Understanding and managing soil acidity – the key to sustainable and productive grazing systems

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Abstract: *The extent and severity of acidic soils in southern NSW is underestimated and much of the on-farm investment in acid soil management focuses on ameliorating existing acid soil problems. Current acid soil management practices are based on guidelines developed for less productive, traditional farming systems. They commonly involve 0–10 cm soil sampling to measure soil pH and exchangeable aluminium, often in response to plants exhibiting acid soil toxicity symptoms. The survey results showed that 39% of sites should be prioritised for liming, based on pH of 0–10 cm soil samples. This percentage increases to 78% when pH was measured in 5 cm increments to 20 cm and the same liming decision framework applied. Finer sampling identifies the depth and severity of acidity in subsurface layers, which better informs liming decisions, species selection and the role for acid tolerant species. Appropriate lime rates, applied at regular intervals, with incorporation when possible, should be able to gradually ameliorate soil acidity at 10–20 cm. There are production and environmental consequences in failing to address soil pH of soils until plants exhibit symptoms of 'acid soil problems'. The highly productive soils, normally with high acidification rates, should be prioritised for early intervention to prevent subsurface acidification. Effective acid soil management programs involving periodic sampling in 5 cm increments enable monitoring of impact of amelioration efforts, calculation of acidification rates and assessment of the effectiveness of acidic soil management efforts: crucial information to develop proactive, long-term management strategies relevant to production and sustainability goals.*

Key words: acidification, stratification, 5 cm increments, monitoring, agroecosystem.

Introduction

Soil acidity is recognized as a major agricultural and environmental problem, which affects more than 50% of agricultural land of central and southern NSW (Cregan *et al.* 1998; Scott et al. 2000; Li *et al.* 2019). A survey conducted in 1997–2003 on commercial paddocks in the medium and high rainfall zones (AAR 500–900 mm) indicated that soil pH (measured in 0.01M $CaCl_2$, pH_{Ca} hereafter) was below 5.0 for about 85% of sites in the 0–10 cm and 10–20 cm sampling depths (Scott *et al.* 2007). Many soils of these regions are strongly weathered and inherently acidic, and furthermore agricultural activities have accelerated acidification (Cregan *et al.* 1998). The optimal soil pH_{Ca} for growth of most plants is between 5.5 and 7.5. Changes in soil chemistry and biology when pH is outside this range adversely impact soil and plant processes resulting in reduced growth and yield (Slattery *et al.* 1999).

Industry focuses on ameliorating soils with an 'existing acidity problem'. Liming activities are commonly initiated in response to soil pH tests from samples collected from the 0–10 cm soil layer and/or when plants exhibit recognised clinical symptoms that are typical of low pH_{Ca} and aluminium toxicity. These symptoms include reduced growth rate, stunted root systems and poor nodulation in legumes, or manganese toxicity in broad leaf plants. However, the health and growth rate of plants can be affected once pH_{Ca} falls below 5.2 before these symptoms begin to be expressed (Cregan & Scott 1998). Subclinical symptoms such as limited root hair development, restricted rooting depth and reduced plant vigour are difficult to detect but were reported in pulse, canola and wheat crops growing in soils with acidic subsurface layers in recent studies (Burns *et al.* 2017; Burns & Norton 2018b; Condon *et al.* 2020). These studies highlighted the prevalence of stratified soil pH profiles and acidic subsurface layers between depth of 5–15 cm, including in some of the most productive soils of south-eastern Australia, although many have a long history of lime application.

The frequency that subsurface acidity is detected in actively managed agricultural land raises concerns about the effectiveness of current acid soil management practices in ameliorating soil acidity and preventing subsurface acidification. Furthermore, it should be noted that soil acidity was the only indicator of soil condition reported to be worsening in the latest NSW State of Environment report (SOE, 2018). This is despite continued increase in the amount of lime used by agriculture to the point where supply was unable to meet demand in 2020–21.

In this paper we present a proactive approach to managing soil acidity and discuss the need for attention to the environmental consequences of acidification in the development of long-term acid soil management strategies. We present soil pH profiles from soils collected from actively managed commercial paddocks in central and southern NSW between 2016 to 2020 and compare experiences of current acid soil management programs with revised management strategies, based on 5 cm sampling increments to a depth of 20 cm. The role for judicious monitoring and early intervention to prevent subsurface acidification in productive soils currently free of clinical acid soil problems is also discussed.

The environmental consequences of soil acidity

Cregan and Scott (1998) highlighted deficiencies in evaluating the influence of soil acidity in a wider farming system/agroecosystem context. They proposed that the effect of soil acidity on plant growth impacts on 'a spectrum of changes with major agricultural and environmental consequences', including reduced yields and microbial activity, failed pasture establishment, colonization of grasslands by acid-tolerant species, loss of ground cover leading to erosion and loss of organic matter, reduced water use, waterlogging, rising watertables, salinisation, eutrophication and reduced stream and groundwater quality.

Low soil pH_{Ca} (<4.8) is associated with modification of biological populations and decreased activity of some microorganisms, such as nitrifiers (Slattery *et al.* 1999). Increasing soil pH of an acidic soil improves microbial activity (Holland *et al.* 2018), although increased activity may also be in response to concurrent improved plant growth. For example, poor nodulation of legumes at low pH is frequently attributed to a negative impact on rhizobia survival and activity. However, the development of functional nodules and nitrogen fixation is also dependent on root development and vigorous growth of the host plant, which is also negatively impact by low pH (Munns 1986; Burns & Norton 2018b).

Severe acidity (pH_{Ca} <4.5) contributes to the breakdown of clay minerals in the soil via dissolution weathering. This coincides with increasing concentrations of soluble forms of aluminium and manganese in the soil solution and leaching of cations such as calcium, magnesium and potassium further down the soil profile (Slattery *et al.* 1999). Breakdown of clay minerals at below pH_{Ca} ~4 is permanent and results in irreversible soil degradation (Kwamee *et al.* 2013).

Holland *et al.* (2018) suggested that agriculture has changed focus from one solely of production to include maintenance of a healthy environment and consideration of the soil's ability to deliver ecosystem services such as nutrient cycling and carbon sequestration. The challenge is to translate the focus into management practices that effectively manage soil acidity. The current environmental report card (SoE 2018) indicates a proactive approach to acid soil management is needed:

> *"On a statewide level, the increasing acidification of agricultural soils due to the intensification of land use continues to be the land degradation issue that contributes most to ongoing declines in soil condition and productivity across NSW"*

(The State of the Environment Report 2018).

Soil acidity in agricultural systems

Soil pH is the principal driver for lime application. The pH scale is used to quantify soil acidity, measuring the negative log concentration of hydrogen ions (H+) in the soil solution on a scale from 1 to 14. The lower the pH the more acidic the soil, with pH_{Ca} of 7 being neutral and becoming more alkali as pH increases. It is a negative logarithmic scale, which means that a small decrease in pH is equates to a large increase in acidity. For example, soil with a pH_{Ca} of 4 is 10 times more acidic than pH_{Ca} of 5 and 100 times more acidic than pH_{Ca} 6. Soil pH is measured either in water or weak calcium chloride solution, the latter providing results that better reflect the conditions experienced in the soil solution by roots and microbes.

Soil pH values usually refer to acidity measurements of soil samples collected from a sampling depth of 0–10 cm. However, as approximately 80% of the root system of annual species is concentrated in the 0–20 cm surface layer (Hamblin& Tennant 1987), the pH of 0–10 cm samples do not accurately describe the soil environment experienced by the majority of plant roots.

The negative impact of soil acidity on agricultural production is generally well understood, limiting crop yield and species options. Application of fine-grade, high quality lime is the practical and widely adopted method of ameliorating acidity and eliminating toxicity symptoms in plants grown on acidic soils in NSW. Liming activities are usually triggered when pH_{Ca} of 0–10 cm soil samples are <4.8 and lime application rates are generally calculated to achieve a target pH_{Ca} 5.0–5.2 (Condon *et al.* 2020). The rationale for these pH values was based on the inverse relationship between low soil pH and toxic aluminium concentrations in the soil solution (Scott *et al.* 2007; Andersson and Orgill 2018) and the assumption that Alex will be maintained below toxic concentrations if lime application occurs to ensure pH_{Ca} remains above 4.8.

Upjohn *et al.* (2005) advised that liming to achieve a pH_{Ca} target of 5.2 in the 0–10 cm soil depth 'will remove most of the problems associated with an acidic soil'. However, in soils with acidity to depth they recommended higher initial lime application rates and a liming regime to maintain pH_{Ca} ≥5.5 in the 0–10 cm depth and gradually increase pH in the 10–20 cm layer, as reported by Li *et al.* (2019). In the late 1990s relatively very high interest rates, low land and commodity prices meant that treatment of subsurface acidification was not considered economically viable (Cregan & Scott 1998). Consequently, the focus was on increased production on lime-responsive sites and rapid return on lime investments, and so the lower target of pH_{Ca} 5.2 was adopted and remains standard practice, irrespective of depth of acidic layers. Minimal investment in acid soil research since the early 2000s has meant that the effectiveness of the acid soil management practices implemented on farm has not been monitored.

Despite intensification of farming systems, low interest rates, favourable commodity prices and large increases in land prices, the current guidelines are outdated and have not been revised for contemporary farming systems. Lime rates of up to 2–2.5 t lime/ha have produced acceptable yields from wheat, canola and lucerne in soils that would have otherwise been too acidic. Producers' soil test results from 0–10 cm sampling depths indicate that traditional practices are successfully maintaining soil pH_{Ca} in industry's aspirational range of 4.8–5.2. However, recent studies have highlighted that this approach to acid soil management has not addressed acidity further down the profile. The amount of lime applied has been insufficient to amend existing acid soil problems below 5 cm and subsurface layers have been acidified (Scott *et al.* 2007; Norton *et al.* 2018; Li *et al.* 2019).

Condon *et al.* (2020) proposed an increase in the soil pH thresholds to trigger liming. The plant and soil function and production potential would be already compromised if lime application is delayed until pH and exchangeable aluminium reach plant critical values, or plants show deficiency or toxicity symptoms associated with soil acidity. They also advocated an increase in pH targets after liming, in order to ameliorate or prevent subsurface acidification, based on field studies by Conyers & Scott (1989) and Li *et al.* (2019). These studies demonstrated movement of alkali from dissolved lime, below the depth of placement when soil pH_{Ca} was maintained above 5.5. An example of the benefit of this practice change has been demonstrated at the long-term field experiment near Book

Book, NSW, where a 'vigorous liming regime' that maintained pH_{Ca} ≥5.5 in the 0–10 cm depth prevented further acidification in the subsurface layers and increased soil pH in the 10–20 cm layer by more than 0.9 units over 18 years (Li *et al*. 2019).

Surveys of commercial paddocks in central and southern NSW identified that most soils exhibited stratified soil pH profiles, with elevated pH in the surface 0–5 cm layer but reduced pH at 5–15 cm (Scott *et al*. 2017; Burns & Norton 2018a). Subsurface acidity is not detected from soil samples collected at traditional sampling depths of 0–10 cm. Finer sampling at increments of 5 cm is necessary to identify the depth and severity of acidity in the subsurface layers. This detailed information is particularly important in guiding liming decisions and species selection, including the role for acid tolerant species (Scott *et al*. 2000).

Methods

Soil samples were collected from 104 sites between 2016 and 2020 from near Albury NSW in the south (35°49'16"S, 148°05'03"E) to near Molong NSW in the north (32°55'27"E, 148°56'26"S) within the medium to high rainfall zone (annual average rainfall 500–900 mm). The paddocks sampled represent productive, actively managed land supporting perennial pastures and/or crops in the mixed farming systems. Acid soil management practices varied between sites from nil liming history to those with up to 4 lime applications over about 30 years, at various rates but commonly at 2–2.5 t/ha of fine grade lime.

Soil samples were taken in 2.5 cm increments to a depth of 15 cm, then from 15–20 cm and 20–30 cm layers at 63 sites, and in 5 cm increments to a depth of 20 cm at the other 41 sites. At each site, soil was collected using 25 mm diameter cores at 20 random locations, composited to designated depths from an area of approximately 100 m^2. Soil pH_{Ca} was measured according to the method used by Rayment & Lyons (2010). The pH of the samples for the 63 sites collected in 2.5 cm increments was averaged to provide mean soil pH for 0–5 cm, 5–10 cm and 10–15 cm layers as a comparison with those on the remaining 41 sites. The pH of the 0–5 and 5–10 cm layers was then averaged to provide an estimated mean of soil pH for the 0–10 cm layer for each site to mimic the current soil sampling regime.

Results and discussion

Soil types of the sites sampled include Yellow, Red and Brown Chromosols, Kandosols and Dermosols with an effective cation exchange capacity (ECEC) of ~4 to ~14 cmol (+)/kg in the 0–10 cm sample (Isbell 1996).

The dataset with 104 sites was firstly grouped based on soil pH from 0–10 cm soil samples depth to simulate current acid soil management practice used by most producers (i.e.:<4.5; 4.5–5.2; and >5.2); then re-grouped based on soil pH_{Ca} of samples collected in 5 cm increments to a depth of 20 cm and presented with a revised liming guideline for acid soil management practice in modern farming systems.

Current liming practice (C): a reactive approach to managing soil acidity

Currently, lime application is triggered when pH_{Ca} decreases to about 4.8, with lime rates targeting pH_{Ca} 5.2 (Helen Burns, unpublished survey data). The presumption is that by maintaining pH_{Ca} of 0–10 cm soil samples between 4.8–5.2, concentrations of toxic forms of aluminium will be kept below critical values for most commercial crop and pasture species. Based on these criteria, Group C1 (n=41 sites), which includes only 39% of the 104 sites, had a critical value pH_{Ca} <4.8 in 0–10 cm (mean pH_{Ca} 4.5 + 0.2) and so were likely to be prioritised for liming, particularly those scheduled to be sown to acid-sensitive crops. Twenty-eight percent (28%) of sites (Group C2: n=29) with pH_{Ca} 4.8–5.2 in 0–10 cm (mean pH_{Ca} 5.0 + 0.1) were marginal for lime application. Acid soil management programs for these would depend on the rotation, the acid-sensitivity of species to be sown and the producers' approach to managing soil acidity.

The remaining 33% of sites (Group C3: n=34) had pH_{Ca} > 5.2 in 0–10 cm (mean pH_{Ca} 5.6 + 0.4). These sites either had inherently high soil pH, in which case it may be assumed that they had no existing acid soil problems, or alternatively they had recently received a significant lime application and acidity in the 0–10 cm surface soil was being effectively managed. Future soil testing would likely be sporadic for Group C3 sites. A 2012 survey indicated that 93% of livestock producers used soil testing but only 18% of these tested their most productive paddocks (Helen Burns, unpublished data).

Under current acid soil management programs, about 2.0 t/ha of lime would be surface applied to sites represented by the mean pH_{Ca} in Group C1. This would increase pH_{Ca} of the 0–10 cm layer from 4.5 to ~5.2, assuming an ECEC of 5 cmol (+)/kg (Upjohn *et al.* 2005). At the next soil testing cycle, commonly at 6 yearly intervals, it is expected that the pH_{Ca} in 0–10 cm would be maintained within the aspirational range of 4.8–5.2. However, although the surface-lime applied provides enough alkali to neutralise acidity at 0–10 cm, there is no guarantee that pH throughout the 0–10cm depth would reach the target pH 4.8–5.2, due to slow lime movement, and is unlikely to influence pH further down the profile (Scott *et al.* 2007).

Maintaining 0–10 cm pH_{Ca} ~4.8–5.2 is common practice among producers operating on the acidic soils of south-eastern Australia (Helen Burns, unpublished survey data), which is only a reasonable short-term approach for soils with pH_{Ca} >5.0 below 10 cm. Numerous studies caution that the likely outcome is elevated pH in the shallow surface layer and further acidification in subsurface layers below 5 cm (Li *et al.* 2019; Burns & Norton 2018a; Norton *et al.* 2018; Scott *et al.* 2017). If this is not addressed, the long-term impact will be loss of agricultural production, reduced biodiversity and diminishing ecological services in farming systems as the depth and severity of soil acidity in the subsurface layers increases. The outcome will be irreversible soil degradation, with crop and pasture options ultimately being limited to acid-tolerant species (Crawford *et al.* 2006). It is essential that these soils are monitored for declining pH in subsurface layers and liming actioned early to reduce risk of subsurface acidification and associated incremental loss of production.

The sites in Groups C2 and C3 are typical of acidic soils that support the most productive farming systems of the targeted area, including Dermosols, Kandosols and Chromosols. The averaged pH of 0–10 cm suggest that these sites are free of acid soil problems. However, if pH stratification is considered there are likely to be soils within these groups with severely acidic subsurface layers (i.e. pH_{Ca} < 4.5). Therefore, production response to lime application on these soils depends on the acid sensitivity of species sown and the depth and magnitude of acidity in subsurface layers (Burns & Norton 2018b), which is not revealed by soil pH of samples collected from 0–10cm.

Revised liming regime (R): a proactive approach to managing soil acidity

The revised liming regime is based on soil sampling in 5 cm intervals, which provides detail essential for development of acid soil management programs that will effectively: (i) ameliorate existing acidic subsurface layers; or and (ii) halt the development of subsurface acidity.

The dataset from those 104 sites were re-grouped into 5 groups as described below and reported in Table 1.

- Group R1: pH_{Ca} <4.8 throughout profile; indicative of inherently acidic soils with limited liming history.
- Group R2: pH_{Ca} <4.8 in layers within 5–20 cm depth; mean pH_{Ca} <5.5 in 0–10 cm depth. Elevated pH in 0–5 cm layer with acidic subsurface layers.
- Group R3: pH_{Ca} <4.8 in layers within 5–20 cm depth; mean pH_{Ca} >5.5 in 0–10 cm depth. Elevated pH in 0–10 cm layer overlying acidic layers.
- Group R4: pH_{Ca} <4.8 layers within 0–10 cm depth; pH_{Ca} > 5.0 in layers within 10–20 cm.
- Group R5: pH_{Ca} 5.0–5.5 within 5–20 cm subsurface layers; increasing with depth at most sites.

Based on revised liming guideline, 87% of sites (Groups R1, R2 and R3) have soil pH_{Ca} <4.8 in subsurface layers (below 5 cm), in which 78% of sites should be prioritised for lime application whereas 9% of site in Group R3 do not require additional lime at present as the mean pH_{Ca} within the 0–10 cm depth is >5.5 (Table 1). Applying lime to the revised target of pH_{Ca} > 5.5 within 0–10 cm will enable pH increases in the 10–20 cm layer over time to an aspirational target of pH_{Ca} >5.0 for the 10–15 and 15–20 cm layers. Only 13% of sites in Groups R4 and R5 have pH_{Ca} >5.0 in these layers.

Table 1. The mean soil pH_{Ca} in 5 cm increments (sampled or calculated from 2.5 cm increment soil samples) at 104 field sites from central and southern NSW, grouped according to mean pHCa of 0–5, 5–10, 10–15 and 15–20 cm layers and the location of acidic layers. Numbers in brackets are standard deviations from the means.

Depth (cm)	Group R1 (n=31)	Group R2 (n=50)	Group R3 (n=9)	Group R4 (n=5)	Group R5 (n=9)
0–5 cm	4.6 (0.2)	5.5 (0.4)	6.2 (0.2)	5.1 (0.2)	5.6 (0.6)
5–10 cm	4.3 (0.2)	4.6 (0.2)	5.4 (0.4)	4.8 (0.2)	5.3 (0.4)
10–15 cm	4.4 (0.2)	4.5 (0.2)	4.7 (0.2)	5.3 (0.2)	5.4 (0.2)
15–20 cm	4.6 (0.3)	4.7 (0.3)	4.7 (0.4)	5.6 (0.3)	5.5 (0.4)

Revised acid soil management guideline

The revised approach to acid soil management we propose requires a considerable shift in mindset. A comparison between the current approach and the changed management proposed is listed in Table 2.

Ameliorating soils with existing subsurface acidity. The pH profile of Group R1 sites is typical of soils with acidity to depth, making up 30% of all sites. There were sites within this group with no history of lime application, while others have received sporadic applications over a long period. In contrast, the pH profile of Group R2 sites (48%), with intense stratification and elevated pH in the surface layer is typical of highly productive soils supporting intensive crop and crop/livestock operations within the

Table 2. Traditional approaches to acid soil management need updating to mitigate and prevent soil acidification in modern farming systems.

Current/traditional management practices	Changed management proposed
Soil test results (i.e. pH, % Al) from samples collected at traditional sampling depth of 0–10 cm guide the decision to apply lime.	Sample at 5cm intervals to a depth of 20 cm in order to detect the extent and depth of acidic subsurface layers. Subsurface acidity is not detected by 0–10 cm soil samples.
Lime* application is triggered when 0–10 cm soil pH_{Ca} is between 4.5–4.8 or when exchangeable aluminium approaches 5%. This prioritises lime application on about 39% of commercial paddocks surveyed in southern slopes and tableland of NSW that are constrained by acidic subsurface layers.	Increase the critical pH that triggers lime application (pH_{Ca} 5.5). Monitor pH of all soils; don't ignore the most productive soils, which are at high risk of acidification. Implement amelioration efforts before subsurface pH reaches critical levels and plants show toxicity symptoms and suffer production loss.
The amount of lime applied is enough to raise pH in the 0–10 cm layer to about 5.2, i.e. sufficient to reduce % Alex to non-toxic levels.	If subsurface acidity is detected, apply enough lime to increase 0–10 cm pH_{Ca} above 5.5. This will neutralise acidity in the surface soil and the lime benefit will gradually move down the profile and increase subsurface pH.
Re-liming intervals are sporadic, guided by crop toxicity symptoms, soil test results or cropping/pasture programs.	Monitor soil pH. If the aim is to increase subsurface pH, maintain 0–10 cm soil pH_{Ca} above 5.5 and relime before subsurface pH declines.
Lime is surface applied and only incorporated by sowing.	Strategic tillage to incorporate lime speeds up the lime reaction and increases the lime effect to the depth of cultivation.
Lime is applied immediately before sowing sensitive species	Delay sowing acid-sensitive species for at least 18 months after lime application to allow time for the lime to react and raise pH.

*NOTE: Reference to liming material assumes the material is fine-grade, high quality lime with neutralising value (NV) > 95 and fine particle (90% passes through a 150 μm sieve).

medium and high rainfall zones. The Group R2 sites had received up to 4 applications of surface-applied lime since the late 1980s, using the traditional target pH_{Ca} of 5.0–5.2. Despite this long history of lime application, the frequency and rates of lime applied was insufficient to prevent subsurface acidification.

Producers with soils represented by Groups R1 and R2 need to adopt very different strategies to ameliorate subsurface acidity. Sites in both groups should be prioritised for lime application, with a revised target pH_{Ca} >5.5 within the 0–10 cm depth. Monitoring these sites and maintaining pH_{Ca} >5.5 will ensure alkali movement and gradual increase in pH below 10 cm (Norton *et al.* 2018; Li *et al.* 2019; Condon et al. 2020).

Although Group R3 sites (9%) were acidic to depth, elevated pH_{Ca} >5.5 to a depth of 10 cm indicates recent applications of relatively high rates of lime. To prevent further decline in subsurface pH, these sites should also be monitored closely to ensure timely lime application to maintain pH_{Ca} above 5.5 in the 0–10 cm layer.

Preventing subsurface acidification. The pH profiles of sites within groups R4 and R5 were typical of highly productive soils of the survey area, with high pH buffering capacity and soil pH within the range suitable for most crops. However, they made up only 13% of sites surveyed. Being highly productive these would also have the highest acidification rates, so must not be ignored in acid soil management programs.

The pH profile of Group R4 sites indicated formation of an acid throttle. The 5–10 cm layer was the most acidic, with pH_{Ca} ranging from 4.6 to 4.9 at various sites. While most commonly grown crops did not display acid toxicity symptoms, reduced root growth in barley and poor root development and nodulation in acid-sensitive legume species was reported at some sites. Such soils exemplified the case for early intervention, particularly if lime incorporation is not an option. Large quantities of lime and considerable time will be required to ameliorate acidic subsurface layers if they form in these soils with high pH buffering capacity. For example, as pH refers to H+ concentration on a logarithmic scale, 1 t lime/ha applied at pH_{Ca} 5.0 increases pH much more than that same quantity of lime applied at pH_{Ca} 4.5. If untreated, subsurface acidification would continue, acidity would move further down the profile and the opportunity for successful and affordable management of subsurface acidity would be missed.

The sites within group R5 (9 sites) are slightly acidic with pH_{Ca} above the aspirational target of 5.0 throughout the profile. However, individual sites have stratified pH profiles, with the 5–10 cm layer the most acidic, as low as pH_{Ca} 5.0 on several sites. Monitoring and early intervention aimed at arresting subsurface acidification is also relevant to these sites.

Monitoring is an essential component of effective acid soil management. A framework that enables monitoring of soil pH change at the paddock or soil zone scale is necessary to measure in paddock acidification rates, assess the effectiveness of acidic soil management efforts and confidently develop proactive, long-term management strategies relevant to producers. An effective monitoring framework includes establishment of geo-located sites on soil types representative of agricultural systems, recording baseline soil data in 5 cm increments and monitoring pH change with periodic soil sampling, e.g. re-testing pH profiles at 3 to 5 year intervals, depending on soil pH buffering capacity and production system (Burns & Norton 2018b).

In collaboration with project partners, Grassland Society of NSW and Holbrook Landcare Network, 60 monitor sites have been established in the central and southern slopes and tablelands of NSW. They represent soil types and management systems typical of mixed farming and perennial pasture systems. Over time, information collected from these sites will inform the response of pH change to management, the rate and depth of acidification, and provide growers and advisors with the confidence to adjust lime rates, re-liming intervals and implement more aggressive programs, such as strategic cultivation to enhance lime incorporation (Crawford et al. 2006; Burns & Norton 2018b).

Conclusions

Our current management of acid soils such as soil sampling in 0–10 cm intervals and generic rules of thumb that inform many liming decisions are proving to be ineffective in addressing subsurface acidity. Reported worsening of the condition of agricultural soils is supported by surveys of commercial paddocks, which show intense pH stratification and subsurface acidity in 87% of sites.

There is a need for producers and advisors to make a mindset shift from treating acid soils to preventing acidification of agricultural soils; a move from reactive to proactive land management. Soil sampling in 5 cm intervals in the surface 20 cm enables the depth and magnitude of acidic subsurface layers to be identified and monitored. This information can then be used to formulate liming strategies; decisions of rate, application method and paddock prioritisation are able to be tactically made. Initiating lime application before acidity develops to an extent that impacts plant function, to when pH_{Ca} is around 5.5 results in greater efficiency of lime application to change pH and facilitates movement of the liming effect to deeper in the soil. These changes represent an effective method of treating and addressing the formation of acidic subsurface layers. The challenge for producers is to prioritise and customise acid soil management actions to achieve medium and long-term production targets and environmental management goals.

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References

Andersson KO, Orgill SE (2018) Soil extension needs to be a continuum of learning; soil workshop reflections 10 years on. *Soil Use and Management* **35**, 117–127.

Burns HM, Condon JR, Li GD (2021) New triggers and new targets for effective acid soil management. Accepted: In 'Proceedings of Soil Science Australia & the New Zealand Society of Soil Science Joint Conference 2021'. Cairns, 27 June–2 July. Soil Science Australia.

Burns HM, Norton MR, Tyndall P (2017) Reduced nodulation of faba bean crops on acidic soils; the role of topsoil pH stratification. In: 'Proceedings of the 18th Australian Agronomy Conference', Ballarat, Australia. (Eds G.J. O'Leary, R.D. Armstrong, L. Hafner) Australian Society of Agronomy.

Burns HM and Norton MR (2018a) Subsurface acidity threatens central and southern NSW cropping areas. In 'Proceedings National Soils Conference 2018'. Canberra, 18–23 November 2018. Soil Science Australia. pp 352-353.

Burns HM and Norton MR (2018b). Legumes in acidic soils: maximising production potential in south eastern Australia. Grains Research Development Corporation, Canberra.

Condon JR, Burns HM, Li GD (2020), The extent, significance and amelioration of subsurface acidity in southern New South Wales, Australia. Soil Research 59, 1–11. https://doi.org/10.1071/SR20079

Conyers MK, Scott BJ (1989) The influence of surface incorporated lime on subsurface soil acidity. *Australian Journal of Experimental Agriculture* **29**, 201–207.

Conyers MK, Heenan DP, McGhie WJ, Poile GP (2003) Amelioration of acidity with time by limestone under contrasting tillage. *Soil & Tillage Research* **72**, 85–94.

Cregan PD, Scott BJ (1998) Soil acidification – an agricultural and environmental problem. In 'Agriculture and the environmental imperative'. (Eds J Pratley, A Robertson) pp. 98–128. (CSIRO)

Crawford, D., Moody, P.W., Merry, R.H., Gazey, C., Wilson, B.R., Hughes, B., Grose, C.J., Dixon, J., and McKenzie, N.J. (2006) Soil acidification, in N.J. McKenzie and J. Dixon (Eds) "Monitoring soil condition across Australia: recommendations from the expert panels", prepared for the National Land & Water Resources Audit, Canberra, pp. 14–26.

Hamblin AP and Tennant D (1987) Root length density and water uptake in cereals and grain legumes: how well are they correlated. *Crop and Pasture Science* **38**, 513–527.

Holland JE, Bennett AE, Newton AC, White PJ, McKenzie BM, George TS, Pakeman RJ, Bailey JS, Fornara DA, Hayes RC (2018) Liming impacts on soil, crops and biodiversity in the UK: A review. *Science in the Total Environment* **610–611**, 316–332.

Isbell, R.F. (1996), The Australian Soil Classification. CSIRO Publishing, Melbourne.

Khawmee, K., Suddhiprakarn, A., Kheoruenromne, I., Bibi, I., & Singh, B. (2013). Dissolution behaviour of soil kaolinites in acidic solutions. *Clay Minerals* **48(3)**, 447–461. doi:10.1180/claymin.2013.048.3.02

Li GD, Conyers MK, Helyar KR, Lisle CJ, Poile GJ, Cullis BR (2019) Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of south-eastern Australia. *Geoderma* **338**, 236–246. https://doi:10.1016/j.geoderma.2018.12.003

Munns DN (1986) Acid tolerance in legumes and rhizobia. In 'Advances in Plant Nutrition.' (Eds B Tinker, A Lauchli) Vol. 2 pp. 63-91. (Praeger Scientific: New York).

Norton MR, Garden DL, Orchard BA, Armstrong P (2018) Ameliorating acidity of an extensively-managed permanent pasture soil. *Soil Use and Management* **34**, 343–353.

Scott BJ, Ridley AM, Conyers MK (2000) Management of soil acidity in long-term pastures of south-eastern Australia: a review. *Australian Journal of Experimental Agriculture* **40**, 1173–1198.

Scott BJ, Fenton IG, Fanning AG, Schumann WG, Castleman LJC (2007) Surface soil acidity and fertility in the eastern Riverina and Western Slopes of southern New South Wales. *Australian Journal of Experimental Agriculture* **47**, 949-964.

Scott BJ, Conyers MK, Burns HM, Evans CM, Fettell NA (2017) Stratification of acidity in the shallow soil surface - experiences in the cropping areas of southern and central NSW. In: 'Proceedings of the 18th Australian Agronomy Conference', Ballarat, Australia. (Eds G.J. O'Leary, R.D. Armstrong, L. Hafner) Australian Society of Agronomy.

Slattery WJ, Conyers M K, Aitken R L (1999) Soil pH, aluminium, manganese and lime requirement. In 'Soil analysis: an interpretation manual.' (Eds KI Peverill, LA Sparrow, DJReuter) pp. 103–128. (CSIRO Publishing: Collingwood, Victoria)

SoE (2018) Soil Condition, The State of Environment Report – 2018. NSW Environment Protection Authority, Sydney. pp. 180–186.

Upjohn B, Fenton G, Conyers M (2005) Liming and soil acidity. *Agfact* AC. 19, NSW Department of Primary Industries, Orange.