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Your Reference number (generally CM9)

Introduction

Acidic soils are an impediment to agricultural production. More than half of the intensively used agricultural land in NSW is affected by soil acidity. While soil acidification is a natural consequence of weathering processes of soil formation, todays agricultural practices increase acidification thus placing limitations on future production. In some areas this results in permanent degradation of NSW soils.

It has been estimated that the cost of soil acidity in terms of annual lost agricultural production in Australia are A$1,585 million[1] And these costs are most pronounced in the high-rainfall regions of New South Wales, Victoria and Western Australia where yield gaps have been estimated to be .1–0.2 t ha−1yr−1[2].

The National Land & Water Resources Audit (2001) identified soil acidity as the most serious land degradation issue for Australian agriculture and estimated that 50 million hectares of Australia's agricultural land are already experiencing impacts from soil acidity in surface layers and a further 23 million hectares in subsurface layers[3]. Subsequent State of the Environment reporting shows soil acidification continues to be have an increasing impact on soil condition[4].

The maps here give a broad overview of pH levels at two soil profile depths for NSW. However, in order to diagnose and manage an acidic soil, a soil test from a reputable laboratory is required of the individual paddock or landscape element(s)

Maps courtesy of Environment, Energy and Science | Department of Planning, Industry and Environment OEH 2018. Digital soil mapping of key soil properties over NSW, version 1.2. Technical Report, NSW Office of Environment and Heritage, Sydney. (prepared by J. Gray)

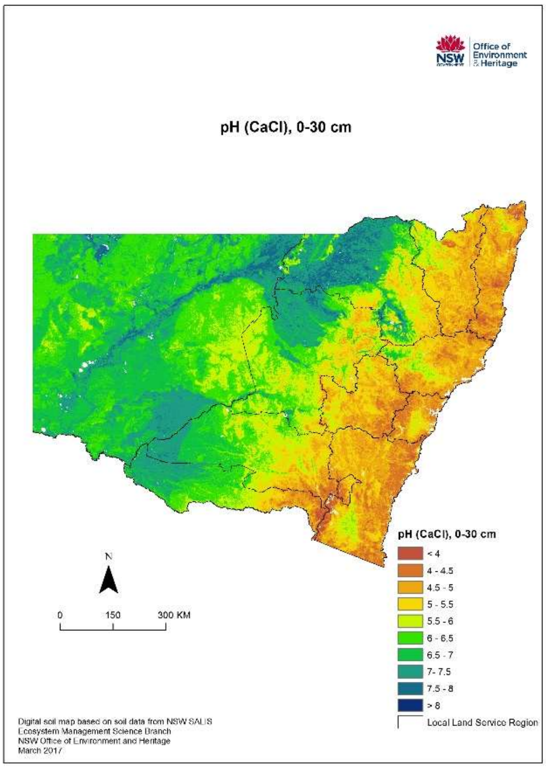

Figure 1. soil pH 0-30cm below surface

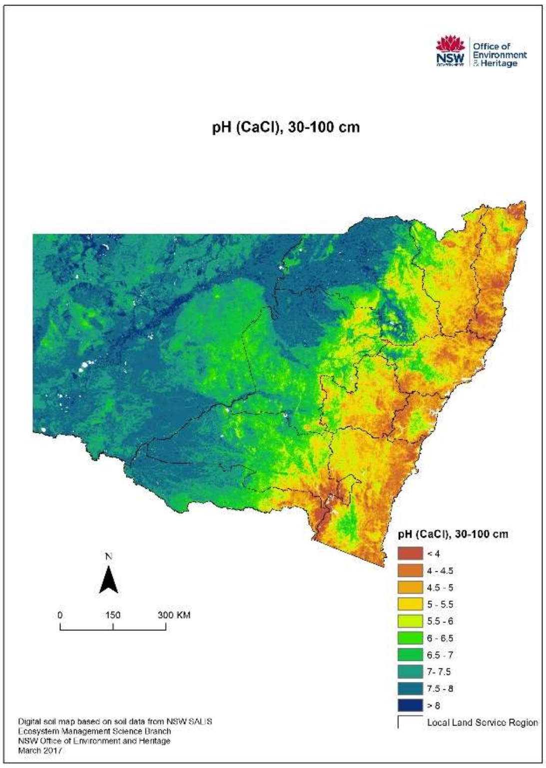

Figure 2. soil pH 30-100cm below surface

What is an acid soil?

- Technically an acidic soil is one with a soil pH_{Ca} below 4.8 in the root zone (0-20cm).
- A soil pH_{Ca} between 5.5 and 8.0 provides the best conditions for most agricultural plants.
- Sometimes soil acidity is a natural characteristic of the soil which may be difficult to improve economically.

If the pH_{Ca} drops below 5.0, plants that are highly sensitive to acidity, such as some legumes and barley, are adversely affected. Plants that are more tolerant of acidity continue to grow normally until the pH_{Ca} falls below 4.8. However, it is important to note that often Rhizobium bacteria are more sensitive to soil acidity than the host plant. This means nodulation and nitrogen fixation will be impaired before the host plant is affected (see table 7). Not only does this have negative effect on the legume itself but the lack of effective nodulation nitrogen fixation reduces the nitrogen contribution of legumes in both crop and pasture systems.

Below pH_{Ca} 4.4 most plants, except the very highly acid tolerant plants like oats, narrow leaf lupins and the native pasture grass Microlaena spp, show a significant reduction in production. Even tolerant species productive capacity will be affected by soil acidity. Although plant death may not be the result production will be sub-optimal

Acidity and alkalinity in any solution is measured as pH. Soil pH is an estimate of the acidity/alkalinity of the soil solution, which is the water that is held in the soil.

The pH scale is logarithmic, which means that every point is an order of magnitude different from that below or above it. For the pH scale in particular this means that a pH of 4 is 10 x more acid than 5 and 100 x more than a pH of 6. (Figure 4).

How can I tell if soil acidity is a problem?

Although reduced production is often the end result., the visual signs of soil acidity are more subtle than the clearly visible symptoms of other soil degradation, A soil test is the most reliable way to assess if a soil is acidic.

The only reliable way to determine if a paddock has an acidic subsurface soil is to

Image 1: Field pH test kit uses the water method and pH values are 0.5 to 0.8 higher than the pH in $CaCl_2$

sample and analyse the 0-5cm, 5-10cm, 10–15, 15-20 cm, and 20–30 cm layers.

A field test using a field soil pH kit or meter is a good place to start (Image 1). It is simple to carry out and will indicate if further investigation with a full laboratory test is required and at what intervals samples should be taken. This level of detail is required decide which management strategies to employ and helps in species selection.

A comprehensive chemical analysis of the surface soil layers (0–5, 5 -10 cm, 10-20 and 20-30cm depths) will give information to assist in determining if a crop or pasture will be affected by acidity. In order to assess whether acid sensitive crops will be affected by subsurface acidity, it is recommended that subsurface be tested for pH (as outlined) especially where reduced tillage has been used. In higher rainfall areas subsurface soil layers are more likely to be acidic. If the pH_{Ca} of the 0–10 cm layer is less than 4.8 then the subsurface soil may be acidic.

Read what are Signs and symptoms for other indicators

The acidity of soil varies throughout the year, and down the profile. The pH in summer is, in most circumstances, higher than that in winter by up to 0.5 of a unit. Therefore, the timing for collection of a soil sample and the sampling depth are important considerations. This is particularly important when making recommendations for winter crops based on analysis of samples taken over summer. In this publication recommendations are made on the basis that the samples for analysis are taken in late summer or early autumn.

What to test

There are two accepted ways to measure soil pH; one in water and one in calcium chloride The pH measured in calcium chloride is on average 0.5 to 0.8 less than pH measured in water, although the difference can vary from nil to 2.0 for different soils, soil textures and salt content. In this publication pH is nominated as pH_{Ca}.

Soil acidity throughout the profile

Examination of soil pH down a soil in profile has revealed that the process of soil acidification within the soil profile results in a stratification of soil pH. This means that the topmost surface of the soil profile (0-5cm) will often have a higher pH than those below. But it is these deeper layers that are important for plants to achieve their productive potential as it is where most plant roots grow. When acidification is not managed it becomes more and more difficult to remediate. The greater the depth of the acidic layer, the greater the effect on plant growth and the more difficult it is to correct. Untreated subsurface soil acidity is long term degradation of the soil.

Whilst models showing the chemical process of soil acidification are very good at explaining the chemical causes, these models do not account for the three-dimensional nature of soil in the paddock. They do not account for movement of acidity within the soil profile nor the fact that a soil profile is not uniform. This spatial variation results in stratification of soil pH down the soil profile in increments

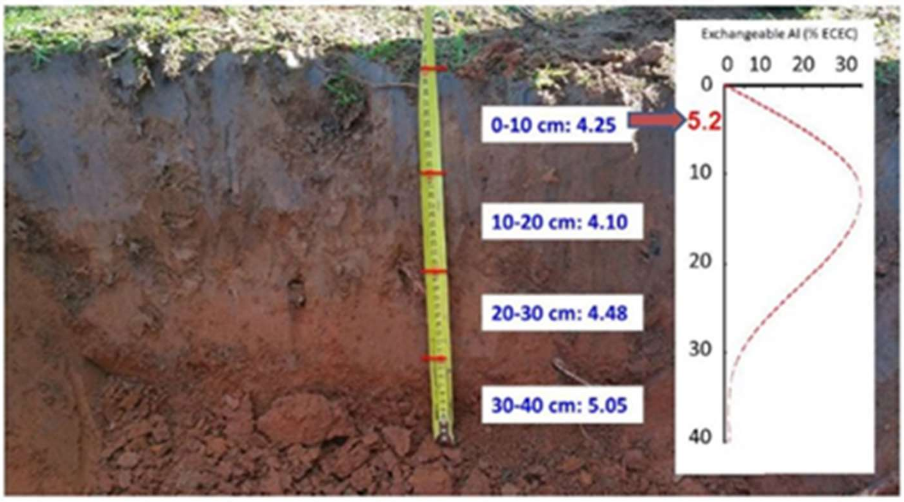

Figure 3: Soil pH change and corresponding exchangeable Aluminium change throughout the soil profile of a Yellow Chromososl at Holbrook, NSW

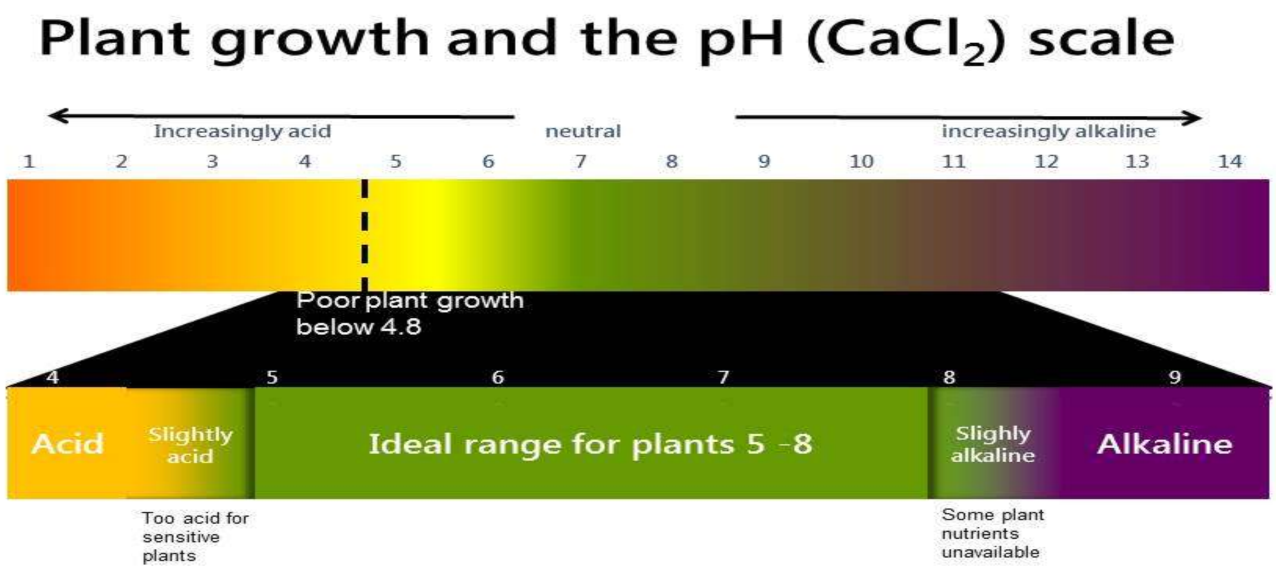

Figure 4: pH scale showing limit for plant growth

as small as 0-5cm, 5-10cm, 10-15cm etc. and can be exacerbated by modern farming techniques such as reduced tillage. For further information on causes of soil acidity and stratification see next section

What causes soil acidification?

- Acidification of the soil is a slow natural process and part of normal weathering.
- Many farming activities cause an increase in the rate of acidification of the soil.
- Changes in soil pH_{Ca} under agricultural use are measured in tens of years rather than thousands of years as in the natural environment.

There are four ways that agriculture contributes to the accelerated acidification of the soil and these are:

- **Removal of produce**
- **Use of fertilisers containing ammonium or urea**
- **movement of nitrate nitrogen sourced from nitrogen fixation or from ammonium fertilisers**
- **Build-up of soil organic matter.**

In some older texts the removal of "base" cations, that is calcium, magnesium, potassium and sodium, is given as a cause of soil acidity. This is misleading, and in a similar vein acidity cannot be corrected by applying calcium.

Rate of acidification

It is possible to estimate the rate of acidification for a given paddock enabling budgeting for future liming programs. But

Table1. The amount of lime needed to neutralise the acidification caused by removal of produce.

Produce removed	Lime requirement kg/t of product/ha
Milk	4
Wheat	9
Wool*	14
Meat*	17
Lupins	20
Grass hay	25
Clover hay	40
Maize Silage	40
Lucerne hay	70

* Uneven deposition of animal excreta in stock camps leads to further acidification.

it is best to use lab test results of your soil to determine liming requirements.

Rainfall is the climatic feature that has the greatest effect on the rate of soil acidification as it influences:

- plant productivity (which includes the amount of nitrogen fixed by legumes)
- movement of nitrate nitrogen

These factors interact in their influence on the rate of acidification.

In the past there has been a misconception that perennial pastures can be used to prevent soil acidification. This is not the cases as previously explained in the previous section. This is not a solution to the acidification of surface soils as plant use of nitrate nitrogen takes place below the zone where H+ ions are released and thus acidification will still occur. Furthermore, recent work [7] found that acidification rates for perennial and annual pastures were the same at the same site. Acidification from nitrate movement under annual pasture is equivalent to the greater product removal under perennial system

Removal of Produce

Grain, pasture and animal products are slightly alkaline and continued removal will lower the soil pH over time. This contribution to acidity is part of the "Carbon cycle". If very little produce is removed, then the system remains almost balanced. Where a large quantity of produce is removed as in the case of hay making (particularly legume hay), the soil is left significantly more acidic. For details on the quantity of lime needed to neutralise acidity relating to common agriculture products see Table 1.

Removal of produce by burning, for example burning of stubble, does not change the acid/alkali balance of the soil, but leads to a redistribution leaving alkali at the soil surface as ash. If the ash is then washed away, as might occur after a fire, this would leave the soil more acidic.

Use of nitrogen fertilisers

The amount of acidification that results from using nitrogenous fertilisers depends on the fertiliser type (Table 2). Fertilisers that contain nitrogen as ammonium, for example ammonium sulphate, acidify the soil within weeks after application. Calcium nitrate and sodium nitrate have a neutralising effect on soil acidity, unless all the nitrate is leached (Table 2) but they are expensive, and use is restricted to horticulture.

Table 2 Acidifying effect of nitrogenous fertilisers and legume-fixed nitrogen in terms of lime required to neutralise the acid

Nitrogen Source	Lime required (kg lime/kg N) for % Nitrogen moved		
	0%	50%	100%
High acidification • Sulfate of ammonium • Mono-ammonium phosphate (MAP)	3.7	5.4	7.1
Medium acidification • Di-ammonium phosphate (DAP)	1.8	3.6	5.3
Low acidification • Urea • Ammonium nitrate • Aqua ammonia • Anhydrous ammonia • Legume fixed nitrogen	0	1.8	3.6
Alkalinisation • Sodium and calcium nitrate	-3.6*	-1.8	0

* Equivalent to applying 3.6 kg lime/ kg N

Using superphosphate fertiliser on crops and pastures does no40t directly acidify the soil. However, its us70e stimulates growth of clover and other legumes, resulting in a build-up in organic matter which in turn increases soil acidity. Also, there is an increase in nitrate nitrogen in the soil that comes with the higher levels of organic matter. This increases the likelihood of soil acidification from movement of nitrate nitrogen.

Applying pure sulphur (sometimes known as “flowers of sulphur”) will acidify the soil. An application of 3 kg of limestone for each kg of sulphur is required to neutralise this affect.

See Minimise acidification for options on product choice and application.

Build-up of organic matter

Over the last 50 years the regular use of fertiliser and improved pastures, particularly subterranean clover, has generally led to increased organic matter in the soil. While increasing organic matter has many benefits, including improvement of soil structure, it also increases soil acidity.

The acidification caused by a build-up in organic matter is not permanent and can be reversed if the organic matter breaks down. However, there will be a permanent change in the acid status of the soil if the topsoil containing the organic matter is eroded or removed.

Increased legume presence may also increase nitrate nitrogen in the soil. This increases the likelihood of soil acidification from movement of nitrate nitrogen, when mineralised nitrogen is not used effectively by the legume

What are the signs and symptoms of acidic soils?

Low pH in soil is a problem for agriculture and the environment because it can affect plant growth through its effect on:

- Nutrient solubility and accessibility
- Biological activity

Change in nutrient solubility and nutrient availability to plants:

Some nutrients may reach toxic levels, while others become insoluble (therefore unavailable) leading to deficiencies. The changes in the solubility of plant nutrients associated with increasing soil acidity:

- *Increased aluminium* (Al^{3+}) in the soil solution, causing stunted root development in crops and pastures (see image 2 & 3). Stunted roots result in reduced capability to access soil moisture and reduced nutrient uptake. In legumes resulting reduced nodulation and nitrogen fixation may also reduce survival
- *Increased manganese (Mn^{2+}) the soil solution,* causing reduced growth in some plants in some soils and toxicity symptoms in susceptible plants. (see images 6, 7 & 8)
- *Reduced solubility of molybdenum, phosphorus, and access to calcium*, while increased Al in the soil solution facilitates the *movement of Ca and Mg* down the soil profile where it is *less accessible* (see image 4 and 5, 9 and 10 and 11)

Some plants are more sensitive to aluminium than to manganese and vice versa. For example, white clover is relatively tolerant of aluminium but sensitive to manganese.

The degree to which soil acidity affects nutrient availability and therefore plant health and growth are affected by the results of soil acidity depends on both pH level, soil type and soil and organic matter levels.

Image 2. Stunted lentil plant growth and root development (left) in severely acidic layer at 4-10 cm (estimated pHCa < 4.5 by field soil pH test kit). The more vigorous plant (right) from the same paddock, with an estimated pHCa of 6.0 to a depth of 0-9 cm. (photo Karl Moore)

Aluminium (Al) Solubility

The actual amount of aluminium and manganese in solution in a soil at a given pH varies between soil type. Different soils

release different amounts of aluminium and manganese at the same pH_{Ca}. Figure 5 shows this; Al concentration increases with drop in pH but there is a large variation due to soil types and organic matter content. Weakly weathered soils that are acidic tend to release toxic amounts of soluble manganese, but lesser amounts of aluminium. Alternatively, highly weathered soils (other than a group of soils high in iron and aluminium oxides) tend to release large amounts of aluminium and lesser amounts of manganese.

Aluminium toxicity does not usually occur in soils where the pHCa is above 5.2. Applying sufficient lime to lift the pHCa above 5.5 will reduce the solubility of aluminium removing it from the soil solution.

Image 3. Stunted roots, with few root hairs and low nodule numbers are typical symptoms of pulse crops collected from sites with severely acidic subsurface layers with > 20% Exchangeable Aluminium. The pHCa of samples collected at 2.5 cm intervals show intense stratification at a Holbrook site (2015)

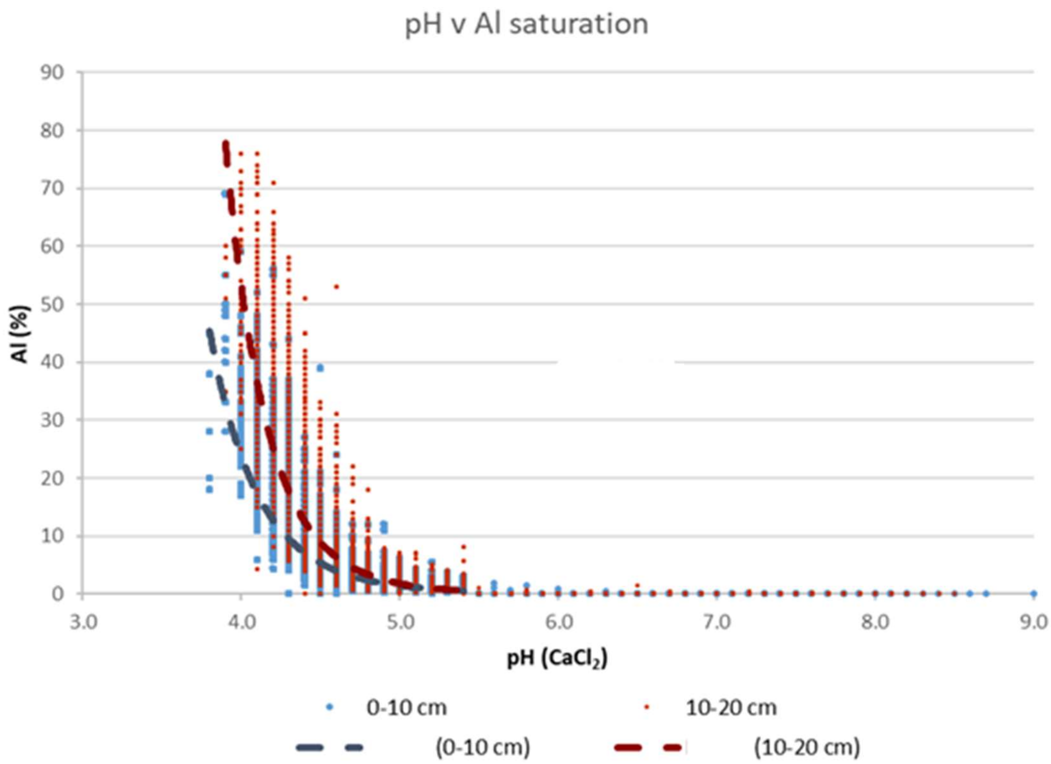

Figure 5. Range of Al concentration with pH of different soil types. (K Anderson)

Table 3 Sensitivity (tolerance) of some crops and pasture plants to soluble soil Aluminium

Exchangeable Al% for yield reduction at medium EC	Legumes	Grasses	Other
Highly sensitive 2-8% Al	• Medics: Barrel, strand, burr & lucerne • Clover: Strawberry, Berseem and Persian • Lentils • Chickpeas • Faba beans	• Tall wheat grass • Buffel grass • Durum wheat, • most barley	
Sensitive 9- 12% Al	• Clover: Red, Balansa White, Bladder • Medics: murex • Lupins: albus	• Wallaby grass (Austrodanthonia linkii), • Phalaris, • Barley: Yambla, • Wheat: Cunningham & Janz,	• Canola
Tolerant 13-21% Al	• Clover: subterranean, arrowleaf, gland	• Red grass (Bothriochloa macra) • Annual & perennial rye-grass, • Tall fescue, • Rhodes grass • Wheat: Whistler, Sunstate & Diamondbird	• Chicory • Fodder rape
Highly tolerant 22-30% Al	• Serradella: Yellow & French, slender • Lotus: Maku • Narrow leaf lupins	• Oats • Cocksfoot • Kikuyu • Paspalum • Common couch • Consol love grass • *Microlaena stipoides* • *Danthonia racemosa* • Themeda spp • Triticale • Cereal rye	

Medium EC is between 0.07 -0.23 dS/m

Different plants show different levels of tolerance to soluble aluminium levels in soil. See Table 3.

The principal effects on plant growth from soluble aluminium in the soil solution are:

1. Reduced root mass and function. The principal effect of aluminium toxicity is to reduce the mass and function of roots. Generally, this is seen in the field as stunted, club shaped roots. This reduces their ability to extract moisture and nutrients from deep in the soil and harvest nutrients. (See image 2 & 3). In legumes it also reduces root signalling of rhizobia resulting in poor nodulation and nitrogen fixation. It can also significantly reduce rhizobia survival

2. Tying up phosphorus. Soluble aluminium immobilises phosphorus in the soil and the plant, causing symptoms of phosphorus deficiency, that is, small and dark-green or occasionally purple leaves. The symptoms become more pronounced as the aluminium level increases. See image 4.

Image 4. Phosphorus deficiency in wheat

Note that applying lime to strongly acidic soils slightly increases plant access to soil phosphorus that is normally of low availability (such as residues of previously applied fertiliser). This effect is usually small, and normal phosphorus applications are still required when lime is used. It is very difficult to predict the amount of phosphorus that may be released from liming due to the complex soil chemistry involved

3. Reduced availability of calcium and magnesium. Very high levels of aluminium in the soil also reduce the uptake and utilisation of calcium and magnesium (images 5, 10 and 11).

Image 5. Calcium deficiency in wheat

Manganese (Mn) solubility

Toxicity from excessive amounts of available manganese can affect the growth of crops, pasture and horticultural crops in soils where pH_{Ca} is less than 5.5, but only in some soils and then only at certain times of the year. Plants require manganese in small amounts for photosynthesis and for several enzymes including those controlling the plant hormones called auxins. Toxic amounts of manganese disrupt photosynthesis and the function of plant hormones.

Because of the complexity of identifying toxicity using soil analysis and visual symptoms, analysis of plant tissue can help to determine if there is a toxic manganese problem. Comparing tissue analyses of healthy areas in a paddock with those where Mn toxicity is suspected, based to visual symptoms, will verify if Mn toxicity is occurring.

Toxic levels of manganese do not affect the productivity of crops and pastures to the same extent as aluminium toxicity. Manganese toxicity effects are sometimes complicated by related problems. The anaerobic conditions associated with waterlogged soils induce manganese toxicity but also other problems such as loss of gaseous nitrogen may result in more yield losses than the toxic manganese.

While both toxicities and deficiencies of manganese can occur in NSW, the main problem is toxicity. However, excessive applications of lime may result in manganese deficiency in some light textured soils. It is important to be aware that not all aluminium tolerant plants will have similar tolerances to high levels of manganese.

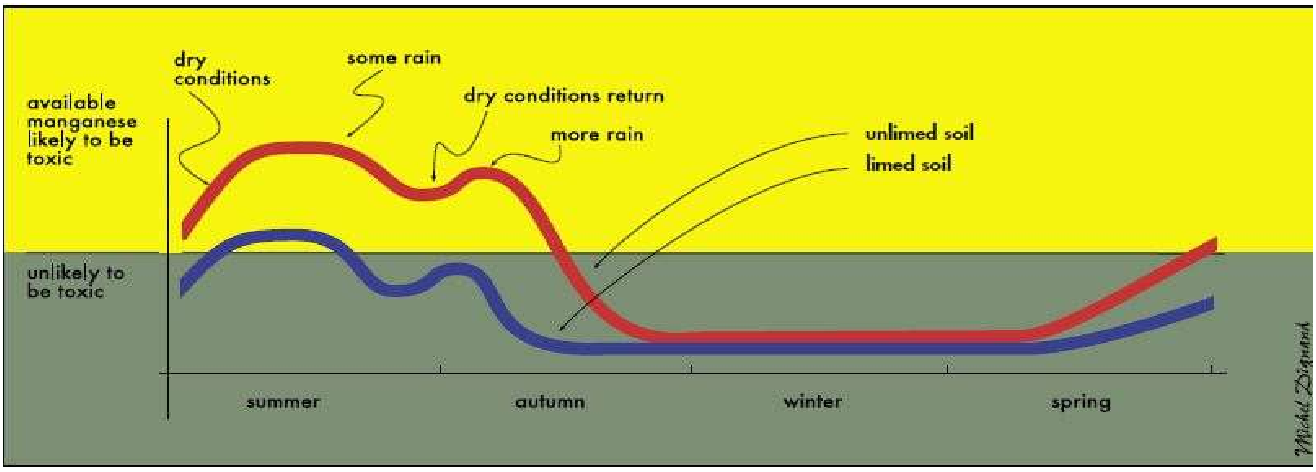

Figure 6. Diagrammatic representation of how manganese availability varies with climate change throughout the year

Seasonal changes in the availability of manganese.

The availability of manganese can vary up to four-fold through the year as shown diagrammatically in Figure 6. Manganese is most available in summer when hot and dry conditions stimulate the chemical changes from an unavailable form (oxidised) to an available form (reduced). This effect is less in a wet summer or in soils that have relatively poor drainage. Therefore, it is important to consider you soils drainage characteristics in addition to manganese and aluminium levels when choosing crop or pasture species

Waterlogged conditions in spring can produce high levels of available manganese. However, low levels of oxygen and loss of nitrogen associated with waterlogging are likely to affect the plants more than the high manganese levels.

Rain in autumn creates a soil environment that favours microflora which convert the manganese back to an unavailable (oxidised) form. It follows that the availability of manganese is at its lowest in winter, although potentially toxic levels may remain if the conditions are too cold in autumn (when soil temperatures are less than 10°C) for the microflora to change the available manganese to the unavailable form.

For more detail see;

Soil acidity and nutrient deficiency cause poor legume nodulation in the permanent pasture and mixed farming zones of south-eastern Australia by B. F. Hackney, J. Jenkins, J. Powells, C. E. Edwards, S. De Meyer, J. G. Howieson, R. J. Yates and S. E. Orgill in Crop and Pasture Science 70(12) 1128-1140

https://doi.org/10.1071/CP19039

The visual symptoms of manganese toxicity in some common agricultural plants are:

Canola: The effect of manganese toxicity is reduced vigour with yellowing of the leaf margins (see image 6). Higher levels of manganese result in yellowing of the whole leaf, necrosis of the leaf margins and greatly reduced vigour or death. In most seasons' canola grows away from the toxic effects of manganese as the solubility of the manganese drops in late autumn.

Image 6. Canola with Mn toxicity

Lucerne, medics, serradella and sub-clover: The effect of excess manganese is reduced seedling vigour and red or yellow leaf margins. High levels of available manganese in autumn can affect germinating pasture legumes. Normal growth rates return with a decrease in available manganese as the season progresses. If warm to hot conditions persist after the first germination the level of available manganese increases renewing the effect and possibly causing death of the seedlings. Lucerne and most medics are highly sensitive, while subterranean clover is only affected by higher levels of manganese.

Image 7. Severe Mn toxicity in Lucerne at Binalong (courtesy R Hayes NSW DPI)

Grasses: Lack of seedling vigour, yellowing at the tips and margins, and some flecking of the older leaves are indicators of manganese toxicity. However, other nutritional problems can have similar effects in grasses and tissue analysis is required to confirm manganese toxicity.

Solubility of other nutrients

Molybdenum (Mo) availability

Many Australian soils are naturally low in molybdenum, but pH can affect Mo solubility also. In soils with relatively high levels of Mo but low soil pH, below pH 5.5, the Mo becomes bound up in iron and/or aluminium complexes. This Mo may become available if soil pH is increased by liming.

All plants need molybdenum in trace amounts to facilitate the use of nitrate nitrogen. Molybdenum deficiency causes an accumulation of unused nitrate nitrogen, resulting in irregular twisting of the leaves. The whole plant may be pale green, and the older leaves can also show chlorotic striping (chlorosis) and burnt leaf margins. See image 8

Image 8. Mo Deficiency in lucerne

Legumes have higher molybdenum requirements than grasses and cereals as molybdenum plays a role in the nitrogen fixing process. Where molybdenum is deficient, nodules may be more numerous but are pale green inside rather than the normal pink (indicating that they are not functional).

The symptoms of a molybdenum deficiency in a legume plant are those of a nitrogen deficiency, that is, pale green to yellow leaves.

Care must be taken when managing a Mo deficiency as adding too may induce copper (Cu) deficiency in livestock

Calcium (Ca) availability

Severe calcium deficiency is very rare and will only occur in deep, sandy, acidic soils that are low in organic matter, or where there has been excessive use of highly acidifying fertilisers. Under these circumstances the percentage of exchangeable calcium of the ECEC can drop to low levels (<40%), leaving the exchangeable aluminium as the dominant exchangeable cation. The symptoms may appear as stubby, unbranched and discoloured roots or as dead growing points in the shoots. The root symptoms are difficult to distinguish from symptoms of aluminium toxicity. See image 6.

Most soils in NSW have an adequate supply of available calcium for field crops, pastures and horticultural crops. Vigorously growing plants in marginal calcium soils will show symptoms on the parts of the plant that are furthest from the main flow of water. Blossom end rot in tomatoes (image 9) and watermelons and poor seed set in peanuts and subterranean clover are examples of the effect of moderate calcium deficiency. More severe calcium deficiency causes death of growing points, for example November leaf in bananas. Low levels of soil calcium also adversely affect the nodulation of legumes. Short term deficiency can cause petiole collapse of young expanding leaves.

Image 9. Ca deficiency in tomato

Magnesium (Mg) availability

Magnesium deficiency has been recorded in seedling crops and pastures in light soils in NSW where there is less than 0.2 meq/100g exchangeable magnesium in the 0 to 10 cm soil layer. Usually these crops or pastures recover by spring as nearly all soils in NSW have an ample supply of magnesium in the subsoil that plants access as their roots extend down the profile.

The signs of magnesium deficiency in cereals are yellowing of the oldest leaves and this can be confused with nitrogen deficiency (Image10). In clovers the symptoms can include reddening of the oldest leaves.

Increased soluble Al in the soil causes leaching of magnesium which may lead to deficiency in plants which can lead to grass tetany. Applying lime or dolomite allows plant roots to grow deeper into the soil and access this magnesium at depth. For more info on grass tetany see these primefacts

Image 10. Mg deficiency in wheat

Changes in biological activity

Sometimes the effect of acidic soils on the growth and production of crops and pastures is not direct but rather through the effect on soil micro-organisms that in turn affect plant growth. Soil organisms are influenced by soil pH. Acidic soil can limit the diversity and function of soil biology impacting on nutrient cycling and resilience.

Soil pH influences both survival and functioning of Rhizobia. Nitrogen fixation by Rhizobia spp. on legume roots is retarded in acidic soils, resulting in lower nitrogen availability and reduced production, poor nodulation in legumes or ineffective nodules (see image 11)

Image 11. Faba bean plants – both at 4th Node growth stage. The plant on the left is from a severely acidic site pHCa <4.5 in layers from 5-30 cm. The plant on the right is from a paddock with a moderately acidic site with pHCa of about 4.8-5.0 at 5 – 15 cm.

Reduced fixation of nitrogen.

Acidity reduces the survival of Rhizobia and the effective infection of legume roots. The sensitivity to acidity varies greatly between species, for example subterranean clover and medics, as can be seen in Table 3 and Figure 7. When a Rhizobia spp is affected by soil acidity it shows as poor nodulation and results in reduced nitrogen fixation. Often Rhizobium bacteria are more sensitive to soil acidity than the host plant, for example lucerne and medics.

Lime pelleting of inoculated legume seed is used to protect the inoculum against drying out and contact with fertiliser. Sowing into bands of lime-super also creates an environment suitable for survival of the inoculum in an acidic soil. However, rhizobia numbers decline very quickly once applied to seed and can rapidly fall below the critical threshold levels required for sufficient nodulation. It is critical to check that inoculant used is within expiry date and treated seed should be sown within 24 hours

Farmers and land managers will see evidence of the above expressed as:

- reduced yields from acid sensitive crops and pastures
- poor establishment of perennial pastures
- failure of perennial pastures to persist
- poor legume productivity and nodulation
- increased need for fertiliser N in crops following legume-based pastures due to poor nitrogen fixation by pasture legumes
- poor regeneration of annual legume species
- reduced tolerance of crops and pastures to environmental stresses such as waterlogging, drought, disease and herbicide damage
- increased incidence of acid tolerant weeds) e.g. sorrel, vulpia spp.

Some of the general signs that may point to soil acidity can also be the result of other land degradation issues;

- reduced yields from acid sensitive crops and pastures
- Poor establishment of perennial pastures
- failure of perennial pastures to persist

Activity of Take-all root disease in cereals.

The fungus that causes the root disease Take-all in cereals, Gaeumannomyces graminis var.tritici, is most active in soils with a pH_{Ca} greater than 4.8, and has a low level of activity in soils with a pH less than 4.6. Liming greatly increases the activity of Take-all. However, Take-all can be effectively managed by implementing an effective crop rotation using non-cereal break crops or strategic fallowing to reduce the fungus. Take-all can build up

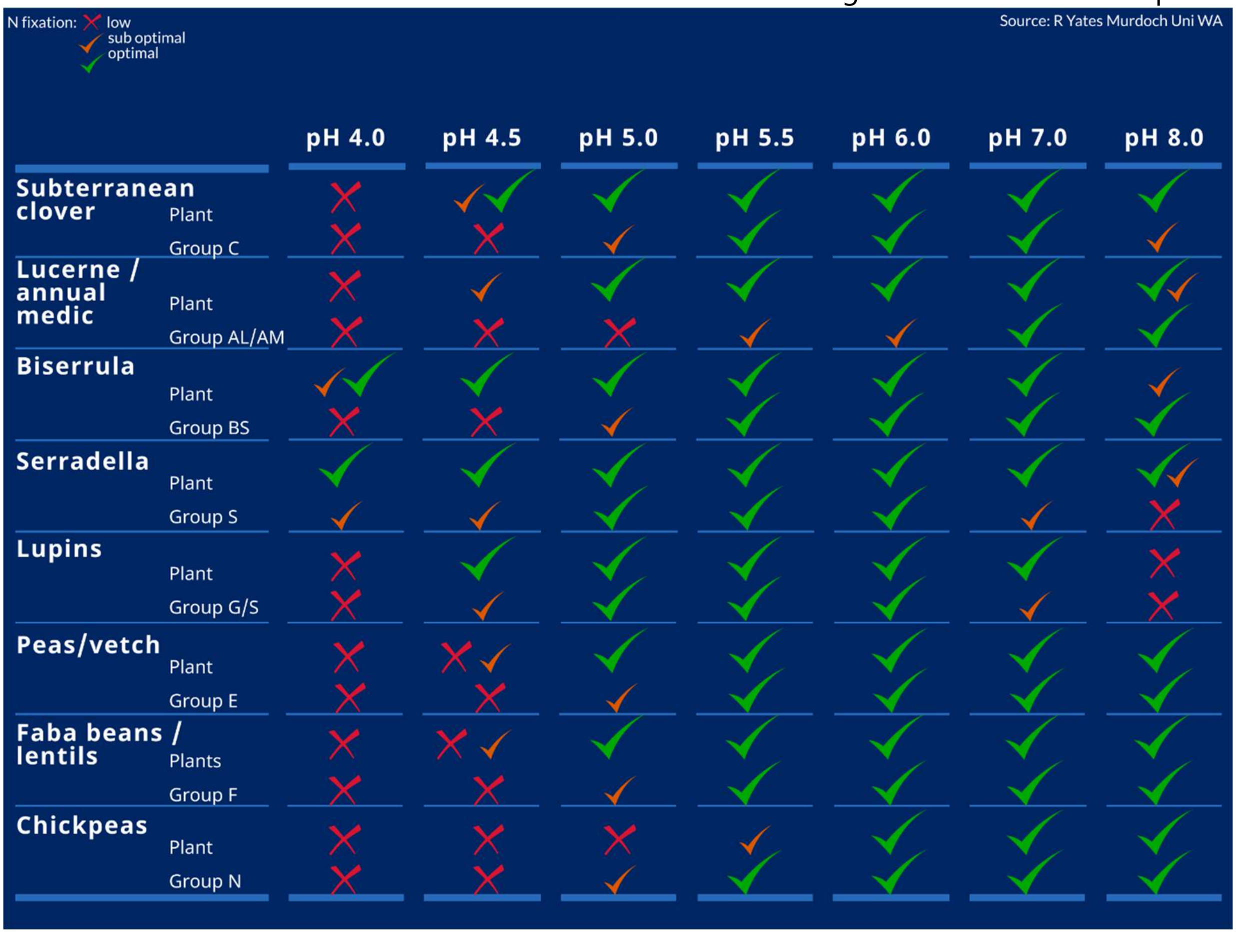

Figure 7. Tolerance of both legume and their rhizobia

rapidly in wet seasons on roots of wheat, barley, triticale and many grasses and will pose a threat in paddocks used for consecutive cereal cropping. A break crop of a broadleaf crop (canola, lupins, peas, etc.) or winter cleaning of grasses from clover or lucerne pastures reduces the threat from take-all and should be done routinely after liming.

How do I manage acid soils?

Effective management of acidic soils will involve a combination of these three management approaches:

1. Minimise acidification
2. Apply a liming product (amelioration)
3. Use acid tolerant crop and pasture varieties

Managing acid soils is most important for the long-term sustainability of farming systems and the soil resource. Management needs to aim at maintaining a profitable farming system and improving soil condition to minimise the degradation caused by soils acidification.

It is understood that agricultural production is an acidifying process. For your chosen production system. Management options available to minimise soil acidification include the types, rate, placement and timing of fertiliser application(s).

The application of limestone or other alkali material that neutralises soil acidity is the only practical amelioration technique. Its effectiveness is determined by product quality, rate and application method.

Acid tolerant plants species can be used to maintain some production whilst implementing amelioration. It is important to remember that acid-tolerant plants can also be responsive to increases in soil pH. In the case of legumes, it is important to consider not only plant impacts but also the possible effects of soil pH on nitrogen fixation. There can be considerable hidden costs in choosing a tolerance rather than amelioration pathway to manage soil acidity.

Achieving a target pH

Historically lime was applied to achieve a soil pH of 5.2 (0-10cm) to remove effect of toxic Al on plant production. However, this will not stop acidification further down the soil profile nor is it optimal for most commercial rhizobia strains. There are significant benefits when pH is maintained above 5.5.

Where acidity occurs below the depth of lime incorporation the neutralising effect will only progress deeper into the soil profile if the surface soil is maintained above pH_{Ca} 5.5.

Any liming needs to be done at least a season prior to sowing a sensitive plant for the effect of liming to have occurred. Lime needs to be applied to the entire layer where the pH is suboptimal to ensure amelioration.

Liming to increase the pH_{Ca} of the 0-10cm layer significantly above 6.0 should be avoided as it may induce deficiency of other plant nutrients such as zinc, boron and manganese in well weathered soils.

What is Lime?

The name used to describe any of several liming materials, including agricultural limestone and dolomite. In the building industry "lime" refers to calcium hydroxide (slaked lime)

Minimise acidification

Where soils are at risk of becoming acidic the future impact of soil acidity can be reduced, but not eliminated, by slowing the rate of acidification. This can be achieved by choosing fertilizers that are less acidifying and managing the movement of nitrate nitrogen in the soil

Use less acidifying fertilisers

Acidification of the soil can be reduced by avoiding the use of highly acidifying fertilisers such as sulphate of ammonium and mono-ammonium phosphate (MAP) (see Table 2). Nitrogen fertiliser (including urea) that is pre-sown should be drilled into narrow bands to slow nitrification and subsequent nitrate movement. Surface application of nitrogenous fertiliser for crops before sowing, even if harrowed, can result in acidification due to nitrate movement. Top dressing nitrate nitrogen to actively growing rather than dormant crops, will result in less acidification risk. (More information on N fertilizer types can be found in table 2).

Correcting acidification caused by using elemental sulfur requires 3 kg of limestone for each 1 kg of sulfur applied. The acidification caused by applying elemental sulphur can be eliminated by using products that contain sulfur in the sulfate form such as gypsum, potassium sulfate and superphosphate.

Reduce the movement of nitrate nitrogen

Nitrate nitrogen (NO_3-N) is highly soluble and moves easily in the soil. When NO_3-N moves away from where it was applied or formed it leaves that part of the soil more acidic. This mostly happens in the topsoil and can occur in very narrow band/layers in the soil profile leading to stratification of soil pH. Use of deep-rooted plants will assist in preventing nitrate N loss from the plant root zone but if acidification has occurred in the topmost soil layer plant use of the nitrate nitrogen further down will not assist in reversing pH decline.

Table 4 lists the factors that affect NO_3-N movement in order of importance. It qualifies the effect of each factor and indicates how the effect can be influenced. The absolute effect of each factor will increase with higher rainfall.

Table 4 factors affecting nitrate movement

Factor affecting nitrate movement	Nature of effect	Reducing the effect
Poor plant growth	Inefficient water use increases leakage of water containing NO3–N into the sub soil and into the water table.	Efficient water use by healthy well managed crops and pastures reduces leakage into the water table.
Nitrogen fixed by clovers in	NO3–N will leach with autumn rain before annual pastures establish.	Perennial pastures will utilise the NO3–N as it comes available soon after rain.
High clover to grass ratio in	High N producing pastures increase NO3–N available to be leached.	Aim for maximum of 30% clover, minimise annual weeds and maximise perennial grass component.
Annual crops	Delay in sowing annual crops will allow the NO3 to move down the profile on the first water front ahead of the roots.	Sow as early as possible after weed control.
Fertiliser	Soluble forms of N are leached away before the plant can use it.	Apply top dressed N fertiliser to actively growing plants according to plant demand for N and N budget guidelines. Band fertilizer where it will be used rather than surface apply
Soil pH	Higher pH increases nitrification thus increasing NO3–N available.	Maintain high productivity (and maximise NO3–N use) with perennial pastures and efficient crop management.
Lack of adsorption onto clay	NO3 is weakly adsorbed by clays, so leaching occurs.	Utilise the nitrogen before it is leached.

Apply lime

To get the best and quickest effect, high quality lime should be finely crushed, evenly spread and incorporated into the part of the soil where acidity is a problem (or as deep as practicable).

Lime moves very slowly through the soil. Incorporation is recommended where possible and where erosion risk is low. Where soil acidity occurs at depth incorporation will hasten the liming effect to the depth of incorporation.

The amount of lime required should be determined using pH in $CaCl_2$ soil test results from an accredited lab and the table 6. Soil samples should be collected using a valid sampling strategy.

Features of lime or liming products

Any liming needs to be done prior to sowing a sensitive crop to ensure lime has had time to react and increase pH in the entire layer where the pH is likely to limit plant productivity.

The liming materials most commonly used are agricultural limestone and dolomite, but other materials are available. Other products that may have a liming value:

- Manures
- Biochar
- Compost mixes

A list of the principal liming materials, together with some of their properties, is given in table 5.

Product quality

Agricultural lime in NSW comes from naturally occurring limestone that is mined and crushed at several plants throughout eastern Australia. The quality or effectiveness of different liming products varies. Prior to 2015, Under the Fertilizer Act 1985 all liming products had to be labelled specifically with lime quality details. The Biosecurity Act 2015 No4 has replaced this earlier act and fineness and neutralising value are no longer required on the product statement. However, you need to know this for each batch of lime purchase to calculate liming rate.

Fineness

The finer particles in a liming material react more quickly in the soil as they have a greater surface area to react with acids. Secondly, they will be better distributed through the soil after incorporation. Most lime crushers in NSW strive to produce a lime that has a particle size where 90% passes through a 150µm sieve. Lime where 99% is less than 75µm is highly reactive but requires special machinery for spreading. Particles larger than 500 µm react very slowly with the soil. There is a compromise between fineness and the cost of production, so there are practical limits on fineness.

Check list before applying lime to achieve a pH of 5.5

- ✓ The following list gives details to be checked to ensure that that a response to liming is likely. This is particularly important when putting in a lime trial or test strip.
- ✓ Identify areas and depths of acidic soil layers (<5.5) using test results (e.g. at 0-5, 5-10, 10-15, 15-20 cm etc. depth intervals).
- ✓ Soil pH is the most limiting manageable soil factor to plant growth.
- ✓ The liming product to be used is sufficiently fine and with a high neutralising value or is the most cost-effective product available.
- ✓ The lime rate is sufficient to achieve a soil pH of 5.5
- ✓ When planting wheat or triticale, Take-all has been controlled.
- ✓ The timeframe is long enough for applied lime to raise the pH to the desired level, especially when sensitive growing plants.

Neutralising value

The neutralising value of a liming material (NV) is its capacity to neutralise acidity. The higher the NV the more pure the product. Pure calcium carbonate (pure limestone) is taken as the standard with an NV of 100. The neutralising value of commercial limestone is usually between 96 and 98. Other liming materials are more reactive than limestone and therefore have higher neutralising values, for example hydrated lime and burnt lime (see table 5).

Obtaining neutralising values calculated for different particle sizes allows the effectiveness of the lime product to be determined by establishing the purity of the different size fractions in it.

Calcium and magnesium content

The proportion of calcium and magnesium in a liming material does not greatly affect the neutralising value. However, the chemical form (carbonate, hydroxide, oxide or silicate) will greatly affect the neutralising value as detailed in Table 5. The hydroxide, oxide and silicate forms are hazardous to health. In extensive cropping and pasture situations, a response to the magnesium in dolomite or magnesite is unlikely as there is ample magnesium in the subsurface layers of most soils in NSW. The choice of a limestone, dolomite or magnesite for crops or pastures depends principally on price and to a lesser extent on the results of plant and soil testing and the crop type. In horticulture, dolomite or magnesite may be required to supply magnesium where it is shown to be deficient through soil or plant tissue testing. Chemical analysis of pure and commercial grades of the principal liming materials is given in table 5

Other products

Recent research work carried out by NSW DPI suggests that the:

- Effects of lime and organic amendments on wheat root growth were not additive.
- Using lower rates of organic amendments with lime is not likely to be effective and feasible
- Organic amendments can effectively reduce the Al and Mn toxicity rather than change soil pH

It is important to remember when retaining crop residues to decrease acidification that not all residues are the same. Crop residues, especially vetch, increased pH, reduced Al and improved ES8 wheat growth in work conducted by NSW DPI whilst lucerne pellets themselves did not. Generally, in-situ generated crop residues do not alter overall soil pH but rather redistribute alkalinity in the soil profile. To achieve maximum alkalisation for maximum pH increase plants must use nitrate as their main nitrogen source, resulting in minimal loss of nitrate from root zones.

Liming material	Neutralising value			Calcium (%calcium)			Magnesium (% magnesium)		
	Pure form	Commercial grades		Pure form	Commercial grade		Pure form	Commercial grade	
		good	Poor to fair		good	Poor to fair		good	Poor to fair
Agricultural lime – calcium carbonate	100	95-98	60-75	40	36-39	28-32	0	Usually <3	
Hydrated (slaked) lime – calcium hydroxide	135	110-120	<105	54	44-49	<40	0	Usually <1	
Burnt lime – calcium oxide	179	128- 150	<120	71	49-58	<45	0	Usually <1	
Dolomite – calcium/magnesium carbonate	109	92-102	60-75	22	21	10-15	13	12	4-7
Burnt dolomite - Calcium/magnesium oxide	214	110-160	80-100	42	25-32	-	25	12-18	-
Magnesium – magnesium carbonate	119	95-105	-	0	0.5-1.0	-	28.6	20-28	-
Burnt magnesite – Magnesium oxide	250	180-220	-	0	1-2	-	60	43-55	-

NOTE: Burnt and hydrated products readily react with atmospheric carbon dioxide and moisture & revert to hydrated and carbonate forms, causing their neutralising values and Ca, Mg analysis to fall with time and exposure

Table 5. chemical analysis of pure and commercial grades of main liming materials

How much

Soil test results must be used to determine liming rate. The results of the soil test are the average of many sub-samples. This means it likely that half of the paddock will have a pH_{Ca} and ECEC less than the average. Liming at a higher rate than that indicated in the table 6 will ensure that this half of the paddock will receive sufficient lime to bring it up to the desired pH_{Ca}.

Although current understanding of how soil pH changes down the soil profile in thin layers under agriculture has increased since the first edition of this publication, liming rates are still determined using an average pH in the top 10cm of soil. At present this is the best method we have of calculating liming rate. In table 6 liming rates to the nearest 1/2t can be determined using the soils ECEC and the increase in soil pH desired.

For example If your soil pH is 4.3 and you want to increase it to 5.5 and you have a low ECEC, say 3 you will need around 2.2 t of lime but to lift the soil pH to the same 5.5 level from a lower pH, say pH 4 then 4t of lime will be required.

Application

Where limestone will not be effectively incorporated due to reduced tillage then apply the limestone years before the most

Table 6. Amount of high-quality lime required to lift pH in top 10cm to 5.5 (Colour codes indicate rates to the nearest 0.5t/ha

Soil Test ECEC (meq/100g)	Lime required (t/ha) to lift pH in top 10cm		
	4.0 to 5.5	4.3 to 5.5	4.7 to 5.5
1	1.8	1.0	0.5*
2	2.8	1.6	0.9*
3	4.0	2.2	1.2
4	4.5	2.7	1.5
5	5.4	3.2	1.8
6	6.3	3.8	2.0
7	7.3	4.3	2.4
8	8.2	4.9	2.7
9	9.1	5.4	3.0
10	10.0	5.9	3.2
15	14.4	8.6	4.7

Key: t/ha
0.5
1
1.5
2
2.5
3
4 + split appn

* It is recognised that low rates of lime application are impractical and over liming can cause nutrient imbalances in these light (sandy) soils (ECEC under 3)

sensitive crop and apply it at a slightly heavier rate. These two actions will enhance lime movement into the topsoil. The time of the year when lime is applied is not important. Limestone begins to react as soon as the soil is moist and incorporated lime reaches its major impact after 12 to 18 months

Incorporation will increase organic matter breakdown, increase weed germination, and reduce trafficability. The advantages of incorporation may be reduced soil and fungal diseases, lower snail and slug population, break up compaction layers, increase lime reaction and pH change. One-off tillage events have been shown to result in limited long-term structural damage. View video explaining strategic tillage risks and recovery and associated publications such as, Is there room for strategic tillage in a no till system? And Strategic tillage booklet

The effectiveness of surface applied limestone can be improved by:

- Use of a fine grade of limestone spread when there is good ground cover to ensure the limestone does not blow or wash away.
- Direct drilling with a tyned seeder after spreading limestone only gives some incorporation,
- Use of superfine limestone, with a particle size as low as 70 microns (0.07 mm). The smaller limestone particles wash down through a sandy or silty soil achieving a distribution within the soil that is similar to the distribution that would have occurred if the limestone had been incorporated. Superfine limestone is mostly used in horticulture.
- Banding of limestone and superphosphate with the seed using direct seeding techniques. Only small amounts of limestone can be applied in this way.

In sandy soils and where the annual average rainfall is greater than 600 mm, limestone applied to the surface may move to 10 cm depth in 2–3 years. As the clay content in the soil increases, or the rainfall decreases, there is less movement of limestone down the profile. A rapid response to surface applied limestone is most likely caused by release of molybdenum or improvement in legume nodulation, and the release of nitrogen from organic matter. Where the soil is acidic to depth it may take many years for the lime effect to move to 20 cm, especially for heavy soils and it is important to keep the top soil (0-10cm) at about 5.5 to assist in increasing the pH in the soil below.

Spreading machinery

Because agricultural limestone is generally fine and large quantities are usually applied, most spreading is done by contractors using 3–5 tonne hoppers and belt fed spinners or drop. Combines and seeders cannot handle the quantity required per hectare and conventional fertiliser spreaders have proved unreliable as the limestone tends to ‘bridge’ over the outlet. This can be overcome by using granulated lime products however the higher cost of these products means that they are often not economical to use.

Dust issues

Most limestone spreaders generate clouds of fine dust. This is the finest portion of limestone and, therefore, the quickest to react with the soil. Traditionally it has been claimed that up to 8% of the lime can be blown away. However, with the move to finer limestone this could be underestimating the problem. Some contract spreaders have a shroud to control the dust. Wetting the limestone with 2–4% by weight of water (400–800 L of water to 20 t of lime) minimises dust.

You can read about the findings of the managing subsoil acidity project

- Amelioration of subsoil acidity using organic amendments
- Alkalinity movement with different lucerne pellet sizes in acidic subsoil
- Comparison of a range of amendments on alleviating Al and Mn toxicity in wheat
- Effectiveness of common brown manures on Ca(NO3)2 in ameliorating soil acidity
- Evaluating rates of organic amendment with lime for treating acid soils
- Which liming material in best

Grow acid tolerant crops and pastures

If a paddock is already acidic, particularly where both the surface and subsurface soils are acidic, the economic and offsite impacts can be reduced by growing acid tolerant crops and pastures.

However, acidification will continue despite the use of acid tolerant plants unless other management options are used to ameliorate soil acidity and or prevent further acidification.

Acid tolerant plants may provide some production from an acid soil but will not prevent it and even tolerant plants respond to amelioration of acidity

Acid tolerant species can help farmers to reduce the impact of soil acidity by

- maintaining cash flow if limestone cannot be applied when required
- Maintaining or increasing production on soils with acidic layers that are too deep to be limed economically or on non-arable land
- Allowing crop and pasture rotation sequences to match the decline of soil pH over a 10-15yr liming cycle
- Increasing water use and groundcover and therefore reducing off site effects

Where the soil is very acidic to depth and sowing acid tolerant species is not practical then retiring land from agriculture may well be the best option for the farm and the environment.

Refer to the list of aluminium tolerant crops and pastures in table 3 when selecting crops and pastures for acidic soils. Tolerance of plants to aluminium closely reflects acid soil tolerance in all soils except the weakly weathered soils.

Manganese toxicity

Applying lime sufficient to lift the pH_{Ca} to above 5.5 will decrease available manganese. Alternatively, the effects of manganese toxicity on autumn sown crops and pastures which are sensitive to manganese can be decreased by sowing on the second autumn rain.

Molybdenum deficiency

Because molybdenum is required in such small amounts a soil test is not a reliable method for assessing if there is a deficiency. The only recommendation is that where the pH_{Ca} of a soil is below 5.5 a response in legumes and some cruciferous vegetables may occur to an application of 50–100 g of sodium molybdate per hectare. This response varies and local information from your district agronomist or fertiliser outlet should be sought before proceeding. An application every 3–5 years (depending on soil type) as a spray of sodium molybdate or molybdenum trioxide, or as a component of a fertiliser, is sufficient for all plants. A lime application that increases pH_{Ca} by one unit increases the availability of both applied and naturally occurring molybdenum, but the degree will depend on the initial pH.

Molybdenum is sometimes added to peat slurry when inoculating legume seed for sowing a new pasture and this is an effective way to achieve a uniform application. However, sodium molybdate is toxic to rhizobia. If molybdenum is to be added to a slurry mix for legume inoculation, then molybdenum trioxide or ammonium molybdate should be used.

Resources

Glossary

Acid(ic) soil: Soils that have a pH_{Ca} of 5.4 or less

Arable land: land that is able to be cultivated

Chlorosis: Abnormal yellowing of plants.

Effective cation exchange capacity (ECEC): The sum of the values in a soil analysis of exchangeable cations (calcium, magnesium, sodium, potassium, manganese and aluminium). The unit of measurement is cmol(+)/kg (previously meq/100 g).

Exchangeable cations: Exchangeable cations are positively charged ions that are loosely bound to negatively charged clay particles and organic matter in soil. The unit of measurement is cmol (+)/kg (previously meq/100 g).

Lime: The name used to describe any of several liming materials, including agricultural limestone and dolomite. In the building industry "lime" refers to calcium hydroxide (slaked lime)

Necrosis: Death of parts of plants, giving a brown shrivelled appearance.

Nitrification: The transformation of ammonium to nitrate by microbes.

Soil pH measurement: Soil pH is measured in two ways in Australia.

1. Mixed and shaken 1:5 soil: 0.01 M CaCl2 (pH_{Ca}).

2. Mixed and shaken 1:5 soil: water (pHw).

pH_{Ca} gives pH values on average 0.5 to 0.8 lower, but with less seasonal variation, than pHw. While most commercial soil testing laboratories use the CaCl2 method, most field pH testing kits and some laboratories use the water method

Soil solution: the water in the soil and its dissolved substances, gases, minerals and organic matter. It is sometimes called the liquid phase.

Valid sampling strategy: A program of representative soil sample collection and analysis that has a clearly defined purpose for a given area to of interest. A sound strategy will outline when to sample, how many samples to collect, how many different zones have been identified in the area of interest and which type of analysis are appropriate for a given purpose. For more info on this see:

A guide for fit for purpose soil sampling by C Gourley and D Weaver

GRDC's crop nutrition factsheets: Soil testing for crop nutrition southern region or northern region

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