Particle Size Determines the Efficiency of Calcitic Limestone in Amending Acidic Soil

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Abstract

There is a commonly held view that limestone particles ≤ 0.25 mm are fully effective in amending acidic soils. However, this is not consistent with some available data.

We assessed the importance of particle size in a field experiment using six particle size segregations covering a range of mean diameters from 3 mm to 0.005 mm. These products were applied at rates of 2.5, 5 and 10 t ha^{-1}. Lime was incorporated in April 1986 and soil samples were collected 6, 12, 24 and 36 months later. The experiment was cropped to wheat in 1986, 1987 and 1989. Effectiveness was evaluated as the capacity of the particle size segregation to increase soil pH, exchangeable calcium (Ca_{ex}) or grain yield of wheat.

No minimum particle size for maximum effectiveness was identified. Throughout the range of particle sizes evaluated, progressively finer particles produced larger increases in pH and Ca_{ex}. Wheat yield was related to soil pH. Changes in soil pH and Ca_{ex} between 6 months and 3 years after lime application were small compared to the changes in the first 6 months.

Fine lime products should be preferred in practice, subject to cost considerations and handling difficulties.

Keywords: acidic soil, exchangeable calcium, limestone, particle size, pH, wheat.

Introduction

Liming is a marginal economic proposition in Australia as the cost of lime is high relative to the value of agricultural products (Hochman *et al.* 1989). Farmer adoption of liming therefore depends on improving the total return on investment and on those returns being rapid. The first step in using limestone efficiently is to have an appropriate product. The two major factors influencing the effectiveness of a limestone product are its purity and its particle size distribution (Tisdale and Nelson 1975). In Tisdale's and Nelson's text particle sizes of ≤ 0.25 mm were regarded as 100% effective. Solubility may also be a relevant factor in the effectiveness of a liming material. The available information on the relative effectiveness of various particle size fractions of limestone is ambiguous. Various studies (Barber 1984) have used different particle size ranges, both in the total range of particle sizes covered and in the internal ranges of the individual particle size treatments. Available studies have also used varying rates of lime application and it might be expected that at heavier application rates, the importance of fineness diminishes. The time between limestone application and the soil analyses also varies greatly, from 5 weeks to 5 years. Fineness should be more

important for short-term reaction. The variables measured to gauge effectiveness also varied, with soil pH, exchangeable calcium (Ca_{ex}), and plant yield, being common variables (Barber 1984). The yield response of plants is a confusing complication because it depends on the shape of the crop's response curve, which is generally not linear with pH.

Hence the aim of this study was to evaluate the relative efficiency of a wide range of well-defined particle size fractions of calcitic limestone, at varying application rates and times after application. Soil pH and Ca_{ex} and wheat yield were measured. The questions that we sought to answer were:

(1) What is the most effective, or perhaps optimal, size of calcitic limestone particle?
(2) How different is the short term result to the long term?
(3) Does relative efficiency vary with the rate of application?
(4) How does the conclusion vary when comparing the results for soil pH, soil Ca_{ex} and wheat yield?

Materials and Methods

Experimental Site

Characteristics of the soil at the experimental site are given in Table 1. The site was typical of the soils developed in footslope positions in the 500–600 mm rainfall area of southern New South Wales. Some of these soils contain appreciable sodium at depth and have a neutral reaction trend; others have a distinct acid reaction trend. This site represents an intergrade situation.

Table 1. Soil properties of the experimental site

Depth (cm)	pH (0·01 M CaCl2)	ECEC[A]	Al (cmol(+) kg^{-1})	Ca	OC (%)
0–10	4·11	2·51	0·61	0·97	0·7
10–20	4·04	1·80	0·67	0·59	n.a.[B]
20–30	4·48	2·33	0·11	1·53	n.a.
30–40	5·16	3·80	0·06	2·38	n.a.
40–50	5·38	6·66	0·06	3·03	n.a.
50–60	5·42	8·91	0	3·47	n.a.

Taxonomy

Dy 3·41/2 (Northcote 1979); yellow podsolic/solodic (Stace *et al.* 1968); albic luvisol (FAO-UNESCO 1974); or aeric albaqualf (Soil Taxonomy 1975)

Clay mineralogy (0–10 cm)[C]

Illite (55±1·1%); Kaolinite (24±5%); quartz (17±1%) and randomly interstratified minerals (3±1%)

[A] Effective cation exchange capacity.
[B] Not available.
[C] Courtesy of CSIRO Division of Soils, Adelaide.

Experimental Design

The experiment was a randomized block design with 31 treatments and four replicates. Plots were 1·2 m wide and 10 m long. The treatments consisted of the control (unlimed), six particle size segregations at three application rates (2·5, 5·0 and 10·0 t ha^{-1}) and 12 commercial liming materials at 5 t ha^{-1}. The results for the commercial products are not reported here. Every sixth plot was a control plot, resulting in a grid of 28 control plots within

the trial, to give an accurate base for measuring lime responses. Within this framework each group of five intermediate plots consisted of a random allocation of three application rates of a given particle size and two of the commercial products. Thus the experiment was similar to a split plot for particle size together with a randomized block for commercial products.

Liming Materials

Six particle size fractions of $CaCO_3$ were derived from a 98% pure calcitic limestone from the Marulan quarry, N.S.W. The initial six segregations were supplied by Southern Limestone Pty Ltd of Moss Vale. The particle diameter ranges were further narrowed by the use of vibrating seed cleaners modified with appropriate commercial screens. Accurate definition of the final six particle size segregations was obtained by screening each through a nest of British Standard sieves. We therefore have a description of both the range and the particle size distribution of the six segregations. It should be noted that the midpoint of each range does not necessarily equate with the mean particle diameter (Table 2).

Liming materials were weighed and hand-spread on the experimental site in April 1986. The lime was incorporated using a rotary hoe 2 days later to about 10 cm depth.

Table 2. Particle size segregations of limestone used in this study

| Particle size | Range | | Mean[B] |
	Mesh[A]	(mm)	diameter (mm)
1	4–8	2–5	3
2	16–30	0·5–1·0	0·6
3	30–60	0·25–0·50	0·35
4	60–100	0·15–0·25	0·20
5	100–200	0·075–0·15	0·11
6	<200	<0·075	0·005

[A] British Standard Sieve (BSS). [B] From particle size distribution by weight.

Soil Measurements

The 152 plots, including buffers, were sampled to a 10 cm depth in April 1986 prior to the application of liming materials. The plot samples consisted of 10 cores per plot. Sampling of all plots subsequently took place in November 1986 (6 months post-liming), and in April of 1987, 1988 and 1989. Soil sampling took place prior to harrowing and sowing in each year.

In addition, we collected samples from the 10–15 cm soil layer of the control plots and the 10 t ha^{-1} rate of the six particle size segregations in April 1988. In 1989 we repeated the 10–15 cm depth sampling and additionally included the 2·5 and 5·0 t ha^{-1} application rates of the finest particle segregation (particle size 6 in Table 2).

The pH in 0·01 M $CaCl_2$ (pH) was determined after a 1 h end-over-end shake at 20°C and in a 1:5 soil:solution ratio extract. Exchangeable Ca (Ca_{ex}) and other cations were determined by leaching 4 g soil with 200 mL of 0·0125 M $BaCl_2$ (Vimpany *et al.* 1985).

Agronomic Procedures

The experiment was sown to wheat (*Triticum aestivum* cv. Millewa) using a drill in May 1986. In subsequent years, the plots were direct drilled during May into residual stubble after harrowing. Following a build up of grass weeds, the site was 'fallowed' in 1988. Hence grain yield data are presented for 1986, 1987 and 1989. 'Fallowing' in 1988 did not involve soil disturbance; weeds were controlled with herbicides. The wheat was sown at 60 to 80 kg ha^{-1} with 130 kg ha^{-1} of fertilizer consisting of 15 kg ha^{-1} of each of N, P, and S. Nitrogen, at up to 50 kg/ha was supplied in winter as ammonium nitrate. Grain was harvested from the whole plot using a small grain harvester.

Statistical Procedures

Test of differences between treatments for individual variables

Data for all observations were analysed by examining the fits for the group of spatial (or neighbour) models given by Gleeson and Cullis (1987). All models were fitted using the computer program SAFE.

Test of parallelism for treatment responses over time

It was of interest to compare pH trends during time. We have fitted one of the models discussed in Verbyla and Cullis (1992) *viz* that due to Gehan. We then tested the hypothesis that the change in pH over time was the same for all particle sizes at a given rate of lime, or that linear regressions for pH on time for different particle sizes were parallel for each lime rate.

Results

Effects of Liming after 6 Months

The increase in soil pH after 6 months, due to each particle size range and for each application rate, is shown in Fig. 1. The finer the particle size, the greater the increase in pH at a given rate of application. This trend applies even at the 10 t ha^{-1} application rate where we expected that fineness would be of less importance. This expectation was realized to a limited extent as shown in Table 3, as the relative efficiency of coarser particles does increase with increasing application rate. However, the effect of increased efficiency at greater application rates is small relative to the effect of particle size. At all three application rates, the increase in pH (ΔpH) due to liming was a function of the average particle diameter. These were:

2·5 t ha^{-1} ΔpH = 2·264 − 0·586 log (particle diameter) $r^2 = -0\cdot99$, $n = 6$;

5 t ha^{-1} ΔpH = 2·875 − 0·697 log (particle diameter) $r^2 = -0\cdot97$, $n = 6$;

10 t ha^{-1} ΔpH = 3·162 − 0·668 log (particle diameter) $r^2 = -0\cdot98$, $n = 6$.

Table 3. Percentage efficiency of particle size in increasing soil pH, relative to the finest particle size, for each application rate of limestone

Application rate (t ha^{-1})	Particle size					
	1	2	3	4	5	6
2·5	9%	34	47	52	58	100
5	13	41	53	61	64	100
10	29	53	55	61	73	100
s.e.d. = 4%						

This indicated that the experiment did not define a plateau where a maximum effect of lime was attained at some particular particle diameter. In fact there was an exponential increase in lime effectiveness as particle size decreased (Fig. 2).

The apparent asymptote in lime effectiveness at low soil pH (Fig. 1) is probably due to localized zones of high pH and Ca around lime particles. This is not necessarily reflected in the bulk soil pH where the greater proportion of the soil remains unaffected by the lime. Cregan *et al.* (1989) report experience of localized soil pH variation, across individual peds, following lime application.
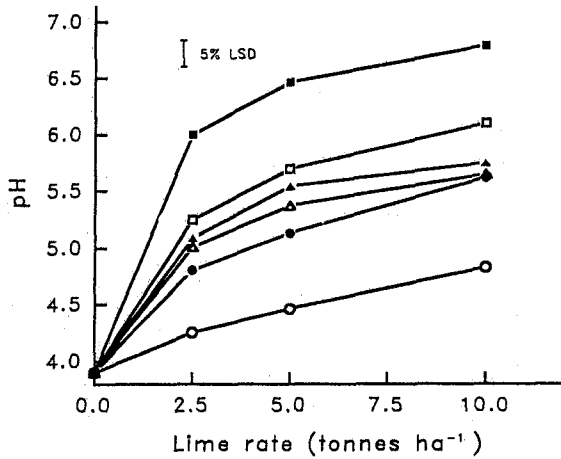
Fig. 1. The effect of limestone particle size on soil pH (0–10 cm) 6 months after incorporation. The particle sizes used had mean diameters of 3·0 mm (○), 0·6 mm (●), 0·35 mm (△), 0·20 mm (▲), 0·11 mm (□) and 0·005 mm (■).
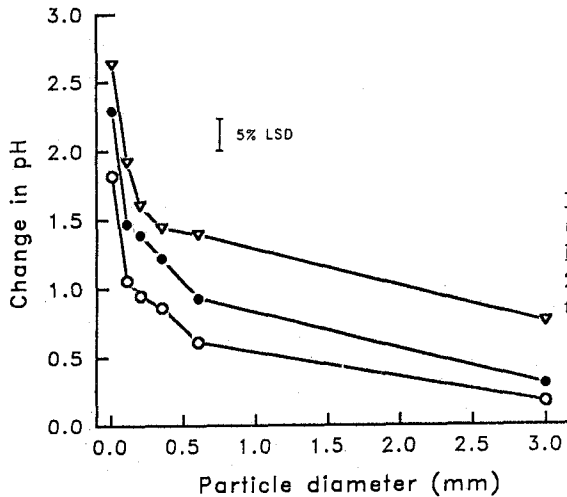

Fig. 2. The increase in soil pH (0–10 cm) due to particle sizes of limestone at three application rates: 2·5 t ha^{-1} (○), 5 t ha^{-1} (●) and 10 t ha^{-1} (▽).

The increase in Ca$_{ex}$ after 6 months, due to each particle size range and for each application rate, showed a similar trend to pH (Fig. 3). Recovery of the Ca applied in limestone was greatest with the finest particle size material: 70, 52 and 42% for the 2·5, 5 and 10 t ha^{-1} application rates respectively. While leaching of excess Ca might be expected to contribute to under-recovery, the decreased recovery from progressively coarser particle sizes suggests that lack of reaction was the major cause for the low Ca recoveries.

Time Trends

The pH induced by liming remained almost stable with time from the measurement at 6 months to that at 3 years (Fig. 4). At each application rate, the six particle size fractions appear to remain almost parallel to the control soil pH. We tested the hypothesis that the lines were parallel but found that they were not ($F_{5,464} = 3·54$, $3·29$ and $2·45$ for 2·5, 5 and 10 t ha^{-1} respectively).
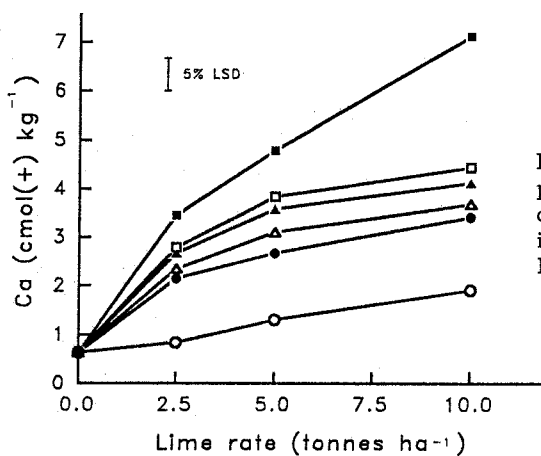
Fig. 3. The effect of limestone particle size on soil exchangeable calcium (0–10 cm) 6 months after incorporation. The legend is given in Fig. 1.
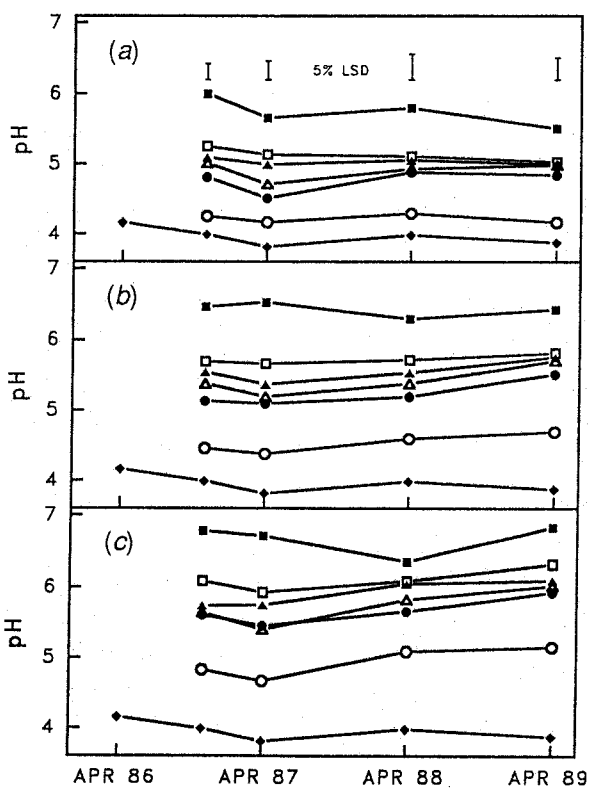

Fig. 4. The changes in soil pH (0–10 cm) from 6 months to 3 years (April 1989) after incorporation of limestone of various particle sizes at (a) $2 \cdot 5$, (b) $5 \cdot 0$ or (c) $10 \cdot 0$ t ha^{-1}. The particle size legend is given in Fig. 1; the pH of the unlimed plot (♦) is also given.

At the $2 \cdot 5$ t ha^{-1} application rate, the finer particle sizes showed a small decline in pH over the latter years (Fig. 4a). At the 5 and 10 t ha^{-1} application rates, the coarser particles had increased the soil pH by a further $0 \cdot 2$ to $0 \cdot 3$ pH units over the following $2 \cdot 5$ years (Fig. 4b,c).

The time trends for Ca$_{ex}$ were similar to those for pH, with the coarser particle size materials giving increased Ca$_{ex}$ with time. This is again evidence that the coarser particle size materials were continuing to react slowly with the soil (Fig. 5).

Effects of Lime on Subsurface (10–15 cm) Soil

The efficiency of a liming material for correcting soil acidity is potentially confounded with any movement below the layer of incorporation. However, at this site, lime movement below 10 cm depth was restricted and is in agreement with the previous findings of Conyers and Scott (1989) at three other sites in the south-western slopes. Table 4 shows the mean increases in subsurface Ca$_{ex}$ and pH, over the unlimed soil, due to liming of the surface soil. The influence of surface-incorporated lime on subsurface soil pH and Ca$_{ex}$ increases with lime fineness and with rate of application. There was an apparently large increase in pH and Ca$_{ex}$ at 10–15 cm in 1988 due to the 10 t ha^{-1} application of the finest material. This effect was absent in 1989 and none of the other lime rates showed evidence of such substantial lime movement in either year. It is possible that episodic lime leaching occurs. In general, the extent of movement of Ca or pH change into the soil below the plough layer was small.

Grain Yield

The grain yield of wheat increased with increasing soil pH (Fig. 6). In 1986 the maximum yield was attained at a pH near 6, whereas in 1989 the maximum yield was attained at pH 5. Yields declined overall during the trial and the yield response to increasing pH became steeper for pH < 5. It is possible that the 1986 yields were greater due to a higher initial N status of the soil and also that liming may have contributed to yield by enhancing N mineralization as well as by the alleviation of aluminium toxicity. Regardless of mechanism, lime responses were obtained in all three seasons and the yield of grain was related to the pH achieved.

Discussion

Effects of Liming after 6 Months

Our finding that there was no plateau of lime particle size effectiveness contrasts with the commonly held view (Meyer and Volk 1952; Adams 1978). This view is that particles finer than $0 \cdot 25$ mm diameter are little or no more effective than $0 \cdot 25$ mm diameter particles in altering soil pH, Ca$_{ex}$ and crop yield. However, our study contained a finer particle size than the studies of Adams (1978) and Meyer and Volk (1952). Further, re-plotting the Adams (1978) data on the basis of estimated particle size diameter, rather than on U.S. mesh size, lessens the evidence for a plateau in lime effectiveness. While the study of Meyer and Volk (1952) gained acceptance (Tisdale and Nelson 1975), our data were more consistent with the contemporary study of Beacher et al. (1952).
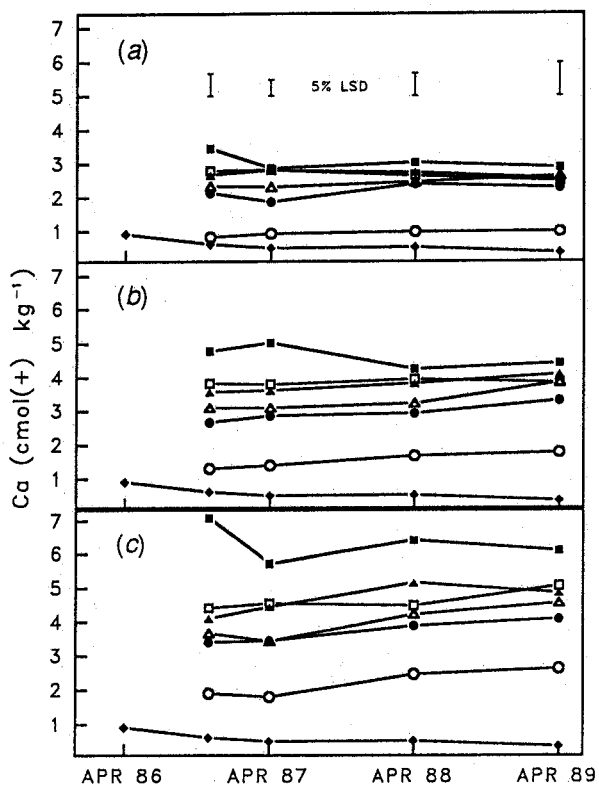
Fig. 5. The changes in soil exchangeable calcium (0–10 cm) from 6 months to 3 years (April 1989) after incorporation of limestone of various particle sizes at (*a*) 2·5, (*b*) 5·0 or (*c*) 10·0 t ha^{-1} The particle size legend is given in Fig. 1; the exchangeable calcium of the unlimed plot (◆) is also given.

Table 4. The influence of surface (0–10 cm) incorporated limestone on the pH and exchangeable Ca of the 10–15 cm layer of soil 2 years (1988) or 3 years (1989) after application

The pH was determined on 0·01 M CaCl$_2$; Ca is expressed in cmol (+) kg^{-1}

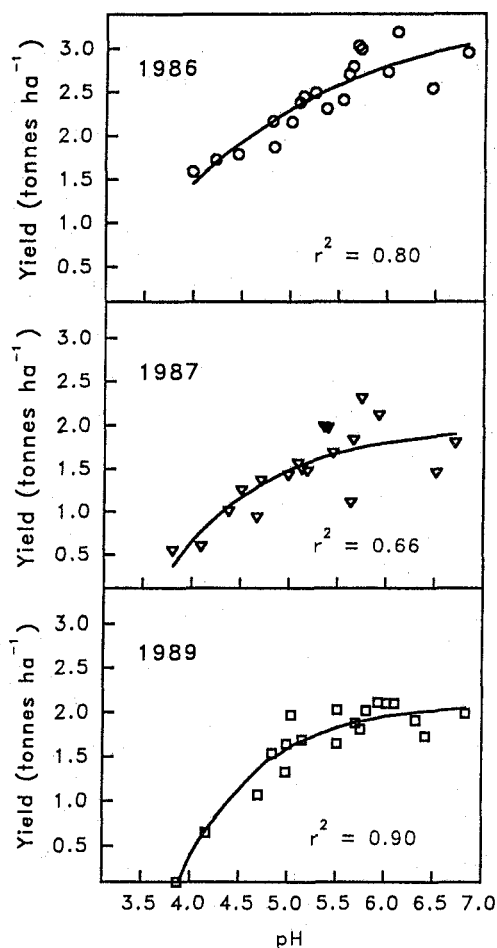| Lime applied		1988		1989	
Size	Rate (t ha^{-1})	pH	Ca	pH	Ca
—	0	4·11	0·40	3·97	0·17
1	10	4·13	0·59	4·08	0·51
2	10	4·22	0·80	4·25	0·81
3	10	4·25	0·82	4·27	0·95
4	10	4·34	1·09	4·28	0·88
5	10	4·43	1·01	4·24	0·75
6	2·5	—	—	4·13	0·46
6	5	—	—	4·21	0·55
6	10	5·25	1·56	4·24	0·57
s.e.d.		0·20	0·24	0·09	0·17

Fig. 6. The relationship between soil pH and wheat grain yield (t ha^{-1}) in the three seasons 1986, 1987, and 1989. The lines are Mitscherlich equations fitted to the data.

It is our conclusion that the 0·25 mm particle diameter only represents 100% relative efficiency if it is the finest particle size in the study. No such plateau in particle size effectiveness existed in our data. The selection of optimum particle size will involve a balance of fineness and cost, the latter including ease of handling.

Time Trends

The data demonstrated a relatively rapid initial effect of limestone, but a much slower rate of reaction after the first 6 months. The observation is consistent with limestone having a solubility which decreases as pH increases. The small decline in pH observed for finer particle treatments and the slight continuing increase in pH for coarser treatments suggests that intermediate treatments may be near to a steady state between lime dissolution and reacidification of the soil. At some time in the future, there may be an acceleration in the apparent acidification rate of these limed treatments as dissolution ceases.

In the experiment described here, the continued reaction of some lime products with the soil may have been a result of the continued soil disturbance resulting from harrowing and the sowing operations. In an undisturbed soil (i.e. in pastures),

this continued reaction may not be observed. Unreacted $CaCO_3$ particles have been isolated 5 years after lime application in a previous study (Conyers and Scott 1989).

Effects of Lime on Subsurface Soil

As the extent of lime movement into the subsurface soil increased with increasing fineness of the limestone, our estimate of the efficiency of each particle size, based on surface soil data, leads to under-estimation of the value of finer particle sizes. This again highlights the importance of fineness for limestone products.

Grain Yields

Some early studies on lime quality measured effectiveness by plant yield. While not denying that this is the end goal, the measurement of lime effectiveness by plant yield is confounded by the location of the data points on the yield response curve. We consider that the effectiveness of lime should be judged by its ability to increase soil pH.

Conclusions and Significance for Agriculture

The majority of the effect of lime on soil pH and Ca_{ex} took place within 6 months. The continued reaction of coarse particles beyond 6 months after liming was slight, being of the order of $0 \cdot 3$ pH units in the following $2 \cdot 5$ years.

Our study did not identify a maximum particle diameter which was as effective as finer particles. In fact, the capacity of limestone to increase soil pH was log-linearly related to particle diameter across the entire range of particle sizes studied (3 mm to $0 \cdot 005$ mm). Grain yield increased with increasing soil pH to a pH of $5 \cdot 0$–$6 \cdot 0$, depending on the season.

In agricultural practice, the results indicate that finer limestone is to be preferred, consistent with cost and ease of handling. A farmer may expect a grain yield increase in the first year after lime application on a responsive acid soil site and the residual benefit extends well into the future.

References

Adams, F. (1978). Liming and fertilisation of utisols and oxisols. In 'Mineral Nutrition of Legumes in Tropical and Subtropical Soils', (Eds C. S. Andrew and E. J. Kamprath.) pp. 377–394. (CSIRO, Aust.: Melbourne.)

Barber, S. A. (1984). Liming materials and practices. In 'Soil Acidity and Liming'. (Ed. F. Adams.) 2nd edn, pp. 171–210. (Am. Soc. Agron.: Wis.)

Beacher, R. L., Longnecker, D., and Merkle, F. G. (1952). Influence of form, fineness and amount of limestone on plant development and certain soil characteristics. *Soil Sci.* **73**, 75–82.

Conyers, M. K., and Scott, B. J. (1989). The influence of surface incorporated lime on subsurface soil acidity. *Aust. J. Exp. Agric.* **29**, 201–7.

Cregan, P. D., Hirth, J. R., and Conyers, M. R. (1989). Amelioration of soil acidity by liming and other amendments. In 'Soil Acidity and Plant Growth'. (Ed. A. D. Robson.) pp. 206–64. (Academic Press: Sydney.)

Food and Agriculture Organisation of the United Nations (1974). 'FAO–Unesco Soil Map of the World.' Vol. 1, Legend. pp. 59. (Unesco: Paris.)

Gleeson, A. C., and Cullis, B. R. (1987). Residual maximum likelihood (REML) estimation of a neighbour model for field experiments. *Biometrics* **43**, 277–88.

Hochman, Z., Godyn, D. L., and Scott, B. J. (1989). The integration of data on lime use by modelling. In 'Soil Acidity and Plant Growth'. (Ed. A. D. Robson.) pp. 265–301. (Academic Press: Sydney.)

Meyer, T. A., and Volk, G. W. (1952) Effect of particle size of limestones on soil reaction, exchangeable cations and plant growth. *Soil Sci.* **73**, 37–52.

Northcote, K. H. (1979). 'A Factual Key for the Recognition of Australian Soils.' Fourth edn. (Rellim Technical Publications: Glenside, S.A.)

Soil Survey Staff (1975). 'Soil Taxonomy.' Agriculture Handbook No. 436. U.S.D.A. Soil Conservation Service. pp. 754. (U.S. Government Printer: Washington, D.C.)

Stace, H. C. J., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J., and Hallsworth, E. G. (1968). 'A Handbook of Australian Soils.' (Rellim Technical Publications: Glenside, S.A.) 435 pp.

Tisdale, S. L., and Nelson, W. L. (1975). Liming. In 'Soil Fertility and Fertilisers'. pp. 412–24. (Macmillan Publishing Co., Inc.: New York.)

Verbyla, A. P., and Cullis, B. R. (1992). The analysis of multistratum and spatially correlated repeated measures data. *Biometrics*. (In press.)

Vimpany, I. A., Holford, I. C. R., Milham, P. J., and Abbott, T. S. (1985). 'Soil Testing Service—Methods and Interpretation.' (New South Wales Department of Agriculture: Rydalmere.)