsum at conventional rates in most years. Better diagnostics are required define what are and what are not gypsum responsive soils.

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