Author/s: Condon, J., Burns, H., Li, G.

Title: The extent, significance and amelioration of subsurface acidity in southern New South Wales, Australia

Journal: Soil Research

ISSN: 1838-675X

Year: 2020

Volume: 59

Issue: 1

Pages: 1-11

DOI: http://dx.doi.org/10.1071/SR20079

The extent, significance and amelioration of subsurface acidity in southern New South Wales, Australia

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Abstract

Soil pH is seldom uniform with depth, rather it is stratified in layers. The soil surface (0-0.02 m) commonly exhibits relatively high pH and overlies a layer of acidic soil between 0.05-0.15 m deep, termed an acidic subsurface layer. Commercial and research sampling methods that rely on depth increments of 0.1 m either fail to detect or under report the presence and/or magnitude of pH stratification. The occurrence of pH stratification and the presence of acidic subsurface layers may cause the extent of acidity in NSW agricultural land to be underestimated.

Though the cause of pH stratification in agricultural systems is well understood, the effect on agricultural production is poorly quantified due in part to inadequate sampling depth intervals resulting in poor identification of acidic subsurface layers. Whilst liming remains the best method to manage acidic soil, current practices of low pH targets (pH_{Ca} 5), inadequate application rates, and no or ineffective incorporation have resulted in the continued formation of acidic subsurface layers. Regular monitoring in smaller depth increments (0.05 m), higher pH targets (pH_{Ca} >5.5) and calculation of lime rate requirements that account for application method are required to slow or halt soil degradation by subsurface acidification. If higher pH is not maintained in the topsoil, the acidification of subsurface soils will extend further into the profile and require more expensive operations that mechanically place amendments deep in the soil. Whilst the use of organic amendments has shown promise to enhance soil acidity amelioration with depth, the longevity of their effect is questionable. As such proactive, preventative management of topsoil pH with lime addition remains the most cost-effective solution for growers.

Keywords acidity, direct placement, lime, organic amendment, soil constraint, stratification

Introduction

Soil acidity is known to hamper agricultural production via associated toxicities of aluminium and manganese, and/or deficiencies of phosphorus, calcium, magnesium and molybdenum (Scott *et al.* 2000). These conditions negatively affect plant growth and impact processes relating to nutrient cycling (Young *et al.* 1995), water use efficiency and soil carbon sequestration (Conyers *et al.* 2012). As such, acidity is considered a major limitation to agricultural production. This paper uses measures of pH as an effective aggregator of problems induced by soil acidity. Whilst the relationship between pH and concentration of toxic ions can vary between soils, relationships exist within individual soils (Bache 1986; Carr *et al.* 1991; Scott *et al.* 2007).

More than 50% of Australian agricultural land has acid (pH_{Ca} <5.5) soil; 35M ha is highly acidic (pH_{Ca}<4.8) (Orgill *et al.* 2018). The area of acid-affected agricultural land in NSW has been estimated and/or mapped (Helyar *et al.* 1990, Lockwood *et al.* 2003) though these are likely to underestimate the current status of soil acidity owing to ongoing acidification and sampling methods that do not account for pH stratification.

Recent research activities in southern NSW, defined here as an area from the Murray River to Orange in the north and from the hillslopes of the Great Dividing Range to the irrigation regions 200 km to the west, have focused on the presence, impact and amelioration of pH stratification within the surface 0.2 m of soil. Research implementing 0.025 or 0.05 m depth increments has identified pH stratification as a common feature of agricultural soils in southern NSW (Geeves et al. 1995). The acidic subsurface layers present in pH stratified soil have been identified to be the major cause of decreased nodulation and reduced production of pasture legumes (McIntosh *et al*. 2018; Hackney *et al.* 2019) and pulse crops (Burns and Norton 2018a). They are also known to influence the performance of acid sensitive wheat cultivars (Scott *et al.* 1999). As such, pH stratification has negative impacts on cropping, grazing and mixed farming enterprises in southern NSW.

Many studies of amelioration of acidic soils have occurred within southern NSW, beginning in the 1980s (Conyers and Scott 1989). Subsequently, the influence of lime quality (Conyers *et al.* 1995b) and particle size (Conyers et al. 2020), the impact of incorporation and tillage (Conyers and Scott 1989; Conyers et al. 2003; Scott and Coombes 2006) on lime movement and effectiveness has been studied. Despite this research, it appears acidity remains a limitation as current liming practices do not address the acidic subsurface layers that are present (Burns and Norton 2018a). Research by Li *et al.* (2019) demonstrated that it is possible to address subsurface acidity given time (18 years) by liming to maintain a pH target of pH_{Ca}>5.5 in the surface 0.1 m. More rapid pH amelioration strategies of deep acidity (>0.15 m) have been the focus of new research in the region. Direct placement of amendments (Condon *et al.* 2018; Li *et al.* 2018; Moroni *et al*. 2018) or use of organic materials that release soluble alkali forms that move to deeper layers have been studied (Nguyen et al. 2018; Nguyen et al. 2019; Butterly et al. 2020).

Much research and extension has also been undertaken in Western Australia (WA) to manage acidic soils (Gazey and Davies 2009). However, due to differences in soil texture between the sands of WA and heavier textured topsoils of NSW, there are very limited opportunities for transfer of effective WA practices (such as deep tillage) to soils of southern NSW.

The aim of this paper is to review the most recent soil based research relating to acidic soil management in southern NSW, within the context of that previously undertaken in the region, in order to identify future research needs and the development of improved practices to identify, manage and prevent acidic soils.

Soil acidity in Southern NSW

Soil acidity is a major constraint for agricultural production (Orgill *et al.* 2018) and widespread acidification has been identified as a threat to long-term agricultural viability (McKenzie *et al.* 2017). Estimates of the extent of acidic soils in NSW (Table 1) have been made by modelling (Gray *et al.* 2015; OEH 2018), expert knowledge and point sampling (Helyar *et al.* 1990) and field survey (Lockwood *et al.* 2003, Scott *et al.* 2007). Each method of estimate generation has limitations that influence the value of the estimate produced.

Insert Table 1 here

Modelling using lithology and remotely sensed data provides a first approximation of the spatial distribution of soil pH. However, to date, these are not able to take account of the influence of management practices, be they acidifying (product removal, N fertiliser use) or alkalising (the application of lime). This being the case, Gray *et al.* (2015) provided moderate (R^2=0.51) agreement with observed soil pH in the 0-0.1 m layer from the Soil and Land Information System

(SALIS) database of NSW, which are obtained via direct sampling. The SALIS pH data have their own limitations. They come from samples taken over a 60-year period and includes soil survey data that often occurs by roadsides, under native vegetation. Williams (1980) demonstrated in a fenceline study that agricultural management could decrease soil pH by more than 1 unit to a depth of greater than 0.2 m in a period of 32 years. Therefore, maps generated using SALIS data from roadside locations are likely to considerably underestimate current acidity in agriculturally managed land. This is supported by Lockwood *et al.* (2003) who noted underestimates of 0-0.1 m acidity from data stored within the Australian Soil Resources Information System (ASRIS; a national soil database system that incorporates the SALIS data for NSW) in comparison with commercial soil testing data gathered from agricultural fields. They estimated the area of NSW with pH_{Ca} <4.8 as being 8.2 Mha based on soil tests but only 5 Mha using ASRIS data. Lockwood *et al.* (2003) attributed this difference to the age of ASRIS data, as acidification continues with time, and the potential biasing of soil testing problematic acidic soil in the commercial soil testing data. Comparisons of the production and economic impact of soil constraints (Orton *et al.* 2018) that are generated from ASRIS data are also likely to underestimate the impact of acidity. Where the impact of soil constraints is compared, it should be noted that as acidity can increase over time in agricultural systems, modelled estimates of its impact are likely to be more erroneous than those constraints that are an inherent soil characteristic, such as sodicity. This is important in the context of determining resource allocation for research.

Where the extent of acidity has been mapped based on field survey, the spatial resolution of the data, the age of data and area from which samples are taken all create limitations of output. As mentioned above, maps created from ASRIS data will include data points taken over an extended time frame and will include non-agricultural sites. The data used to generate the pH maps of Helyar *et al.* (1990) were from the mid-1980s, based on 0-0.1 or 0-0.15 m samples of agriculturally managed land. Scott *et al.* (2007) reported a greater frequency of acidic sites in southern NSW compared to Helyar *et al.* (1990). Soil pH is not a static property and acidification over the period since publication would have decreased pH in most soils under agricultural management.

Perhaps the greatest shortcoming of maps based on field survey is the depth of sampling. The 0-0.1 m 'topsoil' layer is not uniform, rather it contains stratified layers of soil pH (Bromfield *et al.* 1983, Conyers and Scott 1989). Such stratification is common in soils of the mixed farming region of southern NSW (Chromosols, Sodosols, Kandosols and Dermosols), as demonstrated by Geeves *et al.* (1995) who conducted a detailed field survey of agricultural soils of that region and sampled the 0-0.1 m soil in depth increments of 0-0.02, 0.02-0.05 and 0.05-0.1 m.

The use of 0-0.1 m sampling fails to identify acidic layers within that depth because the stratified pH is effectively averaged, thus masking the presence and severity of the acidic layers that exist. To illustrate this, soil pH_{Ca} data collected in 0.025 m depth increments from 31 sites between Albury and Cowra, NSW (Burns and Norton 2018a) were transformed to H^+ concentration. Values within the 0-0.1 m were then averaged prior to back transforming to provide calculated mean soil pH_{Ca} of 0.1 m depth intervals from those sites. These values were then compared with the minimum pH_{Ca} value recorded in any 0.025 m depth interval within the 0-0.1 m interval at each site (Figure 1a). Sampling a single 0.10 m increment in the surface soil overestimated the soil pH of the most acidic 0.025 m increment in all soils. Of the 31 soils, 16 presented a $pH_{Ca} > 5$ in the 0-0.1 m depth but actually had $pH_{Ca} < 5$ in at least one of the 0.025 m layers within the surface 0.1 m. If the same soils had been sampled in 0.05 m increments, the presence of the most acidic layers would have been accurately identified (Figure 1b). The implementation of 0.05 m sampling increments will increase cost of analysis. However, even if sampling to a depth of 0.2 m, the use of 0.05 m intervals would mean an additional two soil pH analyses, assuming two 0.1 m intervals would normally be taken to 0.2 m. The minor costs incurred easily offset potential crop failure, such as that shown by Burns and Norton (2018b), when an acidic subsurface layer was not identified. We recommend using 20 mm diameter soil cores to take intact cores to a depth beyond 0.2 m. These can be pushed out onto a tray and carefully cut into precise 0.05 m intervals to be bagged for analysis. This avoids error associated with the depth of sample but does require some moisture to be present in the surface soil to avoid collapse of the soil once removed from the core.

Therefore, there is a risk that any soil mapping or modelling that reports soil pH in the topsoil as a 0-0.1 m value will underestimate the significance of acidity to agricultural production. It is likely that the areas shown in Table 1 for the pH ranges of pH_{Ca} 5-5.5 (Helyar e*t al*. 1900) and 4.8-5.5 (Lockwood *et al*. 2003) will contain lower pH in layers within the surface 0-0.1 m than reported. Though OEH (2018) modelled pH in 0-0.05 and 0.05-0.15 m layers, the area of pH ranges reported in Table 1 for those depths was similar to that modelled for the 0-0.1 m layer by Gray *et al.* (2015). The modelling was not able to account for the pH stratification evident in the work by Geeves *et al.* (1995) or Burns and Norton (2018a).

Insert Figure 1 here

Given that pH varies temporally (Conyers *et al.* 1997), is stratified vertically (Bromfield 1983) and spatially variable at small or large scale (Conyers and Davey 1990), the use of historic soil pH maps for the purpose of policy development, research resource allocation and land-use has significant shortcomings. For these purposes, a better approach would be to establish a network of monitoring sites, spanning different rainfall zones, soil types and farming enterprises, that can be tracked through time to report changes in soil pH in fine depth increments. This will enable study of the development of pH stratification and quantification of acidification rates of soil layers. The data produced from the network would be of great value for further development of models to provide better approximation of pH stratification and spatial distribution of the response of pH to management through time.

Formation of pH stratification and acidic subsurface layers

In agricultural systems the main processes involved in the formation of pH stratification include the net association and oxidation of organic anions, reduction and oxidation reactions of sulfur and manganese, relative uptake of cations and anions by plants, and net N mineralisation and subsequent nitrification of plant residue returned to the soil surface (Conyers *et al.* 1995a; Evans *et al.* 1998; Paul 2001a,c).

The soil surface receives organic matter return from decomposing plants. This represents a source of alkali from the oxidation of organic anions that have undergone association with H^+ in the soil solution (Tang *et al.* 1999; Paul 2001b). This can increase the soil pH of the surface layer of soil relative to that at depth (i.e. below 0.02 m). Uptake of plant nutrients from different soil layers can influence soil pH as net excess cation uptake in a soil layer results in the excretion of H^+ by the plant into the rhizosphere in that layer. The excretion of OH^- occurs in the case of net excess anion uptake and can often occur lower in the profile as anions tend to leach downwards before uptake (Condon *et al.* 2005). The location of uptake impacts the soil pH at the precise site of uptake.

In circumstances where ammonium- or urea-based fertilisers are added to the soil, the nitrogen (N) transformations of urea hydrolysis, nitrification and uptake of mineral N act to create acidic subsurface layers (Passioura and Wetselaar 1972; Rochette *et al.* 2009). This occurs as each transformation of N acts to alter pH but does not occur at the same location in the profile owing to movement of substrate or product between each N transformation. Similarly, Condon *et al.* (2004, 2005) demonstrated that the vertical distribution of N processes occurring in stock urine patches resulted in the formation of pH stratification, specifically acidic subsurface layers.

The contribution of sulfur reactions to H^+ production and consumption was found to be minor in a study by Conyers *et al.* (1995a) on soils of the Riverina region of NSW. The reactions involving manganese were shown to make only a small (<0.4 mmol $H^+.kg^{-1}$) contribution to the net H^+ change in a field study by Paul *et al.* (2001a), also in the Riverina region of NSW.

The sum of the processes mentioned above cause pH stratification with higher pH at the soil surface and lower pH in subsurface layers (0.05-0.2 m). Because plant uptake and N fertilisers are involved in the formation of pH stratification, we hypothesis differences in pH will occur between the sowing row (where seed and fertilisers are placed) and the mid-row (the space between sowing rows) under controlled traffic farming (CTF) or global positioning system (GPS) guided sowing. To test our hypothesis, soil was collected from a continuously cropped paddock in Burrumbuttock, NSW in February 2020. The site had been cropped (cereal and canola) for 5 years with the use of GPS guidance, placing seed and fertiliser on the same sowing row with a 0.25 m row spacing. From four 70 m x 60 m plots, 20 soil cores (0.025 m diameter) were taken from each plot on the sowing row and 20 cores from the mid-row. Cores were divided into 0.025 m intervals to 0.15 m and a 0.05 m interval from 0.15 to 0.2 m. Soil pH_{Ca} was measured in 1:5 soil: 0.01 M $CaCl_2$ (method 4B2, Rayment and Lyons 2011). The pH_{Ca} in the sowing row was significantly less by 0.5 and 0.3 pH units than the mid-row for the 0.025-0.05 and 0.05-0.075 m layers, respectively (Figure 2). Therefore, the formation of pH stratification occurs at different rates and magnitudes at small (0.25 m) spatial scales. Further research is required to better understand the rate of development of this effect for different sowing equipment, soil types and rainfall zones. Differences in soil pH between the sowing row and mid-row may need to be taken into account when formulating soil sampling strategies for cropped paddocks where GPS guidance systems are used.

Insert Figure 2 here

The application of lime to the soil surface without incorporation can also enhance pH stratification. Burns and Norton (2018a) reported that sites receiving lime within a 5-year period has pH_{Ca} in the 0-0.05 m layer 0.95 pH units greater than the 0.05-0.1 m layer (Figure 3). On sites that had received lime more than 5 years previously, the difference between layers was 0.49 units. Similar results were reported from field experiments of Conyers *et al.* (2003).

Insert Figure 3 here

Significance of pH stratification

Whilst the potential negative impact of soil acidity on plant production is well understood, there is poor awareness of the potential detrimental effect of pH stratification and acidic subsurface layers (Burns and Norton 2018a). This is largely a result of pH stratification not being reported where it exists in research trials or field demonstration plots due to soil sampling in 0.10 m intervals.

There have been few studies where the impact of pH stratification has been quantified. Using a long-term (11 year) liming trial in southern NSW, Scott *et al.* (1999) were able to quantify the influence of acidic subsurface layers on wheat yield (Figure 4). They demonstrated that for a given 0-0.1 m pH_{Ca}, acidity of pH_{Ca} 4.1 in the 0.1-0.2 m layer decreased yield of an acid sensitive wheat (cv. Janz) by approximately 0.7 $Mg.ha^{-1}$ compared with the yield where 0.1-0.2 m soil pH_{Ca} was 5 or 5.3. They also noted that both the 0-0.1 and 0.1-0.2 m layer appeared to contribute equally to yield.

Insert Figure 4 here

In a field survey conducted by McIntosh *et al.* (2018), all legume pastures surveyed had ineffective nodulation and 90% of the sites were acidic (pH_{Ca} <5.5), with more than half the sites (55%) having pH_{Ca} between 5 and 4.5. It should be noted that pH_{Ca} was only reported as 0-0.1 m pH_{Ca}, therefore, even the sites with pH_{Ca} >5.5 are likely to exhibit acidity as demonstrated in Figure 1. The impact of acidic layers on grain legume root growth, vigour and nodulation has been documented by Burns *et al.* (2017). Farley *et al.* (2020) reported that Albus lupin (*Lupinus albus*) shoot growth and nodulation was negatively impacted at soil pH_{Ca} less than 4.8 and greater than 6.5 and concluded that within a pH stratified system both conditions can occur within the surface 0.1 m of a soil profile.

The presence of relatively high pH (pH_{Ca} >6.5) on the soil surface can also slow the rate of herbicide degradation. Farley *et al.* (2020) demonstrated that, for a range of sulfonylurea herbicide concentrations applied to a soil with pH adjusted from pH_{Ca} 4.1 to 7.2, lupin shoot growth and nodulation was impaired by the herbicide at soil pHs 5.7 to 7.2, which are likely to be found at the soil surface of pH stratified profiles. This is significant because the pH of the 0-0.1 m sample depth may indicate that herbicide residues would not exist. However, due to pH stratification there may be surface layers of higher pH where the herbicide has not degraded sufficiently to allow safe establishment of plants sensitive to the herbicide. This may be especially significant for pasture species which are sown in the surface 0.01 to 0.02 m. Thus plant-back periods for herbicides applied to soils that exhibit pH stratification need to be revised.

Crop and pasture selection on acidic soils is influenced by guidelines that provide broad pH and aluminium sensitivity rankings for some species (Scott *et al.* 2000) and occasionally crop varieties (Ryan 2018). Most data relating to crop and pasture response to raising soil pH pertains to amelioration of severely acidic (pH_{Ca} <4.5), responsive soils (e.g. Scott *et al.* 1999). There are no crop or pasture response data that specifically quantifies the potential production loss and cost of the degradation of agricultural systems by unchecked acidification and formation of acidic subsurface layers. Consequently, there is a tendency for growers and advisors to be operating on the financial margin, applying just sufficient lime to maintain pH in the 0-0.1 m above the critical values (e.g. pH_{Ca} 5 to 5.2), which often minimises expression of commonly recognised clinical symptoms of acid soil toxicity, such as aluminium or manganese toxicity. This highlights the traditional focus on amelioration, rather than prevention of soil acidification.

Current widespread acceptance of the role of lime application in productivity of acidic soils (Angus 2018) is influenced by historic research that directly links yield benefit to pH_{Ca} and concentrations of exchangeable aluminium. However, the evidence needed to prompt a shift in industry focus from amelioration and short-term return on lime input investment to one of prevention of acidification requires long-term system research that studies the influence of acidic subsurface layers on plant and soil function. Scott *et al.* (1999) suggested additional system benefits from small movements of the lime effect to 0.1-0.2 m depths (representing the amelioration of acidic subsurface layers), which may take several years to occur, but may contribute to the significant increase in wheat yield they reported. Benefits proposed included increased molybdenum and phosphorus availability or cycling (Holford 1989), improved soil structure (Chan and Heenan 1998) and microbial activity. Failure to secure these benefits could also be considered a net productivity loss and decline in soil function.

Indirect effects of subsurface acidity on plant productivity are difficult to identify and quantify. Whilst the clinical symptoms of low pH and aluminium toxicity (e.g. stunted and distorted root growth, poor plant vigour and yellowing and poor nodulation in legumes) are relatively easily identified, more subtle, sub-clinical, effects of acidic subsurface layers may exist. Burns and Norton (2018b) reported sub-clinical symptoms (e.g. reduced root hair density and reduced nodule number and weight) in patches of poor plant growth within paddocks of grain legumes. These poor patches were found to have acidic subsurface layers (pH_{Ca} <4.8) that were more severe than the healthy areas of the paddocks (pH_{Ca} >4.8). Although plants did not express typical toxicity symptoms, presence of an acid subsurface layer was likely to have compromised plant performance as a result of increased susceptibility to other abiotic and biotic stresses, including waterlogging, herbicide injury and disease (Burns and Norton 2018b). The increased incidence of root disease infection at low pH was attributed to reduced ability of the pH-compromised plants to effectively combat disease and produce compensatory roots. This has been observed in the field at Harden, NSW, where intermittent incidence of Rhizoctonia (*Rhizoctonia solani*) damaged wheat (*Triticum aestivum* cv. Wedgetail) was noted to occur where acidic subsurface layers (pH_{Ca} <4.5) also existed (pers. comm. Andrew Milgate). Research that studies plant response to a singular stress, be it acidity, disease, herbicide residue or other, without understanding the impact of other stresses present, will not identify the possible compounding effects of stresses responsible for observed plant response to the stress studied. There is clearly a need for research that quantifies the influence of pH stratification and acidic subsurface layers on plant function, soil physics, chemistry and biology, crop and soil pathogen and herbicide/pesticide behaviour, all within the context of agricultural systems having economic and ecologic functions.

Amelioration of acidic subsurface layers

Surface application of lime

General best practice to manage acidic soil is to apply agricultural lime. The effectiveness of lime to increase soil pH is determined by the chemical composition, solubility and particle size of the limes applied (Conyers *et al*. 1995b; Conyers *et al.* 2020). The rate of dissolution of lime is also influenced by rainfall (Conyers *et al*. 2003). For these reasons, it is recommended that acid tolerant plants be sown in the 12 to 24 months after lime application (Burns and Norton 2018b) to enable pH to be increased above critical values before acid sensitive plants are sown. This time interval may need to be increased depending on the starting pH, the depth of acidic layers and if lime is not incorporated by cultivation (Conyers *et al*. 2003).

The rate of lime applied is normally determined using decision support systems containing lime requirement models. Such systems utilise data of current pH, organic carbon (OC) and cation exchange capacity (CEC) determined from soil tests, and lime quality factors such as neutralising value and particle size (Hochman *et al.* 1989). Often, historic practice, for example 2.5 t lime.ha^{-1}, is used based on 0-0.1 m soil pH values alone. The pH threshold to trigger liming varies between growers/advisors but is often between pH_{Ca} 4.5 to 4.8 due to the relationship with pH and exchangeable aluminium. However, it is probable that at those pH_{Ca} values in the 0-0.1 m, most soils would contain more acidic layers within that depth (Figure 1). Incorporation would be necessary to mix the lime applied into the most acidic layers present within the 0-0.1 m depth in order to increase the effectiveness of the lime applied. As it is not uncommon for the most acidic layer to occur at 0.1-0.15 m (Burns and Norton 2018a), testing pH of samples collected in 0.05 m intervals to a depth of 0.2 m is recommended. It is important to know the depth and severity of the acidic layers before determining a liming rate and the depth of incorporation required for selected crop or pasture sequences.

The implement used to incorporate lime can influence the effectiveness of lime on crop or pasture performance in the year of application; although differences diminish in subsequent years (Scott and Coombes 2006). The use of offset discs in a study near Wagga Wagga, NSW, were found to be more effective compared with tined implements or harrows. Multiple (two to four) passes of tined implements were required to gain the same effectiveness as offset discs (Scott and Coombes 2006). Compared to surface applied lime, incorporation of lime by tillage with offset discs decreased the time required for lime to influence pH in the 0.05-0.1 m layer in the field (Conyers et al. 2003). In the 0.05-0.1 m layer, it took four years for surface applied lime to have the same effect as lime incorporated by offset discs. Whist that study involved treatments using offset disc and a scarifier (a tined implement with 0.15 to 0.2 m row spacing), no direct treatment comparison of tillage implement on the effectiveness of lime was possible as implement comparisons were compromised by differences in stubble management (burning or retention) and crop rotation.

Though incorporation is not possible in permanent perennial pastures and where erosion risk is high due to landscape gradient, some managers of arable land are choosing not to incorporate due to perceived damage to soil structure by cultivation. The influence of one cultivation event on structural stability was shown to be short lived, between 12 and 24 months, on three contrasting soils in NSW (Conyers *et al.* 2019). Therefore, the risk of lasting structural damage to soil by incorporation of lime once in a 6 to 8-year rotation is negligible, on land at low risk of erosion. Even where growers are incorporating lime, the depth of effective mixing is often less than the depth of incorporation, resulting in persistence of acidic subsurface layers within the 0.05-0.1 m layer (Conyers and Scott 1989; Scott and Coombes 2006; Burns *et al.* 2017). Not only does the cultivation operation fail to achieve the acidic soil management objectives; the production limitation due to acidity remains within the 0-0.1 m layer, often undetected because the 0-0.1 m layer was collected as one sample. Furthermore, a component of the lime applied will remain unreacted in the surface soil, representing inefficiency of lime addition and opportunity cost to the system. It is possible that a lower rate of lime may have achieved the same outcome, at least in the short term.

Lime is sparingly soluble and the rate of dissolution slows as the pH increases, particularly above pH_{Ca} 6.0 (Scott *et al*. 1999). The pH at the soil surface (0-0.025 m) is commonly higher than other layers of the 0-0.1 m in pH stratified soils. Therefore, lime spread on the soil surface without incorporation will react very slowly. Much of the applied lime may remain unreacted for years, dissolving very slowly, with the rate of reaction increasing only when in contact with additional H^+ (Conyers *et al.* 2020). Therefore, the current industry practice of applying lime at rates calculated by liming models that assume incorporation of lime to 0.10 m depth is questionable. A greater percentage of applied lime will dissolve with lower rates of application rather than higher rates (Conyers *et al.* 2020). Production and economic efficiencies of surface applied lime may be improved by more regular application of lower rates which optimise lime dissolution in the surface 0-0.025 m of soil and maximise the downward movement of alkali. This is particularly important given that surface application is the only practical application method for pastures grown on erodible soil. In that context, any unreacted lime may be susceptible to loss from the field by erosion.

It has been demonstrated in the field (Conyers and Scott 1989 and Li *et al.* 2019a) that the soil pH needs to be greater than pH_{Ca} 5.5 in order for bicarbonate from dissolved lime to move below the depth of placement (Conyers *et al*. 2003). Interestingly, in the study of Conyers and Scott (1989), a liming rate of 8 $Mg.ha^{-1}$ was required to increase pH_{Ca} >5.5 in the 0-0.1 m. At the time, this was interpreted by advisors as a general requirement for high rates of lime being needed to move the lime effect deeper in the soil. The reality was that the 8 t $lime.ha^{-1}$ was required due to a very low initial soil pH_{Ca} (4.1). If the pH prior to liming is higher, a much lower rate of lime is required to maintain pH_{Ca} >5.5 and increase pH below the depth of placement (Li *et al.* 2019a).

Under field conditions Li *et al.* (2019a) observed a 0.9 pH unit increase from an initial pH_{Ca} 4.2 in the 0.1-0.2 m layer after 18 years of agricultural production when 0-0.1 m pH was maintained above pH_{Ca} 5.5. In contrast, under management where lime was not applied in the 0-0.1 m layer, acidification of the subsurface soil continued at 0.005 pH units $year^{-1}$ in the 0.1-0.2 m layer representing unchecked long term degradation (Li *et al.* 2019a). This results in an increase of depth of acidic soil layers (Angus 2018; Li *et al.* 2019a), further decrease in agricultural production and greater limitation of species and varietal choice to land managers.

Direct and deep placement of ameliorants

More rapid amelioration of acidic layers present below the depth of incorporation with common farm equipment (often less than 0.1 m) is also possible. Liming materials can be placed directly into the acidic subsurface layers (Davies *et al.* 2019, Price 2020) or soluble alkali sources may be applied to enhance downward movement of amelioration (Nguyen *et al.* 2018, Butterly *et al.* 2020).

Direct placement of prilled lime, applied into the most acidic soil layer (0.075-0.125 m) by a conventional seeder at a rate of 300 kg.ha^{-1}, immediately prior to sowing, was shown to be effective in ameliorating subsurface acidity (pH$_{Ca}$ 4.3) within the sowing row over one season at Wagga Wagga, NSW (Price *et al.* 2020). This was significantly more effective in ameliorating the acidic subsurface layer than surface applied lime (2 Mg.ha^{-1}) incorporated by an offset disc immediately after lime addition. However, the use of direct placement of liming product only increases the soil pH in the sowing row whereas the incorporated surface lime also increased soil pH between sowing rows. Prilled lime may therefore be an effective method of ameliorating the acidic subsurface layers formed in the sowing row (Figure 2) of continuously cropped soil.

Deep placement (0.15-0.3 m) of liming materials (lime, dolomite, reactive phosphate rock and magnesium silicate) was shown to increase soil pH and remove toxic concentrations of exchangeable aluminium under field conditions (Condon *et al.* 2018; Li *et al.* 2018). However, the deep ripping required for placement of materials at depth can have a negative impact on seedling emergence in the year of application. This may occur due to the potential to mix hostile subsoils with topsoil, increased evaporation, or poor seed depth control when seeding on a soil loosened by ripping (Davies *et al.* 2019). Li et al. (2018) reported lower seedling densities in all ripped treatments of a direct placement trial near Cootamundra, NSW. Whilst, Condon *et al.* (2018) demonstrated that in a field experiment where conditions of acidity had been ameliorated, yield increases still occurred in the year of application but only where treatments also provided addition nutrients (reactive phosphate rock or lucerne pellets) to subsurface layers. This was also demonstrated in pot experiments, using the same acidic soil, for a range of organic materials (Lauricella *et al.* 2018).

The productive and economic effectiveness of deep placement of liming materials is possibly limited by the width and row spacing of machinery available, the depth of placement and the effectiveness of mixing of amendment and soil within the ameliorated row. In the field experiments of Condon *et al*. (2018) and Li *et al.* (2018), amelioration only occurred, vertically or spatially, in the soil where amendment was placed. They sowed crops using a 0.25 m row spacing, with GPS guidance, so that sowing rows straddled the deep placed amendments (ripped on a 0.5 m spacing). This sowing method was designed to ensure that each plant had the same access to the amended soil. However, it is possible that plant access to amended soil was hindered by the presence of acidic soil between the sowing row and the amended row.

Soil sampling of land that has been amended by the deep placement of liming agents is complicated by the vertical and lateral variation caused by amended bands. To overcome this, Lowrie *et al.* (2018) developed a multi-coring technique that enables six soil cores to be taken simultaneously and perpendicular to the amendment row. The width of the multi-corer ensures that a six core transect only ever includes one amended row. Soil from each core can then be divided into sampling depth increments providing samples from a two-dimensional representation of the soil perpendicular to the amended row.

It has been demonstrated that organic amendments, either alone (Moroni *et al.* 2018) or in combination with inorganic liming materials (Nguyen *et al.* 2018), can increase soil pH below the site of application compared with lime application alone. It is hypothesised that soluble organic molecules leach to greater depths than lime, thereby reacting with, and ameliorating, deeper acidity. This has been shown to be effective regardless of the depth of initial application (Table 2) (Moroni *et al.* 2018). The addition of organic matter (ground lucerne pellets) in combination with lime appears to enhance the ability of surface applied alkali to move to greater depth (Nguyen *et* *al.* 2018). Nguyen *et al*. (2019) reported an increase of approximately 0.5 pH_{Ca} units in the 0.05-0.1 and 0.1-0.15 m layers when lime was added with lucerne pellets in the surface (0-0.05 m) compared with lucerne pellets alone. This could be an effect of more bicarbonate movement due to higher pH or movement and subsequent oxidation of dissolved organic carbon molecules from the organic matter, as hypothesised by Butterly *et al.* (2020). Regardless, results indicate that it may not be necessary to directly place organic ameliorants at the depth of acidity. It may be possible to enhance the movement of alkali with application of mixes of organic matter and lime, at or near the soil surface.

Insert Table 2 here

However, the alkali released by the organic material in days after application may then be neutralised by acidifying reactions over a period of weeks or months (Nguyen *et al.* 2018). This is mostly likely the result of nitrification of ammonium produced from the decomposition of soluble organic materials (Butterly *et al.* 2020) and subsequent leaching of the nitrate produced. Understanding of the mechanisms involved in such pH change requires more investigation at appropriable fine sampling increments (Black *et al.* 2004). If the mechanisms are as hypothesised, organic matter addition may result in further pH stratification below the site of amendment application as a result of deeper nitrification. The re-acidification reported by Nguyen *et al.* (2018) indicates that application of organic materials containing labile organic nitrogen may not provide long lasting amelioration of soil acidity unless applied with lime.

Preventative management

Amelioration of deep soil acidity (>0.15 m) using adequate rates of surface applied lime is slow and deep placement of ameliorant is expensive and has marginal effectiveness on yield over the 3 to 5 years of most trials on soils of eastern Australia (Davies *et al.* 2019). Therefore, the best management involves combating acidification of the subsurface soil layers to prevent acidification moving to greater depths.

Current soil management practices that involve 0-0.1 m sampling, surface application and ineffective incorporation of lime, applied at rates calculated to be only sufficient to ameliorate toxic aluminium concentrations (i.e target approximately pH_{Ca} 5) and initiated when pH is found to be below pH_{Ca} 4.8 are not addressing the ongoing acidification in the subsurface 0.05-0.15 m (Burns *et al*. 2018a, Li *et al.* 2019a). Many of these practices and triggers are based on a poor understanding by growers and advisors of soil processes associated with acidic soil amelioration and over-simplified guidelines derived from recommendations that were originally developed for conventional tillage systems that included regular cultivation. The response of growers and advisors to soil acidity is reactive, influenced by commonly recognised clinical symptoms that are typical of low pH and aluminium toxicity, such as poor nodulation in legumes and stunted root systems. However, expression of such symptoms is likely to occur after the plant is in a state of reduced function, manifested after the plant is stressed and production potential has already been compromised.

Insert Figure 5 here

It is recommended that a shift be made to more proactive management of acidic soils to avoid acidification of subsurface layers and long-term damage to soil function. Figure 5 represents groupings of NSW soil profiles reported by Burns and Norton (2018b). The sites represented by the severely acidic profile, which have pH values of ‘extreme risk’ to agricultural production, have a calculated 0-0.1 m $\mathrm{pH_{Ca}}$ of 4.6 and would probably be prioritised by growers and advisors to receive a lime application the following year. However, the ‘moderate risk’ with 0-0.1 m $\mathrm{pH_{Ca}}$ calculated to be 5.1 may not be scheduled for lime application. Based on current industry understanding there is a presumption that even crops relatively sensitive to soil acidity (e.g. barley and pulses), would not suffer a yield penalty when sown into soils with 0-0.1 m $\mathrm{pH_{Ca}}$ value of 5.1. However, as reported by Burns and Norton (2018b), pulse crops in such soils, with $\mathrm{pH_{Ca}}$ <4.8 at 0.05-0.15 m are at risk of reduced nodulation and yield; they cautioned that yield of barley and canola may also be compromised. If incorporation of lime is not an option, given the slow movement of alkali from surface applied lime, management practices aimed at ameliorating soil acidity under zero tillage farming systems must shift from mitigation of acidic soil to prevention of acidification. Conyers *et al.* (2003) concluded that while surface applied lime at rates required to remove available aluminium from solution may be satisfactory for maintenance of soil pH at $\mathrm{pH_{Ca}}$ 5, it will not overcome an existing subsurface acidity problem. Thus, while the ‘low risk’ profile in Figure 5 would traditionally be a low priority for lime application, under zero tillage systems these soils should be targeted for maintenance lime rates to maintain pH of the 0-0.1 m layer above $\mathrm{pH_{Ca}}$ 5.5 and potentially avoid further subsurface acidification. Conyers *et al*. (2003) proposed that under such management, alkali movement into the soil below 0.05 m will hopefully exceed the concurrent acidification rate at depth. Research to validate this approach aimed at prevention of subsurface acidification is underway but relies on investment to support long-term field experimental sites.

Conclusions

The extent and severity of subsurface acidity identified by recent surveys of some of the most productive soils of the southern NSW were concerning. There is no coordinated effort by industry to effectively monitor changing soil condition under productive agricultural systems. Maps created from historic data or from models that do not account for the impact of agricultural management practices cannot represent the current status of soil pH or the presence of pH stratification at a landscape or paddock scale. This highlights the urgent need to introduce a framework to monitor change in soil pH that will enable acidification of agricultural soils to be effectively measured and monitored, and the effectiveness of actions to mitigate and/or prevent acidification to be assessed.

Traditional soil sampling protocols, the current industry practice of insufficient liming rates (target pH_{Ca} 5) and poor incorporation of surface applied lime have several impacts. Firstly, as the soil pH is stratified, exhibiting acidic subsurface layers within the surface 0.1 or 0.15 m, the standard practice of 0-0.1 m soil sampling fails to identify the actual extent or severity of the acidity. Therefore, finer sampling at increments of 0.05 m is recommended in order to identify pH stratification for the purposes of diagnosing agronomic problems, managing soil fertility and monitoring the impact of land management on soil properties. Secondly, the acidity below the depth of incorporation remains to limit production, especially of acid-sensitive legumes crop and pasture species. In a farming context, this production loss is made worse given that the grower has expended the funds to apply lime, only to limit the effectiveness of the input expenditure by seeking a suboptimal target and failing to incorporate and improve the effectiveness of the applied lime.

Amelioration of acidic subsurface layers is possible via long-term management of surface soil pH or rapid, but costly direct placement of liming materials into the acidic layer. It has been demonstrated in one study (Li *et al*. 2019) that cost-effective amelioration of acidic subsurface layers is possible over the long term (18 years) by maintaining the 0-0.1 m layer at $pH_{Ca}>5.5$. However, more research is required to determine the most efficient management practices to achieve rapid amelioration of subsurface acidity and to develop strategies to minimise or prevent ongoing subsurface acidification. This may include studies of lime application rate and frequency, incorporation method, timing within rotation, field validation of the interaction between organic matter and lime in the downward movement of added alkali and studies to quantify crop and pasture response to changing pH (both increasing and declining) in soils with stratified pH. The required research needs to span various cropping and pasture production systems over different rainfall zones and should include research that investigates the potential production loss resulting from unchecked acidification and quantify the financial and environmental cost of failing to prevent the ongoing degradation of agricultural systems and loss of soil function. This will need significant investment in long-term sites and multi-disciplinary teams to quantify the soil, microbial, agronomic, environmental and financial impacts of changed practice. Such research would underpin the delivery of evidence-based, consistent and regionally relevant guidelines to growers and advisors.

Without additional research, growers will not have the evidence required to confidently change practice and will continue implementing ineffective management of acidic soils. This will result in continued degradation of subsurface soil and a long-term loss of soil ecological function, including food production, carbon sequestration and provision of biodiversity.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors thank Dr Jonathan Gray (NSW Department of Planning, Industry and Environment) for providing modelled data of pH of NSW (Gray *et al.* 2015 and OEH 2018) and Michelle Miller (NSW Department of Primary Industries) for GIS and spatial analysis of those, and land use data to calculate areas presented in Table 1. The technical assistance of Andrew Price in the analysis of soil pH data for Figure 2 is also greatly appreciated. The manuscript was greatly improved by the suggestions of reviewers. This research did not receive any specific funding.

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Table captions:

Table 1 Comparison of estimated area of agricultural land in NSW (Mha) exhibiting specific soil pH_{Ca} range by survey and modelling methods.

Area estimates of soil pH_{Ca} from Gray *et al*. (2015) and OEH (2018) were calculated based on inclusion of agricultural land uses (22.6 Mha) defined by the Australian Land Use and Management (ALUM) classification for NSW (DPIE 2019), excluding native pastures.

Table 2 Effect on soil pH_{Ca} of lime or ground lucerne pellet (LP) placement within layers of reconstructed soil columns of a Yellow Chromosol taken from Holbrook, NSW.

Note: ***** = indicates significant differences (LSD = 0.196, at *P* = 0.05) of a pair-wise means comparison of treatment relative to the unamended treatment. (Adapted from Moroni *et al.* 2018).

Figure captions

Figure 1. The relationship between mean soil pH of the a) 0-0.1 m (●, regression solid line), b) 0-0.05 m (▽, regression dashed line) and 0.05-0.1 m (■, regression solid line) depth increments and the minimum soil pH of any 0.025 m depth increment within those increment ranges for 31 soils between Albury and Cowra, NSW. Dotted line in a) and b) represents 1:1 isoline.

Figure 2. Soil pH_{Ca} taken on (▼） or between (●）the sowing row (0.25 m spacing) following 5 years of continuous annual cropping with GPS guidance at Burrumbuttock, NSW. Horizontal bars represent LSD (*P*=0.05), ns = no significant difference.

Figure 3. Soil pH_{Ca} stratification resulting from lime application within 5 years (▼, n =33) or more than 5 years (●, n=15) of sampling from locations between Albury and Cowra, NSW. Horizontal bars represent LSD (*P*=0.05), ns = no significant difference. (Adapted from Burns and Norton 2018a).

Figure 4. The relationship between wheat grain yield (cv Janz; $Mg.ha^{-1}$) and soil pH_{Ca} of the 0-0.1 m layer of a site near Jindera NSW, that exhibited 0.1-0.2 m pH_{Ca} of 4.1 to 5.3 in 0.3 unit increments (redrawn from Scott *et al*. 1999).

Figure 5. Mean soil pH_{Ca} profiles of 31 field sites from locations between Albury and Cowra, NSW, characterised as nil (●,n=3), low (▼,n=6), moderate (■,n=12）and extreme (◆,n=10) risk of pH

negatively impacting on agricultural production (Source: Burns and Norton 2018b). Horizontal bars are plus and minus standard error of means.

Table 1 Comparison of estimated area of agricultural land in NSW (Mha) exhibiting specific soil pH_{Ca} range by survey and modelling methods.

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	Area of agricultural land (Mha)						
	Helyar *et al*. (1990)	Gray *et al*. (2015)	OEH (2018)		Lockwood *et al*. (2003)		
pH_{Ca}	0-0.1 m	0-0.1 m	0-0.05 m	0.05-0.15 m	pH_{Ca}	Soil test 0-0.1 m	ASRIS 0-0.1 m
<4.5	5.3	0.7	0.9	1.0			
4.51-5.0	8.4	4.3	4.6	4.5	<4.8	8.2	5.0
5.01-5.5	5.7	5.6	5.6	5.3	4.8-5.5	10.6	12.7
5.51-6.0	5.1	5.1	5.2	5.0	>5.5	18.8	20
6.01-7.0	7.6	4.6	4.5	4.2			
>7.1	2.2	2.3	1.8	2.6			
Total area	34.3	22.6	22.6	22.6		37.6	37.7

Table 2 Effect on soil pH$_{Ca}$ of lime or ground lucerne pellet (LP) placement within layers of reconstructed soil columns of a Yellow Chromosol taken from Holbrook, NSW.

Note: ***** = indicates significant differences (LSD = 0.196, at P = 0.05) of a pair-wise means comparison of treatment relative to the unamended treatment. (Adapted from Moroni *et al.* 2018).

Soil layer (m)	Control	1st layer		2nd layer		3rd layer		1st & 2nd layer		1st and 3rd layer	
	None	lime	LP	lime	LP	lime	LP	lime	LP	lime	LP
1st (0-0.1)	4.6	5.2*	5.1*	4.6	4.6	4.6	4.6	5.1*	5.5*	5.1*	5.2*
2nd (0.1-0.2)	4.2	4.2	4.5*	5.4*	5.5*	4.2	4.2	5.4*	5.7*	4.2	4.8*
3rd (0.2-0.3)	4.2	4.2	4.4	4.2	4.5*	4.7*	5.4*	4.2	4.9*	4.6*	6.0*
4th (0.3-0.4)	4.4	4.4	4.6*	4.4	4.6*	4.4	4.6*	4.4	4.9*	4.4	4.9*

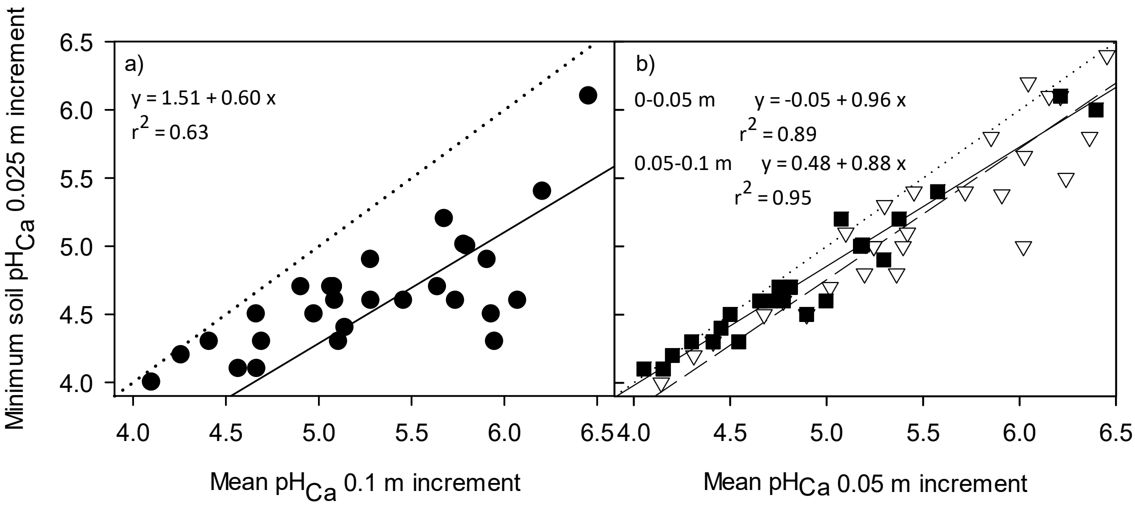

Figure 1. The relationship between mean soil pH_{Ca} of the a) 0-0.1 m (●, regression solid line), b) 0-0.05 m (▽, regression dashed line) and 0.05-0.1 m (■, regression solid line) depth increments and the minimum soil pH of any 0.025 m depth increment within those increment ranges for 31 soils between Albury and Cowra, NSW. Dotted line in a) and b) represents 1:1 isoline.

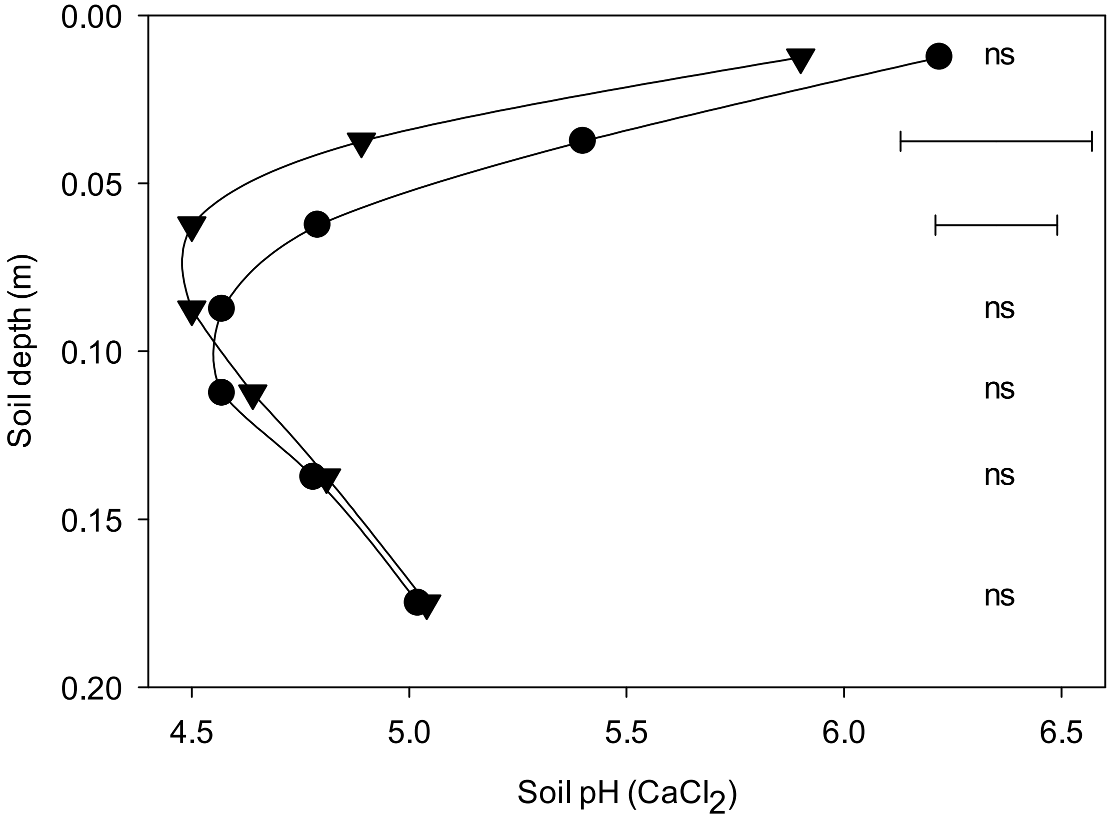

Figure 2. Soil pH_{Ca} taken on (▼) or between (●) the sowing row (0.25 m spacing) following 5 years of continuous annual cropping with GPS guidance at Burrumbuttock, NSW. Horizontal bars represent LSD (*P*=0.05), ns = no significant difference.

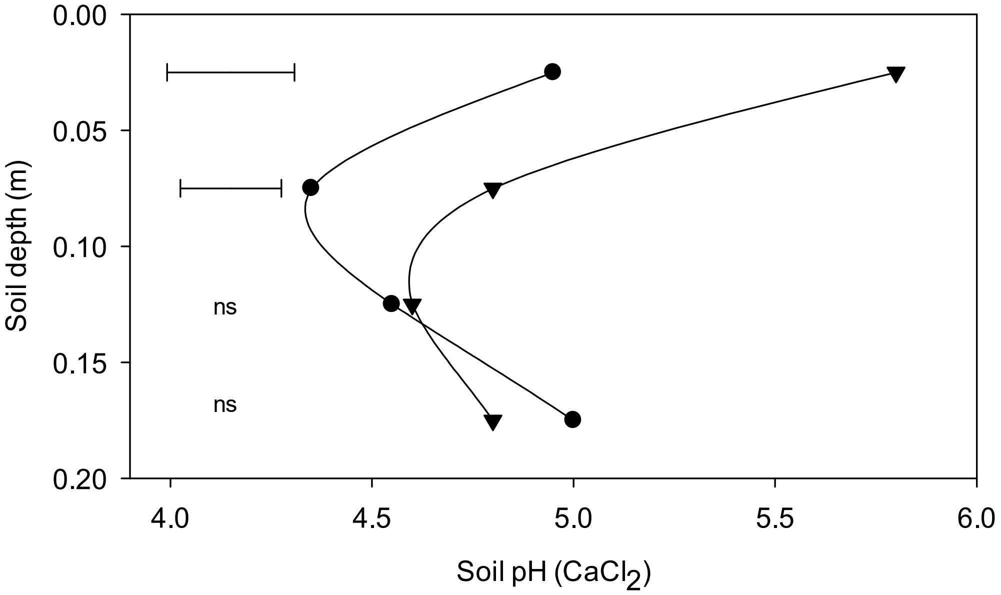

Figure 3. Soil pH_{Ca} stratification resulting from lime application within 5 years (▼, n =33) or more than 5 years (●, n=15) of sampling from locations between Albury and Cowra, NSW. Horizontal bars represent LSD (*P*=0.05), ns = no significant difference. (Adapted from Burns and Norton 2018a).

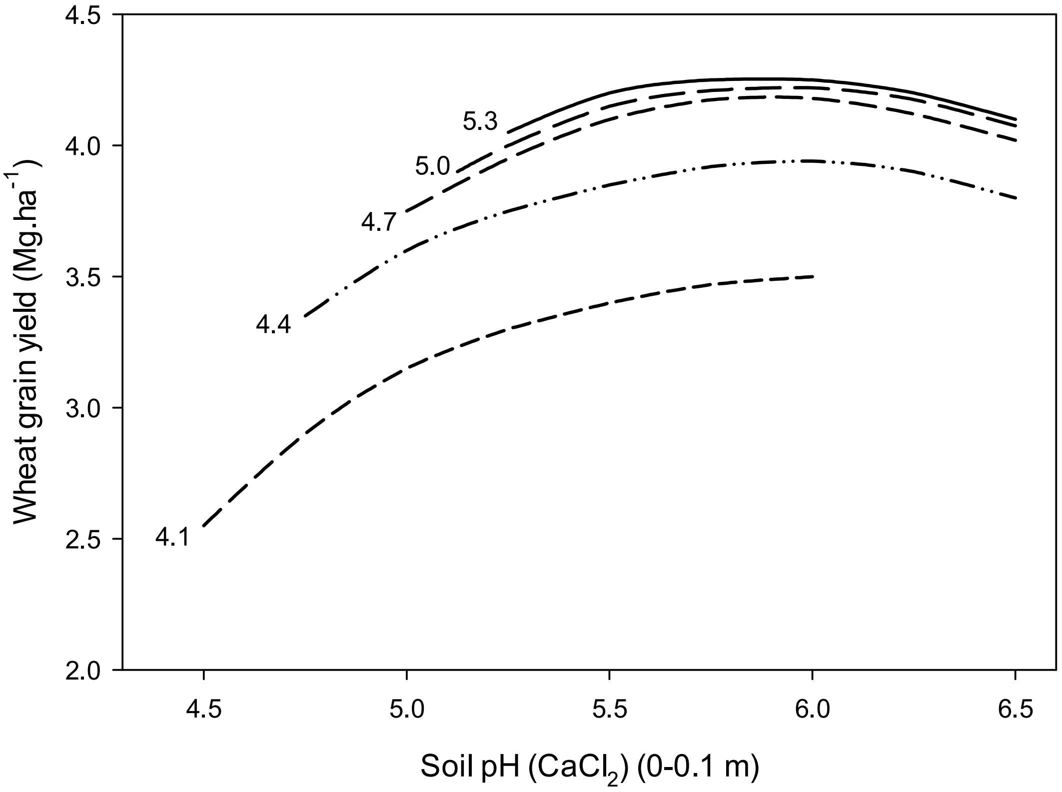

Figure 4. The relationship between wheat grain yield (cv Janz; Mg.ha^{-1}) and soil pH_{Ca} of the 0-0.1 m layer of a site near Jindera NSW, that exhibited 0.1-0.2 m pH_{Ca} of 4.1 to 5.3 in 0.3 unit increments (redrawn from Scott *et al*. 1999).

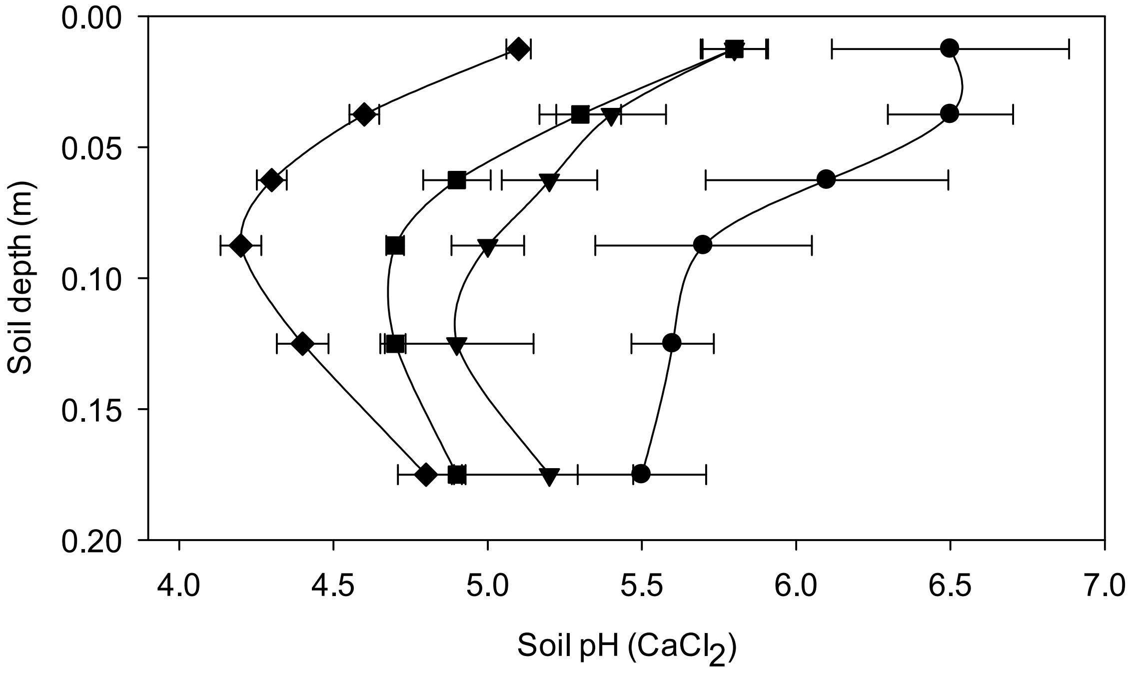

Figure 5. Mean soil pH_{Ca} profiles of 31 field sites from locations between Albury and Cowra, NSW, characterised as nil (●,n=3), low (▼,n=6), moderate (■,n=12）and extreme (◆,n=10) risk of pH negatively impacting on agricultural production (Source: Burns and Norton 2018b). Horizontal bars are plus and minus standard error of means.