Chances in agricultural systems on acid soils in southern Australia

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Introduction

Acid soil infertility has long been known to limit the production of a wide range of agriculturally important plants (1). Consequently, considerable world-wide attention has been given to developing stable and productive farm systems on acid soils (1, *2).* The management options available to counter soil acidity will depend on the soil and nature of the acid soil infertility, the plant species to be grown and finally the efficacy and economics of lime use.

In Europe and North America lime has been used almost exclusively to neutralise soil acidity. However on the naturally acid soils in Australia farm systems have mostly been based on the use of the acid-tolerant legume, subterranean clover, and superphosphate (3) with little use of lime. There is now much evidence showing that this system of dryland farming is slowly making these neutral to acidic soils more acid (4). Associated with this acidification of the soil has been a decline in farm production from both livestock and cropping enterprises.

In this review, the problems caused by soil acidity will be considered for dryland farm systems based on clover-ley or permanently grazed annual pasture. The review will concentrate on recent research in Southern Australia, and will consider the possibilities for practical application of the results.

Soil acidity

Chemistry and pedology

Acid soil infertility can be caused by toxicities of H, Al and Mn and deficiencies of Ca, Mg and Mo. However in most soils the acidic conditions are not uniform throughout the profile and plant roots often are exposed to widely varying conditions of acidity (5). The activities of the toxic components also differ between soils depending on the parent material. The pH of the soil is the most common measurement of soil acidity, and this is measured in either a slurry of soil and water or a slurry of soil and a dilute salt suspension.

Acid mineral soils usually contain appreciable amounts of Al. Aluminium exists in the soil solution as a range of monomeric and polymeric species. The free ion, Al+, is the form toxic to plant growth (6). The biological activity of Al is influenced by Ca, P, organic matter and Mn (5). Aluminium in soil solution is measured as extractable Al, which is a measure of the five monomeric species (7). Manganese oxides usually account for most of the Mn in soils and reduction of the manganese oxides to Mn+ is favoured by acid conditions. Manganese is absorbed by plants as $Mn^{s+.}$ The soil water content, soil temperature, organic matter and microbial content all influence the reduction of manganese oxides (8).

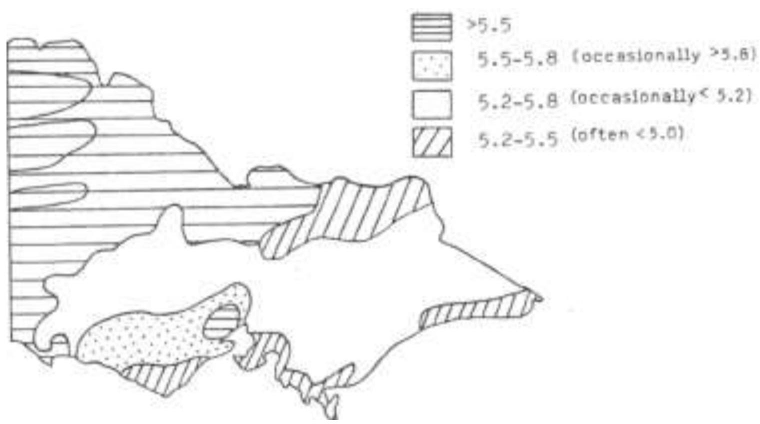
Soil acidity can limit the growth of a wide range of agricultural crops and also the establishment and function of the legume - Rhizobium symbiotic association. Aluminium and Mn toxicities are usually the cause of reduced plant growth (5). High levels of Al and H reduce growth and multiplication of Rhizobium and together with Ca deficiency can also reduce nodule formation. The main effect of low No levels is a limitation of N2 fixation (9). Lime can ameliorate each of the soil acidity components limiting plant growth and the N2 fixing symbiosis.

Soil formation occurs as a function of climate, organisms, topography, parent material and time (10), with the soil formation process proceeding at different rates and varying greatly in different environments (11). Many Australian soils are of great age (12) and have been strongly weathered and leached and are now acid. The extent and depth of acidity developed in the soil profile is dependent on the soil parent material as well as these continuous weathering and leaching processes. Many of these soils are now becoming more acid due to changes brought about by the shift in land-use to dry farming systems with legume based pasture.

Occurrence of soil acidity in Southern Australia

Because of increasing acidity and the associated agricultural problems it is worthwhile considering the areas in Southern Australia where acidity may be limiting production. Maps delineating regions of acid soil based mainly on pedogenic groupings (13), have been constructed (14, 15, Figure 1). However their diagnostic use is quite limited because of variation in acid soil components, depth of acidity and differing climatic and production zones. In New South Wales the area where acidity (pH ($CaC1_2$)<5.0) may be limiting production is estimated at 7 x 10^6 ha, comprising about 50 percent of the agricultural soils in eastern New South Wales (14, 16). In Western Australia there are two distinct agricultural regions where acidity is limiting production, the eastern wheatbelt (15; area 1 x 10^6 ha) and the high rainfall southern region (area, 500,000-750,000 ha; J.S. Yeates pers. comm.). Approximately one third of the agricultural soil in Victoria (Figure 1, area 5 x 10^6 ha) is strongly acid (pH (1:5 H_20) <5.5). In South Australia, soils under permanent pasture in the South-east of the state (area 400,000 ha) have a pH (1:5 H_20) below 5.5 and also parts of the Adelaide Hills and most of Kangaroo Island. The area of strongly acid soils in Tasmania is small, and is mostly associated with permanent pasture (17) and specialist crops (18, 19).

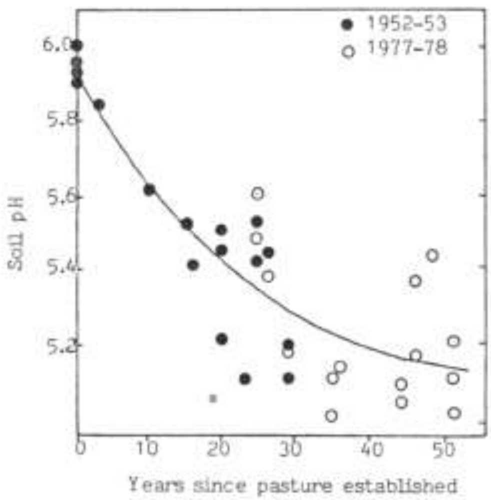
Figure 1. Distribution of acid soils in Victoria.
(map prepared by J.R. Hirth and A. Brown, 1984).



Acidification

The survey of soil pH spanning a number of years in the Crookwell region New South Wales is the most complete report of increasing soil acidity brought about by a change in land-use (Figure 2). This work by Donald and Williams (3, 20, 21) and other reports (22-27) have shown a gradual decline in soil pH with improved pasture, and it is generally concluded that soil acidification is widespread under subterranean clover pastures (14, 16, 28-30). The processes that acidify soil involve acid producing systems associated with increased organic matter (3), nitrate leaching (31, 4) and product removal (31, 32, 4). The addition of acid forming compounds to the soil, such as ammonium-based fertiliser, will also lower the soil pH (31, 33, 34, 27).

Figure 2. The relationship between age of subterranean clover pasture and pH (1:5, water), 0-10 cm. From Williams, 1980 (21).



The use of legumes in pasture has resulted in an increase in the soil organic matter far above the original levels (35). Porter (32) using the Crookwell data (21) estimates the use of subterranean clover and superphosphate has given an extra 44 t/ha of organic matter in the surface 10 cm compared with the undeveloped soil. As this organic matter contains weak acids, the pH of the soil will be reduced towards the pK of the organic acids as long as the pH of the soil is higher than those pK values. The organic matter also increases the cation exchange capacity with a corresponding increase in exchangeable cations including exchangeable hydrogen (3).

Nitrate leaching is also an important source of soil acidification (31, 21, 4), and again the legume is associated because, in most cases, the addition of nitrogen to the system has been from fixation of atmospheric N_2. In both permanently grazed annual pasture and pasture ley, organic nitrogen accumulates in the dry season. Thus the potential for leaching of nitrate beyond the root zone is greater with these systems because of the seasonal pasture (4). Where there is a productive perennial system then nitrate leaching is reduced, and it is likely that the rate of acidification is less (36, 37). Associated with the leaching of nitrate will be the loss of exchangeable bases as counter-ions; although the loss of these cations will not in itself be acidifying the system (31). Williams (21) has shown the decrease in pH beneath a subterranean clover pasture is to a depth of about 30 cm, well beyond the surface horizons where the organic matter accumulated. He concluded that this indicated the importance of factors such as nitrate leaching in contributing to the decline in soil pH.

The absorption of nutrients by plants can influence soil acidity in the short-term, and when the plant is removed from the system the effect on soil acidity can be more lasting (31, 32, 4). In order to maintain intracellular pH and ion balance, plants excrete H^+ ions if the uptake of cations is in excess of anions, and excrete OH^- or NCO when the anion uptake is in excess of cations (38, 39). It is possible to quantify the net effect of nutrient uptake (or the alkalinity of the plant) by titration of the ashed plant (40). As plants usually absorb more cation nutrients than anions the plant products are usually alkaline and an efflux of H^+ into the rhizosphere will have occurred. As long as the plant products are returned to the soil, then there is no net affect on soil acidity. However loss of plant products from the site of plant growth or removal of animal waste to camps (41) results in the depletion of cation nutrients and a pH decrease. The ash alkalinity values for a number of pasture and crop species have been determined and the legumes, which usually do not rely on nitrate uptake, generally have a higher alkalinity than the grasses and cereals (42, 40, 30).

It is difficult to assess the importance of these processes, given their long-term effects, together with the inherent difficulties with interpretation of soil pH data (34). Comparisons of soil pH figures may be misleading because of seasonal variations and solute effects (34). Soil changes associated with pasture improvement (22) and effects of cultivation and erosion (34) may have occurred over the survey period which would affect the quantity and repeatability of the soil sample taken.

Agricultural problems

The productivity of both crop and livestock enterprises based on subterranean clover pasture is believed to have declined due to soil acidity (14, 16, 43-46). A similar problem is encountered with both crops and pasture in assessing whether there has been a decline in productivity that is not associated with management or seasonal changes. Soil acidity, soil compaction, waterlogging, nutrition, disease and climate may all be contributing to the problem. Information can be obtained from field observations and farm records which will allow evaluation of declining productivity. A more thorough diagnostic approach involving soil sampling and field or pot experiments may be required for an understanding of which factors are involved.

Cropping 1) Problems

In some acid soil areas, wheat grain yields have always been poor. These areas include the Pilliga region (47), Narromine and Tomingley regions (C.L. Mullens, pers. comm.) of New South Wales and certain parts of the eastern wheatbelt of Western Australia (15). In these areas the soils are naturally strongly acid both in the topsoil and subsoil. However, there are vast cropping areas in New South Wales, Victoria and Western Australia which have neutral to acid soils where acidity had not been considered as a factor limiting wheat production. It is within these areas that wheat yields on many farms (14, 48) have been declining and growth problems appearing in the crop. The symptoms commonly observed in these wheat crops are patches of stunted growth in a chlorotic condition with plants usually having deformed roots (46).

A survey of wheat crops in North-east Victoria with these symptoms showed that either poor rotation, the presence of hardpans or acid soils could be associated with the poor growth (48). The pH (1:5 H_7O) of these soils ranged from 4.8 to 5.8 in the 0-10 cm layer and usually the pH increased below 20 cm depth. The strongly acid soils had high levels of extractable Al and exchangeable Mn.

Further field observations that indicate involvement of soil acidity are the frequent reports by farmers of poor yields with wheat and barley on areas once considered excellent wheat growing land. High yields however could still be obtained when crops with more acid tolerance such as oats and triticale were grown (14).

2) Liming and tolerance

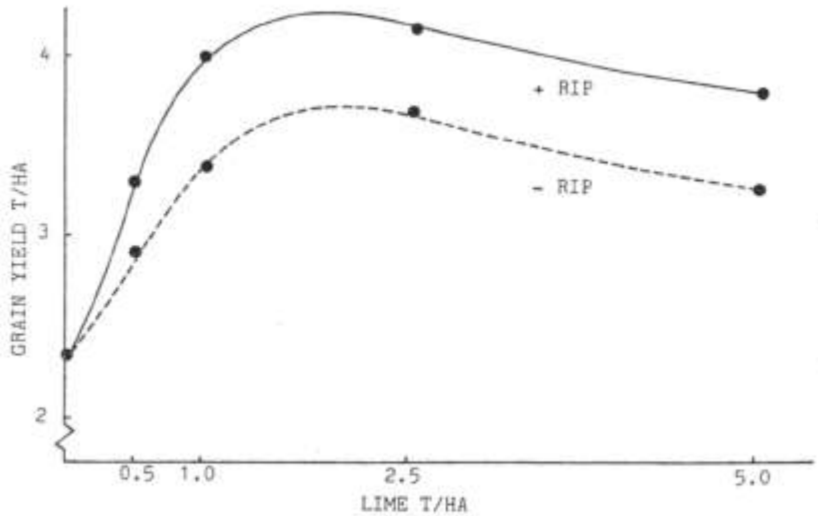
There has been virtually no reports on the use of lime in cropping areas in Australia until the recent recognition that acidity may be a factor causing declining wheat yields. In the late 1970's work commenced on the use of lime to neutralise acidity in cropping areas of New South Wales (43, 47), Victoria (44) and Western Australia (15). The results obtained can be broadly divided into three groups determined by the acidity throughout the soil profile and crop responsiveness to lime application.

Surface soils acidity - lime responsive

Soil acidity (pH 5.0, 1:5 H_70, 1-10 cm) and a hard compacted layer at 8-10 cm depth were problems at the site of a field experiment established in 1981 in the Rutherglen region in North-east Victoria. Rates of lime and deep ripping were the main treatments and fertilisers and trace nutrients were sub-treatments (44).

Large differences were obtained in growth and grain yield with the lime and ripping treatments in each of the four seasons studied (44, 49, Figure 3). In 1981, 1983 and 1984 there was no response to ripping in the absence of lime, but in the drought year (1982), ripping resulted in large yield increases at all lime rates and the grains were heavier from the ripped treatments (49). In the drought (50) deep ripping resulted in increased water use by the wheat regardless of lime treatment.

Figure 3. Grain yield responses to liming obtained at Rutherglen, North-east Victoria, 1984 season.



The acid soils in Northern Victoria and Southern New South Wales have a potential to produce high concentrations of plant available Mn. High concentrations of exchangeable Mn (exch. Mn) can be associated with waterlogged conditions or prolonged dry periods during summer (51, 52). Chemical analyses were done on soil and herbage samples throughout the 1982 and 1983 growing seasons in separate studies in the Rutherglen region (52, 53). However, no pulse of exch. Mn (or any other element) was identified during the pre-anthesis period in either year (53) and any increase in exch. Mn following waterlogging was characterised by a lag time, which was soil temperature dependent (52). Increases in exch. Mn were measured ever summer (52) and the highest exch. Mn concentration coincided with crop sowing time (52, 53). Additions of lime at 2.5 and 5.O t/ha reduced the exch. Mn concentration but lime addition at 0.5 and 1.0 t/ha did not decrease exch. Mn (53). As wheat grain yields were increased substantially with the low lime rates, it is unlikely that the concentrations of exch. Mn were affecting the growth of the wheat.

The effect of lime on the extr. Al in the Rutherglen soil at various depths is shown in Table 1. The low lime rates significantly reduced the levels of extr. Al in the 0-5.0 cm layer. The depth of lime incorporation was increased by deep ripping, with the effect of lime measured to a depth of 17.5-20.0 cm with the higher lime rates. There were no differences over three years in the depth to which the effect of lime was measured, indicating that this effect was most likely brought about by incorporation during the ripping process (DER. Coventry, unpublished results). Et was therefore likely that for this soil, Al toxicity was responsible for the poorer wheat growth and grain yield in the absence of lime.

Table 1. The effect of lime on extractable Al at various depths with and without deep ripping.

a) SITE NOT RIPPED

	Extractable Al (ppm)				
	Lime (t/ha)				
Depth (cm)	0	0.5	1.0	2.5	5.0
0-2.5	10	1	1	4	1
2.5-5.0	14	1	1	4	1
5.0-7.5	31	14	8	5	1
7.5-10.0	50	25	20	20	8
10.0-12.5	48	26	29	43	28
12.5-15.0	46	47	25	45	36
15.0-17.5	37	43	18	46	32
17.5-20.0	34	30	11	39	28

b) SITE RIPPED (40 cm)

	Lime (t/ha)				
Depth (cm)	0	0.5	1.0	2.5	5.0
0-2.5	12	1	1	4	1
2.5-5.0	22	1	1	3	1
5.0-7.5	29	3	1	3	1
7.5-10.0	36	12	1	3	1
10.0-12.5	41	17	8	10	1
12.5-15.0	38	26	6	17	3
15.0-17.5	37	25	3	20	8
17.5-20.0	34	15	1	31	13
Depth x Rip (5%)	n.s.	n.s.	10	10	11

Liming experiments have now been carried out at 12 different sites over 4 seasons in Northern Victoria and include a range of pH values (Figure 4). The soils are more acid towards the eastern margins of this wheatbelt, where the rainfall is highest. These soils are mostly acid in the 0-20 cm soil layer, and on these soils lime has almost always given significant grain yield increases (Figure 4).

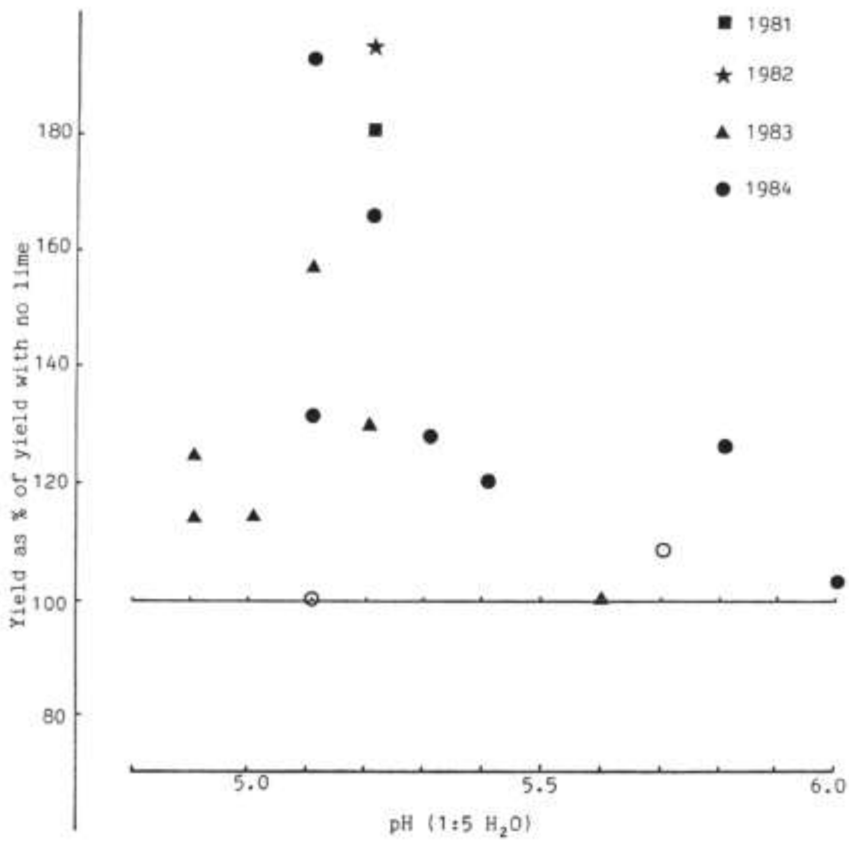


Figure 4. **Summary of wheat yield responses to the application of lime on soils in North-east Victoria. Closed symbols are significant yield responses (P=0.05).**

Subsoil acidity - lime responsive

The acid cropping soils of the South-west slopes of New South Wales can have high extr. Al, high exch. Mn concentrations or both and usually the acidity extends to 30 cm depth. In this situation liming to reduce extr. Al in the surface soil may not be sufficient, and the use of tolerance in the plant, together with lime application, gives the highest yields (43). In the 1981 season at a site east of Wagga the yield of Al sensitive wheat varieties was increased from 35 kg/ ha without lime to 520 kg/ha with 5 t/ha of lime. The tolerant varieties yielded 445 kg/ha without lime and 1220 kg/ha at the high rate of lime (43). Subsoil acidity is also a problem in the Pilliga region (47) and the Narromine and Tomingley (C.L. Mullens, pers. comm.) regions of N.S.W. In the Pilliga soils, acidity is extreme to a depth of 60-90 cm (Table 2) and lime application had little effect on soil pH below 15 cm (47). However liming the surface soil to about pH 5.0 (1:5, H_20) did give large percentage yield increases in 1981 with acid sensitive crops (47) and again in 1983 with acid sensitive crops and to a lesser extent with an Al tolerant wheat variety (A.D. Doyle, pers. comm.). The Al tolerant variety grew well in the absence of lime.

Table 2. **Soil pH and percent saturation of Aluminium with depth, Pilliga scrub region, New South Wales.**

Depth (cm)	pH (1:5, H_2O)	% extr. Al.
0-15	4.5	56
15-30	4.4	79
30-60	4.3	86
60-90	4.5	85

(after Doyle and Bradley, 1982 (47)).

Subsoil acidity - lime non-responsive

The application of lime (up to 4 t/ha) to the surface soil of the acid eastern sandplain in Western Australia rarely improved wheat yields, and at only two of twenty sites did lime increase the yield by more than 10% (15). These acid soils have high levels of extr. Al and low exch. Mn and the subsoil is usually more acid than the topsoil. Two of the non-responsive sites were used to examine the effect of liming the subsoil (15). Soil was removed to 160 cm depth and repacked, with and without lime, into drums fitted in the excavated holes. The wheat growing in the limed drum grew faster and the grain yield was greatly increased where the whole profile was limed (Table 3).

Table 3. Effect on wheat yields of liming to 1.6 m depth two Western Australian acid sandplain soils.

Treatment	Grain Yield (t/ha)	
	Site 1	Site 2
Drums without lime	0.89	0.64
Drums with lime	1.50	1.76
Adjacent plots, undisturbed	1.15	0.48

(After Porter and Wilson, 1985 (15)).

3. Fertiliser use

In the Western Australia acid sandplain the soils are very low in available Mo (56). The application of No improved wheat yields in nearly all the experiments on acid soils between 1981 and 1983, despite its previous application at all of the sites (15). The residual effectiveness of Mo application declines rapidly on these soils over one or two years (57). The addition of Mo also increased (P=0.05) wheat grain yield in the drought year (1982) in the Rutherglen region on a site (Reeves and Coventry, unpublished results) with low available Mo (58).

Liming acid soils can affect phosphate availability in soil and uptake by plants (59). The situation can vary with different soils and there are reports of lime increasing, decreasing and having no affect on phosphate availability (59). Various mechanisms are involved and include both increased or decreased adsorption of newly added phosphate, increased mineralization of soil organic phosphate and an affect on phosphate uptake by removal of Al toxicity. There have been several Australian reports of lime increasing P availability (60, 61) although it has been difficult to obtain significant correlations between available phosphate and pH. A significant interaction was obtained between phosphate and lime application in the 1983 season at Rutherglen with a smaller increase in yield of wheat following addition of superphosphate to the limed plots (DEH. Coventry, J.R. Hirth and T.G. Reeves, unpublished results).

4) Future requirements

Interpretation of soil testes

As soils vary considerably, and crops and cultivars have different levels of tolerance, there is no universal formula or procedure applicable for determining the lime requirements for all acid soils. The concept of a critical pH has been used extensively in North America where liming the soil is common practice (62); the critical pH having been developed for a wide range of soils and crops. En Australia the concept of liming a soil to any given pH has not been developed, and there have been no lime requirement tests introduced that have gained wide acceptance. Cregan (63) adapted a test based on the percentage Al saturation method of Kamprath (7) for use in New South Wales, but the utility of this test is confined to soils with a surface acidity problem (43). The measurement of Al in the soil solution is dependent on soil pH, and many routine soil tests express solution Al as extractable Al (7). However extr. Al is not necessarily an accurate measure of the biological activity of Al in the soil solution (62), as the toxicity of Al is a function of the Al^3 activity (6). As well, the activity and concentrations of Al in the soil solution are influenced by Ca (7), P (59) and organic matter (64). Other lime requirement tests have been developed using the addition of a base to determine the lime requirement (65) but the usefulness of these various tests is usually limited to the soil type for which they were developed (62). Thus the need for a test applicable for use by agronomists in their own acid soil region still exists. En the short-term it is difficult to conceive how not to avoid the use of soil tests regionally developed and validated by field trials.

Crop options

Since 1981, 9000 tonnes of lime have been spread over 12,500 ha in the Rutherglen-Corowa region where the soil acidity is confined to the surface 20 cm. With the limed soil, it should be possible to grow a wider range of crops. An experiment was carried out in 1984 in the Rutherglen district evaluating alternative crops such as rapeseed, chickpea, safflower and peas as well as a range of cereals following soil treatment. Where the soil was limed and ripped, grain yields were increased by 54% for rapeseed, 107% for peas, 204% for chickpea, 84% for oats, 79% for triticale and 43% for barley (T.G. Reeves, pers. comm.). Rapeseed was the most economic crop after the soil treatment.

There is considerable variation in tolerance amongst crop species and between cultivars within species to acid soils. The knowledge of this tolerance often dictates which crop and what variety is grown in an acid soil region (43, 47). There are wheat varieties in use which have moderate tolerance to the various soil acidity factors and these characteristics are heritable (54). Tolerance to Al is heritable and can be easily and quickly identified by the haematozylin stain which makes it amenable to a systematic breeding programme (55).

Subsoil acidity: tolerance and lime applications

Where the soil acidity extends into the subsoil the methods available to farmers to overcome or avoid the harmful effects of acidity are deeper liming of the soil and the use of crops and cultivars with more tolerance to acidity (43). The use of lime is expensive and where the subsoil acidity restricts the benefits of the lime then plants with tolerance to acidity have immediate application. To obtain yield improvements from lime where subsoil acidity is the problem, the depth of incorporation of lime has to be increased. In Western Australia (15; Table 3), United States (66) and Brazil (67) the thorough incorporation of lime at depth has increased crop yield. However banding the lime at various depths was not successful (15). Lime moves slowly in the soil, and at one site it has taken 10-14 years to increase the pH to a depth of 15 cm (60). Deep cultivation after surface lime application does result in deeper incorporation of the neutralising effect of lime and the higher the lime rate the deeper the incorporation (Table 3). Increasing the lime rate is not a practical solution as, apart from the extra cost, there is a risk of overliming the surface soil and reducing crop growth (Fig. 3). The rotary tillers used for deep incorporation of lime in Brazil and the United States are also not practical in Australia. Machinery has been designed for the deep injection into the subsoil of animal and industrial waste products, which may be used as a model for the injection of slurries of lime or gypsum into the subsoil. Such a slurry injector is currently being developed at Rutherglen (A. Ellington, pers. comm.).

Pastures 1) Problems

When acidification of soil associated with pasture improvement was first reported, there was no indication that increased acidity was affecting farm productivity (3). In the last decade there have been many reports of declining pasture productivity which has been associated with increased soil acidity (25, 14, 21, 29). Most of this information has come from farm records of carrying capacity or marketing of produce and consequently also reflects seasonal trends and past management. The problems associated with assessing a real decline in production are not new, and have been reported by Anderson (68) for nutrient depletion in South-east Australia.

The decline of subterranean clover in pasture has been the subject of recent studies (69, 29, 45, 46, 59, 70-73) including six reports in these Proceedings (74-79). It is now widely accepted that farmers are frequently having problems with establishment, growth and persistence of subterranean clover in both permanently grazed and clover-ley farming systems, and that soil acidity is contributing to this decline in productivity (45).

Considerable work has been done in Southern Australia on the effects of soil acidity on the legume/Rhizobium association and on legume growth, and this work has greatly influenced agricultural practices. Consequently much is known about the biology and ecology of Rhizobium, inoculation procedures, nodulation of legumes, effectiveness of the N2 finding association and the nutrition of legumes on acid soils (80-88, 9). The author's main interest is the recent field work concerned with identifying the aspects of legume nutrition and the legume-Rhizobium association affected by increasing soil acidity. This recent research is important, as it will focus on the possible corrective measures to be taken to restore pasture productivity to the levels of the 1950-60's.

2) Liming and Tolerance

In the past five years field experiments have been established in three States to investigate lime requirements of both permanent annual pasture and clover-1ey pasture. With the exception of the Coolup sands of the Swan Coastal plain (23, 89), these sites are located in regions distinct from some of the naturally acid soil regions where the technology for pasture growth on acid soils was developed.

In New South Wales there are 4 sites in the Wagga region which include lime, various nutrients, inoculation and fungicide treatments. In 1983 two of these sites gave significant yield increases to lime, one was unresponsive and one significantly reduced subterranean clover yield (Z. Hochman, pers. comm.). Six sites were established in North-east Victoria in 1981 and at two of the sites lime consistently improved subterranean clover D.M. production over three seasons (75). At one of these sites D.M. production continued to increase with each addition of lime and fertiliser No improved the yield, even at all rates of lime (Table 4). At the second site, D.M. production increased by 12-44% (75) at the low lime rates (0.5, 1.0 t/ha) with smaller yield increases at the higher (2.5, 5.0 t/ha) rates (J.R. Hirth, unpublished results). At the other sites the responses to lime were more variable (75). In the Ballarat region, responses in D.M. production of subterranean clover were obtained in 1984 with the addition of 3.O and 6.0 t/ha to a red basaltic soil but no responses were obtained with this amount of lime added to grey basaltic soils (R.E. Smith, pers. comm.). However the use of 1:1 superphophate-1ime fertiliser in the drill-row gave significant D.M. increase on these grey basaltic soils. This soil is the predominant soil throughout the Western District of Victoria, where poor production of subterranean clover is now recognised as a most serious problem (90; M.E.J. Boyd and B.C. Muir, pers. comma.). In Western Australia 53 sites incorporating rates of lime have been established in the high rainfall regions of the Swan Coastal Plains and the South-Western agricultural region. Twenty eight of these sites have given increases in D.M. which have occurred mainly with subterranean clover (J.S. Yeates, pers. comm.).

Table 4. Dry matter production of subterranean clover with lime and molybdenum addition, Rutherglen, North-east Victoria.

Lime (t/ha) Mo g/ha	1981 October 0	1982 August 0	62	1983 July 0	62
0	3.64	1.27	1.19	2.76	3.01
0.5	4.19	1.24	1.32	2.69	2.97
1.0	4.49	1.47	1.51	2.91	3.21
2.5	4.81	1.40	1.83	2.94	3.21
5.0	4.91	1.83	1.95	3.05	3.10
Lime l.s.d. (5%)	1.04	0.29		0.24	
Mo l.s.d. (5%)	-	n.s.		0.13	

Subterranean clover is an acid tolerant plant (63) and there is a range of tolerance within its cultivars to acidity (91). There also is a wide range of tolerance between Rhizobium species and strains to acidity. It is possible to select Rhizobium for tolerance to acidity using defined media (92) but so far little practical success has been obtained in selecting acid-tolerant Rhizobium for temperate pasture species (93).

Liming for pasture renovation often is not feasible as the existing pasture has to be disrupted for incorporation of the lime and there are considerable costs involved with lime, seed and fertilisers. It is therefore essential that the nature of any lime response be understood, as there are many aspects of the symbiosis and the plants nutrition that may be responding to lime.

Rhizobium/Inoculation

The soil populations of some Rhizobium species can be low in acid soils (85), and liming soils invariably increases the soil populations (94-96, 45). The soil populations of R. trifolii associated with

subterranean clover pastures in South-eastern Australia range from $<10^3$ to 10^6 per g. of soil (97, 70, 78) and are adequate to ensure the continued nodulation of clover. In soil, the H. trifolii population is a mixture of strains and these strains may vary in their infectivity and N2 fixing efficiency (84). Infectivity of individual strains can be affected by acidity (98). In a survey of 44 permanent dryland pastures in Central Victoria, Jones and Curnow (70) found that only 40% and 62% of subterranean clover plants were effectively nodulated in the 1982 and 1983 seasons despite adequate (105/g soil) populations of H. trifolii. The populations of H. trifolii in soil were frequently inadequate after a period of cropping in a clover-ley, with 89% of the twenty-eight fields sampled having less than 103 per g. of soil (45). When inoculated clover seed was sown at two of these sites, the population of R. trifolii built-up quickly irrespective of soil pH (Table 5). However when uninoculated seed was sown, the populations of R. trifolii could still not be detected (<10 per g.) when the soil was not limed (76).

Table 5. R. trifolii populations (log number/g soil) for three seasons after establishment of inoculated subterranean clover at a site treated with lime.

Lime (t/ha)	pH 1:5 H_2O 0-8 cm	1981 March	1982 February	1983 April
0	5.00	ND	4.27	3.58
0.5	5.20	-	4.10	3.08
1.0	5.38	-	3.31	3.75
2.5	5.99	-	5.95	4.45
5.0	6.31	-	5.45	3.90

(After Coventry et al 1984 (45)).

The pH of the surface organic horizon is invariably less acid than the mineral soil below (29, 45, 78), and this organic horizon is likely to be the habitat for colonisation by and survival of rhizobia (45). When this layer is disturbed, such as in some pot experiments (29) or in the crop sequence in a clover-ley rotation (45), the survival of Rhizobium may be jeopardised and problems with clover nodulation follow. Bromfield et al (29) have suggested that nodulation problems may also develop in the field in permanent dryland pasture as a result of a relatively small further increase in acidity.

In some situations the use of superphosphate-lime fertiliser may be sufficient to maintain desired Rhizobium strains and ensure nodulation of clover, but the importance of having competitive and highly effective Rhizobium strains adapted to acid soil conditions is apparent.

Nodule formation and function

Modulation of legumes can be restricted by acidity as the early infection stage of nodule formation is sensitive to both high levels of H and Al and low levels of Ca (99-103). Restricted nodule number need not be a problem as with many legumes an inverse relationship exists between nodule number and nodule size which allows the total nodule volume, or weight per plant, to be maintained (104). This inverse relationship has been reported frequently when comparing legumes grown on acid soils with those grown on limed soils (105-107, 45). However the nodule volume may not reflect the volume active N2 fixing tissue of the nodule, as larger nodules with more degenerative tissue would have less active bacteriod and N_2 fixing tissue (108). This situation of few but large nodules, which has been seen frequently in the field with subterranean clover (29, 45), was obtained in a pot experiment by sowing uninoculated clover seed in unlimed soil (58). These poorly modulated plants were compared with plants with many nodules originating from inoculated seed or limed soil (58). The specific nodule activity (expressed as C2H2 reduced/g. nod. wt/min.) was considerably less with the larger nodules (Table 6). The stimulation of nodulation, brought about by liming the soil (45, 75) has increased the volume of active nodule tissue, thus increasing the N status of the plant and consequently the dry matter produced.

Table 6. Nodulation, N2 fixation activity (C_2H_2 reduction) and N content of subterranean clover grown in pots with inoculation and lime (1.75 g $CaCO_3$/kg soil) treatments.

	Nodules per plant 4 weeks	Nodule Wt (mg) 4 weeks	Specific nodule activity n mol. C_2H_2 reduced/g/min	N content mg/pot 4 weeks
-Inoc.-Lime	1.00	2.360	232	5.814
+Inoc.-Lime	24.95	0.397	1058	9.654
-Inoc.+Lime	23.92	0.428	795	17.512
+Inoc.+Lime	26.86	0.339	948	14.118
L x Inoc. l.s.d. (5%)	6.73	1.048	470	3.883

(After Coventry et al, 1985 (58)).

The requirement of many Australian soils for Mo is well known (80) and with progressive soil acidification, it is likely that there will be an increased number of pasture and ley soils with deficiencies of Mo (20). Molybdenum can be released from soils with lime (88), so it is possible that lime responses are due to alleviating Mo deficiency. At two sites in the Rutherglen region growth and colour responses with subterranean clover have been obtained (75), and at one of these sites the increase in dry matter with the addition of Mo fertiliser occurred irrespective of lime addition (Table 4) indicating the possibility of an absolute deficiency of Mo.

Plant Function

Although subterranean clover is tolerant of soil acidity the establishment and functioning of the symbiosis is more sensitive to high levels of H and Al and low levels of Ca and Mo in the soil, than is the functioning of the plant (106). Legume growth is reduced by Mn toxicity by direct effects on the functioning of the plant. Most Medicago sp. are sensitive to Mn (109, 63). Manganese toxicity produces plant symptoms that are readily identifiable in waterlogged conditions, early in the season and in pot experiments (29, 51, 63, 75)

There also exists a range of tolerance to acid soils in grass species (63) and there have been reports of grasses responding to lime applications (110). A frequent observation made, where pasture productivity has declined, is that the grass composition has changed and species such as Vulpia, Agrostis and Holcus are dominant. The use of more tolerant grass species may arrest this change (111).

Conclusion

A unique situation exists in Southern Australia where the dryland 'system of farming has resulted in acidification of the soil to the extent that farm productivity has been affected. There is now a need for work directed at management systems which would result in reduced activity of the toxic soil components, slowing of the acidification process and maintenance of soil biological activity. Management options such as direct-drill and sod-seeding, stubble management and stock management need investigation within the context of an acid soil situation. At present the use of lime and plant tolerance remain the management options for overcoming the harmful effects caused by soil acidity to agricultural production.

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