Fact Sheet 09
Almond Orchards and Soil Acidification

Richard Merry
CSIRO – Land and Water

Ben Brown
Almond Board of Australia

Welcome to the ninth edition of "All About Almonds", Almond Orchards and Soil Acidification. Fact sheets are distributed to almond growers via email, in addition to being made available for download from the ABA website: www.australianalmonds.com.au (follow links to the login section of the growing page).

1. Background

The formation of acid in soil is a side effect of most forms of modern agriculture and can be particularly important in intensive systems. Many of the soils used in Australian agriculture initially had pH values suitable for growth of most plants or have residual calcium carbonate (lime) that counteracts the effects of any acidity formed. This means that low input agriculture can proceed for some time before the undesirable effects of acidification become evident. The changes in the soil are usually slow and may not be noticed until there are severe production decreases.

However, intensification of agriculture (increased fertiliser use, increased production, etc.) can speed up acidification processes and their undesirable effects. Consequently, there is a need to monitor practices, soil condition (usually with a pH measurement) and when necessary, remediate the soil by liming.

It is important to be aware of the processes leading to acidification and what should be done to protect soil and its capacity to support root growth.

Soil types vary in their capacity to cope with acidification. The main difference is in the time taken to reach a critical point where productivity is affected. This is because soils differ in their pH buffering capacity which is the capacity of a soil to resist pH change. Sandy soils have a lower buffering capacity than clayey soils and if lime is present in the soil, the buffer capacity can be very large. If the plant production system produces acid, in the long term it does not matter what the properties of the soil are as the soil is being acidified – poorly buffered soils reach a critical pH sooner than well buffered soils. Although a pH measurement will indicate the condition of the soil that is critical for plant growth, a buffer capacity or lime requirement measurement is needed to estimate the amount of lime needed to raise soil pH to a target level.

Depending on the pH buffering capacity of the soil and its starting pH, it may take decades to reach a situation where plant production is affected and as the process is often slow, it is usually difficult to separate yield decline from normal seasonal variation. For this reason it is important to maintain a satisfactory soil pH condition to avoid potential productivity losses.

Modern almond production systems in Australia produce acidity when yields increase and particular fertilisers are used, especially those ammonium-containing forms of nitrogen (e.g. sulfate of ammonia, urea, UAN, ammonium nitrate, etc). In drip irrigated orchards, the production system concentrates fertiliser placement, water delivery and nutrient uptake into a relatively small proportion of the total soil volume and this zone has a high potential for rapid acidification – significantly more than sprinkler irrigated orchards. This situation has also been observed in many other drip irrigated crops such as citrus orchards and vineyards.

2. Measuring Soil Acidity

Soil acidity (or alkalinity) is measured by a pH test and is a measure of the concentration of hydrogen ions (H^+) in the soil solution. pH is measured on a negative logarithmic scale between 1 and 14 with 7 being neutral (Figure 1).

Soil pH is often measured using two laboratory techniques; 1) 1:5 solution of soil and water (pH_w), or 2) 1:5 solution of soil and a weak solution of calcium chloride (pH_{ca}). The calcium chloride method which is the more commonly used and reliable method, will produce results that are approximately 0.8 of a pH unit lower than water tests and is less subject to seasonal variation.

Due to the logarithmic scale, a change in soil pH of one pH unit represents a tenfold change in hydrogen ion activity. That is, a small decrease in soil pH results in a large increase in acidity. For example, soil with a pH of 4 is ten times more acidic than a soil with a pH of 5 and 100 more times acidic than a soil with a pH of 6.

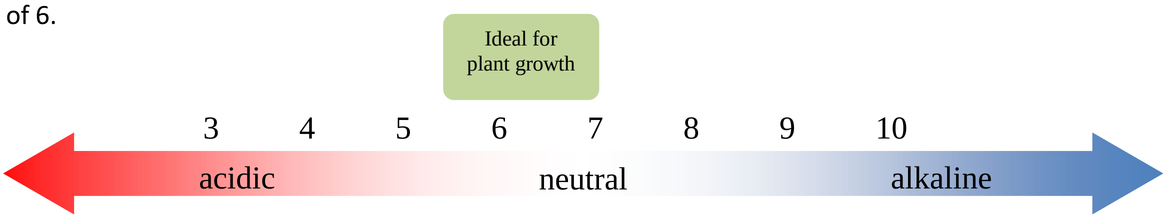

Figure 1 pH Scale

A less common measurement is soil pH buffering capacity. This measurement is more difficult to make and not often carried out. It is the rate of change of soil pH as acid is added. Clays and soils with increased organic matter have a higher pH buffer capacity than sandy soils.

3. Causes of Soil Acidification in Almond Orchards

There are several important causes of soil acidification and the interactions of the acidification processes can be complex (Figure 2). They have been known and studied for a long period of time – even the early farmers (Etruscans, Romans) knew that lime was needed to offset acidity – and liming practices have long been in place in other parts of the world.

The processes of acidification outlined below are known to be the principle causes of soil acidification in agricultural systems and much more significant than external causes of acidification such as acid rain. The two major causes of soil acidification in almond orchards are the use of some nitrogen fertilisers and product (fruit) removal.

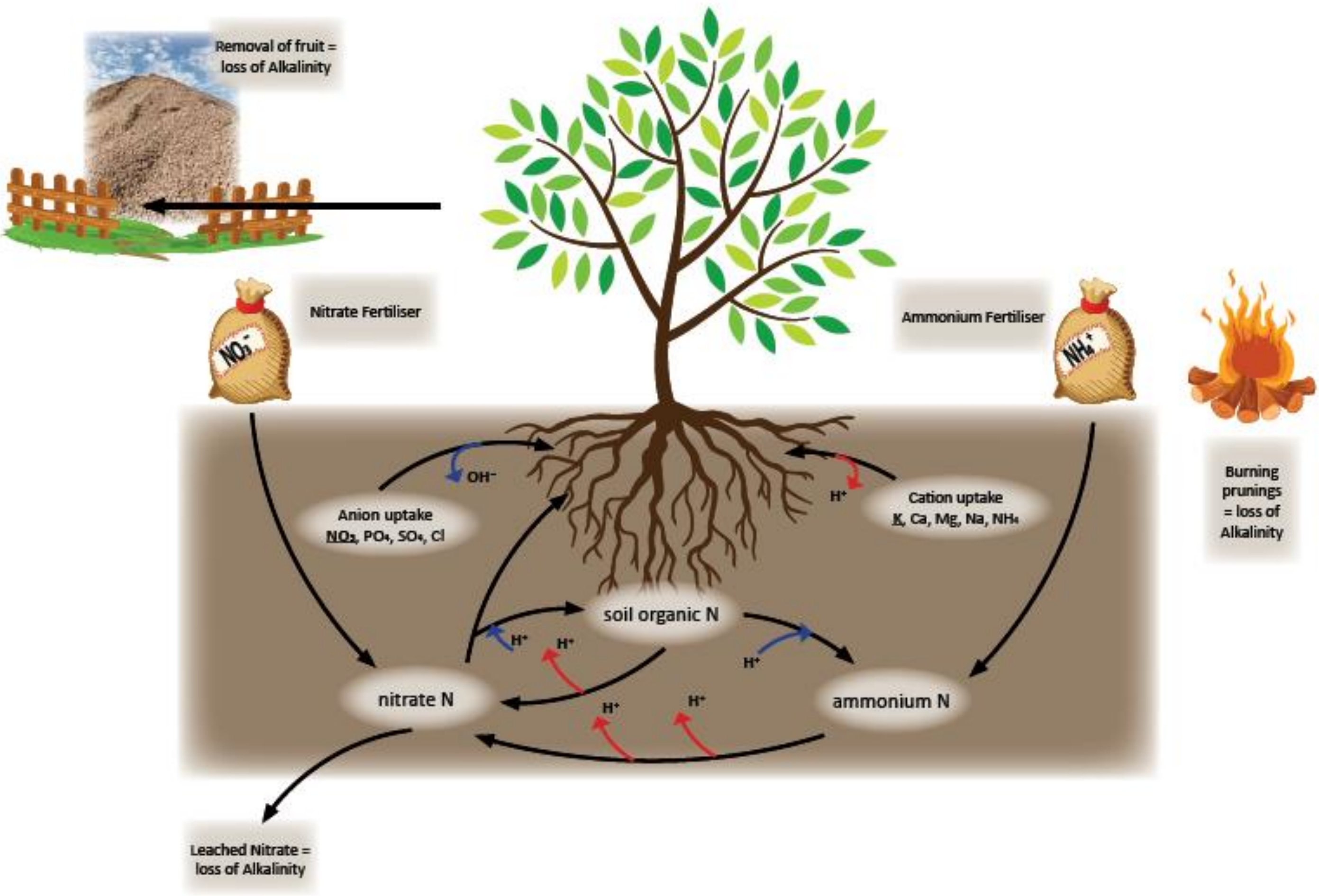

Figure 2 Processes of Soil Acidification in Almond Orchards

3.1 Nitrogen Fertilisers

Nitrogen fertilisers are a major cause of soil acidification when fertilisers containing ammonia are used. Although not exactly the same, urea behaves in a similar way. The processes that are involved are complex and include reactions in the soil, exchanges with the plant root, leaching and volatilisation.

Each ammonium ion (NH_4^+) in the fertiliser is usually transformed to nitrate (NO_3^-) in the soil by bacteria. This process releases two acidifying protons (H^+) for each ammonium ion and one acidifying proton for each amino group (NH_2). The amino group usually comes from the natural decomposition of organic matter.

There is a further process that will determine the severity of the acidification; that is, the fate of the nitrate ion. If the nitrate ion is taken up by the plant, the acidification effect is less than if the nitrate ion were to be leached beyond the root zone. (See the nutrient uptake section below for further explanation of this process).

In practice, scientists mostly use average values for acidification by fertilisers as these values are usually able to account for measured changes in soil acidity (see Table 1).

Fertiliser	Equivalent Lime ($CaCO_3$) Needed to Neutralise Acidity (kg $CaCO_3$ / kg N or S)[b]
Urea	1.8
Ammonium Nitrate	1.8
Ammonium Sulfate	5.4
MAP	5.4
DAP	3.6
Sulfur (elemental)	3.1[c]
N as Nitrate	-3.2[d]

Table 1 The acidity resulting from the use of nitrogen or sulfur in fertilisers. The values presented are the average amount of lime ($CaCO_3$) needed to neutralise the acidity.

Adapted from Adams (1984)
[b] These are average values for nitrogen and can vary ± 1.8 kg.
[c] This assumes complete conversion to acid; for thiosulfates, the value is about 1.6 per unit of S.
[d] This is negative because nitrate uptake by plants increases the alkalinity of soil. This value assumes 10% of the nitrate is leached.

For reasons outlined below, nitrate fertilisers are not acidifying and can make the soil more alkaline. Ammonium nitrate contains two forms of nitrogen, but the acidification from the ammonium component is greater than the alkalinity that results from the nitrate component.

3.2 Other Fertilisers

Whilst most attention is given to the acidification risk from nitrogen fertilisers, some other fertilisers can also cause acidification. They are mainly fertilisers that contain sulfur – elemental or dusting sulfur, and thiosulfates. In these sulfur-containing materials, some or all of the sulfur is acted on by soil bacteria producing sulfuric acid.

Sulfate fertilisers (such as potassium sulfate, magnesium sulfate, zinc sulfate, etc) do not acidify soils. The only obvious exception is ammonium sulfate which acidifies soil due to its ammonium component, not the sulfate component.

It is a common misconception that superphosphate has caused soil acidification. This is untrue. Using superphosphate has enabled legumes and other plants to grow well and it is the consequences of nitrogen fixation, product removal and associated acidification that is really contributing to acidification.

3.3 Nutrient Uptake and Fruit Removal

When plants grow, they usually take up nutrients such as nitrogen (as nitrate, NO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), phosphorus (as phosphate, $H_2PO_4^{2-}$), sulfur (as sulfate, SO_4^{2-}), and others. You will notice these nutrients have a positive (+) or negative (-) charge. In the process where these charged elements are taken up through plant roots, the plant needs to release an element with equivalent charge. This is achieved in one of two ways:

1. When a positively charged 'cation' (eg K^+) is taken up, the plant exchanges an equivalent positive charge by releasing an acidifying proton (H^+).
2. When a negative charged 'anion' (eg NO_3^-)is taken up, the plant exchanges an equivalent negative charge by releasing an alkaline hydroxyl (OH^-).

Most plants take up more positively charged than negatively charged ions and the net effect is soil acidification. In a closed system where all plant matter is recycled on-site, the uptake of more positive charged ions may not be a problem. However, when plant products (e.g. fruit) are removed, the 'alkalinity' developed in the plant material is lost and the soil is left in a more acidic condition. This is made worse in high yielding agricultural systems (e.g. almond orchards) that produce large quantities of removable plant material, such as almond husks, shells, kernels and prunings.

	Ash Alkalinity of Material (kg $CaCO_3$ / kg, dry)	Indicative Dry Yield (kg/ha)	Equivalent Alkalinity Lost (kg $CaCO_3$ / ha)
Husk	0.043	4,980 6,640	215 285
Shell	0.025	1,250 1,660	31 42
Kernel	0.008	3,000 4,000	24 32
TOTAL		**9,230** **12,300**	**270** **360**

Table 2 Annual plant ash alkalinity, yield of product, percentage dry weight and alkalinity (expressed as calcium carbonate equivalent) of almond husk, shell and kernel.

There are ways of estimating the amount of alkalinity removed and some values expected for almonds can be made using an acidification calculator (Thomas, 2009) and are shown in Table 2. The table is based on limited data but shows estimates of the potential alkalinity lost when almond husks, shells and kernels are removed, per kilogram of these materials, and on a per hectare basis. As all of this plant material is lost, soil acidification equivalent to about 300-400 kg of lime ($CaCO_3$) per hectare is lost by product removal alone each year.

In loamy soils without any natural lime, acidification of 300 kg $CaCO_3$ equivalent each year may result in a soil pH decrease of one unit in:

- Sprinkler Orchards (100% wetted area) – approximately 6 to 8 years, or
- Drip Irrigated Orchards (approx 30% wetted area) – approximately 2 to 2.5 years

In sandy soils, which are traditionally the soils selected for almond orchards, this will occur even faster due to the lower buffering capacity of sand. The use of ammonium-containing fertilisers will also quicken this process.

The almond industry's Optimisation Trial (aka CT Trial) has provided an illustration of how quickly and severely soil acidification can occur on an almond orchard which is planted on sandy textured soil, drip irrigated, receives high amounts of ammonium containing fertilisers, achieves high yield, and doesn't have all of its cations replaced by fertigation (e.g. calcium, magnesium).

A statistical analysis of the CT Trial soil data indicates there has been a statistical effect of the scientific treatments on soil pH, with an approximate decrease in pH_{ca} of 0.25 to 0.65 pH unit/year. The result has seen soil pH_{ca} that began at approximately 8.0 in 2001, decrease to 5.5 at 0 to 20 cm (Figure 3).

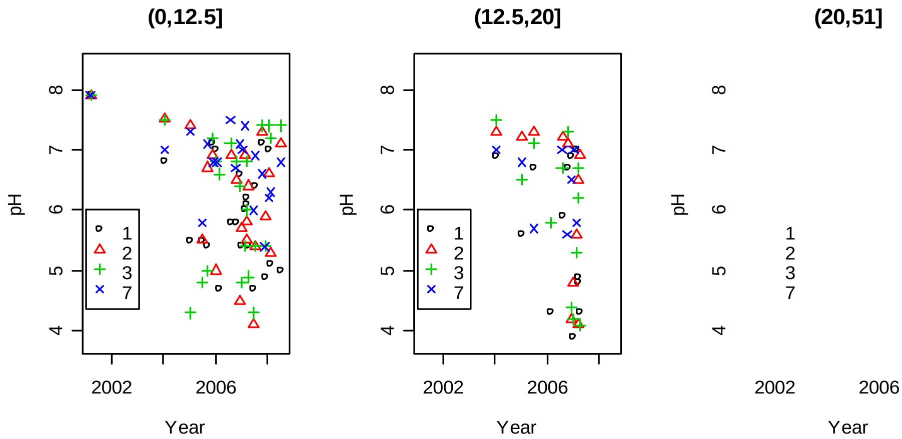

Figure 3 Optimisation Trial, Soil pH at 0-12.5cm and 12.5-20cm

Almonds are deciduous plants, shedding their leaves annually. It is usually assumed that leaves are recycled within the orchard, conserving any of the elements mentioned above. If the leaves, or prunings, are removed or lost from the vicinity of the tree, there will be an additional acidification, but this is thought to be small in comparison to fruit removal at harvest.

3.4 Leaching

As mentioned above, when plants take up nitrate (NO_3^-) - the usual form that plants take up nitrogen from soils - alkalinity is left behind in the soil at the site of uptake. Nitrate usually comes from the nitrification process mentioned above, which is acidifying, or from nitrate-containing fertilisers. Either way uptake of nitrate ions usually assists in making soil more alkaline.

However, there is an exception in situations where there is a high incidence of flushing events due to rainfall or poorly managed irrigation. In these conditions the nitrate in the soil can be leached to a lower point in the soil profile, or even below the rooting zone, and in the process take with it a companion ion. This results in the upper part of the soil profile becoming more acidic and the subsoil more alkaline when more nitrate is taken up from deeper in the soil.

4. Effects of Soil Acidification

Progressive acidification alters soil properties, usually detrimentally unless the soil is very alkaline. In alkaline soils, where pH_w values are higher than 8.5, some acidification may be beneficial and help increase the availability of some nutrients, such as iron (Fe), manganese (Mn) and zinc (Zn). Lowering the pH_w below 8.5 may also improve the efficiency of the nitrification process. As soil acidifies and reaches pH_w values less than 5 to 5.5, significant detrimental changes begin to occur. These effects are outlined below.

4.1 Acidification Effects on Plant Toxicities and Nutrient Availability

When a soil acidifies and the pH_w decreases to below 5, detrimental changes start to occur in the soil. They may not become visually apparent in the plant or its yield loss until the pH_w is much lower, below 4.5. As the soil acidifies, the acidic protons (H^+), which are very reactive, quickly attack minerals in the soil. Firstly, alkaline materials such as lime are used up as it reacts and neutralises the acid. Once the lime has reacted with the acid, it is removed from the soil permanently. Secondly, when most of the lime has been 'used', the acid starts to attack the clay minerals.

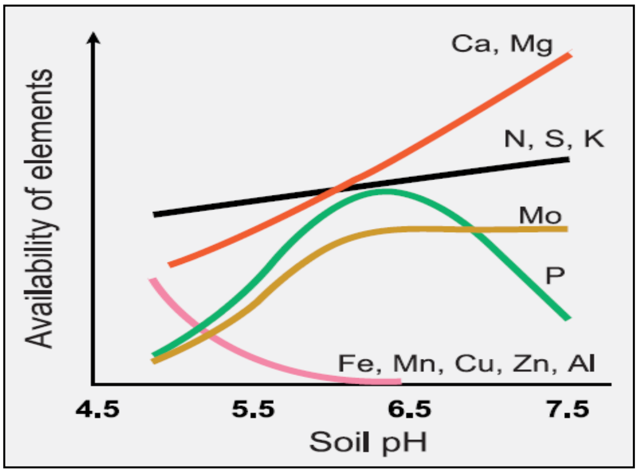

Figure 4 Relationship between soil pH and nutrient availability
(Source: Soil acidity: a guide for WA farmers and consultants)

With increasing acidity (Figure 4), clay mineral decomposition can release elements such as aluminium (Al) and manganese (Mn). Both elements are toxic to plant roots, especially aluminium. Aluminium causes young, growing root tips to become stunted (Figure 5) and roots are often described as 'stubby'. For a plant to be productive its roots must continually grow, so if this is retarded, plant productivity decreases.

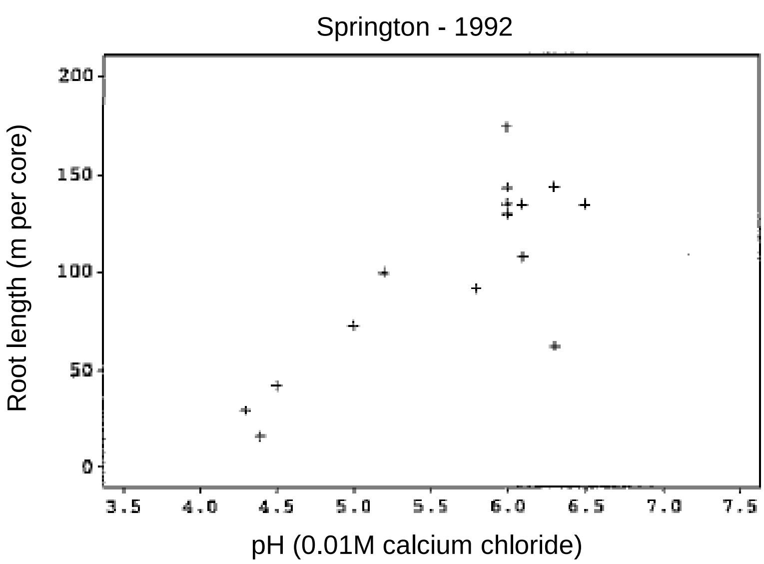

Figure 5 Effect of pH on grapevine root growth (aluminium toxicity), Robinson (2000)

Increased aluminium availability in acidified soils also interferes with the ability of the plant root to take up other elements that are essential for growth, including iron (Fe), calcium (Ca) and magnesium (Mg). Acidification actually increases the solubility and availability of elements like calcium and magnesium, but the low pH and effects of high aluminium prevent uptake. These nutrient elements are then vulnerable to leaching from the soil, so over long periods of time, even mildly acidified soils become impoverished in many nutrients.

Other elements, including many of the trace elements (copper, zinc and manganese) become more readily available to plants. Molybdenum (Mo) does not become more available in acidic soils. It is more available in alkaline soils.

4.2 Urea and Ammonium Conversion to Nitrate

The soil processes that convert urea and ammonium-containing fertilisers to nitrate (nitrification) are enabled by soil microorganisms. The same processes are involved in the conversion of amine nitrogen (from the amino acids in proteins that are part of the soil organic matter) to nitrate. Soil pH_w values below 6 are sufficient to start having a detrimental effect on the efficiency of nitrification and the rates decrease progressively below this pH and become negligible by about pH_w 4.5. Consequently, nitrate availability from ammonium-containing fertilisers and organic matter is reduced in acidic soils.

5. Managing Soil Acidification

Managing almond orchards starts with soil preparation. If a soil is already acidic at the time of orchard establishment, lime should be applied to increase soil pH_w to a value greater than 6.

Orchard fertiliser practices and the rate of product removal can be used as a guide to the likely acidification rate and amount of lime needed to remediate it.

It is very important to manage acidifying fertiliser use to ensure that applications are not excessive. If the soil is likely to acidify, it is important to make an allowance for the purchase of liming materials as part of the orchard fertiliser management plan.

Product removal (husks, shells, kernels) is an important cause of acidification. Since they are removed from the orchard, conservation of their alkalinity is not possible and there is little choice but to:

a) replace all nutrient uptake (that is, more than just nitrogen, phosphorus and potassium) with fertiliser applications, and/or
b) replace the alkalinity lost by using a program of liming.

Soils with naturally occurring lime in surface layers may not show effects of acidification for many years. A soil with 1% $CaCO_3$ has approximately 10,000 kg of lime per hectare 10 centimetres deep. However, soil pH should be monitored annually in high yielding orchards with high fertiliser use, particularly in drip irrigated orchards.

In drip irrigated orchards, most acidification is concentrated in the wetted volume of soil as this is where most nitrification and nutrient uptake occurs, not in the inter-row. This concentration of processes can greatly increase the rate of soil acidification. Work in drip irrigated orchards and vineyards have confirmed this, and this volume of soil should be targeted for pH monitoring and lime application. However, managers should not ignore the inter-row where acidification is usually less or minimal.

6. Remediation of Soil Acidification

Once a soil is acidified, the application of liming materials (lime, dolomite, etc.) is the principal way acidification can be managed. The amount required can be minimised by putting in place management practices outlined above.

Lime application rate is usually based on a pH measurement, identification of a 'target' pH and an estimate of the soil pH buffer capacity. It will also vary depending on the type of lime being used.

Robinson (2000) developed a quick method to estimate buffering capacity by estimating soil texture and using 'rule of thumb' data. The research indicated to raise soil pH by one unit to a depth of approximately 15 cm, the following rates of lime (t/ha) may be required:

- sands, loamy sands 1.0 – 2.0
- sandy loams 2.5 – 3.5
- loams, sandy clay loams 3.5 – 4.0
- loamy clays 4.5 – 5.0

Alternatively, laboratory tests are available.

There can be difficulties in physical application and incorporation of lime in drip irrigated orchards. The soil needs to be moist and the lime 'watered' in. Lime also takes a few months to equilibrate with the soil following application. Consequently, lime application should be followed up with soil pH testing to ascertain is effect.

There can also be difficulties in all orchards if sub-soil layers are allowed to acidify. For these reasons, it is very important to manage acidity before soil deeper than 20 or 30 cm becomes acidified.

Some reversal of acidification can be expected if nitrate fertilisers (for example, calcium or potassium nitrate) are used. There may be cost constraints in using them, but this should be balanced against the cost of applying lime if acidifying fertilisers are used. It should also be noted that fertiliser programs solely based on nitrate-containing fertilisers are not 'healthy' for the plant or fruit.

The chemical properties of irrigation water may also need to be taken into account, depending on its source. Most dam water in high rainfall areas has very low alkalinity. Water from the Murray River has a low and seasonally variable alkalinity. Work assessing dripper irrigated vineyards suggests that it has little beneficial effect in neutralising acidity. However, groundwater from aquifers in limestone which becomes saturated with calcium carbonate can be effective and may significantly raise soil pH. Reclaimed water needs to be analysed on an individual source basis and used with extreme care as some sources have high potassium, sodium and alkalinity, and have potential to cause detrimental changes to the subsoil drainage characteristics.

7. Key Points

- Soil acidification can be a naturally occurring process.
- Horticulture rapidly accelerates the soil acidification process.
- If unmanaged, soil acidification in drip irrigated orchards may occur at approximately three to four times the rate in comparison to sprinkler irrigated orchards due to the rapid exhaustion of such a small, concentrated soil volume.

- Current almond fertiliser programs in drip irrigated orchards are resulting in soil pH values decreasing by approximately of 0.25 to 0.65 pH_{ca} unit/year. The result has seen soil pH_{ca} that began at approximately 8.0 in the year 2001, decrease to 5.5 at 0 to 20 cm by 2008.
- Almond trees take up more positive ions than negative ions, resulting in a potential net soil acidification effect.
- The removal of fruit at harvest exports alkalinity which is not returned to the soil, causing acidification.
- Biggest causes of soil acidification in almonds are fruit removal at harvest and ammonium based fertilisers.
- Other potential causes of soil acidification in almonds are nitrate leaching and removal of prunings.
- Nitrogen fertiliser programs should be more biased towards nitrates (alkaline effect) rather than ammonium (acidifying effect) sources. However, be mindful that nitrate toxicity may be detrimental to fruit quality and nitrate is more readily mobile and susceptible to leaching.
- Fertiliser and acidity management programs should aim to balance nutrients lost, and not just consider nitrogen, phosphorus and potassium. A survey of industry leaf analysis has shown decreasing calcium and magnesium concentrations. Use of dolomitic limestone and calcium nitrate for acidity management will help replace lost calcium and magnesium.
- Monitor soil pH annually.
- Remediate soil acidification with lime applications. Lime applications are to be calculated on current soil pH values, a target soil pH value and an estimate of the soil pH buffering capacity. Re-monitor soil pH.

References

Adams, F (1984) Crop responses to lime in the Southern United States. In 'Soil Acidity and Liming' 2nd Edition. F Adams (editor) pages 211-259, Agronomy No 12, American Society of Agronomy, Madison, Wisconsin.
Helyar, KR, and Porter, WM (1989) Soil acidification, its measurement and the processes involved. In 'Soil Acidity and Plant Growth", AD Robson. (editor), pp 61-101, Academic Press, Sydney, Australia.
Kennedy, IR (1992) Acid Soil and Acid Rain. 2nd Edition. Research Studies Press Ltd., Taunton, Somerset. (Technical, requiring knowledge of chemistry).
Robinson, JB (2000) Managing Soil Acidification. Proceedings: Eight Australian Wine Industry Technical Conference, pp45-48
Thomas, B (2009) Calculators of Soil pH Change – Almond Orchards. In: Managing Soil Degradation in Orchards Which Utilise High Fertiliser Inputs. National Landcare Programme – Community Support Component, Project No. 64264. (calculator available for download at http://australianalmonds.com.au/industry/resources_reports_fact_sheets)

For further information contact Ben Brown, Industry Liaison Manager

Published by Almond Board of Australia, *PO Box 2246, Berri, South Australia 5343*
Telephone (08) 8582 2055 Facsimile (08) 8582 3503

ACKNOWLEDGEMENTS
The input and suggestions made by Australian almond processors, marketers and growers.
This project has been facilitated by HAL in partnership with the Almond Board of Australia and has been funded by the Research & Development levy. The Australian Government provides matched funding for all HAL's R&D activities.