Land application of lime-amended biosolids

Deborah Pritchard[1], David Collins[1], David Allen[2] and Nancy Penney[3]

[1]Curtin University of Technology, Northam, Western Australia 6401
[2]Chemistry Centre (WA), East Perth, Western Australia
[3]Water Corporation of Western Australia, Leederville, Western Australia 6001

* Corresponding author: Deborah Pritchard, Curtin University of Technology, Muresk Institute, Northam, Western Australia 6401, pH: +61 8 9690 1554, Fax: +61 8 9690 1500, email d.pritchard@curtin.edu.au

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Abstract

Soil acidification is an increasing problem throughout many agricultural regions in Australia typically on lighter-textured soils that have a low buffering capacity to changes in soil pH and/or that may be naturally acidic. Crops and pastures grown on acidic soils are subject to problems such as aluminium toxicity (particularly in the subsoil), nodulation failure in legumes and a reduced availability of some nutrients. Lime and dolomite are products that are commonly applied to neutralise soil acidity and improve plant productivity with application rates often determined by their neutralising value and particle size of the product, and the pH buffering capacity (lime requirement) of the soil. To investigate the effect of lime amended biosolids (LAB) as a product for neutralising soil acidity and for improving crop growth, four rates of LAB (0, 5, 10 and 15 t DS/ha) and four equivalent rates of lime product (0, 2.3, 4.6 and 6.7 t/ha) were applied to an acidic red/brown sandy loam in the central wheatbelt of Western Australia. In addition, one rate of dewatered biosolids cake (DBC) at 7 t DS/ha was included to enable comparison to be made to this product. The experiment was conducted over three years and sown to wheat (*Triticum aestivum*), canola (*Brassica napus*) and then wheat in 2005, 2006 and 2007, respectively. Plants were sampled at 8 weeks and at harvest to determine the effect of LAB, lime and DBC on crop growth, nutrient uptake and grain yield. Samples of surface soil (0-10 cm) were collected and analysed at harvest for pH and major nutrients. Soil pH increased significantly with increasing rates of LAB or lime at the end of the first year, with similar values recorded between equivalent values of lime product. There was no significant change in soil pH following the addition of the DBC treatment. No further changes in soil pH had occurred by the end of the second year. The growth of both wheat and canola in the first two years was affected to a greater extent by nutrients (typically nitrogen) in the LAB than by the reduction in soil acidity. Measurements on wheat yield in the third year of the experiment and changes in soil pH in the surface (0-10 cm) and subsoil (10-20 cm) will provide further information as to the long term effects of LAB in agriculture and allow recommendations to be made regarding best practise land application rates.

Introduction

Approximately 50% of agricultural land in Australia (50 million ha) have surface soil values of less than 5.5 ($CaCl_2$), resulting in reduced productivity of extremely acid-sensitive plants and are below the optimum to prevent subsurface acidity (Australian Agriculture Assessment 2001). The majority of Western Australian soils may be naturally acidic and are light-textured, with a low buffering capacity to change in soil pH and in severe cases can result in aluminium toxicity in sensitive plant species (particularly in the subsoil), nodulation failure in legumes and a deficiency in some nutrients, such as molybdenum. An estimated 178,000 tonnes (t) of lime was applied to farming properties in Western Australia during 1994/95 as an ameliorant against soil acidity. A typical application rate of lime is around 2 t/ha, with rates determined by the neutralising value and particle size of the lime and the pH buffering capacity (lime requirement) of the soil (Moore *et al*. 1998).

A total of 10,000 t dry solids (t/DS) of lime-amended biosolids (LAB) were produced during 2005/06 from the Subiaco Wastewater Treatment Plant (WwTP) and applied to agricultural soils surrounding Perth. The production of LAB at Subiaco WwTP involves the addition of quicklime (CaO) as a post-treatment to secondary treated dewatered sludge cake to raise the pH of the mixture and destroy pathogens. Prior to this study, no research had been conducted in Western Australia to investigate the neutralising value of LAB, monitor the plant response to LAB or to establish the economic value of LAB in agriculture. Research had previously investigated plant response to anerobically digested dewatered biosolids cake (DBC) produced by Perth's two other major WwTPs as part of the National Biosolids Research Program (NBRP) (McLaughlin *et al*. 2007). The Water Corporation of Western Australia promotes the beneficial use of biosolids, particularly within agriculture. Alternatively, if deemed unsuitable for agricultural land application, the potential landfill costs of LAB would escalate to almost $2 m/pa (i.e. 34,000 wet tonne @ $57/t) (Penney 2005).

There is a need to establish suitable agricultural loading rates for LAB to ensure that plant needs are being met, plant growth is not compromised and to establish the neutralising value of LAB. There is also potential to seek a return on the value of the lime input, estimated at $14,000/pa in 2005/06. If successful, this form of biosolids stabilisation/ production may be considered for future sludge handling for other WwTPs in the Perth region (Penney 2005). This paper investigates the effects of LAB on the growth and yield of wheat and canola to changes in soil pH on an acidic soil in the central wheatbelt in Western Australia between 2005 and 2007.

Materials and methods

A field experiment was established at Wongamine, 90 km north-east of Perth, Western Australia in 2005 to study the effect of LAB on plant growth and yield using a wheat (*Triticum aestivum* L. cv. Calingiri) and canola (*Brassica napus* L. Surpass) cropping sequence. The region has a Mediterranean climate with cool, wet winters and hot, dry summers and an average rainfall of 390 mm. The soil was acidic red/brown loamy sand, or a Red Chromosol as described by the Australian Soil Classification (Isbell 1996). Some properties of the <2 mm fraction in the top 0-10 cm surface are as follows: 90% sand, 5% silt, 5% clay; 4.7 pH ($CaCl_2$) 0.01*M* (1:5); 5.3 mS/m EC (1:5); 0.87% Organic carbon (W/B); 0.071% total N; 243 mg/kg total P; 48 mg/kg bicarbonate extractable P; 4.3 mL/g P Retention Index; 94 mg/kg bicarbonate extractable K; 7.06 cmol(+)/kg total exchangeable cations (Ca, Mg, Na, K and NH_4) (Chemistry Centre WA, Report 05A493/1-3).

The experiment consisted of nine treatments arranged in a completely randomised block design with three replicates. Each plot was 20 m long by 2 m wide. There were combinations of four rates of LAB, four rates of lime and one rate of dewatered biosolids cake (DBC).

The DBC was included in the study as it is the predominant biosolids product produced by Perth WwTPs and thus provides for comparative research in terms of crop yield (Pritchard & Collins 2006). The DBC was sourced from Beenyup WwTP, which has a typical analysis consisting of 20% DS, 50,000 mg/kg total N and 25,000 mg/kg total P and pH 7. The LAB from Subiaco WwTP has a lower nutrient content with a typical analysis comprising 35% DS, 30,000 mg/kg total N, 10,000 mg/kg total P and pH 13; with an expected neutralising value of 44.9%, reflecting the proportion of lime in the product.

Rates of LAB and DBC were determined by multiples of the nitrogen limited biosolids application rate (NLBAR) using the following DEP *et al.* (2002) formula:

NLBAR = Crop N required / plant available N

The amount of crop N required is determined as the amount of N removed by a crop in a given year. The plant available N is determined from the proportion of organic N and inorganic N that is expected to be available to plants from the biosolids in the first season using a 20% mineralisation rate of organic N and 50% volatilisation rate of ammonium. Thus 1xNLBAR for the LAB = 10.3 t DS/ha (i.e. 64 kg N/ha / 6,207 mg/kg).

The four rates of LAB were applied at 0, 0.5, 1 and 1.5xNLBAR (i.e. 0, 5.2, 10.3 and 15.4 t DS/ha, respectively) and the DBC was applied at the standard rate of 1xNLBAR (i.e 7 t DS/ha). At present, the standard application rate of LAB being applied to land is 5 t DS/ha, which is lower than DBC as it is calculated on the lime content typically applied by farmers in the region rather than on the N value. Agricultural lime is commonly applied in Western Australia at rates between 1 and 2 t/ha. In this experiment, agricultural lime was applied at 0, 2.3, 4.6 and 6.9 t/ha to enable comparison to the four rates of LAB used. Thus at 1xNLBAR, the LAB (10.3 t DS/ha) would be expected to provide the equivalent in neutralising value to the 4.6 t/ha lime treatment. The lime used in the experiment had a neutralising value of 96% and was <0.25 mm in size. All lime treatments were supplied with a basal fertiliser dressing of 100 kg/ha urea (46% N) and 100 kg/ha diammonium phosphate (DAP: 20% N, 18% P) annually to supply a total of 66 kg N/h and 18 kg P/ha. This rate of inorganic N was selected to be comparable to the N in the 1xNLBAR treatments for both the LAB and the DBC.

The experiment was sown to wheat in 2005, canola in 2006 and wheat in 2007. Prior to each seeding operation, the site was cultivated with discs and a knockdown herbicide applied (Roundup™ at 1L/ha). Lime and biosolids products were applied as a once off treatment in 2005 by hand and incorporated during the seeding operation using a 12-row disc combine. The lime treatments received DAP at seeding and were top-dressed with urea 12 weeks after sowing at tillering, annually. The treatments containing biosolids products did not receive additional fertiliser and consequently the residual value of the nutrients could be examined over time compared with the freshly applied inorganic fertiliser treatments. The nil treatment did not receive any fertiliser in 2005 and 2006, so the response to all added nutrients could be established, and in 2007 a single application of LAB at 1xNLBAR was applied to establish the response of freshly applied LAB relative to the other treatments. The seeding dates over the three years were as follows: wheat 4/06/05, canola 07/06/06 and wheat 25/05/07.

For each crop species, plant establishment was measured in each plot over three x 1 m rows (0.54 m^2). The total dry matter (DM) of shoots was measured at 8 weeks after seeding and prior to harvest over 3 x 1 m rows following drying at 70^{o}C for 24 h. Grain yield was determined using a mechanical plot harvester and sub-samples of grain retained. Shoot and grain material were prepared by grinding (<0.5 mm) and the concentration of N measured by Leco and the concentrations of various other nutrients measured by ICP-AES. Following each harvest, composite soil samples were collected from the surface (0-10 cm) of each plot and sieved <2 mm and then analysed for pH ($CaCl_2$ 0.01*M* 1:5) to compare the neutralising effect of LAB to agricultural lime. At the end of three years, soil samples were collected from depth (10-20 cm and 20-30 cm) to investigate the effect of lime application on change in subsoil pH. Composite soil samples from the surface (0-10 cm) of each plot were analysed for organic C (%W/B), total N and bicarbonate available P (0.5*M* $NaHCO_3$ 1:100) in 2006 and 2007. All analysis were performed by the Chemistry Centre (WA) East Perth, which is accredited by the National Association of Testing Authorities (NATA) using approved methodologies.

Data were analysed for differences between the treatments using an ANOVA model in GENSTAT 5 Release 4.1 program (Lawes Agricultural Trust, Rothamsted Experimental Station, UK). A single least significant difference (l.s.d.) value of *P* at the 5% level of significance was used to compare different treatment means.

Results and discussion

Soil pH

At the rates of LAB used, soil pH ($CaCl_2$) in the 0-10 cm depth increased significantly from 4.4 in the nil treatment (0 LAB) to 5.8 at 0.5xNLBAR, 6.4 at 1xNLBAR and 7.2 at 1.5xNLBAR as measured eight months after application ($P<0.05$, Table 1). These values remained relatively constant for each treatment over the following two years. In comparison, there was no significant increase in pH following the application of DBC at 1x NLBAR ($P<0.05$, Table 1). Increase in soil pH following the use of lime-amended biosolids (N-Viro soil) has also been reported in central New South Wales by Cooper (2005) with a linear relationship observed between the amount of NVS applied and soil pH ($r^2 = 0.0854$, $P<0.001$).

The neutralising value of the LAB was similar to that provided by equivalent rates of agricultural lime and was not unexpected, given that the rates of LAB were chosen to be comparative to agricultural lime in terms of their neutralising content. An increase in soil pH would be expected to enable farmers to better manage acidic soils, such as in LAB at 0.5xNLBAR where the pH had increased from 4.4 to 5.8 at 20 months and remained elevated over the following two years (Table 1). This is the typical application rate of LAB currently being applied by farmers in Western Australia. From this preliminary investigation, the neutralising value of the lime in the LAB was similar to the predicted value of 45%. This value is consistent with that reported by Sloan and Basta (1995) for a 1:1 dewatered sewage sludge and cement kiln dust mixture, which is reduced to 28% if less kiln dust is added (Cooper 2005).

Soil pH in the subsoil depth below 10 cm is currently being measured to provide a more comprehensive indication as to overall soil chemical changes.

Table 1: Effect of lime-amended biosolids (LAB), dewatered biosolids cake (DBC) and lime on soil pH in the 0-10 cm depth at 8, 20 and 32 months after application, and average over all years

	pH ($CaCl_2$) 1:5			
Treatment	**8 months**	**20 months**	**32 months**	Mean over all sampling dates
LAB 0	4.4	5.2	*	4.8
LAB 0.5	5.8	5.6	5.7	5.7
LAB 1.0	6.4	6.3	6.7	6.5
LAB 1.5	7.2	7.0	6.7	7.0
DBC 1.0	4.8	4.9	4.8	4.8
Lime 0 t/ha	4.3	4.7	5.3	4.8
Lime 2.3 t/ha	5.6	6.3	6.1	6.0
Lime 4.6 t/ha	6.5	6.9	6.6	6.7
Lime 6.9 t/ha	6.6	7.0	6.7	6.8
LAB 1.0 (2007)*			6.6	
l.s.d (P = 0.05)	*0.84*	*0.65*	*0.49*	

LAB=Lime-amended biosolids, DBC=dewatered biosolids cake, biosolids products expressed as multiples of the nitrogen limiting biosolids application rate (NLBAR), Lime rate as t/ha and basal fertiliser applied to all lime treatments (Urea + DAP) annually

** Freshly applied 1xNLBAR LAB was applied as a replacement to the control in year three (2007)*

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Shoot dry matter

The site was responsive to N and/or P as indicated by the increase in shoot dry matter in shoot dry matter at 8 weeks in all treatments containing fertiliser as compared to the nil fertiliser (LAB 0) (P>0.05, Table 2). The shoot dry matter of wheat (2005) and canola (2006) in the basal fertiliser treatments were no different to the treatments containing applications of LAB or DBC. In the third year (2007) the shoot dry matter of wheat, however, was higher overall in the freshly applied basal inorganic fertiliser treatments compared with the biosolids treatments (P>0.05, Table 2). These results were consistent with previous research by Pritchard and Collins (2006) in Western Australia three years after application of DBC at 1xNLBAR compared with freshly applied inorganic fertiliser as measured by shoot growth at 8 weeks from sowing.

Table 2: Effect of lime-amended biosolids (LAB), dewatered biosolids cake (DBC) and lime on shoot dry matter (DM)/20 plants at 8 weeks after sowing over three years

Treatment	**Dry Matter (g/20 plants)**		
	Wheat 2005	**Canola 2006**	**Wheat 2007**
LAB 0	5.69	2.90	*
LAB 0.5	11.73	5.31	10.19
LAB 1.0	18.61	6.74	10.96
LAB 1.5	17.61	7.80	12.96
DBC 1.0	16.34	7.19	11.47
Lime 0 t/ha	14.42	6.44	13.68
Lime 2.3 t/ha	13.24	10.21	14.63
Lime 4.6 t/ha	15.07	7.33	13.32
Lime 6.9 t/ha	14.06	7.98	15.24
l.s.d (P = 0.05)	*4.95*	*3.26*	*2.93*

LAB=Lime-amended biosolids, DBC=dewatered biosolids cake, biosolids products expressed as multiples of the nitrogen limiting biosolids application rate (NLBAR), Basal = Urea + DAP, Lime rate as t/ha
** Freshly applied 1xNLBAR LAB applied as a replacement to the control and yielded 16.32 g/20 plants*

Grain yield

The primary export crop in Australia, wheat, yields on average 1.62 t/ha (2000-03) (ABARE 2003). The grain yield of wheat at harvest in this experiment measured between 2.05 t/ha (2005) and 2.60 t/ha (2007) in the un-limed standard basal fertiliser treatment and was used to calculate relative yield values (bold, Table 3). The application of lime did not improve grain yield in any year above that of the control, except in the 2.3t/ha lime treatment in the final year (P<0.05, Table 3). Lime rates higher than 2.3 t/ha tended to have a net effect of decreasing cumulative grain yield of wheat and canola over the three years of the experiment. The overall benefit of liming this site would be best studied by growing an acid sensitive plant species or a legume.

Grain yield in the LAB treatments generally declined over time relative to the freshly applied basal fertiliser treatment. This was most noticeable in the 0.5xNLBAR treatment with yields of wheat reduced in all years (P<0.05, Table 3), suggesting that these plants were nutrient deficient. Therefore, additional inorganic fertiliser would need to be applied at 0.5xNLBAR to provide adequate crop yield, which was on average 82% relative to that of the inorganic fertiliser treatment over the three years. Grain yield in the LAB at 1xNLBAR was no different (P<0.05) to the inorganic fertiliser over all years, although these declined with time as the residual nutrient value declined. Grain yield of wheat in freshly applied LAB in the third year (2007) was no different (P<0.05, Table 3) to the freshly applied fertiliser control treatment.

The highest yield of wheat in the first year was measured in LAB at 1.5xNLBAR, although it had a significantly (P<0.05) greater number of small or pinched grain (32.9g/100 seeds) compared to the control (41.9g/100 seeds). This would suggest that the potential yield was lower than achieved although it is uncertain why as soil moisture was not limiting at the end of the season. Plant symptoms were similar to that caused by the root disease Take-all

(*Gaeumannomyces graminis var. tritici*), which is more severe in soils following liming (Loughman *et al.* 2000). Subsequent investigation of plant root samples indicated a higher incidence of Take-all in the limed plots compared to the control plots. In 2006, canola yields were highest in this treatment, highlighting the residual value of nutrients in the biosolids in the second season without additional fertiliser application.

Overall the grain yield of wheat and canola for both the LAB and the DBC in the 1xNLBAR treatments (i.e 10.3 t DS/ha and 7 t DS/ha, respectively) were comparable over three seasons. The large differences in soil pH caused from the addition of LAB did not affect crop yield compared to the DBC, although the difference in soil pH was in the order of 6.5 and 4.8, respectively. Therefore, from this study, the preferred application rate of LAB would be to apply at 1xNLBAR, as is currently used for DBC.

Table 3: Effect of lime-amended biosolids (LAB), dewatered biosolids cake (DBC) and lime on grain yield of wheat (2005), canola (2006) and wheat (2007)

	2005		2006		2007	
Treatment	**Grain yield of wheat (t/ha) and % relative to the control**		**Grain yield of canola (t/ha) and % relative to the control**		**Grain yield of wheat (t/ha) and % relative to the control**	
LAB 0	1.23	60%	0.90	60%	*	
LAB 0.5	1.66	81%	1.24	83%	2.15	83%
LAB 1.0	2.20	107%	1.33	89%	1.91	73%
LAB 1.5	2.21	108%	1.65	110%	2.25	87%
DBC 1.0	1.97	96%	1.42	95%	1.96	75%
Lime 0 t/ha	**2.05**	**100%**	**1.50**	**100%**	**2.60**	**100%**
Lime 2.3 t/ha	1.97	96%	1.40	93%	3.23	124%
Lime 4.6 t/ha	1.90	93%	1.15	77%	2.61	100%
Lime 6.9 t/ha	2.06	100%	1.36	91%	2.52	97%
l.s.d (P = 0.05)	*0.254*		*0.316*		*0.720*	

LAB=Lime-amended biosolids, DBC=dewatered biosolids cake, biosolids products expressed as multiples of the nitrogen limiting biosolids application rate (NLBAR), Lime rate as t/ha and all contain basal fertiliser (urea + DAP)
** Freshly applied 1xNLBAR LAB applied as a replacement to the control yielded 1.96t/ha (75% relative to control)*

Concentrations of nutrients in plant and soil samples

The concentrations of nutrients in shoot and soil samples were examined to determine the effect of soil pH and treatment on the uptake of critical nutrients. Concentrations of N in shoot samples at 8 weeks and grain samples at harvest were similar between the inorganic fertiliser treatments and 1xNLBAR biosolids treatments for wheat and canola over the three years suggesting that the NLBAR was comparable to freshly applied inorganic N. As would be expected, the total concentration of soil N was lower in the 0 (nil fertiliser) and LAB at 0.5xNLBAR and higher in the LAB at 1.5xNLBAR (P<0.05), reflecting the relative loading rates of N at these applications (data not presented). Although grain yield was maximised at rates higher than LAB at 1xNLBAR, the effect of changes to soil mineral N was not monitored and should be investigated further to ensure that the formula on which the NLBAR is based is accurate for these soils and environmental conditions.

The concentration of P in the dry matter of shoots at 8 weeks over three years was significantly higher (P<0.05) in the inorganic fertiliser treatments than in the biosolids treatments (Reports 05A222, 06A100 and 07A094: Chemistry Centre of WA, data not presented). Although high loading rates of P were applied in the biosolids treatments, the inorganic P treatments appeared to provide plants with a more readily available early source of P as indicated by 8 week shoot P concentration. The background concentration of available soil P in the nil treatment at 20 months after the start of the experiment was 41 mg P/kg and had increased to 62 mg P/kg in the inorganic fertiliser treatment, 79 mg P/kg in LAB at 1xNLBAR and 114 mgP/kg in LAB at 1.5xNLBAR (Report 06A271: Chemistry Centre of WA, data not presented). The concentration of P in shoots of wheat in the first year at 8 weeks was higher in DBC (0.33%) than LAB (0.23%) at equivalent NLBAR, but would be expected given higher initial concentrations of P in DBC. The increased soil concentration of P in the LAB was not reflected by increased P concentrations in shoot or grain samples. Previous work by Pritchard (2005) suggested that discrepancies between the soil P result and P uptake could be explained by the method used to sieve soil samples (<2 mm), which inadvertently removed large particles of biosolids. In addition, inorganic fertiliser P was shown to be 67% more effective than biosolid P.

Grain yield of wheat and canola were similar in all four rates of lime (P>0.05, Table 3), suggesting that soil pH was of marginal influence to grain yield and N and P uptake over the two seasons. On this acidic soil, high application rates of lime raised the pH to neutral with negligible effects on plant growth. It should be mentioned that increasing rates of lime and LAB significantly decreased concentrations of manganese (Mn) in the shoots of wheat, although concentrations remained above the critical values reported by Reuter & Robinson (1997). The likely explanation for this trend is related to the solubility of Mn, which declines with increasing pH (Moore *et al.* 1998), also noted by Christie *et al.* (2001) in barley shoots grown in alkaline-stabilised biosolids and by Brown *et al. (*1977) in wheat and soybean grown in lime-stabilised biosolids. Also of interest was the increase in concentration of sulphur (S) in shoot and grain samples of both wheat and canola as the rate of LAB increased compared with inorganic fertiliser treatments (P<0.05), and which may have contributed to higher yields in LAB at 1.5xNLBAR. No other nutrient appeared to be affected by any of the treatments.

The cost of lime in the LAB is valued at approximately $1.50/t and therefore if full cost recovery for the lime was implemented, the LAB at 1xNLBAR would cost the farmer $15/ha. However, the main benefit of LAB would be from the nutrient content of the biosolids product rather than the lime content. The current rate of LAB being applied at present (0.5xNLBAR) is too low to sustain crop growth without the application of additional inorganic fertiliser. Thus it is recommended that the application rate be increased to that based on the N content rather the lime content. The longer-term effects on soil pH would need to be monitored prior to any economic value being placed on the LAB. In addition, the use of LAB on neutral or alkaline soil, particularly of low buffering capacity would not be recommended given the large potential increase in soil pH.

Conclusions

The current application rate of LAB at approximately 5 t DS/ha may be inadequate to satisfy the optimum production of wheat and canola in a typical cropping rotation in Western Australia unless additional inorganic fertiliser is applied. It is suggested that the rate of LAB be based on the N content of the product to be consistent with DBC land application rates and applied at 1xNLBAR, i.e. approximately 10 t/ha. This rate of LAB is higher than typically applied in Western Australia at present although the increase in soil pH from the lime contained in the product at 1xNLBAR does not appear to have an adverse effect on soil or plant parameters. The application of LAB would not be recommended on soil types that were not acidic due to the large potential increase in soil pH. The benefit of LAB over the three seasons investigated appeared to be from the nutrient value of the recycled nutrients (typically N and P) as would be obtained from DBC, rather than from the reduction in soil acidity. The application of LAB would save the farmer costs in having to purchase and spread lime on acidic paddocks, although no improvement in plant yield was noted as a result of a change in soil pH. Further work is ongoing to measure changes in sub-soil pH.
Further work needs to be conducted on the mineralisation and volatilisation rates of N estimated in the NLBAR calculation to accurately quantify plant available N.

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