Plant and Soil **45**, 531–542 (1976) Ms. 2863

# EFFECT OF pH AND PHOSPHATE ON SOLUBLE SOIL ALUMINIUM AND ON GROWTH AND COMPOSITION OF KIKUYU GRASS

by AZMI S. AWAD, DAVID G. EDWARDS* and PAUL J. MILHAM

Biological and Chemical Research Institute, N.S.W. Department of Agriculture, P.M.B. 10, Rydalmere, N.S.W. 2116, Australia.

SUMMARY

Kikuyu (*Pennisetum clandestinium* Hochst) grew relatively poorly on the Wollongbar krasnozem at soil pH values below 4.36. At these low pH values dry matter yields were increased by raising the pH or by application of high rates of phosphate. Both treatments decreased the concentration of soluble soil–Al on which the concentration of Al in tops was linearly dependent ($r = 0.95$).

The inverse relationship found between plant growth and Al concentration, when present in excess of $\sim$ 1.5 μg/g soil and $\sim$ 90 μg/g tops, is suggestive of Al toxicity. However, at Al concentrations causing severe yield reductions, the Ca concentration in kikuyu tops was approaching deficiency levels. The Al–Ca antagonism was further demonstrated by the reduction in Ca–uptake caused by increased concentrations of soluble soil–Al under constant conditions of exchangeable Ca and of pH. The yield-reducing effects of Al toxicity *per se* and Al–induced Ca deficiency are therefore confounded.

## INTRODUCTION

Nitrogen fertilization is an important method used to increase yield and extend seasonal distribution of kikuyu (*Pennisetum clandestinium* Hochst) pastures grown on the krasnozems of the subtropical north coast of N.S.W.[8]. In this region, $(NH_4)_2SO_4$ is the cheapest and therefore the commercially preferred form of N-fertilizer. It has been applied commercially at annual rates equivalent to 300 kg N/ha and experimentally to 1000 kg N/ha.

On experimental plots four annual treatments of $(NH_4)_2SO_4$ (336

* University of Queensland, Department of Agriculture, St. Lucia, Qld. 4067, Australia

kg N/ha) decreased pH of the Wollongbar krasnozem from 5.0 to 4.36. This acidifying side-effect[35] was a cause of concern because it could aggravate the deficiencies of Mo[2 31], P[2 11 30], N[2] and Ca[11 30] which have been reported on this soil and could induce Mn[21] and Al[14 28 34] toxicities. The occurrence of Al toxicity on sensitive species is suggested by a recent report that *Glycine wightii* grew poorly although adequately supplied with Mo, P and Ca[26].

Some studies on Al toxicity in soil have related plant performance to soluble Al, but most have used exchangeable Al as the criterion. Evans and Kamprath[12] determined both soluble and exchangeable Al and concluded that the most consistent measurement in terms of plant response to liming, on a range of soils, was soluble Al. Apart from this advantage, the determination of soluble Al allows direct comparisons to be made with the many solution culture experiments in which only soluble Al is present. Soluble rather than exchangeable Al can also be expected to reflect more precisely the environment at the soil solution – plant root interface. For these reasons we prefer to relate plant performance to soluble Al.

The current experiment was undertaken to study the interaction of soil pH with soluble Al concentration in the Wollongbar krasnozem and their effects on the growth and chemical composition of kikuyu.

## MATERIALS AND METHODS

The soil used in this study was collected from the upper 15 cms of the field plots mentioned in the Introduction. Aside from its nitrogen fertilizer history, this basaltic red loam (krasnozem) is typical of the soils which cover an extensive area on the well-drained uplands of the north coast of New South Wales. The chemical properties of these soils have been described by Colwell[9].

### *Pot technique*

Crushed, air-dry soil was filled into 15-cm diameter pots (1600 g/pot) lined with polythene bags. Fertilizers were applied on a surface area basis, 1.8 mg/pot being equivalent to 1 kg/ha. The experiment was designed as a factorial combination of six pH levels and three phosphate treatments, with four replications.

The pH levels (4.09, 4.24, 4.36, 4.84, 5.44 and 6.19) were obtained by using three $Al_2(SO_4)_3$ treatments (6.2, 3.1 and nil tonnes/ha) and three $CaCO_3$ treatments (2.5, 5.0 and 7.5 tonnes/ha). The P treatments were 22 ($P_1$), 225

($P_2$) and 450 ($P_3$) kg P/ha applied as $Na_2HPO_4.12H_2O$. A dressing incorporating $(NH_4)_2SO_4$ (split into three equal amounts totalling 672 kg N/ha) and the following salts at the rates (kg/ha) indicated in parenthesis: KCl (105), $ZnSO_4.7H_2O$ (22), $Na_2B_4O_7.10H_2O$ (22) and $Na_2MoO_4.2H_2O$ (1.3), was applied to each pot. Lime was mixed throughout the soil volume and all other treatments were applied as solutions to the soil surface.

Four kikuyu plants were established in each pot. Soil moisture was adjusted to 90 per cent of field capacity by the daily addition of deionised water. The plant tops and roots were harvested 70 days from planting and dried in a forced-draught oven at 85°C for 24 hours.

Analysis of variance was performed by standard statistical methods. Curves in the Figures were fitted by inspection.

*Methods of chemical analysis*

Soil pH and soluble Al[10] were determined on a 1:2 (w/v) extract in 0.01 *M* $CaCl_2$. Available P was extracted by $NH_4F$ solution and determined colorimetrically as its reduced phosphomolybdate complex[6]. Exchangeable bases were leached using 0.025 *M* $BaCl_2$ and Ca, Mg, Na and K measured by atomic absorption spectrophotometry[20].

Plants were analysed for N by a Kjeldahl method and for Mo by a colorimetric dithiol procedure following $HClO_4/HNO_3$ digestion[13]. The HCl extract of material ashed at 450°C was analysed for Ca, Mg and Mn by atomic absorption spectrophotometry and for P and Al by colorimetry[20] and fluorimetry[10] respectively. Nitrate was measured potentiometrically[27].

## RESULTS*

Raising the soil pH above 4.36 increased exchangeable Ca (Table 1), but lowered the concentration of soluble Al (Fig. 1). There was a similar effect on the Ca and Al concentrations in the plant (Table 2). The concentrations of Mo, N and $NO_3$–N in kikuyu tops were increased (Table 2). Above pH 4.8 plant growth was not affected (Fig. 2).

Decreasing the soil pH (below 4.36) increased exchangeable K and soluble Al concentrations in the soil (Table 1). Concentrations of Ca and Mo in the plant tops were decreased and those of Al and Mn increased. Each pH drop caused a significant decrease in growth of tops (Fig. 2). Root growth followed similar trends but was less affected by treatments (Fig. 2).

Applications of $Na_2HPO_4$ increased the concentrations of ex-

* Statements in the Results and the Discussion regarding significant effects refer to the 95% confidence level except where specified to the contrary.

TABLE 1

Effect of pH level and P treatment on soil chemical properties: available P (μg/g), and exchangeable bases (meq/100 g)*

| Soil pH ** | P 1 | P 2 | P 3 | Ca 1 | Ca 2 | Ca 3 | Mg 1 | Mg 2 | Mg 3 | Na 1 | Na 2 | Na 3 | K 1 | K 2 | K 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.09 | 8.4 | 34.2 | 50.7 | 1.8 | 2.0 | 1.9 | 0.8 | 0.9 | 0.8 | 0.4 | 1.8 | 3.8 | 0.46 | 0.25 | 0.27 |
| 4.24 | 8.4 | 35.0 | 38.2 | 2.2 | 2.1 | 2.4 | 0.9 | 0.8 | 1.0 | 0.4 | 2.1 | 4.2 | 0.45 | 0.26 | 0.23 |
| 4.36 | 9.1 | 34.0 | 36.4 | 2.4 | 2.3 | 2.6 | 0.9 | 0.8 | 0.8 | 0.5 | 2.0 | 3.7 | 0.31 | 0.24 | 0.23 |
| 4.84 | 6.7 | 22.4 | 38.2 | 10.0 | 9.9 | 10.8 | 1.0 | 0.7 | 0.9 | 0.4 | 1.6 | 3.9 | 0.24 | 0.22 | 0.21 |
| 5.44 | 7.4 | 17.5 | 43.1 | 19.3 | 17.6 | 17.9 | 1.0 | 0.8 | 0.7 | 0.4 | 1.5 | 3.9 | 0.21 | 0.18 | 0.16 |
| 6.19 | 10.8 | 19.0 | 37.5 | 24.1 | 25.3 | 22.9 | 0.8 | 0.8 | 0.8 | 0.4 | 1.8 | 3.4 | 0.17 | 0.16 | 0.14 |

* Means of four replicates presented on a dry weight basis.
** LSD 5% = 0.048.

changeable Na and available P and decreased that of soluble Al without affecting soil pH. Growth of tops and roots was significantly increased to the $P_2$ treatment level at each pH. However, at pH $< 4.36$ top growth continued to increase to the $P_3$ treatment level

TABLE 2

Effect of pH level and P treatment on chemical composition of kikuyu tops*

| Soil pH | % P 1 | % P 2 | % P 3 | % N 1 | % N 2 | % N 3 | % Ca 1 | % Ca 2 | % Ca 3 | % Mg 1 | % Mg 2 | % Mg 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.09 | 0.261 | 0.233 | 0.270 | 4.69 | 4.50 | 4.85 | 0.10 | 0.11 | 0.09 | 0.33 | 0.33 | 0.27 |
| 4.24 | 0.212 | 0.228 | 0.299 | 4.67 | 4.67 | 4.60 | 0.16 | 0.10 | 0.11 | 0.36 | 0.35 | 0.32 |
| 4.36 | 0.188 | 0.258 | 0.377 | 4.21 | 4.71 | 5.01 | 0.16 | 0.14 | 0.11 | 0.30 | 0.29 | 0.34 |
| 4.84 | 0.154 | 0.242 | 0.353 | 5.62 | 5.27 | 5.37 | 0.36 | 0.36 | 0.40 | 0.33 | 0.39 | 0.41 |
| 5.44 | 0.152 | 0.253 | 0.395 | 5.32 | 4.24 | 5.63 | 0.44 | 0.45 | 0.41 | 0.33 | 0.36 | 0.36 |
| 6.19 | 0.182 | 0.275 | 0.375 | 5.11 | 5.05 | 5.15 | 0.66 | 0.60 | 0.50 | 0.30 | 0.36 | 0.37 |
| | μg/g Mo 1 | μg/g Mo 2 | μg/g Mo 3 | μg/g $NO_3$–N 1 | μg/g $NO_3$–N 2 | μg/g $NO_3$–N 3 | μg/g Mn 1 | μg/g Mn 2 | μg/g Mn 3 | μg/g Al 1 | μg/g Al 2 | μg/g Al 3 |
| 4.09 | 0.20 | 0.28 | 0.30 | 5,227 | 1,750 | 530 | 355 | 262 | 191 | 442 | 267 | 183 |
| 4.24 | 0.35 | 0.20 | 0.20 | 3,500 | 1,131 | 620 | 373 | 183 | 183 | 365 | 145 | 112 |
| 4.36 | 0.28 | 0.32 | 0.20 | 2,853 | 2,816 | 3,583 | 211 | 178 | 195 | 142 | 100 | 118 |
| 4.84 | 0.80 | 0.62 | 1.02 | 6,915 | 6,170 | 5,900 | 258 | 206 | 206 | 50 | 67 | 83 |
| 5.44 | 1.12 | 1.04 | 0.80 | 7,230 | 6,853 | 6,416 | 145 | 176 | 131 | 42 | 60 | 65 |
| 6.19 | 0.98 | 0.82 | 0.82 | 6,630 | 4,507 | 4,538 | 136 | 187 | 138 | 40 | 40 | 50 |

* Means of four replicates presented on a dry weight basis.

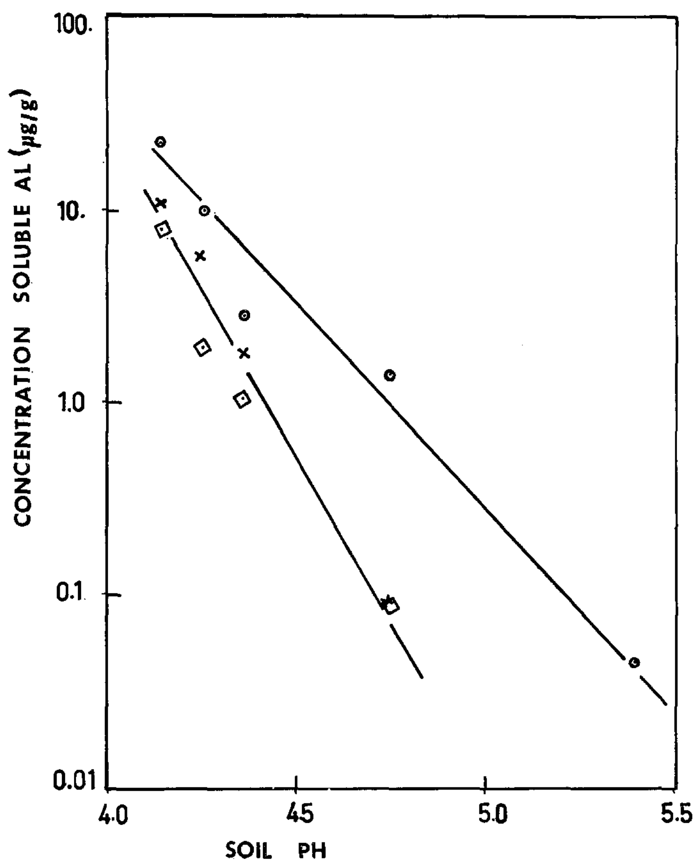


Fig. 1. Relationship between soil pH and soluble Al at three levels of applied P ($P_1$ -○-, $P_2$ -×- and $P_3$ -□-).

(Fig. 2). Concentrations of P were increased in tops (Table 2) and in roots (data not presented).

## DISCUSSION

Published data on chemical composition of kikuyu and other grasses suggest that Mg, N, Mo and Mn were in adequate supply to permit maximal growth during the experiment. Mg in tops exceeded 0.25 per cent, the level considered to cause no growth-limitation for kikuyu[7]. Values for N were well above the 3.11 per cent reported to be non-limiting for kikuyu[5]. There are no data available on the deficiency levels of Mo for kikuyu. However, all Mo levels exceeded the

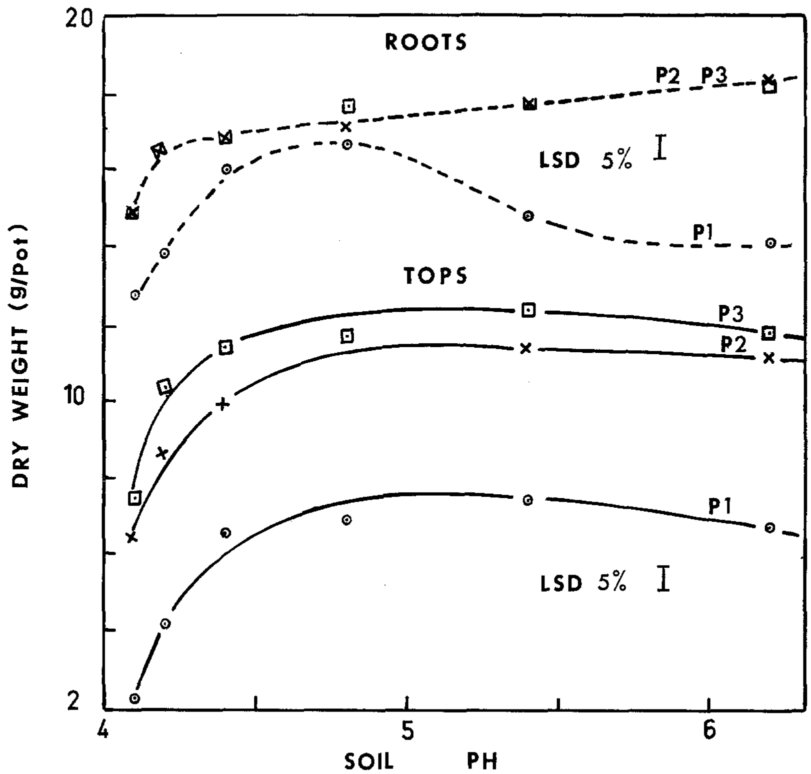


Fig. 2. Growth of kikuyu as a function of pH and P treatments.

0.1 μg/g concentration reported[1] to be generally sufficient for grasses and the critical range reported for ryegrass tops (0.1–0.3 μg/g)[25]. The highest Mn level found (373 μg/g), is lower than the levels reported to be toxic to sensitive legume species[3 21]. Since grasses are generally less sensitive to Mn toxicity[18], it is therefore unlikely that kikuyu growth was restricted by excessive Mn concentrations in this experiment.

Increasing the pH and the phosphate applications increased the available P (Table 1) and P uptake. However, because of the effects of these treatments on plant growth, the minimum concentration of P in the tops (0.15–0.18 per cent) and roots (0.15–0.17 per cent) occurred at the lowest P treatment in combination with pH $> 4.36$ (Table 2). These P concentrations are lower than the critical level (0.22 per cent) reported for tops of 45-day-old kikuyu plants[5]. The plants in this experiment could be expected to have a slightly different critical P concentration because they were 70 days old. But since critical P concentrations usually decline with age, as reported for *Trifolium subterraneum*[16], it would be expected that the critical value for the 70-day-old plants harvested in this experiment would be less than the value of 0.22 per cent P reported for 45-day-old plants. It is therefore suggested that P is limiting growth only in the P1 treatments at pH values $> 4.36$. Hence, the yield increases associated with the higher levels of applied P at pH $< 4.36$ are attributed to the reduction in soluble Al concentration that they caused and not to improved P nutrition.

The observed P accumulation in kikuyu tops under conditions of low pH ($< 4.36$) and low P supply is consistent with results previously reported for other species which show a considerable degree of tolerance to Al toxicity[4 14 28]. This behaviour contrasts with that reported in species sensitive to Al toxicity, *e.g.* lucerne[4 14 28] and phalaris[28], in which P accumulation in the tops is reduced. Although the present experiment provides some evidence of increased P accumulation in kikuyu roots at the lower pH values, there is no evidence that Al retards growth by rendering the plant tops P deficient.

*Aluminium toxicity*

The rapid increase in the concentration of soluble Al in the Wollongbar krasnozem with decreasing pH (Fig. 1) parallels previously reported results[14 31]. At all pH levels where soluble Al was detected, Al concentration was depressed by increasing applications of phosphate. The lower the pH, the greater the depression caused by any given phosphate increment (Fig. 1). These effects have usually been attributed to rapid precipitation of Al phosphates[17] or to surface chemisorption[15].

The yield of kikuyu tops was limited in those treatments in which the soluble Al concentration was greater than about 1.5 μg/g soil. This value is of the same order as that reported by several other workers for Al toxicity in plants grown both in soils[14] and nutrient solutions[4 28] at specified Al concentrations. Solution Al concentrations above 0.5 μg/ml have been shown to restrict the growth of those legumes considered to be sensitive to Al toxicity[4 28] while tolerant legumes have shown no growth reduction at 2.0 μg/ml[4] or higher[18]. Growth of Al-sensitive barley varieties has been restricted

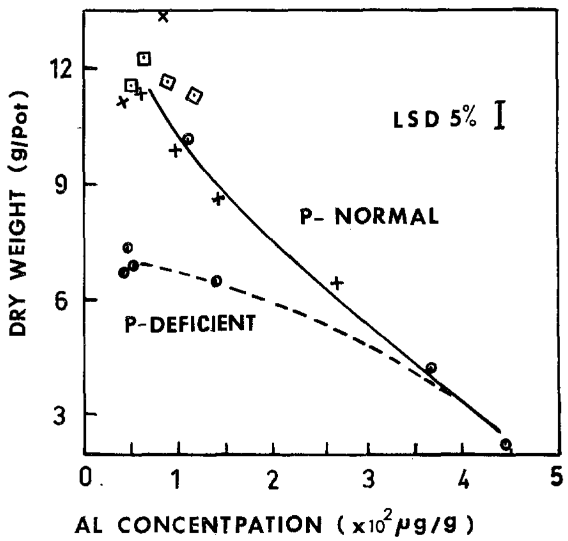


Fig. 3. Al concentration in kikuyu tops and top growth at different rates of applied P.

by soluble Al concentrations as low as 0.5 µg/ml[23 24]. Similarly, yield reductions in kikuyu tops were associated with plant Al concentrations above ~ 90 µg/g, since Al concentration in tops (Y) was correlated (r = 0.95) with the concentration of soluble soil – Al (X) in the equation, $Y = 19.24X + 62.64$. Al-tolerant species such as rice[33] and subterranean clover[28] did not exhibit a yield reduction until concentrations in excess of 300 µg/g and 400 µg/g respectively were reached. Consistent with Al concentrations increasing beyond 90 µg/g in kikuyu tops, it was observed that the top/root ratios declined, particularly in the low P treatment. A similar decline in top/root ratio of Al-sensitive species has been observed previously[4 28]. Therefore the current data do not allow any firm conclusions to be drawn regarding the Al tolerance of kikuyu.

The almost linear, inverse relationship between top growth and Al concentration when in excess of about 90 µg/g, was modified when phosphate supply limited growth (Fig. 3), *i.e.* in the $P_1$ treatments at pH values > 4.36. Excluding the latter treatments, which involved a phosphate response *per se*, the major portion of the growth responses caused by phosphate treatments can be attributed directly to their action in depressing the concentration of soluble Al in the soil (Fig. 1). The negative interaction between Al and applied P is in agreement with literature pertaining to Al toxicity on acid soils[28]. However, the data do not provide unequivocal evidence of Al toxicity *per se*, because Al affected Ca nutrition.

*Calcium deficiency*

The relationship between Ca concentration and growth of tops (Fig. 4) is characterised by two distinct regions. When Ca was < 0.11 per cent (which occurred only at pH < 4.36), yield increased sharply

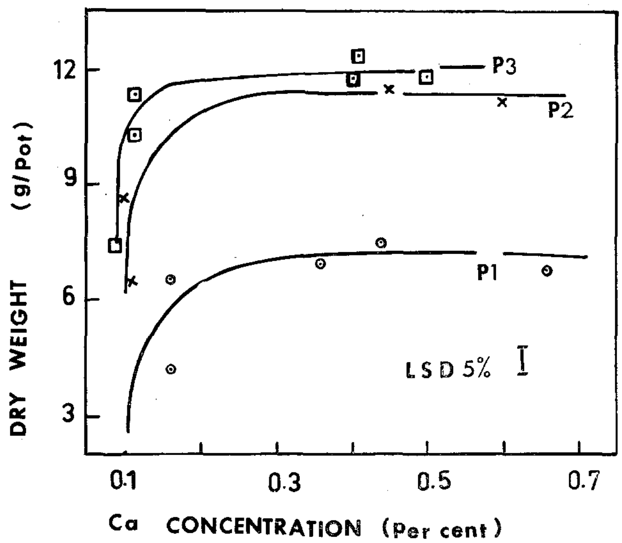


Fig. 4. Ca concentration in kikuyu tops and top growth at different rates of applied P.

with very little increase in Ca concentration; thereafter, Ca concentration increased rapidly with little increase in top yield. The poverty adjustment at pH < 4.36 suggests that Ca was limiting kikuyu growth when present at < 0.11 per cent in the tops, although slightly lower functional requirement values (0.05–0.10 per cent Ca) have been reported for several other grasses[22].

Plant growth responses to liming materials[29 30 31] together with the low exchangeable Ca levels[9] of the Wollongbar krasnozem have, in the past, given rise to speculation that the soil is Ca deficient. Even though our results show similar trends, we question the validity

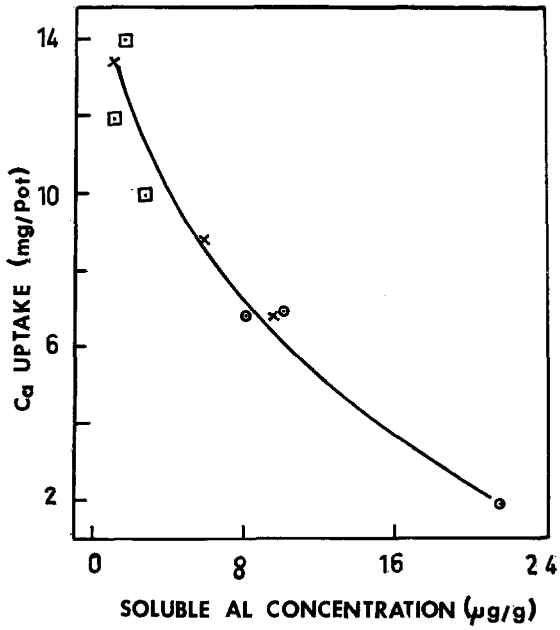


Fig. 5. Ca-uptake at three levels of exchangeable Ca (1.9 -○-, 2.2 -×- and 2.5 -□- meq/100 g) as affected by the concentration of soluble soil -Al.

of the logic behind this speculation, on the basis of the well known concomitant effect of liming on the solubility of soil Al[15 32].

*Aluminium–calcium interaction*

The negative interaction between Al and Ca is clearly demonstrated by the hyperbolic relationship between their respective concentrations in the aerial portion of the plants (Table 2). More importantly however, this experiment allows us to show the antagonistic effect of soluble Al on Ca uptake at a constant level of exchangeable Ca, because P treatments affected soluble Al concentration but not pH or exchangeable Ca. Thus at any one exchangeable Ca level and at the corresponding pH (1.9, 2.2 and 2.5 meq Ca/100 g and pH 4.09, 4.24 and 4.36 respectively), increasing the level of applied P and thereby decreasing the level of soluble Al, resulted in a proportionate increase in Ca uptake by plant tops (Fig. 5). It is therefore evident that excess soluble Al was the principal cause of both depressed growth and Ca uptake in this experiment. This result substantiates previous proposals that Al depresses the uptake and translocation of Ca[19 32], and that in acid soils, Al excess and Ca deficiency are interrelated[32].

ACKNOWLEDGEMENTS

The authors thank Mr. G. O'Neill for the statistical analyses, Mrs. K. Kemp, Mr. J. Kennedy and Mrs. A. Maksvytis for technical assistance and Mr. N. Elkadomi for preparing the figures.

Received 23 June, 1975

REFERENCES

1 Anderson, A. J., Molybdenum deficiencies in legumes in Australia. Soil Sci. **81,** 173–182 (1956).

2 Anderson, A. J. and Arnot, R. H., Fertilizer studies on a basaltic red loam soil from the Lismore district, N.S.W. Aust. J. Agric. Res. **4,** 29–43 (1953).

3 Andrew, C. S. and Hegarty, M. P., Comparative responses to manganese excess of eight tropical and four temperate pasture legume species. Aust. J. Agric. Res. **20,** 687–693 (1969).

4 Andrew, C. S., Johnson, A. D. and Sandland, R. L., Effect of aluminium on the growth and chemical composition of some tropical and temperate pasture legumes. Aust. J. Agric. Res. **24,** 325–339 (1973).

5 Andrew, C. S. and Robins, M. F., The effect of phosphorus on the growth, chemical composition, and critical phosphorus percentages of some tropical pasture grasses. Aust. J. Agric. Res. **22,** 693–706 (1971).

6 Bray, R. H. and Kurtz, L. T., Determination of total, organic and available forms of phosphate in soils. Soil Sci. **59,** 39–45 (1945).

7 Cassidy, N. G., Observations on nutrient deficiencies in kikuyu grass (*Pennisetum clandestinum*). Queensl. J. Agric. Anim. Sci. **29,** 51–57 (1972).

8 Colman, R. L., Future use of nitrogen fertilizers on pastures and crops in subtropical New South Wales J. Aust. Inst. Agric. Sci. **36,** 224–232 (1970).

9 Colwell, J. D., Observations on the pedology and fertility of some krasnozems in northern New South Wales J. Soil Sci. **9,** 46–57 (1958).

10 Cook, M. G., Determination of soil aluminium by fluorescence. Soil Sci. Soc. Am. Proc. **32,** 292–293 (1968).

11 Crofts, F. C., Pulsford, J. S. and Jenkins, H. V., Legume nitrogen on red basaltic soils of the Richmond River district of New South Wales. J. Aust. Inst. Agric. Sci. **21,** 94–98 (1955).

12 Evans, C. E. and Kamprath, E. J., Lime response as related to per cent Al saturation, solution Al, and organic matter content. Soil Sci. Soc. Am. Proc. **34,** 893–896( 1970).

13 Gupta, U. C. and MacKay, D. C., Determination of molybdenum in plant materials using dithiol. Soil Sci. **99,** 414–415 (1965).

14 Helyar, K. R. and Anderson, A. J., Effects of lime on the growth of five species, on aluminium toxicity and on phosphorus availability. Aust. J. Agric. Res. **22,** 707–721 (1971).

15 Hsu, P. H., Fixation of phosphate by aluminium and iron in acid soils. Soil Sci. **99,** 398–402 (1965).

16 Jones, M. B., Ruckman, J. E. and Lawler, P. W., Critical levels of P in sub-clover (*Trifolium subterraneum* L.). Agron. J. **64**, 695–698 (1972).

17 Kittrick, J. A. and Jackson, M. L., Common ion effect on phosphate solubility. Soil Sci. **79**, 415–421 (1955).

18 Labanauskas, C. K., Manganese. *In* Diagnostic criteria for plants and soils (Ed.: Chapman, H. D.), 264–285. University of California, Division of Agricultural Science, Riverside 1966.

19 Lance, J. C. and Pearson, R. W., Effects of low concentrations of aluminium on growth and water and nutrient uptake by cotton roots. Soc. Soil Sci. Am. Proc. **33**, 95–98 (1969).

20 Leece, D. R. and Short, C. C., A routine procedure for the nutrient-element analysis of peach leaves utilizing atomic absorption spectroscopy. N.S.W. Dep. Agric., Div. of Science Services Bull. No. F**78** (1967).

21 Löhnis, M. P., Manganese toxicity in field and market garden crops. Plant and Soil **3**, 193–222 (1951).

22 Loneragan, J. F. and Snowball, K., Calcium requirements of plants. Aust. J. Agric. Res. **20**, 465–478 (1969).

23 MacLean, A. A. and Chiasson, T. C., Differential performance of two barley varieties to varying aluminium concentrations. Can. J. Soil Sci. **46**, 147–153 (1966).

24 McLeod, L. B. and Jackson, L. P., Water soluble and exchangeable aluminium in acid soils as affected by liming and fertilization. Can. J. Soil Sci. **47**, 203–210 (1967).

25 McNaught, K. J., Diagnosis of mineral deficiencies in grass-legume pastures by plant analysis. *In* Proc XI Internat. Grassl. Congr. (Ed.: Norman, M. J. T.) 334–338. Univ. of Qld. Press, St. Lucia, Qld. 1970.

26 Mears, P. T. and Barkus, B., Response of *Glycine wightii* to molybdenized superphosphate on a krasnozem. Aust. J. Exp. Agric. Anim. Husb. **10**, 415–425 (1970).

27 Milham, P. J., Awad, A. S., Paull, R. E. and Bull, J. H., Analysis of plants, soils and water for nitrate by using an ion-selective electrode. Analyst **95**, 751–757 (1970).

28 Munns, D. N., Soil acidity and growth of a legume. Aust. J. Agric. Res. **16**, 733–766 (1965).

29 Parbery, N. H., The basaltic and associated soils of the far north coast district of New South Wales. N.S.W. Dep. of Agric., Regional Soils Series No. **2**, 1939.

30 Parbery, N. H., Declining fertility in red laterite soils. Experiments on the effects of added phosphate and liming materials. Agric. Gaz. N.S.W. **57**, 291–297 (1946).

31 Parbery, N. H., The effect of molybdenum on clover growth on laterite soils. Agric. Gaz. N.S.W. **57**, 343–347 (1946).

32 Soileau, J. M., Engelstad, P. O. and Martin, J. B., Cotton growth in an acid fragipan sub-soil. II. Effects of soluble calcium, magnesium and aluminium on roots and tops. Soil Sci. Soc. Am. Proc. **33**, 919–924 (1969).

33 Tanaka, A. and Navasero, S. A., Aluminium toxicity of the rice plant under water culture conditions. Soil Sci. Plant Nutr. **12**, 55–60 (1966).

34 Vlamis, J., Acid soil infertility as related to soil solution and solid phase effects. Soil Sci. **75**, 383–394 (1953).

35 Wolcott, A. R., Foth, H. D., Davis, J. F. and Shickluna, J. C., Nitrogen carriers. I. Soil effects. Soil Sci. Soc. Am. Proc. **29**, 405–410 (1965).