Soil Acidification — An Agricultural and Environmental Problem

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Soil acidity is both a serious agricultural and an environmental problem and affects in excess of 35 million hectares of agricultural land. Acidification is ongoing with rates of acidification, expressed as lime equivalence, varying from near zero in unfertilised low fertility systems to 150 kg ha^{-1} yr^{-1} in high rainfall areas, with rates as high as 1710 kg ha^{-1} yr^{-1} in intensive agriculture. This is driven by the N and C cycles operating through nitrate leaching and product removal. Some fertilisers also acidify. Acid soil adversely affects plants through aluminium and manganese toxicities, hydrogen ion (H^+) toxicity, and deficiencies of molybdenum, calcium, magnesium and phosphorus. Changes in biology of the soil also occur as pH declines, as most organisms have an optimum pH range for growth. A reduction in pH can change the spectrum of diseases and their pathogenicity. The major management strategy in agriculture is lime application, but this appears to be economically unattractive in many situations. For farming/grazing land on the south-western slopes of NSW, lime application alone may represent 1.5 to 3 times the value of the land. Most of the acidification which has affected subsoils (>20 cm depth) cannot be treated profitably.

Soil acidity has environmental consequences. The nature of off-site effects of soil acidity is not well documented nor accepted. We believe that off-site effects of soil acidity are driven by the under-utilisation of water in situ. This excess water can erode surface soil, causing turbidity in streams and siltation of river systems, as well as phosphorus contamination. Excess water lost down the soil profile carries nitrate and contaminates groundwater in addition to raising the watertable to produce waterlogging or salinisation down slope.

1 INTRODUCTION

Soil acidity is a serious agricultural and an environmental problem and affects in excess of 35 million hectares of agricultural land (Anon. 1995*a*). Most Australian research and scientific reviews have focused on soil acidity as an agricultural production problem. The reduction in soil pH can decrease the production of both crops and pastures, and restrict the choice of agricultural species that can be grown by farmers (Scott and Fisher 1989; Helyar 1991). In this review we also consider off-site consequences of acidification of agricultural soils as well as those directly relevant to agricultural production.

Soil acidity is measured using the pH scale (the negative logarithm of the hydrogen ion concentration) which spans values from 1 to 14, with 7 being neutral. All values less than 7 are acid; however, only pH_{Ca} values below about 5.2 (1:5 soil : 0.01 M $CaCl_2$) cause problems for plant growth. An important aspect of the pH scale is that it is a logarithmic scale, so that pH 5.2 is 10 times more acid than pH 6.2, and soils of pH 4.2 are 100 times more acid than the pH 6.2 soil. For this review, problem acid soils are considered to be soils with a $pH_{Ca} \leq 5.2$.[1]

The current acidity status of soils in Australia is the result of a combination of natural processes and agricultural impact. Natural processes operate on a near geological time scale, therefore emphasis should be given to how agricultural practice is accelerating acidification. For example, in some situations 20–30 years of agriculture has resulted in a similar amount of acidification as 'natural' processes in tens of thousands of years. Soil acidification is important not only because of its current impacts, but because the areas affected and the intensity of the problem will increase rapidly with time.

Agricultural problems become environmental issues when they cause the permanent destruction or degradation of a non-renewable resource (in this case the soil) or when there are off-site systemic impacts emanating from that problem. Soil acidification and the resultant highly acid soil can satisfy both these criteria, although the nature of off-site effects is not well documented or accepted. In fact, one comprehensive review by the Bureau of Rural Resources claims that government intervention (to encourage lime use to treat acid soils) is 'unlikely to find favour with policy makers because... soil acidity is confined with no off-site effects' (Evans 1991). We disagree with this view and believe that soil acidity restricts plant growth and water use, leading to off-site effects through the water cycle. This culminates in the turbidity of streams, siltation of dams and nitrate contamination of a rising watertable accompanied by down-slope waterlogging and saltation.

[1] Note: In some papers referred to in this chapter, soil pH is measured in a soil : water suspension (pH_w). The pH values determined in this way are generally about 0.8 pH units higher than those determined when using the 0.01M $CaCl_2$ method (pH_{Ca}).

2 EXTENT AND SEVERITY

Spatial Distribution

There have been few studies that have systematically mapped the distribution of pH on a state-wide basis. Helyar *et al.* (1990) surveyed NSW and found that there were 13.5 million hectares of soils below pH_{Ca} 5.0, including 8.5 million hectares of agricultural land. They found that over 40% of agricultural land that received >500 mm average annual rainfall was affected by low pH. Elsewhere there have been numerous regional and state-wide assessments, which when combined, contribute to a relatively clear picture (Anon.1995*a*). These data are summarised in Table 1.

Table 1. Extent of acid soils in Australia (ha × 10^6)

State	Highly acidic (pH_{Ca} < 4.8)	Moderate acidity (pH_{Ca} < 4.9–5.5)	Slight acidity (pH_{Ca} < 5.6–6.0)
New South Wales	13.5	5.7	5.1
Victoria	3.0	5.6	5.5
Western Australia	4.7	4.7	n/a
South Australia	2.8	n/a	n/a
Queensland	8.4	32.0	n/a
Tasmania	1.0	n/a	n/a

Subsoil Acidity

One important aspect of soil acidity (i.e. subsoil acidity) has not been quantified spatially, although it is recognised as an important attribute. Most current survey data (Table 1) refer to soil pH in the 0–10 cm zone, although much research indicates that acidification of the subsoil is occurring either concurrently with, or subsequent to surface (0–10 cm) acidification. The significance of this phenomenon is that subsoil acidity increases the stress that plants experience in highly acid soils as it can result in yield loss and an inability to absorb water and nutrients due to damage to the root system (Scott *et al.* 1997; Leech *et al.* 1998). Subsoil acidity is very difficult and expensive to ameliorate.

Rate of Acid Addition

Of critical importance to the future of agriculture and the significance of acidification as an ecosystem problem is the rate at which acid is being added to the soil. The evidence of accelerated acidification is now becoming more comprehensive and unambiguous. Table 2 summarises published Australian data. Acidification rates are expressed in terms of the amount of pure lime (calcium carbonate) required per hectare each year to balance acid addition.

Table 2. Calcium carbonate required to balance net acid addition from various Australian farming systems

Farming System	Location	Lime required kg ha^{-1} yr^{-1}	Acid addition mechanism (%)	Reference
Grazed pasture	NE Victoria	39	–	Ridley *et al.* (1990*a*)
Pasture-grazed hay	NE Victoria			Ridley *et al.* (1990*b*)
Fertilised		71	C = 65, N = 35	
Fertilised and lime		118	C = 42, N = 58	
Unfertilised		8	C = 100	
Continuous lupins	Rutherglen, Vic.	530	N = 100	Slattery *et al.* (1998)
Continuous wheat	NE Victoria	230	N = 100	
Lupin	Rutherglen, Vic.	200		Coventry and Slattery (1991)
	NE Victoria	263		
Wheat – lupin	WA	14–27	–	Loss *et al.* (1993)
Pasture		8–10	–	
Cereal – pasture	WA	8	C = 100	Dolling *et al.* (1994)
Wheat continuous + N		17	C = 98	
Pasture – crop		20	C = 81, N = 19	
Pasture 2 – crop 1		41	C = 61, N = 39	
Pasture		46	C = 75, N = 25	
Pasture – cereal (% pasture)				
33S[A]	Wagga, NSW	114	C = 21, N = 79	Helyar *et al.* (1997)
33L		126	C = 20, N = 80	
50S		124	C = 29, N = 71	
50L		142	C = 28, N = 72	
67S		126	C = 35, N = 65	
67L		124	C = 36, N = 66	
Annual crop/pasture	Wagga, NSW	46–95	N	Conyers *et al.* (1996)
Grazed annual pasture	Crookwell, NSW			Helyar and Porter (1989)
Granite soil 55 yr		173	C = 59, N = 40	
Basalt soil 25 yr		210	C = 47, N = 51	
Grazed kikuyu perennial pasture	North coast NSW			Helyar *et al.* (1990)
0–300 kg $^{-1}$ yr^{-1} $(NH_4)_2 NO_3^-$ N		0	N/A	
700 kg $^{-1}$ yr^{-1} $(NH_4)_2 NO_3^-$ N		400	(N)	
Kikuyu $(NH_4)_2 SO_4^-$ N fertilised		1065	(N, S)	Awad and Edwards (1977)

Table 2. (continued)

Farming System	Location	Lime required kg ha^{-1} yr^{-1}	Acid addition mechanism (%)	Reference
Paspalum/ White Clover				Helyar *et al.* (1990)
125 kg superphosphate/ha/yr		62	(N, C)	
250 kg superphosphate/ha/yr		129		
500 kg superphosphate/ha/yr		182		
Perennial pasture	Northern Tablelands, NSW			Helyar *et al.* (1990)
188 kg superphosphate/ha/yr		138	(N, C)	
375 kg superphosphate/ha/yr		125		
Irrigated rice-based farming	Murrumbidgee and Coleambally			Helyar *et al.* (1990)
Alluvial light clays	Irrigation Areas,	520	(N)	
Red clays	NSW	385	(N)	
Grey self-mulching clays		500	(N)	
Summer crop–fallow	Tropical and	90	C = 19, N = 81	Moody and Aitken
Tobacco	subtropical,	Nil		(1997)
Grass pasture (hay)	Queensland	310		
Crop–pasture rotation		90		
Sugarcane		170	C = 58, N = 42	
Table grapes		130	C = 30, N = 70	
Bananas		1710	C = 20, N = 80	
Stylosanthes pasture	Semi-arid tropics, QLD, NT	126 (mean, n = 7)	(N)	Noble *et al.* (1997)

[A] Rotation length: S, short, L, Long.

Notes: 1. Most data (except Ridley *et al.* 1990*b* and Helyar *et al.* 1997) are based on acid addition relative to a control, this may result in an underestimate of acidification.

2. Where acid addition mechanisms have not been determined, the suggested main mechanisms are in parentheses.

The data from Table 2 highlight the variability in acid addition rates across environments and farming systems. The rate of acid addition or (as expressed here) the amount of lime required to balance that addition, reflects the propensity of the farming system and environment to generate excess acid. The rate of decline of soil pH is influenced by the net rate of acid addition and the capacity of the soil to resist pH change (buffering capacity). Net acid addition rate in turn is a function of balance between alkali and acid producing processes. Unfortunately, many modern productive farming and grazing systems, both temperate and tropical, result in accelerated acidification. The processes which generate acid are explained in detail in the next section.

3 CAUSES OF ACCELERATED ACIDIFICATION

In natural systems, soils acidify over long periods of time, often tens of thousands of years. This slow change indicates that acid addition is almost balanced by alkali production to give a small net acid addition. What is happening in many agricultural systems is that acid addition substantially exceeds balancing reactions. The mechanisms of acid addition have been extensively explored and explained for agricultural systems where acid rain is not a measurable contributor (Helyar 1976; Helyar and Porter 1989). These acid addition processes, with the exception of the use of acidifying fertilisers, are the same as in natural ecosystems.

The main mechanisms of acid addition in agriculture are through changes to the nitrogen and organic carbon cycles and these are:

(a) the use of legumes that fix nitrogen and increase soil organic nitrogen which nitrifies and is subsequently leached;
(b) the removal of products and waste products (e.g. manure) high in residual alkalinity; and
(c) the use of acidifying nitrogen and elemental sulfur fertilisers.

Acid addition in a legume-based system is partly due to loss of nitrate by leaching with excess water. Poor use of water by some agricultural systems is the driver of this acid addition (Passioura and Ridley 1998). Excess cation uptake by the root system results in accumulation of alkalinity in plant material. Net acidification can occur if product is removed. In addition the vertical location of the processes of cation/anion uptake and organic matter accumulation and decomposition can cause spatial redistribution of pH within the soil profile. Increases in soil organic matter levels, if derived from material grown on the soil, can acidify the soil. Acidification can also be rapid in intensive farming systems where heavy applications of nitrogenous fertiliser are used, both in irrigated (e.g. rice) and dryland (e.g. sugarcane) systems.

It is clear that the relative importance of each of these mechanisms depends upon the environment and the farming system used.

The nitrogen cycle dominates acid addition in the potentially very productive, higher rainfall zone of eastern Australia (>500 mm average annual rainfall). Soil nitrogen status can reach high levels in annual legume-based pasture and cropping systems. Nitrogen fixation and nitrification of the organic nitrogen with the subsequent leaching of the nitrate causes rapid acidification in both systems (Table 2). The nitrate production/leaching process of acid addition assumes importance if nitrate is leached beyond the depth of plant root systems. In this situation there is acidification of the profile in the rooting depth. Since nitrate is highly soluble and moves with soil water, nitrate loss will be common where there is a regular downward flow of water beyond the root system. Such flows are common (Bond *et al.* 1997) and are associated with rising groundwater and salinity as well as acidification. The movement of nitrate out of the root zone is accentuated in annual winter-growing pastures where there is little growth over summer (i.e. no sink for the water or nitrate) and the decomposition of plant residues (particularly of legumes which may be high in organic nitrogen) produces a ready source of nitrate. At the start of the season, in autumn, much of the nitrate

leaches through the soil before the annual pasture or crop has developed an effective root system (Simpson 1962). The flux of nitrate can be locally concentrated and this is accentuated by the presence of grazing animals. Urine patches can have >400 kg N/ha, and this can be excessive for even actively growing plants to absorb (Black 1992).

Combinations of acid addition processes are at work in all farming systems. Although all published examples of very rapid acidification are associated with changes to the nitrogen cycle through either legume-sourced nitrogen or ammonium-based fertilisers (Helyar *et al.* 1990; Mason *et al.* 1994), changes to the carbon cycle via organic matter accumulation and product removal can also make important contributions (Ridley *et al.* 1990*a*; Dolling and Porter 1994; Dolling *et al.* 1994; Helyar *et al.* 1997). However, there is some uncertainty about the comparability of data from the various sources as methods for estimating key chemical attributes, particularly soil buffering capacity, have not been standardised.

The importance of product removal to acid addition or alkali requirement to balance the process for various farming activities can be gauged from Table 3. It can be seen from these data that removal of some products, e.g. lucerne (*Medicago sativa*) hay, is highly acidifying when compared with say wheat grain or wool production.

Table 3. Calcium carbonate required to replace the alkali removed in farm products (adapted from Slattery *et al.* 1991)

Product	Alkali removed per tonne of product (kg of $CaCO_3$ equivalent)	Common yield range at Wagga (t ha^{-1})	Lime required to balance acid addition kg ($CaCO_3$ ha^{-1} yr^{-1})
Hay - lucerne	60	3–6	180–360
- mixed grasses	44	3–4	132–176
Lupin	20	1.5–3.0	30–60
Barley	8	2.5–5.0	20–40
Wheat	9	2.5–5.0	22.5–45.0
Lambs	0.6 kg $CaCO_3$ $lamb^{-1}$	6–12 lambs ha^{-1}	3.6–7.2
Wool	0.08 kg $CaCO_3$ kg^{-1}	35–70 kg wool ha^{-1}	2.8–5.6

The form of the N fertiliser strongly influences acidification rates (Pierre 1928). The acidifying potential of the various nitrogen fertiliser forms is shown in Table 4 for zero or 100% of the applied nitrogen being leached as nitrate. Note the acidification caused by the ammonium forms even without leaching, and the increase in acidification with leaching for all forms other than pure nitrate fertiliser. The negative value (alkali addition) for nitrate fertilisers, where no leaching occurs, results from the plant uptake of this nitrate or from alkaline denitrification.

The choice of the appropriate fertiliser for use in a given situation should take these costs and benefits into account as well as the fertiliser cost itself.

Table 4. Soil acidification rates expected from various forms of nitrogen fertilisers (kg of lime per kg of N added) (Cregan and Helyar, 1986)

Fertiliser and acidification class	No leaching of nitrate formed	100% of nitrate formed is leached
Most acidifying — ammonium fertilisers:		
Sulfate of ammonia (ammonium sulfate)	3.7	7.1
MAP (monoammonium phosphate)		
Medium acidification:		
DAP (diammonium phosphate)	1.8	5.3
Low acidification:		
Urea		
Ammonium nitrate	0	3.6
Aqua ammonia		
Anhydrous ammonia		
Biologically fixed (legume) N		
Alkaline fertilisers:		
Sodium and calcium nitrate[A]	–3.6	0

[A] Seldom used in Australian agriculture due to high cost per kg N.

In addition to the net acidification of the soil profile there is also a sometimes rapid, redistribution of acidity within the profile due to the accelerated acidification caused by agriculture. This acidification and redistribution results in a typical acidified soil profile. The surface (0 to 2–4 cm) has relatively high pH and is underlaid by a highly acid strata to a depth of up to 15 cm. Beyond this depth the soil, usually but not always, becomes less acid (Conyers and Scott 1989; McLaughlin *et al.* 1990). There are also effects further down the profile which can make certain depths more or less acid. These effects are the result of a close interplay between the carbon and nitrogen cycles over the depth of plant root penetration. The pattern of cation/anion uptake within the root system may vary in space and time, and determines the acidity or alkalinity of root excretion. Excess cation (e.g. Ca, Mg) uptake results in acid excretion and excess anion uptake produces an alkaline rhizosphere at the site of uptake (Israel and Jackson 1978; Marschner *et al.* 1986). Therefore the production of NO_3^-N in the surface soil (1–10 cm) may acidify that strata but the uptake of that same NO_3^-N, say at 50 cm depth, may induce an alkaline reaction at the site of uptake. Also the return of organic anions in faeces and plant material, with subsequent oxidation, creates a less acid surface layer.

Additionally, in grazed systems the deposition of high rates of urea in urine patches and the subsequent transformations create a powerful mechanism for pH profile change and acidification (Black 1992).

4 THE NATURE OF THE SOIL ACIDITY PROBLEM

The problems presented by low pH for plant growth begin to be expressed once soil pH falls to below pH_{Ca} about 5.2. The critical pH varies with soil type and plant species, depending on the factors associated with depression in plant growth and the sensitivity of the plant to toxicities and deficiencies induced at low soil pH (Rowell 1988). The main components of the acid soil problem are aluminium (Al) toxicity, manganese (Mn) toxicity, hydrogen ion (H^+) toxicity, and molybdenum (Mo) deficiency. Nutrient deficiencies including calcium (Ca), magnesium (Mg) and phosphorus (P) are also commonly found in low pH soils as these soils are often of low fertility and have a low effective cation exchange capacity (ECEC; Helyar 1987). ECEC is the sum of the positively charged elements, calcium, magnesium, potassium, sodium, manganese and aluminium; it is measured in cmol(+)/kg soil. Higher values are an indication of greater potential fertility. Aluminium as a proportion of ECEC can be used as an index of Al solubility and plant phytotoxicity. Changes in biology of the soil also occur as pH declines because most organisms have an optimum pH range for growth. A reduction in pH can change the spectrum of diseases and their pathogenicity (Robson and Abbott 1989).

Although the severity of a soil acidity problem can be described in a broad way by pH, this index alone is not an adequate indicator of the problems a plant may experience in a low pH soil. Therefore the effect of soil acidity on plant growth is dependent on the intensity of the problem, the tolerance of the legume species grown and its associated rhizobia to the specific problems, as well as to the presence of other potentially interactive factors such as moisture stress, physical impedance of root growth or waterlogging. The gross manifestations of soil acidity on plant growth and, in turn, pastoral production include: failure of pasture establishment (Flemons and Siman 1970), reduced forage yields and stocking rates (Cregan *et al.* 1979), reduced seed set in annual legumes (Hochman *et al.* 1990), nodulation failure and low rates of nitrogen fixation (Jenson, 1943; Evans *et al.* 1988), reduced ground cover leading to erosion (Cumming 1980), colonisation of grasslands by acid-tolerant plant species (Davey *et al.* 1984) and reduced water use by acid-affected plants (Simpson *et al.* 1979; Kennedy *et al.* 1987). Thus the impact of soil acidity does not result in a particular, observable phenomenon, but a spectrum of ecological changes with major agricultural and environmental consequences.

Aluminium toxicity

Aluminium toxicity is usually considered to be the most important plant nutritional problem of low pH soils (Foy 1984). Below about pH_{Ca} 5.2, Al becomes increasingly soluble in soil solution, although the pH at which Al comes into solution and the amount and form of Al at a particular pH is determined by a series of relationships involving both organic and inorganic constituents; the nature and importance of these have been comprehensively reviewed by Ritchie (1989). The Al–pH relationship has been described for many soil types (Kamprath 1978; Bromfield *et al.* 1983*b*; Coventry *et al.* 1989; Chartres *et al.* 1990; Hochman *et al.*

1990). Aluminium is not required for plant growth and very small amounts of soluble Al are toxic to sensitive species (Helyar and Anderson 1970). Toxic Al interferes with cell division, cell elongation, DNA synthesis, and the uptake and transport of essential nutrients, particularly P (Foy 1984). The expression of phytotoxic Al is most noticeable on the roots where, due to the inhibition of cell division, most plants develop a typically 'knobby' root system in which lateral roots cease growth after breaking through the cortex. Where toxicity is severe, growth of the primary root system may also be reduced, resulting in a thickened stubby appearance (Helyar 1978).

The section of the root system most affected is the developing root tip and surrounding meristematic tissue. The same tissue is principally responsible for the uptake of water and nutrients and is colonised by rhizobia, the bacteria required for symbiotic N_2 fixation. Nutrients vary in their ability to be absorbed from different sections of the root tip: calcium appears to have a strong dependence on tissue near the root tip for absorption, whereas phosphate and nitrate ions are absorbed elsewhere (Gregory 1988). There are therefore two ways in which Al toxicity affects plant growth: the direct effect of Al toxicity impairs plant function, and the indirect effect of reduced root length and density. Both are important. For example Cornish *et al.* (1984) have shown that uptake of P from the soil is positively and linearly correlated to root length. Root length and depth are known to be important also in determining water-use and uptake of other essential nutrients (Pearson 1974; Hamblin and Hamblin 1985). Since the primary effect of Al toxicity is on root growth, the whole profile through which roots can proliferate needs to be considered. Acid subsoils, high in soluble Al, can restrict root growth in these zones and are now recognised as a major limitation to plant production (Adams *et al.* 1967; Pinkerton & Simpson 1981; Scott 1986; Scott *et al.* 1997).

The effects of high Al in the soil solution on nitrogen fixation are important and complex. They involve the impact of Al on host plant growth including root growth, growth of the rhizobia, the effectiveness of the symbiosis and interactions between these three components. The subject has been reviewed extensively by Munns (1976, 1977, 1978, 1986) and Coventry and Evans (1989). From these reviews and other published papers, some themes of importance emerge: (a) nodule function and symbiotic fixation will be limited by plant demand through a plant's ability to absorb water and nutrients, to fix carbon through photosynthesis and grow (Munns 1977); (b) in the soil solution, Al and low pH can both adversely affect nodulation, and Ca can modify their influence on fast growing rhizobia (Wood *et al.* 1984*a*; Munns 1986); (c) Al toxicity (Wood *et al.* 1984*b*; Kim 1985), low pH and Ca (Munns 1970; Richardson *et al.* 1988) are important factors influencing the limitations for the 'acid sensitive' steps in the infection of the legume root hair by the rhizobia; (d) rhizosphere pH changes induced by imbalances in root uptake of cations and anions from the soil solution, and reaction between root exudates and mineral nutrients, may play a key role in influencing the timing and rate of nodulation (Israel and Jackson 1978; Marschner *et al.* 1986; Munns 1986); (e) for most species, including subterranean clover (*Trifolium subterraneum*), nodulation and growth of symbiotically N-dependent plants are more sensitive to Al toxicity/low pH than the host plant (Kim 1985; Munns 1986); and (f) annual

legume species and varieties of subterranean clover vary in their ability to nodulate under low pH and Al toxicity (Howieson and Ewing 1989). For subterranean clover, which is regarded as an Al-tolerant species (Helyar and Anderson 1970), the Al tolerance ranking of the variety did not correlate well with its ability to nodulate (Kim 1985). The effects of pH on legume growth are further described under the section on hydrogen ion toxicity.

Raising soil pH can overcome Al toxicity problems as Al is insoluble and unavailable to plants at pH_{Ca} greater than about 5.2. The most common and practical means of raising soil pH is by using lime. Lime use can alleviate the toxic effects of Al and result in a more branched and finer root system as well as an increased root length and a greater potential to absorb water and nutrients (Foy 1974; Pearson 1974). The availability of other plant nutrients can be influenced by the resultant increase in pH. The addition of Ca (with liming) can also benefit the legume–rhizobia symbiosis. Thus liming to overcome Al toxicity may also lead to plants accumulating more or less nutrients in their shoots due to the changed availability of other plant nutrients in the soil, as well as to the potentially greater root exploration of Al sensitive species following liming.

Manganese toxicity

Excess uptake of divalent Mn is the second major toxicity factor affecting plant growth on acid soils. Most soils contain sufficient Al for toxicity to occur at low pH, but reducible Mn may be too low for the development of elevated soil solution Mn^{2+}. This depends on the mineralogy of the parent material and the extent of Mn losses due to leaching during soil formation (Helyar 1987; Schlichting and Sparrow 1988). Manganese toxicity is generally considered less important than Al toxicity because it is less widespread as a problem associated with acid soils. Nevertheless, on highly acid soils there are often toxic levels of both soluble Al and Mn (Pearson and Hoveland 1974).

Manganese exists in soils as the plant-available Mn^{2+} and the unavailable Mn^{3+} and Mn^{4+} forms. Plants suffer from toxicity when reduction of the Mn^{3+} and Mn^{4+} oxides to Mn^{2+} exceeds the rate of oxidation of Mn^{2+}, and so Mn^{2+} increases to toxic concentrations. The balance between plant-available and unavailable forms is influenced by the soil, pH, aerobic biological activity of the soil, redox potential, organic matter including root exudates, moisture content and temperature (Siman *et al.* 1974; Uren 1981; Foy 1984; Schlichting and Sparrow 1988; Ritchie 1989). In the low pH soils of south-eastern Australia, with winter rainfall and dry summers, soil Mn^{2+} levels fluctuate from season to season, depending on what combination of chemical and biological factors dominates the oxidation–reduction reactions. The dynamic nature of these relationships is illustrated by the seasonally elevated levels of Mn^{2+}. Divalent Mn is high in autumn following near sterilisation of surface soil by extremes of heat during summer, and in winter following waterlogging (Siman *et al.* 1974; Sparrow and Uren 1987). These conditions stop biological oxidation, but favour chemical reduction (Siman *et al.* 1974).

Manganese, unlike Al, produces characteristic toxicity symptoms in plant shoots. The expression of Mn toxicity tends to be proportional to uptake. The

symptoms for a wide range of crops and pastures have been documented by Foy (1983) and Helyar (1978). In subterranean clover, toxicity is first associated with marginal leaf chlorosis, then a reddening of leaf margins which sometimes turn purple. In severe cases necrosis also occurs (Helyar 1978). There is general agreement that manganese has more direct effects on shoot rather than root growth (Rios and Pearson 1964; Adams 1981; Foy 1983). Andrew and Hegarty (1969), in their evaluation of the response of a range of tropical and temperate legumes to manganese excess, also consistently found shoot growth to be affected proportionally more than root growth. In tropical legumes the ratio of shoot/root weight of the Mn-sensitive species was consistently lower than for those exhibiting tolerance. There was no similar trend within the temperate species which, as a group, exhibited a similar tolerance of Mn. Reduction in root growth with increasing Mn is thought to reflect the impact of Mn toxicity on shoot growth (Rios and Pearson 1964). Evans *et al.* (1987) consider that the reduction in total root growth could contribute to a reduction in N^2 fixation by subterranean clover suffering Mn toxicity. Plants are affected more by Mn toxicity at low temperatures (Foy 1984) but, as temperatures rise, plants may increase their Mn uptake (Helyar 1978). These temperature × Mn interactions may be important for annual winter-growing legumes like subterranean clover, which make their early seedling growth during the coolest months. This interaction may partially explain the observation of Siman *et al.* (1974) who claimed that young subterranean clover seedlings (grown in winter) were more severely affected by Mn toxicity than older plants (growing during the warmer spring).

Hochman *et al.* (1990) reported more lime responses during autumn and winter than during spring and the most consistently responsive site was high in exchangeable and reducible Mn. Unfortunately, there was no accompanying plant tissue analysis to confirm whether Mn toxicity was a factor and they attributed the seasonality of response to the rate of *R. trifolii* colonisation and frequency of nodulation (Evans *et al.* 1988). Evans *et al.* (1988) also demonstrated significant negative correlations between exchangeable Mn and nodulation (number per g root in soil 0–10 cm) in September at two sites, although Mn was not considered to be implicated in the lack of growth of the rhizobial population. If there is a strong Mn × temperature interaction with subterranean clover, liming to reduce toxicity in winter may be important.

Species and even varieties within species vary in their tolerance of Mn toxicity. In his review of the effects of Mn toxicity on legume growth, Helyar (1978) has summarised available reports on toxicity levels for a wide range of species. The annual legumes, subterranean clover and barrel medic (*Medicago truncatula*), are moderately tolerant and sensitive respectively. Evans *et al.* (1987) evaluated 18 subterranean clover strains for tolerance to Mn in solution culture and found a wide range of tolerance. At least four strains were substantially more tolerant than the recommended varieties of similar maturity type. This difference between strains confirmed the earlier indications of potential intraspecies differences reported by Osborne *et al.* (1981). Evans *et al.* (1987) also reported that Mn toxicity reduced nodule number and nitrogenase activity. Similarly, nodulation responses following liming, observed in the glasshouse experiment, were attributed to the

alleviation of Mn toxicity (Coventry *et al.* 1987*a*). From these reports it would appear that both the host and some aspects of the legume/rhizobia association are affected by Mn toxicity. The effects of Mn toxicity on plant growth are generally associated with interference to enzyme and hormonal activity and have been reviewed in detail by (Helyar 1978; Foy 1983; 1984; Scott *et al.* 1987; Burnell 1988; Campbell and Noble 1988).

Liming can lower Mn availability and consequently the concentration in leaf tissue (Gupta 1972; Siman *et al.* 1974; Coventry *et al.* 1987*a*). Generally, raising soil pH_w to about 5.5–6.0 will overcome toxicity (Kamprath 1984; Schlichting and Sparrow 1988), but where toxicity is severe due to highly reducing conditions, liming may be insufficient to eliminate toxicity (Graven *et al.* 1965; Siman *et al.* 1974). Incomplete lime reaction with the soil may also lead to the failure of lime to reduce Mn toxicity (Myers *et al.* 1983). The antagonism between Ca and Mn for plant uptake can contribute to lowered tissue Mn following liming, although on acid soils the raising of pH is thought likely to be the primary effect (Sutton and Hallsworth 1958; Coventry *et al.* 1987*a*).

Hydrogen ion toxicity

In low pH soils the direct impact of H^+ on plant growth in the field is generally secondary to the effects of Al and Mn toxicities. The toxicity of H^+ to plant growth has been demonstrated in solution culture experiments. H^+ toxicity has been shown to be of importance to nodulation by rhizobia (Graham and Parker 1964) and for growth of a wide range of plant species (Edmeades *et al.* 1991). The effective nodulation of both subterranean clover (Munns 1978; Kim 1985) and lucerne (Munns 1978) was affected by low pH. In these studies there was a trend for *Bradyrhizobia* spp. to be less affected by low pH than *Rhizobium* spp. and for increasing Ca to modify pH effects. The mechanisms controlling the success of the rhizobial infection process have been described by Richardson *et al.* (1988). They found that low pH and low Ca reduced production of flavones exuded by roots, which were essential for the expression of nodulation genes in *R. trifolii*. At low pH, *Rhizobium* growth and nodulation gene induction were inhibited. These processes of flavone exudation, *Rhizobium* growth and the expression of nodulation genes are necessary for the infection by *Rhizobium* of the root hair, since the flavones are only recognised by *Rhizobium* during the log phase of growth. The adverse effects of H^+ on these acid-sensitive processes can be reduced by adequate levels of Ca. These findings may help to explain the many recorded responses by clover and medic on low pH soils to the pelleting and banding of lime with seed (Anderson and Moye 1952; Loneragan *et al.* 1955; Roughly and Walker 1973).

Similar findings with *Medicago* species were made by Howieson *et al.* (1992), who determined that the better ability of the more acid-tolerant species *M. murex*, *M. polymorpha* and *M. aculeata* was due to their ability to produce exudates at low pH that triggered the expression of the nodulation gene. Acid-sensitive species such as *M. truncatula* and *M. littoralis* did not possess this capability unless lime was used.

Molybdenum deficiency

The first reports of Mo deficiency in pasture legumes were for subterranean clover in South Australia (Anderson 1942). At this time, very small amounts of added Mo were found to be as effective in correcting Mo deficiency as large applications of lime (Anderson and Ortel 1946; Ortel *et al.* 1946). Since these first discoveries, Mo deficiency has been found to be widespread on acid soils (Hudson and Cradock 1954; Anderson 1970; Donald and Prescott 1975). Generally, these Mo-deficient soils have been in the higher rainfall zone (Barrow 1978) and where pH_{Ca} is <5.0, although deficiencies have been recorded in higher pH soils. The importance of Mo deficiency is likely to increase with time as many soils in southern Australia acidify under current farming practice (Helyar *et al.* 1990).

Mo availability in the soil solution is largely influenced by soil mineralogy and pH. At low pH, Mo is strongly adsorbed to soil colloids such as the hydrous oxides of aluminium and iron (Jones 1957; Reisenauer *et al.* 1962). When pH is increased by liming, Mo rapidly becomes more soluble. This is probably due to molybdate being exchanged for hydroxyl ions, although the validity of this mechanism was questioned by Barrow (1978) who evaluated other possibilities. Davies and Jones (1988) claim that plant Mo uptake will commonly increase two- to three-fold per pH unit as pH^w is increased from 4.0 to 7.0. The ability of the soil to absorb Mo also dictates that the amount of Mo required to overcome deficiency increases with declining pH. Liming to raise soil pH may, alone, be insufficient to overcome Mo deficiency. Such an absolute Mo deficiency was reported in northern Victoria by Coventry *et al.* (1987) who suggested that, for best yields at two of their experimental sites, Mo fertiliser needed to be used, in addition to liming.

Both legume and non-legume plants require Mo as an essential part of their nitrogen metabolism. However, the rhizobia associated with legumes have a higher requirement for Mo than the host plant (Robson 1978). Molybdenum is involved in two enzymes, nitrate reductase and nitrogenase. Nitrate reductase is required by all plants as the first step in plant nitrate assimilation, whereas nitrogenase is involved in complex reactions that reduce N^2 to NH^4 and is central to the fixation of nitrogen by legumes (Streeter and Barta 1984). Given the role Mo plays in nitrogen nutrition, it is not surprising that the symptoms of Mo deficiency for plants are similar to those of nitrogen deficiency, with general chlorosis in legumes and a mottled paleness and leaf burn of mature leaves in non-legumes (Robson and Snowball 1986). In addition the nodules in legumes are usually very small and numerous with green rather than pink pigmentation (Anderson 1956).

Acid soil infertility

Low fertility is a common characteristic of many naturally highly acid soils, as well as soils that have acidified from agricultural practice (e.g. McLachlan 1980). Frequently, the acidity and metal toxicities which characterise these soils extend to depth and are associated with low cation exchange in the subsoil. The acidified profiles described by Bromfield *et al.* (1983b) show acidification and cation leaching of the surface 30 cm or 60 cm soil depth after 25 and 55 years respectively, of

fertilised subterranean clover. The implication of declining pH on cation and anion availability for plants has been reviewed by Helyar (1987). A further complicating factor is the need to consider nutrient availability following liming of low fertility acid soils (Lipsett 1980). Although liming reverses many of the problems of low pH, the bac kground of low fertility for many Australian soils (Williams and Andrew 1970) and the large inputs of Ca^{2+} and HCO_3^- may induce nutrient deficiencies.

Reported negative effects of lime application are induced deficiencies of micronutrients, e.g. boron and zinc, reduced phosphate availability and suppressed availability of K and Mg. These effects have been considered in detail (Kamprath and Foy 1971; Adams 1978; Foy 1984). Of concern in south-eastern Australia is the effect of lime on boron nutrition of annual legumes and lucerne, particularly on light textured soils derived from granite or sandstone (Dear and Weir 1987). Dear and Lipsett (1987) reported that with subterranean clover grown on acid granite-derived duplex soils from Tarago and Berridale, NSW, boron application increased seed yields seven- and twofold, respectively. This was despite there being either negligible or only slight increases in forage yields. The application of lime to these soils was found to greatly accentuate the boron deficiency and the application of boron increased seed yield 55-fold on the Tarago soil and eightfold on the Berridale soil. Such a reduction in seed set with liming would greatly reduce winter productivity and persistence of subterranean clover in subsequent years.

Plant disease

Evidence of the effect of soil acidity on the presence and pathogenicity of soil-borne fungal diseases shows no clear trends, with diseases being both more severe (Murray *et al.* 1987) and less severe following liming (McKenzie *et al.* 1972). For annual legumes the only group of diseases that interact with pH appear to be the root diseases caused by *Pythium* spp. Surprisingly, this factor is given little consideration in Johnstone and Barbetti's (1987) review on pasture disease, despite soil acidity being widespread and perhaps the major emerging nutritional constraint to annual legume growth in southern Australia. Hochman *et al.* (1990) reported no effect of lime on root health or seedling survival for subterranean clover swards affected by *Phytophthora clandestina* sp. nov. Although Stovold (1974), again with subterranean clover, found *Pythium irregulare Buisman.* associated with acidified soils high in Al and Mn, there was no evidence of a disease–pH relationship. In contrast, a number of reports found that lime reduced the incidence of damping off in lucerne and barrel medic (Kleinig 1965; McKenzie *et al.* 1972). Robson and Abbott (1989) suggest that for this type of fungus, host health and growth rate may play an important role in disease development. This would explain the reduction in disease in lucerne and barrel medic and the lack of effect with subterranean clover, and is consistent with the remarks of Stovold (1974).

It is the seedling stage of annual legume growth that is most likely to be affected by fungal diseases. Barbetti (1984) reported that the greatest damage from soil-borne fungi was usually between weeks 6 and 16 of plant growth. However Kleinig (1965), McKenzie *et al.* (1972) and Andrew (1963) all reported plant loss with lucerne and barrel medic in the period immediately before and

after emergence. McKenzie *et al.* (1972) identified and implicated the fungus *P. irregulare*. The timing of fungal attack is probably dependant on the fungus principally responsible for damage, its virulence and host susceptibility. *Phytophthora clandestina* is more likely to be favoured by previous warm, moist soil conditions typical of an early start to the season, whereas *P. irregulare* would be more common when conditions are cooler. It would seem logical that plant roots stressed by factors associated with acid soil would be both less capable of resisting attack and have a reduced ability to recover. Whether these factors are interactive or simply additive is unknown. Given the importance of seedling establishment to pasture productivity, more information is desirable.

Subsoil acidity

Subsoil acidity was first recognised as an agronomic problem of consequence in Australia due to the failure of lucerne to grow satisfactorily on acid soil, particularly during dry periods, even when the surface had been limed. These events have been described in detail by Simpson and Lipsett (1973) in their first paper on subsoil acidity and infertility in the Australian literature. Further investigation was slow to develop, probably because acid subsoils were perceived to be a problem only for lucerne. Further, the extent and severity of subsoil acidity had yet to be defined. Many agriculturalists, including researchers, were still seeking further low-input solutions such as Mo use, and inoculation and lime pelleting. It was not until Pinkerton and Simpson (1981) published their glasshouse studies on the effect of subsoil acidity on a wide range of tropical and some temperate forage species that plants other than lucerne were considered. The importance of subsoil acidity has been recognised since Williams (1980) published a description of the pH profile of the 'unimproved' and the 'improved' clover pasture sites described previously by Donald and Williams (1954). This work illustrated the development of subsoil acidity under subterranean clover pastures on the Southern Tablelands, and was followed by that of Bromfield *et al.* (1983*b*) and Porter and Wilson (1984), clearly establishing subsoil acidity as an important and probably widespread phenomenon. More recent work, e.g. Helyar *et al.* (1990), Ridley *et al.* (1990*b*) and Carr *et al.* (1991), has more clearly defined the extent and severity of the problem.

Management of Acid Soils

The technologies and management systems for the treatment and management of acid soils have now been extensively researched and described. They can be categorised according to the characteristics of the acid soil problem as follows:

- soils where acidification extends to 20–30 cm depth;
- soils where acidity extends deep into the profile, possibly down the whole rooting depth of the species grown; and
- situations where, in current farming systems, the process and magnitude of accelerated acidification are known and maintenance lime requirement can be estimated.

Table 5. Technologies for the management of soil acidity

Soil acidity category	Technology for management	Comment/ease of implementation	Key reference
I. AMELIORATION			
Surface acidification 0–30 cm			
Land arable	Liming and incorporation by cultivation	Wide application	Adams (1984) Cregan *et al.* (1989)
Non arable	Surface liming	Difficult where steep/rough; slow movement down profiles	Scott *et al.* (1997)
Surface and subsoil acidity	High lime rates and deep tillage	High cost, need suitable soil, special equipment	Coventry (1991)
	Lime slotting	Limited amelioration	Kirchhof *et al.* (1995)
	High rates of surface lime and acidifying fertiliser, acid-tolerant grass.	High cost, requires leaching	Sumner (1995)
	Nitrate fertiliser, with acid-tolerant grass	High cost, requires leaching	Adams and Pearson (1969)
	Gypsum	Suitable only for some soils, requires leaching	Sumner (1995)
	Other amendments	At present high cost or only experimental	e.g. Smith *et al.* (1995)
II. MAINTENANCE			
Acid addition from changes to N cycle		Agronomic practices to increase water and N use.	Helyar (1991)
		Use less acidifying fertilisers	Pierre (1928)
		Use deep rooted perennial grasses	Passioura and Ridley (1998)
		Use of lime (possibly trees) necessary for urine patches	Black (1992)
Acid addition from changes to C cycle	Cultivate soil to oxidise OM	OM benefits usually greater than problem from acid addition	Helyar (1991)
	Minimise removal of crops with high residual alkalinity	may reduce profits	Helyar (1991)
	Feedback hay/ stockfeed in clover paddocks	Not always practicable	Helyar (1991)

Note: For many situations, optimal treatment will involve a number of technologies and management strategies.

Table 5 summarises the technologies available to address the range of acidity problem situations in agriculture. Further details on acidity problems and their management are provided in comprehensive reviews by Cregan *et al.* (1989) (lime use/acid addition management); Helyar (1991) (mechanisms and management) and Sumner (1995) (subsoil management). Despite the breadth and detail of these papers, they have a tight agricultural focus and are somewhat deficient in evaluating the acid soil problem in a wider farming systems/agroecosystem context. Such an approach is important since soil acidity generates negative off-site impacts (externalities).

5 SOIL ACIDIFICATION AS AN ENVIRONMENTAL PROBLEM

To satisfy the criteria described in the Introduction, clear evidence needs to be produced that there is either permanent degradation or off-site effects.

Most of the acidification which has affected subsoils (>20 cm depth) cannot be treated profitably. The depth to which the soil has acidified determines the ease of subsoil amelioration and the cost involved. For example, if a soil of medium texture has acidified to pH <4.5 to a depth of 60 cm, the lime requirement to ameliorate the full acidified profile would probably be of the order of 15–20 t ha^{-1} of lime at a spread cost of \$70 t^{-1}. Such treatment would cost \$1000 to \$1400 ha^{-1} for the lime and lime spreading only. For farming/grazing land on the south-western slopes of NSW, this treatment alone may represent 1.5 to 3 times the value of the land. Such relativities between land value and profile liming would not be uncommon over much of Australian extensive agriculture. Hochman *et al.* (1989) compared the ratio of lime cost/annual output value for various agricultural enterprises in a range of countries and highlighted that extensive grazing and farming enterprises have the highest ratios. These observations still apply.

Sumner (1995), in his extensive review of the amelioration of soil acidity, claims that the technology now exists to ameliorate subsoil through either lime incorporation or minimum disturbance techniques. These rely on continued liming of topsoils to near neutrality, combined with large inputs of acidifying nitrogen fertilisers. The cost of such strategies will prohibit their use in Australia to only the highest return/intensive enterprises. High cost amelioration strategies will have little place in extensive industries such as the wool industry, which over the past 20 years has had a return on capital investment of –3.5%. The question of whether degradation is permanent is argued to be simply an economic one. The argument follows that if a resource (land) becomes valuable enough with time, as it eventually will since land is a finite resource, the soil will be 'rehabilitated'. However, these assumptions have little factual substance and the costs may be extreme and rehabilitation impossible. Certainly, in today's terms in many agricultural systems, rehabilitation is economically impossible and subsoil acidification can be considered permanent.

Acidification is not independent of other land degradation phenomena. A highly acidified soil not only limits plant growth and hence agricultural production

but has impacts throughout the agroecosystem. The off-site effects or externalities of soil acidification have not been well documented and the absence of a coherent case has mitigated against significant government assistance to address the problem (Purtell and McCallum 1986; Evans 1991).

To provide a framework through which the systematic impacts of soil acidification can be traced, a simple model has been constructed (Fig. 1). The main components of this model were developed at a workshop on soil acidity chaired by Dr W.M. Porter at Wagga Wagga in 1995. In outline the acidification of soils reduces plant growth and microbial activity. The effect of this is to cause reduced ground cover and water use, culminating in increased soil surface erosion, stream turbidity and siltation of both streams and dams. Unused water also exits the site by infiltrating to the watertable, causing a rise in the groundwater. When the watertable reaches near to the soil surface there is waterlogging and possibly salinisation. Nitrogen fixation and cycling are impaired by soil acidity, and N addition as fertiliser is required. Unfortunately, this fertiliser is frequently in an ammonium form. The leaching of nitrate derived either from the soil or ammonium fertiliser, feeds back to worsen the soil acidity problem. Other aspects (erosion, salt and waterlogging) further impair plant growth and water use and exacerbate the off-site water-driven problems. The challenge now is to quantify the various off-site impacts and to understand better the linkages and feedbacks in the systems.

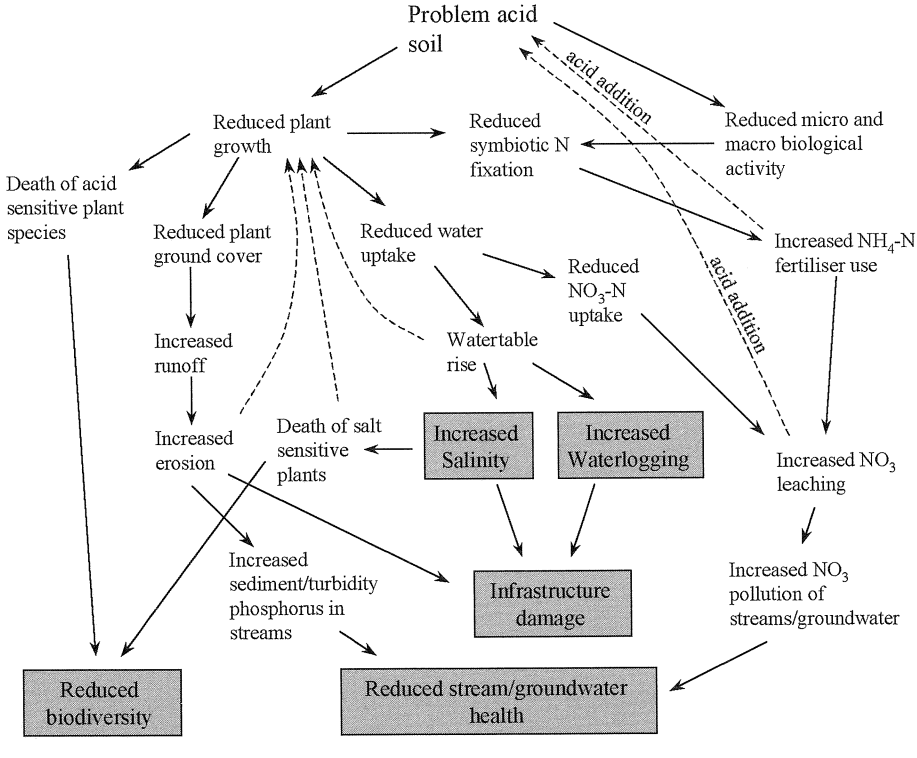

Fig. 1. Systemic impacts of soil acidification including off-site impacts (components in boxes represent major external impacts).

Table 6 specifies each component of the model and attempts to establish the magnitude of the impacts and the source of the data.

The technical and managerial solutions necessary to recover and stabilise degradation of farm resources are extremely complex and require financial resources to implement them. This requires very high levels of technical competency and management skills. The combination of attributes required is likely to be present in no more than 15% of farms (Passioura and Ridley 1998). So what happens on the remaining 85% of farms where accelerated acidification is a continuing process? The key questions are: "Has 'the market' failed in relation to land degradation generally, and for soil acidity specifically?" and, "Is society prepared to tolerate the consequences?" Passioura and Ridley (1998) claim that the overriding rural environmental problem is the off-site loss of unutilised water and nitrogen, and the solution is beyond the resources of the majority of farm managers.

Table 6. The knowledge base for acid soils and their off-site impacts.

Model component	Comment	References/reviews
Problem acid soils	Well documented $>30 \times 10^6$ ha	Helyar *et al.* (1990) Anon. (1995*a*)
Reduced plant growth	Extensive research on crop and pasture lime responses	Cregan *et al.* (1989), Coventry (1992)
Reduced ground cover	Limited data	Conyers and Davey (1990), Cumming (1980)
Species change	Acidity tolerance/sensitivity well understood	Scott and Fisher (1989)
Microbiological activity	Extensive data on rhizobiology	Coventry and Evans (1989) Glenn and Dilworth (1991)
	Disease understanding not comprehensive	Robson and Abbott (1989)
Macrobiology	Understanding developing	Lobry-de-Bruyn and Conacher (1990), Lee (1985) Hirth *et al* (1996)
Reduced water use and nitrate uptake	Much new data, high rates of deep drainage and NO_3^-N wastage	Ridley *et al.* (1997), Passioura and Ridley (1998)
Increase runoff	No direct evidence	
Watertable rise	Much new data - salinity modelling	Taylor and Clifton (1993), Eberbach (1998)
Erosion	Deficient	Cumming (1980)
NO_3^-N leaching	Significant new research	Ridley *et al.* (1997)
Stream flow/ stream pollution	Evidence from catchment monitoring	Walker and Reuter (1996)
Waterlogging	Acidity as a component of wider catchment mismatch between water supply and use, poorly documented	Passioura and Ridley (1998), Woolley (1991)

It is worth evaluating the current state of degradation due to acidification (natural and induced) separately from the present rate of acid addition to problem soils. This highlights what action is required to ameliorate the current problem, as well as annual additions of lime required as a maintenance application to match ongoing acidification.

If we conservatively assume that of Australia's 35 million hectares of problem acid soils 20 million hectares are important and productive agriculturally, that all problems can be overcome by amelioration to a depth of 20 cm, and that 5 t ha^{-1} of effective lime is required to achieve this amelioration, then the Australian lime requirement could be said to be 100 Mt. On an annual basis for this same 20 million hectares it is assumed that the acid addition rate is equivalent to 100 kg lime ha^{-1} yr^{-1}. This would require an annual prophylactic application of 2 Mt.

There is a large difference between the lime being applied (about 1.5 Mt in Australia) and that needed. This is understandable since lime is an expensive outlay and the profitability of many, particularly grazing enterprises, is low. However, there are sectors within the farming community that are using lime. For example, in the south-western slopes of NSW, lime use is common practice for those farmers who have profitable cropping enterprises which include canola. By 1998, lime had been used on about 60% of these farms in the area (G. Fenton, pers. comm.). The farmer's decision to use lime with canola is supported by an economic analysis, just as is the decision not to use lime by nearby graziers occupying highly acid soil which continues to acidify. Both managers are acting rationally but the grazier's resource is degrading further and 'his' problem is affecting others beyond his farm gate.

6 CONCLUSIONS

The water cycle is a unifying concept which links many of the significant land degradation/agricultural productivity problems, and has been clearly emphasised by others (Pratley 1987; Anon. 1995*b*; Passioura and Ridley 1998). A simple but profound conclusion can be drawn: if farming systems can be designed and managed to maximise *in situ* water use, this will maximise agricultural production while concurrently minimising environmental degradation. A further, but critically important aspect, which is largely ignored by the scientific literature and inadequately assessed by various consultancy reports to government on the soil acidity problem, is the off-site impact of the acid soil problem (as described in this chapter).

Debate on management of acid soils from a government policy viewpoint has concentrated on the economics of lime use, farmer management options (see Table 5), farmer knowledge/education and research needs. This is a logical approach when the externalities of soil acidity are unrecognised or rejected. All these issues have now been investigated or acted upon with a good level of success in some regions. However, the widespread adoption of lime use accompanied by acid addition minimising management strategies has not occurred.

The quantification of off-site impacts of soil acidity is lacking and acceptance of these environmental effects is argued. As a result government has not addressed the question of its response to these issues. We need the development of a policy relating to land managers who are permanently degrading a finite and non-renewable resource (a rational decision given the farming cost:price relationships), and strategies for optimising social and environmental goals within our 'farming' systems. Options other than agriculture or a changed concept of agriculture should be considered for achieving solutions to some environmentally related agricultural problems.

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