Reviewing lime applications for acidic sands: Products, rates and incorporation techniques

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Key findings

- A lack of grain yield response to lime rates and products trialled at Bute is most likely due to the slightly acidic (pH $CaCl_2$ 4.8 – 6.1 in the 0-30 cm) nature of the site. However, it is important to monitor soil pH profiles similar to this for pH declines in the future.
- Grain yield response to incorporation method has been variable across the seasons. Lentils showed the greatest benefit in both 2020 and 2023 seasons, while the cereal yields have been unresponsive.
- Treatments which incorporated lime by spading, increased molybdenum tissue concentration (0.35 – 0.37 mg/kg) compared to the no-till control (0.24 mg/kg) in barley in year four.
- Predicta rNod samples taken four years after the trial commenced showed, the application of lime (regardless if surface applied or incorporated) has increased the level of group E/F rhizobia persisting in the soil.
- Both trials contained treatments which have increased soil pH since lime was applied. However, the depth where this pH change has occurred was different in the lime product compared to the lime incorporation trial.

TRIAL 1 - LIME COMPARISON TRIAL

Why do the trial?

The use of new pH mapping technologies has increased the awareness and identification of soil acidity in many districts. However, there are several aspects of soil acidity management which remain a problem for growers and this trial will focuses on three key areas outlined below.

1. Lime source

Currently there are numerous lime sources available to growers with differing quality, accessibility and cost. A trial will investigate the effectiveness of four different lime sources available in the region including a local source from a farm near the trial.

2. Lime rate and product particle size

Previous research has based lime rates on total neutralising value (TNV), a measure of lime purity which does not factor in particle size. This means finer lime products have tended to be more responsive on a tonne for tonne comparison as they react in the soil more quickly. However, the effective neutralising value (ENV) considers the TNV and particle size, giving a better indication of how fast a product will react in soil. Lime sources, particularly hard rock sources, are generally priced based on the ENV, which means that for a given investment in lime higher rates of a lower quality product (larger particle size) can be applied compared to higher quality products. Total product volume also has implications for freight and spreading costs and these factors need to be considered in the decision.

3. Decline of soil pH from sulphur (S) applications

The form of S fertiliser selected for this trial was elemental S. After application, elemental S undergoes oxidation releasing H+ ions and this is an acidifying process. This treatment has been included to accelerate pH decline and demonstrate the implications of continued pH decline on crop productivity.

How was it done?

Site selection and soil properties

The trial was established at Bute, SA (-33.77356, 138.05399). The paddock had been continuously cropped for many years in a wheat, barley, lentil/lupin rotation. No lime has previously been applied to the paddock. Soil cores were collected pre-seeding 2019 and segmented in 0-10 cm, 10-30 cm and 30 -100 cm.

The Bute soil is a red sand over sandy clay, transitioning at a depth between 25 – 40 cm. In general soil nitrogen, phosphorus, potassium and sulphur were present in adequate to high levels (Table 1). The site had low levels of organic carbon (0.5%), low cation exchange capacity and low salinity.

Table 1. Soil properties for soil acidity trials Bute, SA 2019.

Depth	**cm**	**0-10**	**10-30**	**30-100**
DGT P	µg/L	119 (High)	39	
Colwell P	mg/kg	23 (Adequate)	20	
PBI		14.7 (Very low)	28	
Potassium Colwell	mg/kg	149 (Adequate)	202 (Adequate)	
Available nitrogen	kg/ha	25	22	39
Sulfur	mg/kg	4.2	1.6	3.8
Available Sulphur	kg/ha	6 (Low)	4	37
Organic Carbon	%	0.53 (Moderate)	0.52 (Moderate)	
Conductivity	dS/m	0.057	0.038	
	ECe	0.798 (Low)	0.532 (Low)	
Exchangeable Cations (CEC)	CEC	3.45 (Low)	6.03 (Low)	
	ESP	2.0 (Low sodicity)	2.7 (Low sodicity)	

Soil pH was analysed in 5 cm depth increments from 0- 30 cm. Soil pH in the top 0 -5 cm was 6.08 (Table 2). The pH in the 5 – 25 cm depths were acidic ranging from 4.84 to 5.57.

Table 2. Starting soil pH in the soil acidity trials Bute, SA 2019.

Depth	pH $CaCl_2$
0 – 5 cm	6.08
5 – 10 cm	4.96
10 – 15 cm	4.84
15 – 20 cm	5.18
20 – 25 cm	5.57
25 – 30 cm	6.01

Trial design

The trial was a randomised completed block design with three replicates and plot sizes of 22 m x 2 m. Lime treatments were implemented at the site on 18th April 2019. Four lime sources were selected with two rates of each lime source, a nil and a sulphur treatment (Table 3). The lime and sulphur treatments were applied to the soil surface and all plots were deep ripped and levelled/incorporated with an offset disc to a depth of approximately 100 mm. Lime rates were based on raising the soil pH to 6 for each soil depth sampled (Table 2) and the assumed lime requirement of 1000 kg lime/5 cm soil/pH unit. On average 3470 kg/ha of pure lime was required and a low and high rate of 2000 and 4000 kg/ha was selected for this trial (Table 3).

Table 3. Sulphur and lime products, effective neutralising values (ENV) and applied rates for the Bute lime product trial established in 2019.

Treatment	Product	ENV (%)	Rate at 100% ENV (kg/ha)	Rate at ENV (kg/ha)	Rate (dry product) (kg/ha)	Moisture content (%)	Rate (wet product) (kg/ha)
1	Control						
2	Sulphur				700		700
3	Kulpara	59%	2000	3390	3400	~2%	3400
4	Kulpara	59%	4000	6780	6800	~2%	6800
5	Angaston	93%	2000	2151	2200	6%	2329
6	Angaston	93%	4000	4301	4400	6%	4659
7	Spalding	65%	2000	3077	3100	20%	3720
8	Spalding	65%	4000	6154	6200	20%	7440
9	Venning	33%	2000	6061	6000	~2%	6000
10	Venning	33%	4000	12121	12000	~2%	12000

Crop and soil assessments

Over the past five seasons the trial has followed a barley, lentil, wheat rotation. Various in season assessments have occurred and are summarised below (Table 4) for each trial year.

Table 4. Summary of seeding details and crop measurements over the past four years of acidity trials at Bute, SA.

Year	Rainfall	Crop, seeding date and fertiliser	Crop and soil assessments
2019	Annual: 240 mm GSR: 213 mm	Spartacus CL barley at 70 kg/ha 16th May 2019 DAP:Urea (32:10) at 100 kg/ha	GreenSeeker NDVI 20th August and 20th September Grain yield and grain quality
2020	Annual: 390 mm GSR: 301 mm	PBA Hallmark XT lentil at 50 kg/ha 13th May 2020 MAP at 60 kg/ha	Plant emergence GreenSeeker NDVI 21st July, 20th August and 15th September Grain yield
2021	Annual: 346 mm GSR: 234 mm	Chief CL Plus wheat at 100kg/ha 27th May 2021 DAP at 100 kg/ha	Plant emergence GreenSeeker NDVI on 12th July and 8th September Grain yield and grain quality
2022	Annual: 451 mm GSR: 314 mm	Commodus CL Barley at 68 kg/ha 28th May 2022 MAP Zn at 55 kg/ha + Urea 45 kg/ha	Pit face soil sampling* 4th April Greenseeker NDVI 11th August Tissue test 11th August Grain yield
2023	Annual: 362 mm GSR: 225 mm	Hurricane lentil @ 50 kg/ha 12th May 2023 DAP at 70 kg/ha	Pre-seeding Predicta rNod* Plant emergence Greenseeker NDVI 28th July and 1st September Grain yield

**only for selected treatments in trial 2*

Results and discussion

Crop emergence and NDVI

In three trial seasons plant emergence has been assessed and shown lime product or rate has had no impact on crop emergence. The average plant emergence for all treatments was 2020 lentil 87%, 2021 wheat 61% and 2023 lentil 97% (data not shown).

In the three cereal phases there has been no NDVI response to lime rate or product (data not shown). For lentil there was one season (2020) where a NDVI response to lime product was observed (Table 5). Poor crop growth is often observed in more sensitive crops such as lentils and therefore a response to lime may appear more rapidly compared to cereals. Early in the season (July and August) there was no response to lime product or rate. However, by September there were treatment effects for lime product (Table 5). The Angaston and Spalding products had the highest NDVI values (average 0.744). These two products had the highest ENV of those trialled at 93% and 65%, respectively. The locally sourced product (Venning) was similar to the control at this date and the Kulpara product was slightly lower. The sulphur treatment was significantly poorer, 2.6%, than the control and 4.4% poorer than the best treatments. When the trial was sown to lentils again in 2023 (year 5) no NDVI differences were observed for lime product or rate.

Table 5. Greenseeker NDVI recorded on 21st July, 20th August and 15th September in the lime product comparison trial at Bute, SA 2020.

Product	NDVI 21 July	NDVI 20 Aug	NDVI 15 Sept
Control	0.345	0.600	0.728 b
Sulphur	0.363	0.604	0.709 d
Kulpara	0.343	0.575	0.718 c
Angaston	0.358	0.618	0.742 a
Spalding	0.354	0.609	0.745 a
Venning	0.350	0.602	0.725 b
Pr(>F)	ns	ns	0.04

Grain yield and quality

Over the past five seasons there have been no differences in grain yield among the lime product, rates and sulphur treatments compared to the control (Table 6). The lack of grain yield response is most likely due to the slightly acidic nature of the site. The starting soil pH (Table 2) ranged from 4.8 to 6.1 across the 0-30 cm depths sampled. Soil samples collected in the control in 2022 were also within this range (Table 7). The adverse effects of soil acidity increase with lower pH values. A recent summary (Christopher et al. 2021) categorised soil pH in the 5-6 range for cereals and lentils as 'yield losses may be possible depending on soil, season and variety'. This was compared to soils with pH < 5 which are 'consistently likely to have poor crop production regardless of soil, season and variety'.

For the cereal phases of the rotation there have been no differences in grain quality for any of the treatments to date (data not shown). In 2019 barley quality averaged 64.4 kg/hL test weight, 87.4% retention, 2.8% screenings and 9.9% protein. In 2021 wheat averaged 78.1 kg/hL test weight, 1.3% screenings and 11.3% protein. In 2022 barley averaged 64.2 kg/hL test weight, 90.4% retention, 2.7% screenings and 10.7% protein.

Impact of treatments on trace elements

Barley tissue test data showed the only trace element to be affected by lime application was molybdenum (Mo). It is well known that the soil availability of Mo declines with acidification. The addition of lime regardless of product and rate increased Mo concentration ranging from 0.27 mg/kg to 0.33 mg/kg (Figure 1). This indicates lime was increasing soil pH and increasing the availability of Mo compared to the control (and sulphur treatment).

Table 6. Grain yield (t/ha) summary for the lime product comparison trial from 2019-2023 Bute, SA.

Product	Rate (kg/ha)	2019 Barley	2020 Lentil	2021 Wheat	2022 Barley	2023 Lentil
Control		3.43	2.43	5.02	5.55	1.97
Sulphur	1000	3.31	2.28	4.96	5.55	1.84
Kulpura	3400	3.70	2.32	5.16	5.73	1.79
Kulpura	6800	3.33	2.33	4.98	5.82	1.81
Angaston	2300	3.15	2.38	5.17	5.68	1.87
Angaston	4600	3.14	2.67	5.00	6.12	1.90
Spalding	3700	3.40	2.47	5.08	5.51	1.74
Spalding	7450	3.55	2.37	5.09	5.83	1.91
Venning	6700	3.34	2.53	5.09	5.92	2.06
Venning	13400	3.39	2.39	5.04	5.73	1.90
(P≤0.05)		ns	ns	ns	ns	ns

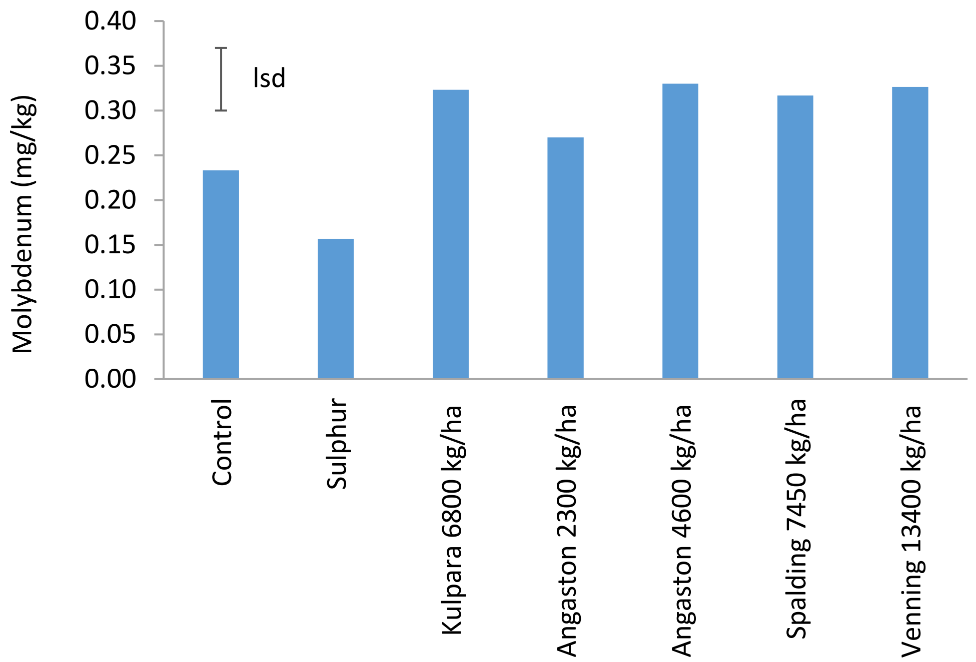

Figure 1. Concentration of molybdenum (mg/kg) in barley tissue test (sampled 11th August) from lime product comparison trial 2022 Bute, SA.

Soil pH - three years after lime application

Soil samples were taken from a selection of treatments pre-seeding in 2022 and analysed for pH (Table 7). The results show lime source has affected the soil pH in the 0-5 cm surface layer. The Angaston, Spalding and Venning lime sources at high rates all increased soil pH 6.75, 6.63 and 7.01 respectively, compared to the control 6.02. The Angaston low rate and Kulpara high-rate treatments had an intermediate response and were no different to the top performing products / rates or the control. All 0-5 cm samples were within the 6 - 8.5 pH range preferred for crop production (Hughes 2020).

In sampling depths below 5 cm soil pH was not different for any of the lime sources and rates trialled. This suggests lime has only moved 5 cm into the soil profile three years after application to the surface. The results also show the sulphur treatment has not accelerated pH decline compared to the control in this timeframe.

Table 7. Soil core pH sampling for lime product comparison trial 2022 Bute, SA.

Source	**Lime rate (t/ha)**	**0-5 cm**	**5-10 cm**	**10-20 cm**	**20-30 cm**
		pH ($CaCl_2$)			
Control	0	6.02 b	5.47	5.59	5.95
Sulphur	0	6.00 b	5.88	6.07	6.98
Kulpara	6800	6.50 ab	6.09	5.58	6.57
Angaston	2300	6.52 ab	5.73	5.35	5.98
Angaston	4600	6.75 a	6.38	5.85	6.11
Spalding	7450	6.63 a	6.29	5.55	6.23
Venning	13400	7.01 a	6.58	5.88	6.72
	P value	0.014	0.157	0.993	0.819
	LSD (0.05)	0.54	ns	ns	ns

TRIAL 2 - COMPARISON OF LIME INCORPORATION TECHNIQUES

Why do the trial?

Acidic layers of soil are increasingly being identified in the topsoil (0-10 cm) and subsurface soil (10-30 cm) of no-till farming systems. Stratified low pH soil layers need appropriate lime treatment to maintain and prevent the decline of soil pH further. Surface application of lime alone is unlikely to raise the pH in subsurface layers quickly. Recent work has reported lime movement as little as 1 cm – 2.5 cm per year (Fleming et al. 2020, Burns et al 2017). Given the slow movement of lime, incorporation and mixing of surface applied lime to depth is expected to accelerate the movement of lime.

There are a range of machinery options that can provide different levels of lime incorporation and to different depths, such as cultivation, deep ripping with or without inclusion plates, spading and combinations of these. This trial was designed to investigate which of these are most effective on a sandy soil with stratified soil acidity at Bute.

How was it done?

Site selection and soil properties – refer to TRIAL 1 (above)**.**

Trial design

A factorial trial was established including seven incorporation treatments (Table 8) and the application of Angaston Penlime Plus lime (0 and 4660 kg/ha). Each treatment contained three replicates and plot dimensions were 22 m x 2 m. The lime rate was calculated based on raising the soil pH $CaCl_2$ to 6 for each soil depth sampled (Table 2) and the assumed lime requirement of 1000 kg pure lime /5 cm soil/pH unit. The product used in this trial was Angaston PenLime Plus with an ENV 93%.

The lime, offset disc, deep ripping and inclusion ripping treatments were implemented at the site on 18th April 2019. The lime treatment was applied to the soil surface first and followed with the incorporation treatment. Spading treatments were implemented on 10th May after opening rains had been received to enable spading to a depth of 30 cm.

Table 8. Incorporation treatments for the Bute lime incorporation trial established in 2019.

Treatment	Incorporation	Description
1	No-till (Control)	No incorporation prior seeding
2	Offset disc	Single pass with a three-point linkage 1.8 m offset disc to a depth 100 mm
3	Deep rip	Deep ripped to 500 mm with an Agroplow ripping machine, tyne spacing 450 mm
4	Inclusion ripping	Deep ripped to 500 mm with short inclusion plates, using an Agroplow ripping machine, tyne spacing 450 mm
5	Spade 5kmh	Spading using a 1.8 m Farmax spader at 5 km/h, single pass
6	Offset and Inclusion	As per offset disc treatment, followed by inclusion ripping treatment
7	Offset Inclusion Spade	As per offset disc treatment followed by inclusion ripping treatments and then spaded at 5 km/h

Crop and soil assessments – refer to TRIAL 1 (above).

Results and discussion

Crop emergences and NDVI

In three trial seasons plant emergence has been assessed. Lime rate and incorporation technique did not impact lentil establishment in 2020 or 2023 (data not shown). In 2021 the spading treatments improved wheat emergence with an average score of 8.6 compared to the remaining treatments averaging 6.4. However, a follow up establishment score was conducted to assess the overall plant establishment for the whole plot and no differences between treatments were evident (data not shown).

Lime incorporation technique has produced different NDVI responses in each of the last four trial years. In 2019 barley NDVI was unaffected by lime rate or incorporation technique (data not shown). In the subsequent years, early NDVI (July) was also similar for all treatments (data not shown). In 2021, very minor NDVI differences were measured in September. However, in 2022 and later in the season (August and September) differences in NDVI emerged among the incorporation treatments (Table 9). Lentil in 2020 and 2023 were highly responsive to incorporation treatment. All incorporation treatments had higher NDVI compared to the control, except for the offset disc.

There has been no NDVI response to lime rate (0 or 4660 kg/ha) in any season.

Table 9. GreenSeeker NDVI assessments for 2020 - 2023 in Bute, SA lime incorporation trial.

Treatment	2020		2021	2022	2023
	Lentil		Wheat	Barley	Lentil
	20th Aug	15th Sept	8th Sept	11th Aug	1st Sept
No-till (Control)	0.45 c	0.58 d	0.85 d	0.71 c	0.60 cd
Offset disc	0.46 c	0.59 d	0.86 bc	0.72 c	0.56 d
Deep rip	0.59 b	0.71 bc	0.86 cd	0.76 b	0.66 bc
Inclusion ripping	0.63 ab	0.75 ab	0.86 bc	0.78 ab	0.66 b
Spade 5 km/h	0.62 ab	0.70 c	0.87 b	0.78 ab	0.71 ab
Offset and Inclusion ripping	0.67 a	0.78 a	0.88 a	0.80 a	0.68 b
Offset Inclusion Spade	0.66 a	0.74 abc	0.87 b	0.80 a	0.74 a
Pr(>F)	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (0.05)	0.05	0.04	0.01	0.03	0.06

Grain yield and quality

There has been no interaction between lime rate and incorporation method (data not shown) for grain yield or quality in the five years. When analysed individually lime rate (0 or 4660 kg/ha) has had no impact on grain yield, except in 2020 (lentils). On average lentil grain yield was 2.39 t/ha where lime was applied compared to nil lime at 2.25 t/ha. As discussed in Trial 1 the general lack of response to lime application maybe due to the slightly acidic nature of the soil at the Bute site. Please see above for more detailed discussion.

Incorporation method alone has resulted in positive and negative grain yield responses during this research (Table 10). In the cereal phases, grain yields from incorporation method were either similar or slightly reduced (spading treatments) compared to the control.

The two seasons where lentils were sown both showed positive grain yield responses to incorporation methods (Table 10). In 2020 lentil grain yield was increased by an average of 27% for all incorporation methods excluding the offset disc. In 2023 lentil grain yields were highest in the spading and offset disc + inclusion ripping treatments (1.96 – 2.11 t/ha, 11-20%). These three incorporation treatments had the highest levels of soil mixing or topsoil inclusion.

Across the three cereal years there has generally been no effect on grain test weight for the incorporation methods and lime rates trialled (Table 11). In two seasons (2019 and 2022) there was no difference in test weight for any treatments. In 2021 incorporation method impacted test weight however, these differences were of little consequence as all grain samples were above 76 kg/hL (minimum required for maximum grade). Similarly, screening levels have been low and the same for all incorporation methods averaging 2.8% in 2019, 1.3% in 2021 and 2.6% in 2022.

Grain protein response to incorporation methods has produced varying outcomes across the cereal phases. In year one there was no protein response with all treatments averaging 9.9% (data not shown). In year three and four the spading treatments consistently had higher protein levels to the no-till control (Table 11). One of the reasons for the higher protein levels is the spading treatments may be mineralising more soil available N for the crop to access due to the burying of organic matter. The spading treatments were removing approximately 10 kg N/ha and 13 kg N/ha more in 2021 and 2022, respectively compared to the no-till (control).

Table 10. Grain yield (t/ha) results for the Bute lime incorporation trial 2019 - 2023.

Incorporation method	**2019**	**2020**	**2021**	**2022**	**2023**
	Barley	**Lentil**	**Wheat**	**Barley**	**Lentil**
No-till (Control)	3.69 a	1.81 b	5.23 a	5.90	1.76 cd
Offset disc	3.63 a	1.88 b	5.17 ab	5.86	1.66 d
Deep rip	3.61 a	2.33 a	5.33 a	5.70	1.76 cd
Inclusion ripping	3.61 ab	2.55 a	5.31 a	5.81	1.91 bc
Offset and Inclusion ripping	3.43 abc	2.44 a	5.16 ab	5.93	2.02 ab
Offset Inclusion Spade	3.34 bc	2.61 a	5.01 b	5.87	2.11 a
Spade 5 km/h	3.26 c	2.63 a	5.01 b	5.72	1.96 ab
Pr(>F)		<0.001	0.024	0.272	<0.001
LSD 0.05	0.28	0.32	0.22	ns	0.17

Table 11. Test weight (kg/hL) and protein (%) results for the Bute lime incorporation trial 2021 and 2022.

	2021 Wheat		**2022 Barley**	
Incorporation	**Test weight (kg/hL)**	**Protein (%)**	**Test weight (kg/hL)**	**Protein (%)**
No-till (Control)	77.8 abc	11.2 c	64.7	10.1 b
Offset disc	78.1 ab	11.4 bc	64.0	10.2 b
Deep rip	78.2 a	11.3 c	64.2	10.2 b
Inclusion ripping	78.1 a	11.4 bc	64.3	10.4 b
Offset and Inclusion ripping	77.9 ab	11.7 b	63.6	10.4 b
Offset Inclusion Spade	77.4 bc	13.0 a	63.9	11.7 a
Spade 5kmh	77.1 c	12.6 a	64.1	11.4 a
Pr(>F)	0.025	<0.001	ns	<0.001
LSD 0.05	0.65	0.38	ns	0.6

Plant tissue test

Similar to trial one, tissue test data showed the only trace element to be affected by lime application or incorporation method was molybdenum (Mo). The treatments where lime was spaded increased Mo content (0.35 – 0.37 mg/kg) compared to the no-till control (0.24 mg/kg). This indicates lime was increasing soil pH and increasing the availability of Mo where lime had been spaded into the soil. The deep rip and inclusion ripping treatments did not increase Mo levels compared to the no-till (Figure 2).

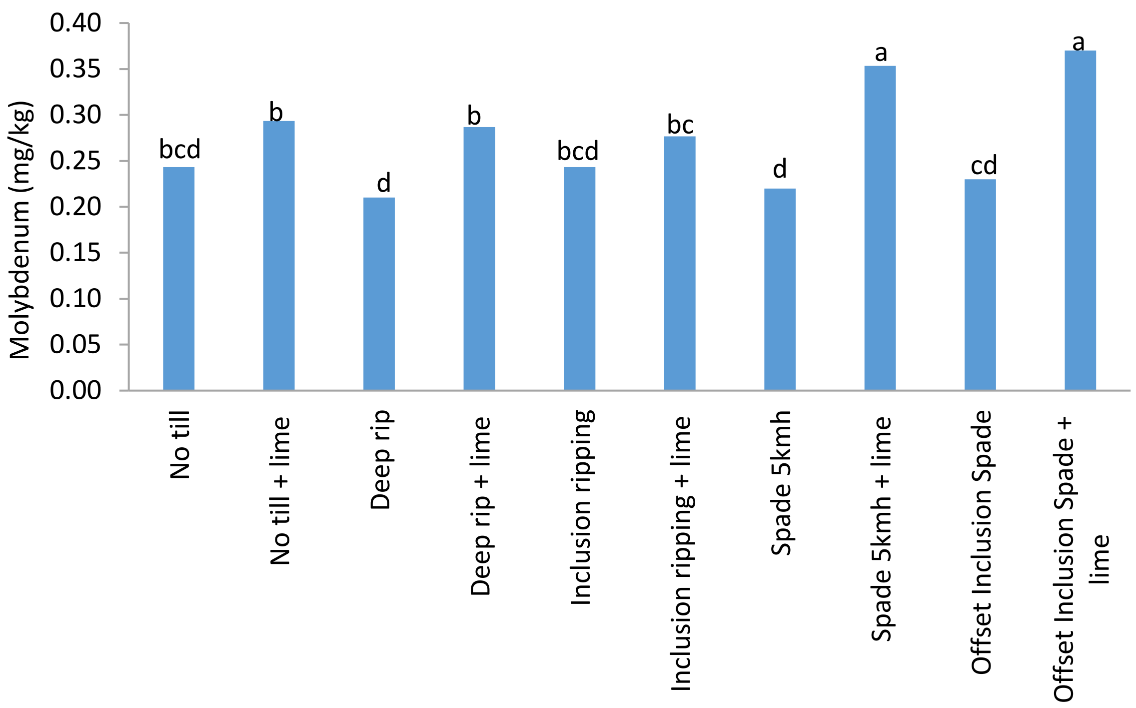

Figure 2. Concentration of molybdenum (mg/kg) in barley tissue test (11th August 2022) from lime incorporation trial 2022 Bute, SA. Incorporation x lime rate = (P≤0.05) LSD 0.05.

Soil pH - three years after lime incorporation

Pit face sampling

In 2022 soil sampling pre-seeding assessed soil pH at depth in the deep and inclusion ripping treatments plus and minus lime (Table 12). Soil samples were taken on the rip line ('on-rip') and in the adjacent soil ('off-rip') to compare if incorporation of lime had increased soil pH compared to undisturbed areas (i.e natural movement of lime only). When the main factors (lime x incorporation x sampling position) are analysed together soil pH changes in the 5-10 cm layer were evident. The results show ripping (deep or inclusion) with lime increased soil pH on the rip line (6.85 and 6.43) compared to where no lime was applied (average no lime on-rip = 5.42). In the off-rip sampling locations soil pH was also increased in the deep ripping treatment (6.26) but not the inclusion ripping. Overall, the results show the use of short inclusion plates has not improved soil pH compared to deep ripping alone.

Table 12. Soil pH ($CaCl_2$) pit face sampling for lime, incorporation, and sampling position in lime incorporation trial 2022 Bute, SA.

Lime rate (kg/ha)	**Incorporation**	**Position**	**0-5cm**	**5-10cm**	**10-20cm**	**20-30cm**
0	Inclusion ripping	Off-rip	5.80	5.36 c	5.05	6.46
0	Inclusion ripping	On-rip	5.91	5.51 c	5.44	6.15
0	Deep rip	Off-rip	6.01	5.22 c	4.97	5.99
0	Deep rip	On-rip	5.85	5.33 c	5.42	6.01
4660	Inclusion ripping	Off-rip	6.33	5.42 c	5.20	6.10
4660	Inclusion ripping	On-rip	6.71	6.43 ab	5.68	5.96
4660	Deep rip	Off-rip	6.83	6.26 b	5.64	6.35
4660	Deep rip	On-rip	6.70	6.85 a	6.18	6.38
Lime × Incorporation × Position		Pr(>F)	0.404	<0.001	0.364	0.298
		LSD (0.05)	ns	0.42	ns	ns

The impact of lime application alone (regardless of incorporation method and sampling position) has had a positive impact on soil pH. Lime application has increased the soil pH in the 0-5 cm, 5-10 cm and 10-20 cm layers (Table 13). Both the 0-5 cm and 5-10 cm layers are now within the 6-8.5 pH range preferred for crop production (Hughes 2020). The 10-20 cm layer has also increased by 0.46 pH unit on average.

Soil sampling on and off the rip line was also significant irrespective of lime application or incorporation method. Regardless of incorporation technique, on-rip samples had a higher pH on average in 10-20 cm (most acidic) layer compared to off-rip. This suggests higher pH soil from either above or below is being moved into the ripping zone. This may be important in creating pathways through acid throttles in other soil profiles.

Table 13. Average impact of lime addition in pit face soil pH ($CaCl_2$) samples lime incorporation trial 2022 Bute, SA.

Lime rate (kg/ha)	**0-5 cm**	**5-10 cm**	**10-20 cm**	**20-30 cm**
0	5.89 b	5.36 b	5.22 b	6.15
4660	6.64 a	6.24 a	5.68 a	6.19
Pr(>F)	<0.001	<0.001	0.009	0.847
LSD (0.05)	0.16	0.21	0.36	ns

Segmented deep core sampling

In addition to the pit face sampling, selected treatments were cored using a deep soil probe and segmented in depths (Table 14). There was no interaction between lime and incorporation for changing soil pH. However, the lime application alone had increased soil pH in the 0-5 cm, 5-10 cm and 10-20 cm sampling depths (Table 15). This is consistent with the findings from the pit face soil sampling. Irrespective of lime, treatments with increasing disturbance had greater increase of soil pH in the 5-10 cm layer.

Table 14. Soil pH ($CaCl_2$) results for the segmented core sampling 11th May 2022 for the lime incorporation trial Bute, SA. See Table 15 for output from ANOVA.

Incorporation	**Nil**		**Deep rip**		**Inclusion**		**Deep rip Spade**		**Offset disc Inclusion Spade**	
Lime	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
0-5 cm	6.0	6.9	5.8	6.8	5.9	6.8	5.8	6.9	5.8	6.6
5-10 cm	5.3	5.9	5.3	6.2	5.4	6.3	5.5	6.8	5.5	6.6
10-20 cm	5.1	5.9	5.1	5.9	5.7	6.3	5.3	6.4	5.6	6.5
20-30 cm	6.0	6.3	6.0	6.9	6.8	6.7	6.1	6.8	6.4	6.8

Table 15. ANOVA output for segmented core sampling as displayed in Table 14.

Depth	**Factors**	**P value**	**LSD (0.05)**
0-5cm	Incorporation	0.55	ns
	Lime	<0.001	0.16
	Incorporation × Lime	0.818	ns
5-10cm	Incorporation	0.001	0.15
	Lime	<0.001	0.16
	Incorporation × Lime	0.148	ns
10-20cm	Incorporation	0.358	ns
	Lime	0.002	0.48
	Incorporation × Lime	0.97	ns
20-30cm	Incorporation	0.508	ns
	Lime	0.076	ns
	Incorporation × Lime	0.64	ns

Soil rhizobia – season four

Soil chemical properties such as pH affect both the survival of rhizobia in soil and the formation of nodules. Four years after the trial was established (pre-seeding 2023), rhizobia numbers were assessed using the Predicta rNod test. All samples contained adequate levels of group E/F rhizobia, ranging from 621 – 2609 rhizobia/g soil. Generally, 100 – 1,000 rhizobia /g soil are required for adequate nodulation of the target crop species. Values higher than 5,000 rhizobia/g soil suggest a negligible response to inoculation is likely.

The application of lime, regardless if it was surface applied or incorporated has increased the level of group E/F rhizobia (Table 16). There was almost double the number group E/F rhizobia (2108/g soil) where lime was applied compared to the nil (1105/g soil). The application of lime has raised the pH in the 0-10 cm layer and resulted in more favourable conditions for the rhizobia to survive.

The group G/S rhizobia were detected at similar levels to the group E/F in all samples. There was no difference in Group G/S rhizobia for the incorporation methods or lime rates trialled (Table 16). However, they were still adequate rhizobia levels for lupin and serradella nodulation to occur.

Table 16. Average soil rhizobia concentrations for lime rates in the lime incorporation trial sampled prior to seeding, 2023.

Lime rate (kg/ha)	**Group E/F rhizobia/g soil**	**Group G/S rhizobia/g soil**
0	1105 b	2126
4660	2108 a	2067
Pr(>F)	<0.01	0.822
LSD (0.05)	595	ns

Group E/F legumes nodulated = Field pea, lentil, vetch and faba bean
Group G/S legumes nodulated = Lupin and serradella

Lentil dry matter and nitrogen fixation – season four

In season four lentil dry matter and N fixation showed a positive response to incorporation, regardless if lime was applied or not (Table 17). Treatments with higher levels of disturbance/incorporation (offset disc + inclusion ripping) resulted in higher lentil dry matter, averaging 4.73 t/ha. This was an increase of 1.17 t/ha compared to the no-till (control) at 3.59 t/ha. The increase in dry matter was also associated with higher levels of N fixation. Similarly, the treatments with higher levels of incorporation were able to fix more N, 98 – 101 kg N/ha compared to the no-till control at 68 kg N/ha.

Table 17. Average lentil dry matter and N fixation in the lime incorporation trial, sampled September 2023.

Incorporation	**Dry matter (t/ha)**	**N fixed (kg N/ha)**
No-till	3.59 b	68.0 b
Offset disc	3.55 b	68.7 b
Deep rip	4.00 ab	82.2 ab
Inclusion ripping	3.76 b	69.8 b
Offset + Inclusion ripping	4.72 a	101.0 a
Offset + Inclusion ripping + Spading	4.74 a	98.4 a
Spading	4.31 ab	98.9 a
Pr(>F)	0.022	0.041
LSD (0.05)	0.84	27.7

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