

**SODIUM, CATION EXCHANGE AND CROP RESPONSE  
IN ACID KWAZULU-NATAL SOILS**

by

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## ABSTRACT

In many acid, highly leached South African soils, Na levels are very low. Applications of Na to highly leached soils may be advantageous in some situations as Na has been shown to interact with soil acidity, P availability, and K nutrition of plants.

It was found that an increased level of Na at constant anion concentration in the soil solution resulted in lower soil solution pH and  $Al^{3+}$  activity, and improved maize root penetration into an acid subsoil (pot trial). In another pot trial, Na did not improve lucerne root growth into the same subsoil.

In a field trial on a limed, low-Na soil with severe subsoil acidity, the effects of four rates of Na, three Na carriers, and three rates of gypsum on maize growth were compared. In three out of four seasons grain yield responses to the Na applications were positive, and of a similar magnitude to the response to gypsum (455-925 kg ha<sup>-1</sup>). In another field trial with maize, responses to Na (of up to 1027 kg grain ha<sup>-1</sup>) were recorded in two out of three years on plots with topsoil acid saturations of greater than 45%. The reason for the responses to Na was probably improved subsoil rooting as a result of modified soil solution composition in the presence of Na.

In a field trial with Italian ryegrass on an acid, highly weathered soil, the effect of sodium applications were investigated at different levels of lime and K. In the first season, 200 kg ha<sup>-1</sup> Na as NaCl increased dry matter yield from 11289 kg ha<sup>-1</sup> to 12815 kg ha<sup>-1</sup>. Sodium responses were possibly due to enhanced P uptake, or Na substitution for K, or a combination of the two mechanisms. No consistent lime x Na interaction was observed. Potassium and Na applications

affected the mineral balance of the herbage produced. Potassium depressed herbage Ca, Mg and Na concentrations, and Na depressed herbage Ca and Mg where herbage K was low, but had no effect on herbage K. Where soil P and K reserves are marginal, ryegrass pastures may benefit from Na applications.

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## DECLARATION

I hereby declare that the whole of this thesis, except where otherwise indicated in the text, is my own original work and that the results obtained have not been submitted by me in respect of a degree at any other university.

A handwritten signature in blue ink, appearing to read 'A.D. Manson', is positioned above the printed name.

**A.D. MANSON**

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## 1. INTRODUCTION

In South African agriculture, Na is usually regarded as a problem element due to the detrimental effect it can have on the physical properties of soils. These problems are most significant at fairly high levels of Na which are usually found in neutral to alkaline soils. On the other hand, in many of the acid, highly leached South African soils, Na levels are very low, frequently being less than  $0.1 \text{ cmol}_c \text{ kg}^{-1}$  (van der Eyk *et al.*, 1969, pp.120-236). As most important crop plants were originally selected as a result of their performance on 'chemically fertile' soils which probably had moderate Na levels, the possibility exists that applications of Na to highly leached soils may be advantageous in some situations. Improved plant performance may accrue from the direct effects of the element on plant metabolism, its effect on the soil chemistry, or via its influence on the interaction of plant roots with the soil (due to changes in the rhizosphere). If applications were limited so that exchangeable sodium percentages remained below five, negative effects would (in most cropping systems) probably be limited to lower infiltration rates due to increased soil dispersion at the soil surface.

When considering the effects of Na on plant metabolism, it is apparent that the ability of plants to utilize Na varies greatly between families, genera, species, and even varieties of the same species. Sodium has been found to be essential as a micronutrient for a wide variety of species which use the  $C_4$  and CAM photosynthetic pathways (Brownell, 1979). In addition, irrespective of whether Na is required as a micronutrient or not, plant species may also differ in their ability to accumulate Na in their shoots and leaves. Natrophiles (Na accumulators) often show positive yield responses to Na fertilization, especially in cases where K supply is sub-optimal, suggesting that Na may proxy for K in some physiological roles (Flowers & Läuchli, 1983). This substitution has important implications in the field of pasture quality (Mundy, 1983; Horn, 1988), but other (poorly understood) effects of sodium in aspects such as water relations, carbohydrate metabolism and nitrogen metabolism are also potentially important.

Response of plants to soil-applied sodium may not be due to the direct effect of the element itself on the plant, but rather to its effects on other soil factors important for crop growth. Many of these effects are related to modifications by Na of the interactions between other ions and the adsorbing surfaces within soils. The low preference that cation exchange surfaces in soils show

for the  $\text{Na}^+$  ion not only accounts for the effect of sodium on soil dispersion, which has been extensively reviewed (e.g. Shainberg & Letey, 1984) and will not be covered here, but also influences factors such as soil solution acidity and phosphorus solubility.

In the following chapters, work related to these various effects will be discussed, with special attention being given to the possible consequences of applying Na to highly leached, acid soils.

Initial indications were that the potential benefits of applications of Na to acid soils may be substantial. Preliminary work showed that for maize (a plant which apparently shows little response to Na as a nutrient), a potentially important effect of Na might be that of alleviating soil acidity, especially subsoil acidity, and Chapters 3, 4 and 5 deal with this aspect.

Many pasture species (including ryegrass and clover which are important in areas with acid soils) respond to Na as a nutrient, so benefits from Na fertilization are likely. The potential of Na as a partial substitute for K in Italian ryegrass, as well as possible improvements in the efficiency of lime and phosphorus fertilizers are dealt with in Chapter 6.

A summary of the results from these experiments and a general discussion is given in Chapter 7.

## 2. LITERATURE REVIEW

This review concentrates on effects of Na on plants and on non-saline and non-sodic soils to identify situations where applications of Na to agricultural soils may be beneficial.

### 2.1 PLANT RESPONSE TO APPLIED SODIUM

#### 2.1.1 Sodium as an essential plant nutrient

Sodium is an element which is not normally considered an important plant nutrient, but it was shown in the 1950's, with work done on the blue-green alga *Anabaena cylindrica* (Allen & Arnon, 1955) and the bladder salt bush *Atriplex vesicaria* (Brownell & Wood, 1957), that certain plants had a specific requirement for Na. However, later work was unable to explain why many species did not respond to Na (Brownell, 1968) and it was only after the discovery of the C<sub>4</sub> dicarboxylic photosynthetic pathway (Hatch & Slack, 1966) that it was realized that only C<sub>4</sub> species showed a response to levels of Na as low as 0.1 mM (Brownell & Crossland, 1972; Brownell, 1979).

Many C<sub>4</sub> species have been shown to require Na to prevent chlorosis of leaves and to maintain the reproductive cycle, whereas the C<sub>3</sub> species that have been shown to require Na for maximum growth or yield (such as sugar beet) are capable of normal growth without the element. These C<sub>3</sub> plants also require far higher Na concentrations in their growth medium before they respond to the element than do Na-deficient C<sub>4</sub> plants.

Table 2.1 gives the response of a variety of plant species to low levels of Na, and it is apparent that for almost all those with the C<sub>4</sub> photosynthetic pathway, Na is necessary for normal growth.

It appears, however, that in common with the C<sub>3</sub> species in Table 2.1, certain C<sub>4</sub> species, including *Zea mays* (maize), *Saccharum officinarum* (sugar cane) and *Sorghum vulgare* may not have a specific requirement for Na (Hewitt, 1983). Ando *et al.* (1985) demonstrated that tropical grasses (all C<sub>4</sub> species) also vary in their response to Na. They showed that *Chloris gayana* (Rhodes grass), *Panicum dichotomiflorum*, *Echinichloa cara-galli* (Japanese millet) and three varieties

of *Panicum coloratum* responded to less than 0.1 mM Na in nutrient solutions, whereas *Eleusine coracana* (African millet), *Sorghum vulgare*, and two varieties of *Panicum maximum* failed to show a large positive yield response to Na.

The physiological role of Na in those C<sub>4</sub> plants which apparently require it for growth is still not clear, but Grof *et al.* (1986) draw attention to the similarities between Mn-deficient plants and Na-deficient C<sub>4</sub> plants with respect to changes in chlorophyll *a* fluorescence, low chlorophyll *a/b* ratios and disturbance of chloroplast ultrastructure. They suggested therefore that Na deficiency may cause disturbance of the light-harvesting and reaction centres in the mesophyll chloroplasts.

Because the Na requirement of the C<sub>4</sub> plants is low, Na deficiencies are unlikely to be important except possibly in highly leached soils far enough from the sea to prevent substantial inputs of marine Na.

Table 2.1. Sodium requirements of a variety of plant species (after Brownell, 1979).

Species	Lesions in plants not receiving Na	Significance of yield increase due to 0.1 mM Na	Probable pathway
Gramineae			
<i>Hordeum vulgare</i> (barley)	None	5%	C <sub>3</sub>
<i>Poa pratensis</i> (Kentucky blue grass)	None	N.S.	C <sub>3</sub>
<i>Echinochloa utilis</i> (Japanese millet)	Chlorosis & necrosis	0.1%	C <sub>4</sub>
<i>Cynodon dactylon</i> (Bermuda grass)	Chlorosis	1%	C <sub>4</sub>
<i>Chloris barbata</i> (purple top chloris)	Chlorosis	0.1%	C <sub>4</sub>
<i>Chloris gayana</i> (Rhodes grass)	Chlorosis	0.1%	C <sub>4</sub>
<i>Panicum maximum</i> (Guinea grass)	Chlorosis	N.S.	C <sub>4</sub>
<i>Panicum milioides</i>	None	N.S.	C <sub>3</sub>
<i>Eleusine indica</i> (crowsfoot grass)	Chlorosis	0.1%	C <sub>4</sub>
Cyperaceae			
<i>Kyllinga brevifolia</i>	Chlorosis	1%	C <sub>4</sub>

Table 2.1. (Continued).

Amaranthaceae			
<i>Amaranthus tricolor</i>	Chlorosis & necrosis	0.1%	C <sub>4</sub>
Chenopodiaceae			
<i>Chenopodium capitatum</i>	None	N.S.	C <sub>3</sub>
<i>Beta vulgaris</i> (sugar beet)	None	N.S.	C <sub>3</sub>
<i>Atriplex nummularia</i> (oldman saltbush)	Chlorosis	0.1%	C <sub>4</sub>
<i>Atriplex semibaccata</i> (berry saltbush)	Chlorosis & necrosis	1%	C <sub>4</sub>
<i>Atriplex vesicaria</i> (bladder saltbush)	Chlorosis & necrosis	0.1%	C <sub>4</sub>
<i>Atriplex hortensis</i> (garden orache)	None	5%	C <sub>3</sub>
<i>Atriplex glabriuscula</i>	None	N.S.	C <sub>3</sub>
<i>Kochia pyramidata</i>	None	N.S.	C <sub>3</sub>
<i>Kochia childsii</i>	Chlorosis & necrosis	1%	C <sub>4</sub>
<i>Halogeton glomeratus</i>	Smaller, curved leaves, wilting	1%	C <sub>4</sub>
Cruciferae			
<i>Brassica oleracea</i> (cabbage)	None	N.S.	C <sub>3</sub>
Leguminosae			
<i>Trifolium repens</i> (white clover)	None	N.S.	C <sub>3</sub>
Solanaceae			
<i>Lycopersicon esculentum</i> (tomato)	None	N.S.	C <sub>3</sub>
Compositae			
<i>Lactuca sativa</i> (lettuce)	None	N.S.	C <sub>3</sub>

### 2.1.2 Crop yield responses to applied sodium

Despite the ability of most soils to supply enough Na to satisfy any plant needs at micronutrient levels, there are many reports of positive responses to Na applied to crops in both field and pot trials. In many cases positive responses have been obtained in C<sub>3</sub> plants which do not require Na as an essential nutrient in the sense discussed in the previous section.

Harmer *et al.* (1953) summarized the effect of Na applications on a variety of crops grown on a muck soil. Their assessments of crop responses are reproduced in Table 2.2, which draws attention to a negative interaction between Na and K in their effect on crop yield in that many crops only respond to Na applications when K is deficient. In fact, even for those crops classified as responding to Na when K is sufficient, response to Na is generally better when K supply is low.

Table 2.2. Comparative response of crops to Na (after Harmer *et al.*, 1953).

Response with insufficient K		Response with ample K	
Group 1. None to very slight	Group 2. Slight to medium	Group 3. Slight to medium	Group 4. Large
buckwheat	alfalfa	cabbage	celery
red clover	asparagus	celeriac	mangel
corn	barley	kale	sugar beet
cucumber	broccoli	kohlrabi	swiss chard
lettuce	brussels	pea	table beet
onion	sprouts	radish	turnip
parsley	carrot	rape	
parsnip	chicory	wheat	
peppermint	ladino clover		
potato	horse-radish		
rye	millet		
soybean	mustard		
spearmint	oat		
spinach	rutabag		
squash	salsify		
strawberry	tomato		
sunflower	vetch		
white bean			

Sugar beet (*Beta vulgaris*) responds well to fairly large Na applications despite its lack of response to Na as a micronutrient and is one of the few crops that receive Na as a fertilizer on a large scale. Durrant *et al.* (1974) examined 216 field trials using Na and K fertilizers. Those conducted on mineral soils as opposed to peaty soils showed that sugar beet responds to large Na applications, especially at low K levels (see Table 2.3). Other work confirms the positive response of sugar beet to Na (El-Sheikh & Ulrich, 1970; Hamid & Talibudeen, 1976) and shows that both red table beet and fodder beet (also varieties of *Beta vulgaris*) respond in a similar way (Harmer & Benne, 1941; Lehr, 1951).

Table 2.3. Response of sugar beet sugar yield ( $\text{Mg ha}^{-1}$ ) to Na in 101 field experiments conducted on mineral soils (after Durrant *et al.*, 1974).

K treatment	Group of experiments	No. of trials	Applied Na ( $\text{kg ha}^{-1}$ )				Pooled S.E.
			100	150	200	250	
Without K	Series II	17	+0.62				-
	Series IV	42	+0.57		+1.56		$\pm 0.054$
100-168 $\text{kg K ha}^{-1}$	Series II	17	+0.28				-
	Series IV	42	+0.39				$\pm 0.054$
	Series V	19		+0.43			$\pm 0.043$
	Series VI	23				+0.07	$\pm 0.064$
252 $\text{kg K ha}^{-1}$	Series IV	42	+0.21				$\pm 0.054$

Other root crops (turnip, mangel, radish) also respond to Na fertilizers (Table 2.2) and Lehr (1951) supplied supporting evidence for turnips. Of the other crops in Groups 3 and 4 of Table 2.2, celery responded positively to Na in trials carried out by other workers (Truog *et al.*, 1953; Mercik *et al.*, 1976), as have cabbage and kale (Bolton & Penny, 1968; Costigan & Mead, 1987), confirming the assessments of Harmer *et al.* (1953) given in Table 2.2. As a group, brassica crops, generally, appear to be fairly responsive to applications of Na.

For cereals, however, results are less consistent. The placement of oats in the group of plants responding to Na only under conditions of K-deficiency is supported by the work of Lehr (1953) and Wehunt & Collins (1953), but with barley, Bolton & Penny (1968) observed no response to Na despite the results of Lehr & Wybenga (1958) which supported the assessment of Harmer *et al.* (1953) who place it in Group 2 (Table 2.2). Maize is generally regarded as being a crop which does not show a positive response to Na, despite the small response to Na obtained in pots by Cope *et al.* (1953). Smith *et al.* (1978) classified maize and sorghum as natrophobes, meaning that they translocate very little Na to their shoots, which precludes the possibility of significant substitution of K by Na.

The legumes also vary considerably with respect to their response to Na. White clover is recognised as a sodium-accumulator (Smith *et al.*, 1978), and the results of Mundy (1983) support its placement in Group 2. Lucerne translocates little Na to its leaves (classing it as a

natrophobe), but may accumulate it in the stems (Smith *et al.*, 1978). Cope *et al.* (1953), Truog *et al.* (1953), and Montasir *et al.* (1966) all found that Na resulted in slight lucerne yield increases when low K-supply was probably limiting growth. On the other hand, no positive responses of beans or soybeans to Na are known (Table 2.2).

Several other crops have shown inconsistent responses to Na. The classification of spinach as showing little response to Na can be questioned following the responses to Na shown by Lehr (1949) and Montasir *et al.* (1966); potato is another Group 1 crop which has been known to respond to Na (Verona & Benvenuti, 1953). Although the results of Woolley (1957) support the placing of tomato in Group 2 by Harmer *et al.* (1953), the variation of response to Na between different tomato varieties (Gerloff, 1976), indicates that genotypic variation may explain inconsistencies found with other crops. Sugar beet, red beet, celery and peas also show considerable genotypic variation with respect to their response to Na (Harmer *et al.*, 1953; Draycott & Russell, 1974; Gerloff, 1976; Marschner *et al.*, 1981).

Forage grasses were not considered by Harmer *et al.* (1953), but many of them show marked negative interactions between the effects of Na and K on yield. Figure 2.1 shows the dramatic effect Na has on the K-requirement of Rhodes grass (*Chloris gayana*). Similar results were obtained by Mundy (1983) with perennial ryegrass (*Lolium perenne*), by Nowakowski *et al.* (1974) with Italian ryegrass (*Lolium multiflorum*), and by Gammon (1953) with pangola grass (*Digitaria decumbens*). Bermuda grass (*Cynodon dactylon*) and Star grass (*Cynodon plectostachys*) responded positively to moderate salinity levels (Langdale & Thomas, 1971; Langdale *et al.*, 1973) and so they may also respond positively to Na under conditions of low soil Na and K. Grasses which show a low capacity to translocate Na to the shoots (natrophobes), and are therefore unlikely to show significant responses to Na include kikuyu, *Paspalum dilitatum* and *Eragrostis curvula* (Gammon, 1953; Smith *et al.*, 1978).



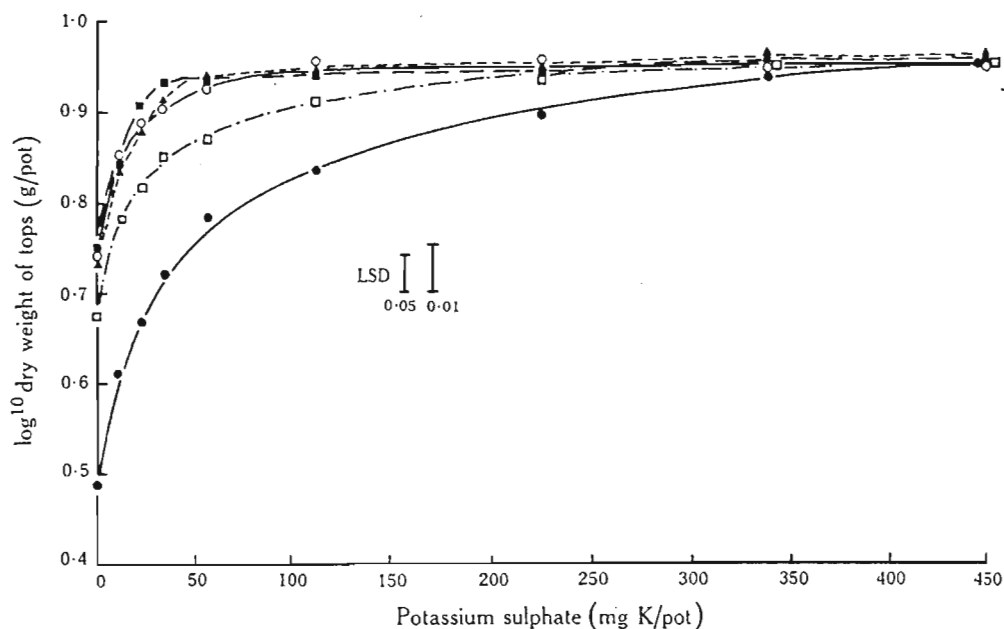


Figure 2.1. The effect of applications of potassium sulphate and sodium sulphate on the dry matter yields of Rhodes grass. Sodium sulphate applications ( $\text{mg kg}^{-1}$  soil): ● 0; □ 33.5; ○ 66.5; ▲ 100; ■ 200 (Smith, 1974).

Cotton is a crop not considered by Harmer *et al.* (1953) which has been shown to benefit considerably from Na under field conditions (Cooper *et al.*, 1953; Lancaster *et al.*, 1953; Marshall & Sturgis, 1953). Joham (1955), using a nutrient culture technique, found that boll yield was increased by Na when either K or Ca were deficient.

As most of the above results were obtained with crops grown in soil (either in field or pot trials), it is difficult to separate the direct effects of Na on plant growth from possible secondary effects. These may include enhanced availability of K from the soil (Flowers & Läuchli, 1983), enhanced availability of soil phosphate (Ryden & Syers, 1975; Barrow & Shaw, 1979), and higher soil solution pH (Raupach, 1951; Gupta *et al.*, 1981; Baker *et al.*, 1983). As a result it is necessary to discuss Na effects on plant physiology separately from these soil effects.

### 2.1.3 Sodium in plant physiology

#### 2.1.3.1 *Sodium and potassium nutrition*

The most obvious effect of Na on plant metabolism is its K-sparing action. In many plants minimum tissue-K levels required for optimum plant growth are lower if the tissue contains Na. Flowers & Läuchli (1983) and Leigh & Wyn Jones (1984) consider it probable that Na substitutes for K in certain roles in the plant, but is unable to replace it in others. Plants may utilize Na in the process of osmotic adjustment, the maintenance of plant turgor (through the replacement of vacuolar K) and the transport of plant metabolites. Functions of which Na is not likely to be capable probably include activation of certain enzymes, involvement in protein and chlorophyll synthesis, and turgor regulation of stomatal guard cells (Flowers & Läuchli, 1983; Leigh & Wyn Jones, 1984).

Critical leaf K concentrations for attainment of 90% yield in Italian ryegrass decreased from 35 g kg<sup>-1</sup> to 8 g kg<sup>-1</sup> with an increase in Na concentration in nutrient solution (Hylton *et al.*, 1967). Figure 2.2 shows a similar result for perennial ryegrass (Mundy, 1983). The effect on the K-requirement of Rhodes grass (Smith, 1974) is shown in Figure 2.3 where the K-content in plant tops required for 95% yield decreased from almost 30 g kg<sup>-1</sup> to 5 g kg<sup>-1</sup> when at least 66.5 mg Na<sub>2</sub>SO<sub>4</sub> kg<sup>-1</sup> was added. Costigan & Mead (1987) determined critical leaf K concentrations required for maximum growth of cabbage and lettuce seedlings (up to 14 days old), and found that the presence of Na decreased critical leaf K from 22 g kg<sup>-1</sup> to zero in cabbage and from 43 g kg<sup>-1</sup> to 10 g kg<sup>-1</sup> in lettuce. For tomato, Besford (1978) found that increased Na concentrations in solution culture increased Na uptake and decreased the concentration of K required in the leaves to prevent severe K-deficiency symptoms.

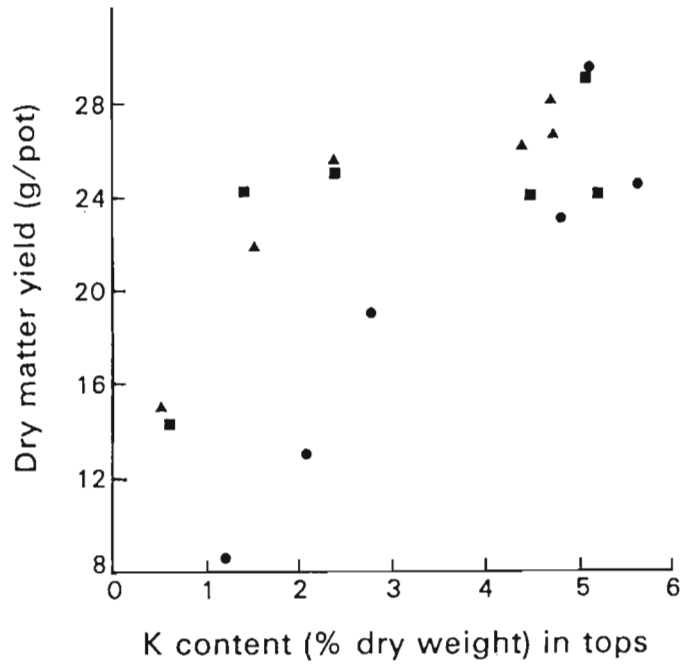


Figure 2.2. The relationship between dry matter yield and K concentration in the tops of ryegrass grown in sand culture. Concentration of Na applications (mM): ● 0; ■ 5; ▲ 15 (Mundy, 1983).

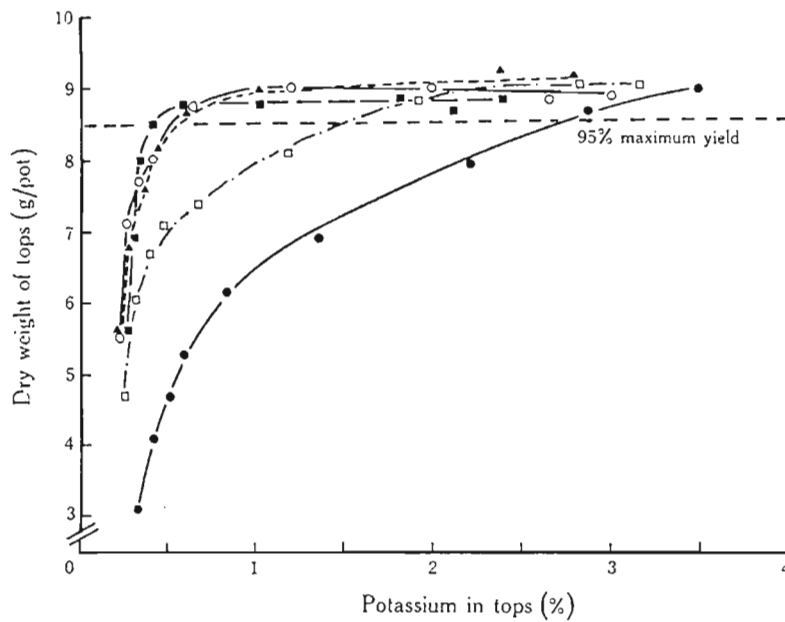


Figure 2.3. The effect of application of potassium sulphate and sodium sulphate on the relationship between dry matter yield and potassium concentration in the tops of Rhodes grass grown in pots. Sodium sulphate applications (mg kg<sup>-1</sup> soil): ● 0; □ 33.5; ○ 66.5; ▲ 100; ■ 200 (Smith, 1974).

Some plants, including barley, wheat and rye, exhibit efficient  $K^+$ - $Na^+$  exchange at the root cortex (Jeschke, 1984). This may be the reason for the increased leaf-K concentrations observed in some plants in response to increased Na. Schultz *et al.* (1979) observed higher K levels in the herbage of clover and lucerne grown in pots with extra Na, which under certain conditions also increased yield. Lessani & Marschner (1978) presented results that show an increase in K-uptake by maize due to the presence of NaCl in the nutrient medium, and ap Griffith & Walters (1966) found that the K content of *Phleum pratense* and *Lolium perenne* roots was increased by  $Na_2SO_4$  applications to their nutrient media when nitrogen supply [applied as  $(NH_4)_2SO_4$ ] was low.

### 2.1.3.2 *Sodium and aluminium toxicity*

Kinraide & Parker (1987) and Ryan *et al.* (1994) showed that Al toxicity in wheat could be alleviated and root elongation promoted by the addition of  $Na^+$  ions to nutrient solutions. Carr *et al.* (1991) and Carr & Ritchie (1993) found that the ratio of the concentration of Al to Na in 0.005 M KCl extracts was correlated with the incidence of Al toxicity in wheat over 53 field experiments in Western Australia. They found that this index was superior to Al concentration alone when comparing responses at different sites and in different seasons.

Tadano & Gotoh (1995) also found that Na modified the reponse of crop plants to Al in solution culture. They found that the growth of maize at 2 mM Na was decreased by Al, but Al did not affect growth at 100 mM Na. With rice, growth was not affected by Al at 2 mM Na, but was improved by Al at 100 mM Na.

### 2.1.3.3 *Cation-anion balance in plants*

Plants that accumulate more cations than anions (other than  $H^+$  and  $OH^-$ ) which are usually those that take up little  $NO_3^-$ , are known to acidify their rhizospheres, and the uptake of K via an energy-dependent exchange for  $H^+$  is probably a major factor contributing to this effect (Leonard, 1985). On the other hand, many plant species which take up Na can excrete  $Na^+$  in exchange for  $H^+$ , thus reducing the acidifying effect (or intensifying an increase in pH in cases where anion uptake exceeds cation uptake). Results consistent with this mechanism include those of Cunningham (1964), who showed that the cation-anion balance was shifted in favour of anion

uptake in Italian ryegrass containing substantial Na, and those of Jarvis & Hopper (1981) who found that when perennial ryegrass was grown in nutrient solution, more acid was required to maintain the pH of the solution if that solution contained Na. This Na<sup>+</sup> efflux in exchange for H<sup>+</sup> may be important in plants which are known to acidify their rhizospheres (such as legumes which utilize "fixed" atmospheric N<sub>2</sub>) as it may be necessary to prevent a rise in cytoplasmic pH (Skulachev, 1978, cited by Wyn Jones & Pollard, 1983).

#### 2.1.3.4 *Carbohydrate metabolism*

In sugar beet, Na has effects beyond those attributable to simple substitution for K; applications of Na are known to increase leaf sucrose levels and improve translocation of sucrose to the root. This may be the result of decreased starch synthesis in the leaf due to inhibition of the enzyme starch synthase, which is stimulated more by K than by Na (Hawker *et al.*, 1974).

In maize and bean leaves, and carrot and radish roots, the activity of acid invertase, an enzyme involved in the breakdown of sucrose, has also been found to be reduced by Na, resulting in higher sucrose levels (Ricardo & Sovia, 1974; Hawker & Walker, 1978). Italian ryegrass and flax are other plants that are known to increase their sucrose contents in response to Na (Moskolov & Aleksandrovskaya, 1962, cited by El-Sheikh & Ulrich, 1970; Nowakowski *et al.*, 1974) and improved quality of tomato fruit due to higher total soluble solids (mainly sugars) and higher total acidity was found to result from NaCl applications (Mizrahi & Pasternak, 1985).

The improved palatability of grasses associated with Na applications (Finck, 1982, p.335; Poeschel, 1987, cited by Horn, 1988) may be a result of increased sucrose levels. As improved palatability improves feed uptake and thus weight gain in cattle, this could make applications of Na particularly beneficial on pastures.

Transport of carbohydrates can also be increased by Na. Joham & Johanson (1973) showed that translocation of sucrose in excised cotton roots was stimulated by Na if Ca was deficient. The K-sparing action of Na taken up by other plants could include substitution for K involved in carbohydrate translocation, where the latter is known to play an important role (Marschner, 1971).

In spinach, Na may enhance carbohydrate translocation more than K and Hawker *et al.* (1974) found that replacement of K by Na resulted in preferential root growth at the expense of shoot growth in three-week-old plants. They suggest that under field conditions, improved rooting could result in increased yields due to better water and nutrient uptake. Other workers have shown that Na can increase spinach yield (Lehr, 1953; Montasir *et al.*, 1966).

#### 2.1.3.5 *Water relations*

Improved root growth with Na applications was also observed in lucerne (Cope *et al.*, 1953) and in cotton (Johanson & Joham, 1971), but Na may also improve plant water relations due to the osmotic effects of higher levels of Na and sucrose. Plants can improve their water retention by increasing the level of osmotically active solutes in their cells (Mengel & Kirkby, 1987, pp.199-200, 228-229), i.e., Na<sup>+</sup> can be used in vacuoles, and sucrose in the cytoplasm. This may explain why Na can increase succulence in certain halophytes (Jennings, 1968, 1976), as cell expansion is known to have "large requirements for osmotic solutes" (Greenway & Munns, 1980).

With regard to the water relations of sugar beet, increased cell volume is the primary response to Na (Marschner & Possingham, 1975), as leaf water osmotic and turgor potentials are not significantly changed (Milford *et al.*, 1977). Improved yields of sugar beet under conditions of moderate water stress in both field trials (Durrant *et al.*, 1978) and pot trials (Milford *et al.*, 1977) were accounted for by an increased tolerance of water loss due to the higher water contents of the leaves. Hamid & Talibudeen (1976) showed that for both barley and sugar beet grown in pots, NaCl applications increased dry matter yields and decreased the transpiration coefficient (water used g<sup>-1</sup> dry matter), but for beans NaCl lowered both yield and water use efficiency. Harmer & Benne (1945) observed that in celery, Na increased yield and decreased wilting, resulting in a crisper, more marketable product.

#### 2.1.3.6 *Nitrogen metabolism*

Hylton *et al.* (1967) showed uptake of NO<sub>3</sub>-N by Italian ryegrass to be accelerated by both Na and K in solution, and they suggested that the cations are therefore likely to be important in N-nutrition. Smith *et al.* (1980) obtained similar results with perennial ryegrass; both NO<sub>3</sub>-N and

total N were increased by Na (Table 2.4). Nitrate reductase activity was also increased by Na, but this was attributed to the higher  $\text{NO}_3\text{-N}$ . On the other hand, Nowakowski *et al.* (1974) found that the N concentration in Italian ryegrass was lower when Na and K levels were high, but they attributed this to a dilution effect due to the increased yields obtained in the Na and K treatments. They found, however, that Na and K reduced the proportion of N found as non-protein N, including  $\text{NO}_3^-$  and  $\text{NH}_4^+$ , and increased the proportion of protein N.

Table 2.4. Effect of sodium chloride on dry matter yield of leaves and  $\text{NO}_3\text{-N}$  and total N in leaves of perennial ryegrass grown in a sand culture medium (after Smith *et al.*, 1980).

Concentration of NaCl (mM)	Dry-matter yield <sup>1</sup>	$\text{NO}_3\text{-N}$ <sup>2</sup> (ppm)	Total N <sup>2</sup> (%)
1.0	9.7	725	4.11
4.0	9.8	740	4.12
7.0	9.9	825	4.36
10.0	9.6	1000	4.35
13.0	8.4	1275	4.66
LSD <sub>0.05</sub>	0.6	119	0.31

<sup>1</sup> Cumulative total over four cuts (g per pot)

<sup>2</sup> Mean values of four cuts (expressed on a dry matter basis)

Further indications of the involvement of Na in N-nutrition are the increased N concentrations in barley, Bermuda grass and Star grass under conditions of induced salinity stress, which appeared to stimulate protein production (Langdale & Thomas, 1971; Langdale *et al.*, 1973; Helal *et al.*, 1975). Protein content was also increased by Na in cotton leaves under conditions of K-deficiency (Joham & Amin, 1965; Amin & Joham, 1968).

The role of Na in plant metabolism is therefore far from simple, and the many interactions with other factors in plant growth, make its effects difficult to predict. There are, however, certain situations where application of Na as a fertilizer may have advantages and because cultivated pastures are becoming increasingly important on acid, low-Na soils in KwaZulu-Natal, pasture quality aspects related to Na will be discussed in more detail.

### 2.1.4 Pasture quality

Improved animal production per hectare on pastures is not only a function of the yield of fodder produced, but also of the quality of that fodder. In Figure 2.4, which shows ways that pasture quality can influence animal performance, the most obvious effect of Na applications to ryegrass pastures (for example) would be on their chemical composition. For example, Nowakowski *et al.* (1974) have shown how plant carbohydrates, protein, and Na and K levels can all be manipulated through adjustment of Na and K fertilization without dramatically influencing yields.

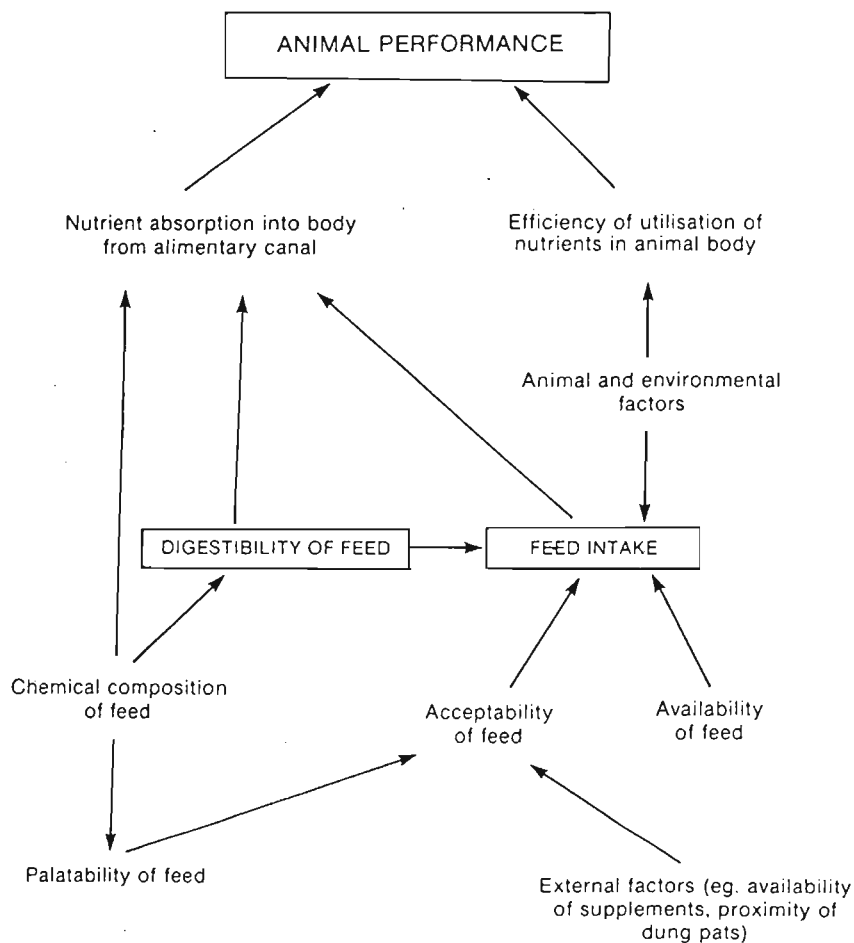


Figure 2.4. A scheme showing the relationship between different variables which influence animal performance (Bransby, 1981).

#### 2.1.4.1 *Sodium nutrition of ruminants*

Although Na is not an essential element for many plants, it is essential for animals, and sheep and cattle fed with fodder low in Na have been shown to respond to Na supplementation (Joyce & Brunswick, 1975; Archer & Wheeler, 1978; Standing Committee on Agriculture: Ruminants



Subcommittee, 1990, p. 172). Smith & Middleton (1978) calculated that the Na content of pasture plants ( $\text{g kg}^{-1}$  on a dry matter basis) should exceed 0.7 for sheep, 1.0 for beef cattle and 2.0 for lactating dairy cows, to prevent Na deficiencies in situations where no Na supplementation occurs. If the pasture species used was a natrophobe such as lucerne, sorghum or kikuyu, attainment of these levels would not be practically feasible (Smith *et al.*, 1978) and Na supplementation would be necessary, but species such as ryegrass and white clover can be fertilized with Na to ensure adequate levels of the element in the plant.

Sodium supplementation is an alternative to the use of Na as a fertilizer, but fertilization of pastures would overcome the problem of variable intake associated with the use of salt licks or the addition of Na to drinking water (Sherrell, 1984; Beringer, 1988).

#### 2.1.4.2 *Effects of replacing plant potassium with sodium*

The substitution of Na for K in certain pastures could also be used to advantage. High levels of K in pastures have been associated with low Mg absorption by the rumen which leads to hypomagnesemia (grass tetany) and decreased herd fertility (Martens & Blume, 1986; Beringer, 1988). Hypomagnesemia is a problem on Italian ryegrass pastures in Natal (Miles *et al.*, 1986), and as fertilization with Na has been shown to lower the plant K concentration required for maximum yields of this grass it is possible that such a strategy may help in the alleviation of this problem (Cushnahan *et al.*, 1995). One should note, however, that fertilization with Na may not decrease plant uptake of K from soils with high levels of that element (Nowakowski *et al.*, 1974). It has also been suggested that the incidence of bloat may be related to the Na content of pastures and that a lower K:Na ratio in forage may contribute to the alleviation of bloat (Turner, 1981), but more recent work does not support this suggestion (Carruthers *et al.*, 1988).

Chiy *et al.* (1993) found that cows grazing a perennial ryegrass pasture amended with Na fertilizer gained more live weight and produced more milk and milk fat than those grazing a pasture with no added Na fertilizer. Fertilization with Na was found to increase herbage Na concentrations, decrease herbage K concentrations, and increase grazing and drinking times (Chiy & Phillips, 1993; Chiy *et al.*, 1993; Phillips *et al.*, 1999). Poeschel (1987, cited by Horn, 1988) also found that Na can improve the palatability of grass and thus increase food uptake and weight gains of

heifers and lactating cows. However, not all studies have found that Na fertilization improves cow production as Cushnahan *et al.* (1996) found that herbage intake, milk yield, milk fat concentration, and live weight were not affected by Na fertilization.

The use of Na as a substitute for K on ryegrass pastures on low-Na soils may significantly reduce fertilizer costs. Optimum yields on low-Na soils often require plant K levels of  $30 \text{ g kg}^{-1}$ , so that a high-producing ryegrass pasture may use  $400 \text{ kg K ha}^{-1}$  in a season. If a 50% return of K to the pasture through the animal is assumed, the annual K requirement could be as high as  $200 \text{ kg ha}^{-1}$  (N. Miles, personal communication, 1988). As the presence of more Na in the soil could halve the amount of K required in the plant (Mundy, 1983; Figure 2.2), annual K inputs may be reduced by as much as  $100 \text{ kg ha}^{-1}$ , which would make an appreciable difference to the profitability of the animal enterprise.

As mentioned earlier, plant effects are, however, not the only likely consequences of Na applications to soils, and in the following section, reports on the chemical effects of moderate Na applications to low-Na soils are discussed.

## 2.2 SOIL EFFECTS OF SODIUM

### 2.2.1 Sodium and cation exchange

Cation exchange surfaces in soils have a low affinity for Na relative to the other important exchangeable cations (Ca, Mg, K and Al). As a consequence of this, even if exchangeable Na levels in soils are relatively low, Na is often the dominant cation in the soil solution. Menzies *et al.* (1994) found that, for a set of 60 acid Australian soils, Na generally dominated the soil solution cations, despite fairly low levels of exchangeable Na (in topsoils, mean and median exchangeable Na were  $0.14 \text{ cmol}_c \text{ kg}^{-1}$  and  $0.08 \text{ cmol}_c \text{ kg}^{-1}$  respectively; and mean and median CEC were  $5.91 \text{ cmol}_c \text{ kg}^{-1}$  and  $4.36 \text{ cmol}_c \text{ kg}^{-1}$  respectively). As a result, for a particular anion concentration in solution and at exchangeable sodium percentages (ESP) of less than about three, a soil with more exchangeable Na is likely to have lower solution levels of Ca, Mg, K and Al. Such a soil is also likely to have a higher soil solution pH (Raupach, 1951; Gupta *et al.*, 1981;

Baker *et al.*, 1983). Other data of (M. Buyeye, personal communication, 1986) indicated that, for a range of salt concentrations, the pH of NaCl suspensions of an acid KwaZulu-Natal subsoil were significantly higher than for the equivalent KCl suspensions.

Another consequence of the cation exchange reactions involving Na is their effect on the measurement of pH buffer capacity (pHBC) as highlighted by Aitken & Moody (1994). They showed that when soil suspensions were titrated with equivalent concentrations of NaOH and  $\text{Ca(OH)}_2$ , pH values with NaOH were significantly higher than those with  $\text{Ca(OH)}_2$ . On average, pHBC determined with  $\text{Ca(OH)}_2$  was 2.2 times the pHBC with NaOH. The effect of Na is also likely to be marked in other cation exchange systems, such as that used in the "resin suspension" method of lime evaluation (Bornman *et al.*, 1988) which has become popular in South Africa recently. Using this method, the reaction of equivalent amounts of  $\text{Na}_2\text{CO}_3$  and  $\text{CaCO}_3$  with the acid resin suspension would probably result in a higher pH in the case of  $\text{Na}_2\text{CO}_3$ , resulting in a more favourable evaluation per unit carbonate reacted.

Although K levels in the soil solution are less affected by Na than those of Al, Ca and Mg, lower solution K levels induced by the presence of Na may adversely affect plant uptake of K. The step that probably limits the rate of K uptake is the diffusion of that ion through the soil to the root, and assuming this takes place only in the soil solution, low soil solution K is likely to depress plant uptake of K (Barber, 1985). However, Graham-Bryce (1965) showed that K-diffusion probably also occurs within the exchange phase, which would make K uptake less sensitive to its concentration in the soil solution than is suggested by Barber (1985).

Cope *et al.* (1953) drew attention to a positive effect of Na on K availability. They showed that NaCl applications to soil in pots enhanced the release of non-exchangeable K. This may occur as a result of either a lower soil solution concentration of K (Sparks & Huang, 1985) or by the ability of the highly hydrated  $\text{Na}^+$  ion to reverse collapse of the layers of 2:1 aluminosilicate clays.

### **2.2.2 Solubility of soil phosphate**

Sodium has been shown to enhance the solubility of phosphate sorbed by the soil after application in soluble forms. Lehr & van Wesemael (1952) studied phosphorus (P) desorption from a range

of Dutch soils equilibrated with 0.005 N to 0.05 N  $\text{NaNO}_3$  and  $\text{Ca}(\text{NO}_3)_2$  solutions. They found that increasing ionic strength depressed the solubility of P, and that  $\text{Ca}(\text{NO}_3)_2$  resulted in a greater depression than  $\text{NaNO}_3$ . These authors explained their results in terms of the solution effects on Ca concentration, which in turn affected the solubility of calcium phosphates.

Helyar *et al.* (1976a,b) obtained similar results in adsorption studies using gibbsite. At the same pH, Na, K and Mg in the equilibrating solution all had similar effects on the amount of P sorbed, whereas Ca (and other divalent cations of similar size) increased the amount of P sorbed on gibbsite surfaces. They attributed this result to the formation of a complex of phosphate with the divalent ions on the gibbsite surface. They suggested that the different effects of K, Mg and Na salts found in soils could be attributed to the variation in their ability to displace exchangeable Ca into the soil solution.

Ryden & Syers (1975), by contrast, found that the cation and ionic strength effects on P-sorption appeared to be mainly kinetic, with all treatments tending towards a similar P-fixation with time. This appears to rule out the possibility that precipitation or dissolution of stable Ca-P compounds or complexes control solution P levels as equilibrium is approached. They therefore favoured an explanation, supported by Barrow & Shaw (1979) in which the charge of the adsorption surface plays a role. Barrow & Shaw (1979) studied desorption of soil phosphate and also found that the rate of this reaction varied depending on whether Ca, Mg, K or Na was the dominant cation in solution (Figure 2.5). The more rapid desorption of P in the Na system was attributed to the inability of the  $\text{Na}^+$  ions to approach the negatively charged surface as closely as the other cations, so inducing a larger negative potential at that surface.

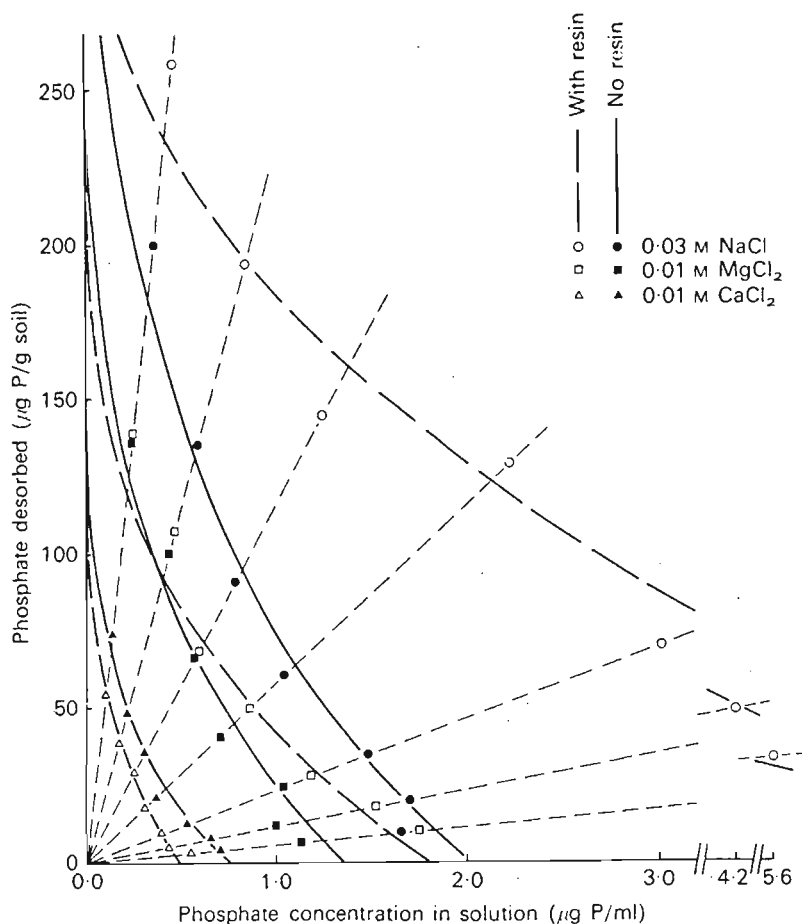


Figure 2.5. Desorption of phosphate after 96 h, and at seven solution:soil ratios, by 0.03 M NaCl, 0.01 M MgCl<sub>2</sub> or 0.01 M CaCl<sub>2</sub>. The radiating dashed lines represent the following solution:soil ratios in anticlockwise sequence: 6, 12, 24, 60, 120, 240 and 600. The broken lines and open symbols indicate treatments which included cation exchange resin previously equilibrated with the appropriate solution (Barrow & Shaw, 1979).

### 2.2.3 Plant uptake of phosphate

Although a predominance of Na in the soil solution may improve phosphate solubility, it may also adversely affect plant uptake of phosphorus because negatively charged cation exchange sites in the apoplasm (free space) of plant roots are unlikely to be as well "screened" as they would be if Ca was the dominant cation in the soil solution (Haynes, 1980). The importance of solution Ca in P-uptake was demonstrated by Robson *et al.* (1970), who showed (using a flowing solution culture experiment with *Medicago truncatula* and *Medicago tornata*) that an increase in Ca concentration from 0.25 to 2.5 mM increased plant uptake of solution P by between 21 and 49% at a P concentration of 0.2 µM. Phosphorus concentrations in plant tissues were increased by

between 11 and 21%.

The overall effect of applied Na on the plant availability of P in soil is therefore difficult to predict, but Lehr & van Wesemael (1956) did find that summer wheat grown in certain soils was able to take up more phosphate from a  $\text{NaNO}_3$ -treated soil than from one treated with  $\text{Ca}(\text{NO}_3)_2$ . However, increases in P-uptake were obtained on soils with higher P-levels and of a higher pH (greater than five) than are generally found in acid, low-Na, South African soils, and most of the P-sorption studies mentioned in the previous section were also done using less acid soils, making further research necessary before an assessment of the possible Na effects on phosphorus use in South Africa can be made.

The observation that the presence of Na can modify the relationship between ionic strength and pH led to a hypothesis explored in this thesis that additions of relatively small amounts of Na to acid, low-Na soils may increase soil pH and decrease levels of phytotoxic Al, thereby ameliorating the effects of soil acidity on crop growth. The possible effect of Na in highly acid subsoils, which are expensive to ameliorate (Farina & Channon, 1988a; Shainberg *et al.*, 1989; Farina, 1997), appeared to present particularly attractive possibilities. The experiments discussed in the following chapters were designed to investigate the effects of Na on soil acidity and crop growth, as well as the potential for the use of Na as a replacement for K fertilizer in Italian ryegrass.

### 3. CATION TYPE AND IONIC STRENGTH EFFECTS ON THE SOLUTION COMPOSITION OF AN ACIDIC SUBSOIL

#### 3.1 INTRODUCTION

The effect of changing soil solution ionic strength on solution pH is well documented (Schofield & Taylor, 1955; Russell, 1961, p.104) and is particularly relevant to the study of highly leached, acid soils in which even moderate applications of fertilizer salts can be expected to produce large relative increases in ionic strength with a commensurate suppression of soil solution pH and increased phytotoxicity of Al (Friesen *et al.*, 1980).

At any particular ionic strength, the nature of the electrolyte can be expected to influence soil solution pH according to a lyotropic series which depends on ion valence and size. For a soil with a particular quantity of exchangeable acidity, a soil solution containing a high proportion of a weakly adsorbed ion like  $\text{Na}^+$  should have a higher pH than one with a larger proportion of the more strongly adsorbed ions such as  $\text{Ca}^{2+}$ . While evidence for this has been documented for near-neutral to alkaline soils (Raupach, 1951; Gupta *et al.*, 1981; Baker *et al.*, 1983), little attention has been paid to the same effect in acid soils and its possible implications.

A large proportion of the high-potential soils available for dryland cropping in both South Africa and the rest of the world have strongly acidic subsoil horizons which restrict root development and crop yield (Farina & Channon, 1988a; Shainberg *et al.*, 1989; Farina, 1997). Although gypsum application offers an economically viable means of amelioration in many situations, high rates of application (greater than 5 000 kg ha<sup>-1</sup>) and hence considerable capital outlay are often necessary (Shainberg *et al.*, 1989). In these soils, the manipulation of soil solution ionic strength and Na levels, and thereby pH and aluminium solubility, may offer low-cost alternatives to gypsum or deep liming as means of alleviating subsoil acidity.

This chapter reports on a comparison of the effects of different salts (Na, K, Ca and Mg chlorides) on the solution composition of an acid subsoil, at ionic strengths which are likely to be encountered under field conditions.

### 3.2 MATERIALS AND METHODS

The B21 horizon (200 to 400 mm) of a clay loam of the Pinedene form, Goudini family (Soil Classification Working Group, 1991), an Aquic Hapludox (Soil Survey Staff, 1990), was sampled near Geluksburg (28°31'S and 29°21'E) in northern KwaZulu-Natal, South Africa. Some of the properties of this highly weathered subsoil are listed in Table 3.1. From the exchangeable cation data, it is apparent that it is strongly acidic, with acid cations ( $\text{Al}^{3+}$  and  $\text{H}^+$ ) making up over two-thirds of the effective cation exchange capacity. The sampling site supports a wide range of soil acidity-related field trials with maize and is well documented elsewhere (Mendes *et al.*, 1985; Farina & Channon, 1988a).

Table 3.1. Selected properties of the Pinedene subsoil used.

Clay ( $\text{g kg}^{-1}$ )	415
Organic C ( $\text{g kg}^{-1}$ )	8.0
Clay minerals <sup>1</sup>	
kaolinite	50-75%
mixed-layer 14Å/10Å clays	25-50%
illite	10-25%
vermiculite, goethite, gibbsite, quartz	Trace
haematite	Possible (trace)
Exchangeable cations <sup>2</sup> ( $\text{cmol}_c \text{ kg}^{-1}$ )	
Ca	0.65
Mg	0.34
K	0.17
Na	0.01
Al+H	2.55
Effective CEC (ECEC)	3.71
Acid saturation <sup>2</sup> (%)	69
pH (KCl)	4.16

<sup>1</sup>X-ray diffraction (J.C. Hughes, personal communication, 1999).

<sup>2</sup>Methods given in Appendix 1.



To 200 g subsamples of air-dried soil, 90 mL aliquots of the following solutions were added: distilled water as a control, and 0.4, 1.0, 4.0, and 10.0 mmol<sub>e</sub> L<sup>-1</sup> solutions of each of NaCl, KCl, MgCl<sub>2</sub> and CaCl<sub>2</sub>. These 17 treatments were duplicated, and then incubated at 25°C for four days.

Using an immiscible dense liquid displacement method (Kinniburgh & Miles, 1983), 20 to 30 mL of solution was separated from each soil sample. Supernatant pH was determined immediately using a Radiometer PHM 85 pH meter and "monomeric" aluminium (sum of Al<sup>3+</sup>, Al(OH)<sup>2+</sup>, Al(OH)<sub>2</sub><sup>+</sup>, and Al(OH)<sub>4</sub><sup>-</sup>) immediately thereafter by the 8-hydroxyquinoline method (Bloom *et al.*, 1979). Sodium, K, Mg and Ca were determined by atomic absorption flame spectroscopy, NH<sub>4</sub><sup>+</sup> by ammonia electrode after addition of NaOH, Cl<sup>-</sup> by potentiometric titration using a silver electrode, Si by colorimetry (Weaver *et al.*, 1968) and F with a fluoride electrode. Neither SO<sub>4</sub><sup>2-</sup> nor NO<sub>3</sub><sup>-</sup> could be detected using the methods of Hue & Adams (1979) and Cataldo *et al.* (1975), respectively. The activities of free ions in solution were computed using the Davies equation after speciation of metals and ligands by means of the GEOCHEM ion association model (Sposito & Mattigod, 1979, incorporating revisions up to March, 1986). The use of a revised version of GEOCHEM (Parker *et al.*, 1987) did not result in significantly different results for this data set. In the computation, soluble aluminium-fluoride complexes were excluded because the 8-hydroxyquinoline method used for aluminium detects only a very small fraction of these complexes (Hodges, 1987). Equilibrium constants used for the hydrolysis of Al<sup>3+</sup> to Al(OH)<sup>2+</sup> and Al(OH)<sub>2</sub><sup>+</sup> were those suggested by May *et al.* (1979).

### 3.3 RESULTS AND DISCUSSION

#### 3.3.1 Effect of cation type

Figure 3.1a shows that for each of the salts used, pH decreased as ionic strength increased. However, the addition of Ca, Mg and K chlorides resulted in a greater pH depression, than the addition of sodium chloride of equivalent concentration.

Aluminium concentration was also strongly related to electrolyte concentration and type of cation

in the soil solution (Figure 3.1b). Aluminium concentration was as low as  $5 \times 10^{-7} M$  in the control treatment (distilled water) and as high as  $10^{-4} M$  in the most concentrated Ca, Mg and K treatments.

Figure 3.2 shows the concentrations of the different cations in the soil solutions resulting from the different treatments. Calcium (II) and  $Mg^{2+}$  displace similar quantities of basic cations ( $Ca^{2+}$ ,  $Mg^{2+}$ ,  $K^+$  and  $Na^+$ ) and acidic cations ( $H^+$  and  $Al^{3+}$ ) from the exchange complex. It is also clear from Figure 3.2 that  $K^+$  displaces similar quantities of cations to those displaced by the divalent cations despite being monovalent, indicating that the commonly observed selectivity for  $K^+$  shown by soil clays (Goulding, 1983) is operative in this soil. Along with the low hydration energy of  $K^+$ , factors which may possibly contribute to the high selectivity for  $K^+$  of this soil are the presence of specific K-adsorption sites on siloxane surfaces of kaolinite and the influence of even more K-selective sites associated with the interstratified 2:1 clay minerals indicated in Table 3.1 (Jensen, 1973; Udo, 1978; Goulding, 1983).

The sodium ion, on the other hand, is both monovalent and strongly hydrated, and has a low affinity for charged surfaces. A larger proportion of the added  $Na^+$  ions therefore remains in the soil solution than is the case for the other cations (Figure 3.2). The varying effect of the different cations on the solution levels of  $NH_4^+$  is shown in Figure 3.3. Whereas K, Ca and Mg displace similar quantities of most exchangeable cations into the soil solution, in the case of  $NH_4^+$  it can be seen that  $K^+$  displaces more  $NH_4^+$  than even the divalent  $Ca^{2+}$  or  $Mg^{2+}$  ions. This feature can be attributed to the well known similarity in size and hydration energy of  $NH_4^+$  and  $K^+$ , and coincides with the generally held view (Bohn *et al.*, 1979, p152) concerning the similar specificity with which  $K^+$  and  $NH_4^+$  are held by phyllosilicate surfaces compared with other metal cations.

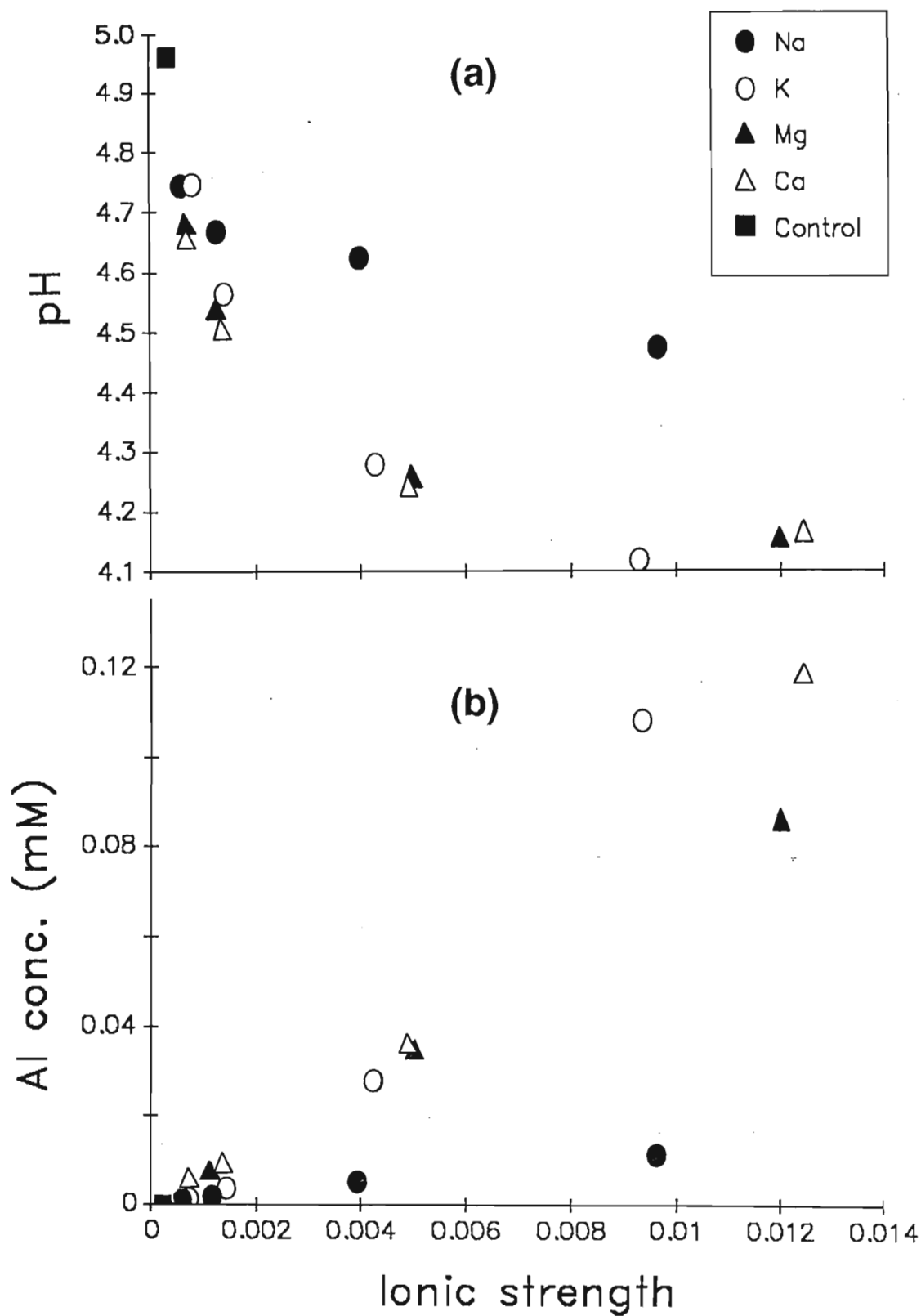


Figure 3.1. The relationships between ionic strength and (a) pH and (b) Al concentration in soil solution, after wetting soil with distilled water (control) or solutions of varying concentration of metal chlorides.

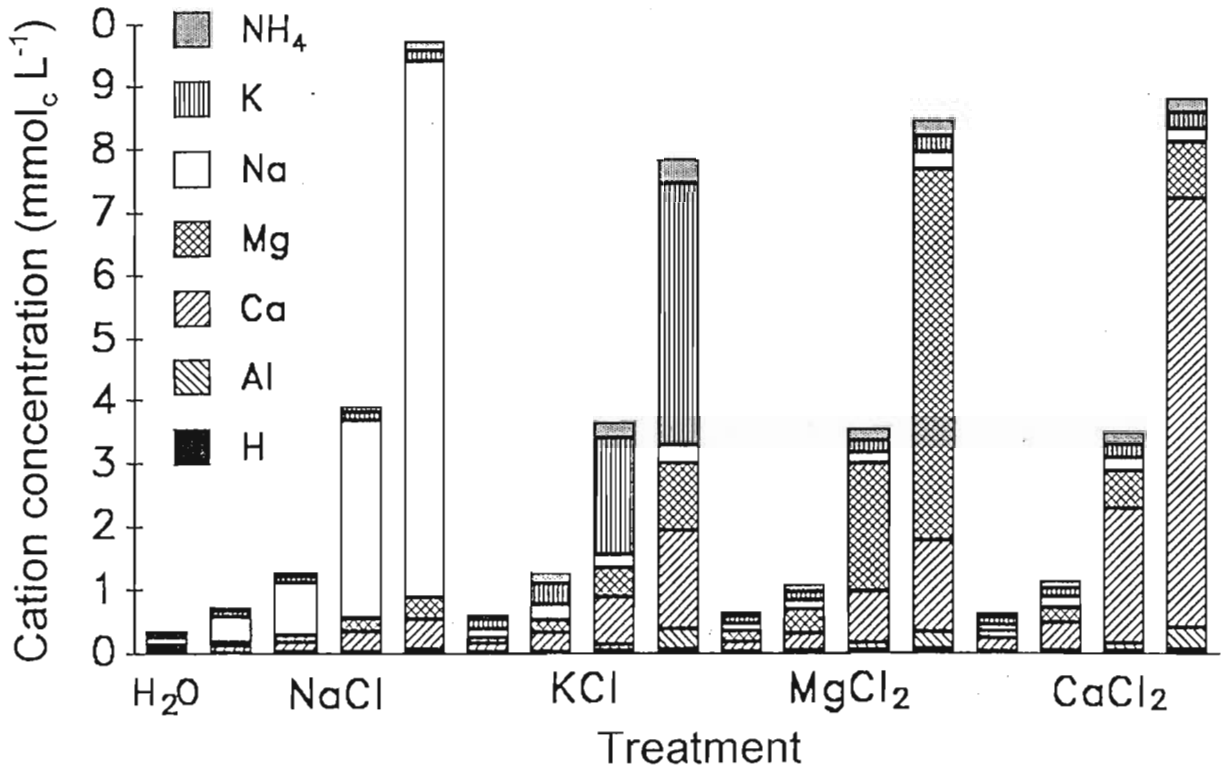


Figure 3.2. Equivalent concentrations of cations in soil solution after wetting soil with water or different salt solutions (the four bars for each salt correspond to initial concentrations of 0.4, 1, 4, and 10  $\text{mmol}_c \text{L}^{-1}$  from left to right).

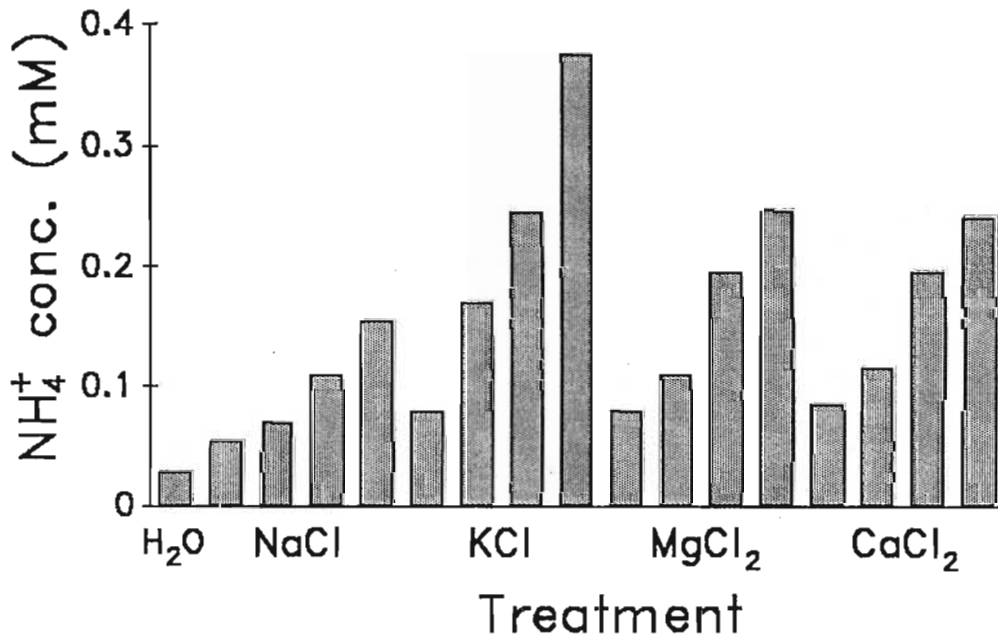


Figure 3.3. Ammonium concentrations in soil solution after wetting soil with water or different salt solutions (the four bars for each salt correspond to initial concentrations of 0.4, 1, 4, and 10  $\text{mmol}_c \text{L}^{-1}$  from left to right).

### 3.3.2 Aluminium solubility

Although the increase in Al solubility accompanying salt addition in Figure 3.1b could be accounted for by cation exchange, the near constancy of the aluminium hydroxide potential (Figure 3.4) suggests possible equilibration of the soil solution with gibbsite which is present in this soil (Table 3.1).

Since, however, the clay fraction is dominated by kaolinite (Table 3.1), the argument that solution Al levels are possibly controlled by dissolution of solid mineral phases would be incomplete without considering solution composition in relation to kaolinite solubility. In Figure 3.5 the solution composition points are seen to cluster closely around a point which would correspond to the intersection of the gibbsite solubility line with that of a kaolin having a solubility closer to that of halloysite than of a low defect kaolinite. (Undersaturation with respect to quartz is also suggested). The possibility that a metastable kaolin does influence the solution composition is reinforced by the X-ray diffraction data for this soil (Table 3.1) which showed kaolin reflections that are considerably broadened as well as shifted from the usual 0,72 nm (001) spacing to a value of about 0,74 nm, characteristic of a high-defect kaolin.

### 3.3.3 Possible implications for aluminium toxicity

The ionic strength effect reported here confirms an effect which, though known, is often overlooked, namely that a soil normally considered to be strongly acidic on the basis of measurements in 1 M KCl and other saline soil extracts may, in its virgin state, have a soil solution composition which would not normally be regarded as being sufficiently acidic to jeopardize the growth of many crop species. Percival *et al.* (1996) found this to be true for a set of 14 New Zealand subsoils. By contrast, these results show that the high ionic strengths which would result from high inputs of soluble fertilizers can generate detrimental levels of acidity. The soil solution pH may fall to a value close to that of the 1 M KCl soil pH (1:2.5 soil:solution) which is 4.1 in this case, and Al<sup>3+</sup> activity may increase to potentially toxic levels of greater than 10<sup>-5</sup> M.

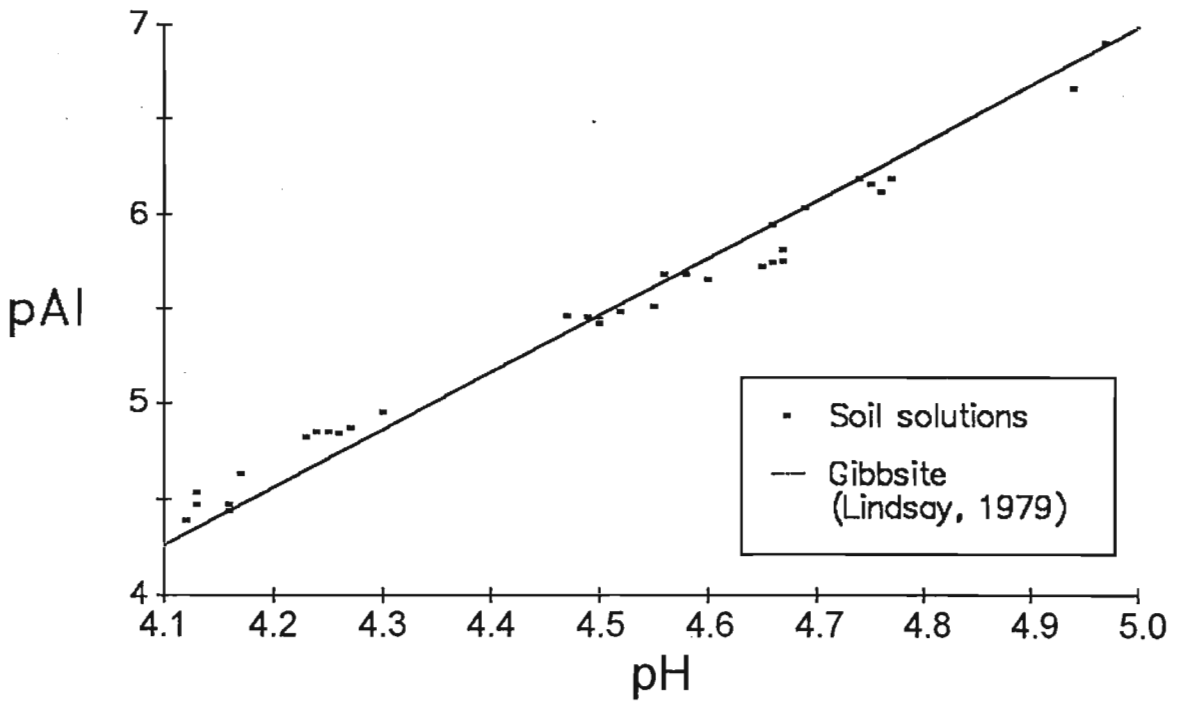


Figure 3.4. A plot of pAl ( $-\log[\text{Al}^{3+}]$  activity) against pH for the 34 soil solutions resulting from treatment with water and different salts. The solid line represents gibbsite equilibrium solubility (after Lindsay, 1979, p. 60).

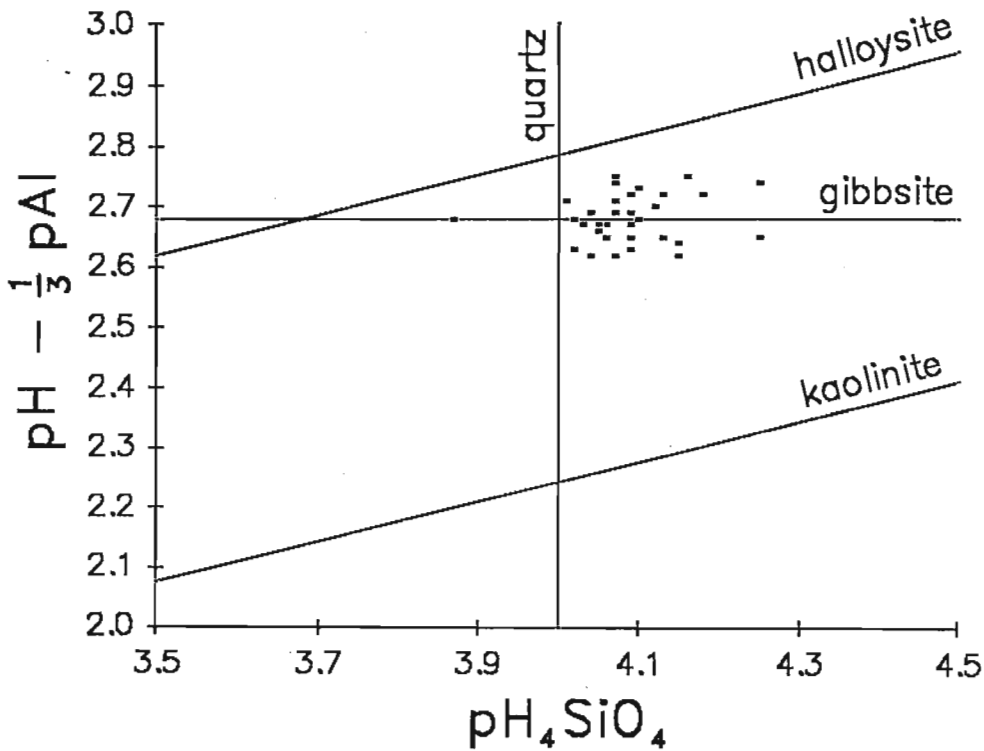


Figure 3.5. Aluminimum hydroxide potential ( $\text{pH} - \frac{1}{3} \text{pAl}$ ) plotted against silica potential ( $\text{pH}_4\text{SiO}_4$ ) for the 34 soil solutions. Solid lines reflect equilibrium solubilities of the indicated mineral species (after Lindsay, 1979, pp. 58-60).

The results also indicate that additions of low amounts of sodium (less than  $2 \text{ mmol}_c \text{ kg}^{-1}$ ) to low-sodium soils may contribute to the alleviation of acid soil toxicity. If, for example, the fertilizer chloride and nitrate leached into acid subsoils was accompanied mainly by sodium (applied as perhaps  $\text{Na}_2\text{CO}_3$  or  $\text{Na}_3\text{PO}_4$  to the topsoil) rather than  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$  (as would normally be the case), soil solution pH would be higher and may allow improved rooting.

The possible effects of such an approach were tested in a small pot trial using maize and white clover as test crops. Plants were established in 300 g of ameliorated topsoil placed in tubes above the acid subsoil that was used in the incubations described above, but which had been pretreated with NaCl and KCl solutions ( $10 \text{ mmol}_c \text{ L}^{-1}$ ). The plants were grown for three weeks in a glasshouse, with daily watering to field capacity. Clover roots penetrated the subsoils in both treatments with no observable differences between the two treatments, but differences in maize root penetration into the acid subsoil were striking (Figure 3.6).



Figure 3.6. Differences in maize root penetration into the acid subsoil pretreated with NaCl and KCl solutions ( $10 \text{ mmol}_c \text{ L}^{-1}$ ).

The differences observed in the pot trial prompted an unreplicated field trial at the Geluksburg site, and a positive response to NaCl treatments there led to the establishment of the field trial reported on in the next chapter.

The close correspondence of solution ion activity products with the solubility products of the dominant Al-containing minerals in the clay fraction of this soil led to the suggestion (M.V. Fey, personal communication, 1987) that the potential for Al toxicity to develop may be predicted by a simple pH measurement. However, neither a water pH value at wide soil:solution ratios (e.g. 1:2.5) nor a value obtained in molar salt solutions (e.g. KCl) alone is likely to be satisfactory, since both treatments result in conditions far removed from those in the field. On the other hand, the pH of a freshly separated solution equilibrated with the soil in proportions not exceeding saturation of the pore space, might prove useful in identifying a possible hazard to plants in the form of aluminium toxicity. Difficulties associated with the extraction of such a solution, however, together with the weak pH-buffering capacity of low-ionic-strength soil solutions are probable reasons for the lack of adoption of such a technique in routine soil-testing laboratories. Percival *et al.* (1996) confirm that sample handling between the time of solution extraction and that of the pH measurement must be minimal. Another problem is that interpretations of acidity measurements made at low ionic strength (whether they are pH or Al measurements) is that their usefulness depends on the predictability of possible changes in the composition of the soil solution between the time of sampling and the period of root growth.

Another important consequence of the Na – cation exchange phenomenon is the effect that Na has on the difference between water pH and soil solution pH (the only difference between the two measures being the amount of water added). The data of Percival *et al.* (1996) show, for 13 of the soils they studied, that solution Na (expressed as an equivalent fraction of the total soluble cations) can explain 43% of the variation in this pH difference, which ranges from 0.12 to 0.87 units (Figure 3.7). Data for one soil (Shannon, IS00331) was excluded from this analysis as its soil solution pH was 0.64 units higher (rather than lower) than its water pH. This effect of Na is obviously of importance to anyone using water pH as a measure of soil solution acidity.



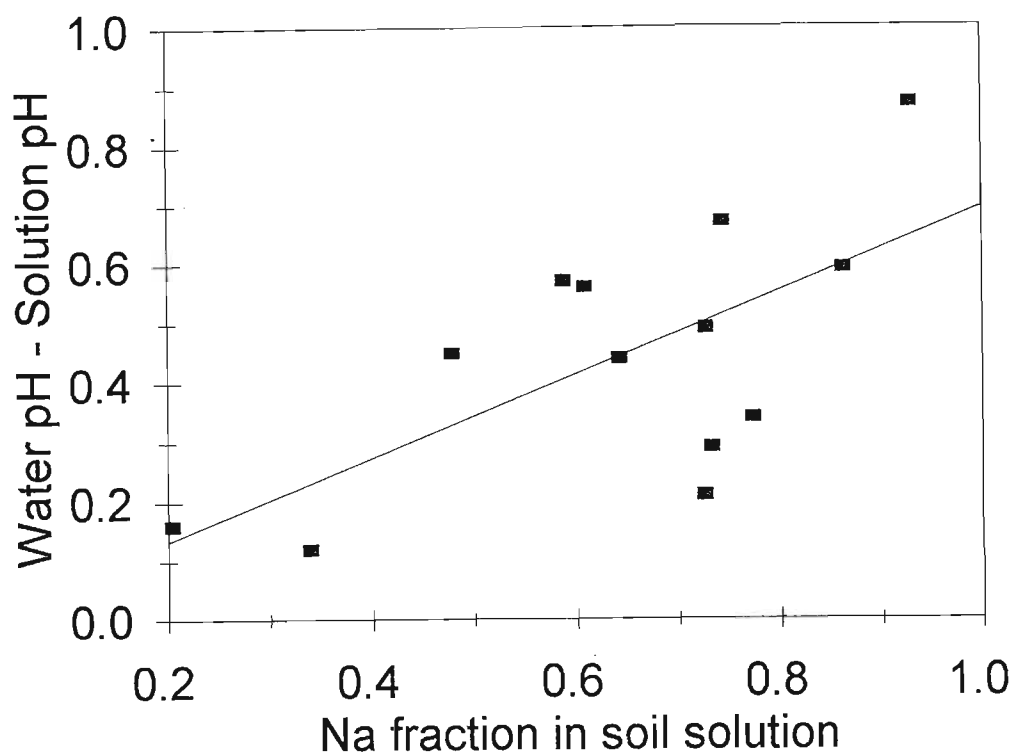


Figure 3.7. The relationship between the difference between water pH and soil solution pH, and soil solution Na expressed as a fraction of total solution cations ( $\text{Na}/[\text{Na} + \text{Ca} + \text{Mg} + \text{K} + \text{NH}_4]$ ) for 13 soils (after Percival *et al.*, 1996).

In general, the sensitivity of soil solution acidity to ionic strength and exchangeable Na complicates the interpretation of any single index of soil acidity, even in a relatively simple system where Al-hydroxide potential is predictable. Problems associated with identifying soils which are likely to present an Al-toxicity hazard are discussed further in Chapter 7.

## 4. THE RESPONSE OF MAIZE TO SODIUM AND GYPSUM IN THE PRESENCE OF SUBSOIL ACIDITY

### 4.1 INTRODUCTION

In the previous chapter, it was suggested that topsoil applications of Na to soils with acid subsoils may offer an alternative approach to the problem of poor subsoil root growth, as the presence of Na had been shown to modify both soil solution pH and  $Al^{3+}$  activity. This chapter reports the results of a field trial designed to test this hypothesis by comparing the effects of different forms of Na, with the effects of gypsum on maize production and subsoil acidity. The trial was designed to test possible differences between different sources of Na, and possible interactions with gypsum.

### 4.2 MATERIALS AND METHODS

The trial was carried out near Geluksburg, KwaZulu-Natal ( $28^{\circ}31'S$  and  $29^{\circ}21'E$ ), at a site with a mean annual rainfall of approximately 950 mm. The soil is similar to that described in Chapter 3. The topsoil had been limed and had a low acid saturation, but the subsoil was highly acid (Table 4.1).

Table 4.1. Selected properties of the topsoil (0-150 mm) and upper subsoil (300-450 mm) of the Pinedene at the experimental site.

	Topsoil	Subsoil
Clay ( $g\ kg^{-1}$ )	399	421
Organic C ( $g\ kg^{-1}$ )	14.2	9.0
Exchangeable cations <sup>1</sup> ( $cmol_c\ L^{-1}$ )		
Ca	3.69	0.84
Mg	1.83	0.36
K	0.32	0.13
Na	0.01	0.01
Al+H	0.18	2.15
Effective CEC (ECEC) <sup>1</sup>	6.02	3.48
Acid saturation <sup>1</sup> (%)	3	62
pH (KCl)	4.50	4.01

<sup>1</sup>Methods given in Appendix 1.

This trial had a  $3^3$  design (three Na carriers at three rates and three rates of gypsum) with added control plots (zero Na at the three levels of gypsum). There were two replicates, with three blocks of 12 plots per replicate. Each block included a control plot (zero Na) at each level of gypsum. Sodium carriers were NaCl, Na<sub>2</sub>CO<sub>3</sub>, and NaNO<sub>3</sub>, and Na rates were 50, 100, and 200 kg ha<sup>-1</sup>. Nitrogen levels were balanced by adjusting the application rates of N fertilizer (limestone ammonium nitrate) in the plots receiving NaNO<sub>3</sub>, and dolomitic limestone was used to balance the acid-neutralising capacity of the Na<sub>2</sub>CO<sub>3</sub>. Gypsum rates were 0, 4 000, and 8 000 kg ha<sup>-1</sup>. Gypsum was applied at the commencement of the trial and Na treatments were applied before planting in 1988, 1990, and 1993.

The trial was established in spring 1988 and run for five seasons. The maize cultivars used, planting and harvest dates, and sampling dates are given in Table 4.2. The trial was not harvested in the 1991/92 season due to a severe drought in January 1992. Monthly rainfall data for the growing seasons are given in Table 4.3. Basal N, P, K and S fertilizers and lime were applied to the topsoil (0-20 cm) at rates known to be sufficient for maximum yield.

Leaves (below and opposite the cob) were sampled at silking and analysed for N, P, K, Ca, Mg, Na, Zn, Mn and Cu by the methods described in Appendix 1. Cobs were harvested by hand (border rows excluded), the mass of grain plus cob measured and grain yield (corrected to 12.5 % moisture) calculated after determination of shelling percentage and moisture content.

Table 4.2. Cultivars, and planting, sampling and harvesting dates for the Na level x carrier x gypsum trial.

Season	Cultivar	Planting date	Topsoil sampling	Leaf sampling	Harvest date	Subsoil sampling
1988/89	RO430	9 Nov	12 Dec	1 Feb	9 Jun	19-22 Jun
1989/90	RO430	15 Nov	18 Dec	1 Feb	22 Jun	12-13 Sep
1990/91	PAN6552	4 Dec	20 Dec	13 Feb	3 Jun	-
1991/92	PAN6552	14 Nov	2 Dec	6 Feb	Not harvested	-
1992/93	Trial not planted					
1993/94	PAN6552	30 Nov	28 Dec	10 Feb	29 Jun	-

Table 4.3. Seasonal rainfall (mm) at the Geluksburg site (Farina *et al.*, 1999; G. Jacobsz, personal communication, 1999).

Month	Season							
	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96
October	97	57	59	103	44	193	50	11
November	59	145	13	159	93	79	8	146
December	146	148	141	170	56	22	80	270
January	124	62	267	34	90	147	190	367
February	303	121	104	88	158	219	44	182
March	56	10	6	42	109	133	103	64
Total	785	543	590	596	550	793	475	1040

Soil samples were taken at six depth intervals to a depth of 900 mm as described by Farina & Channon (1988a). These samples were analysed for Ca, Mg, acidity and pH (1 mol L<sup>-1</sup> KCl) and K (Ambic-2). Acid saturation was calculated using the method described in Appendix 1. Exchangeable Na was measured by atomic absorption after extraction with ammonium acetate (1 M, adjusted to pH 7). The pH and Al, Ca, Mg, K and Na concentration of distilled water extracts were determined using the methods described in Chapter 3.

### 4.3 RESULTS AND DISCUSSION

From the results of the soil analyses for the first season, it was clear that the topsoil pH of one plot (plot 9) was anomalously high (Table 4.4), so in all statistical analyses for this trial that plot was treated as a missing plot.

Table 4.4. Soil pH (KCl) for plot 9 compared with the range and mean for the other 71 plots of the trial.

Sampling date and depth	pH (KCl); Plot 9	pH (KCl); range for remaining plots	pH (KCl); mean for remaining plots
12 Dec 1988; 0-150 mm	6.70	4.20-5.10	4.54
19 Jun 1989; 0-150 mm	6.44	4.18-5.40	4.58
19 Jun 1989; 150-300 mm	5.83	3.97-4.78	4.18

#### 4.3.1 Exchangeable cations

The results in Tables 4.5 and 4.6 show that the leaching of Ca, Mg and SO<sub>4</sub> into the 300-450 mm depth zone of the gypsum-treated plots increased the exchangeable Ca and Mg and decreased the extractable acidity, resulting in decreased acid saturation. Sodium treatments, however, had no significant effect on KCl-extractable Ca, Mg, K, or acidity, but subsoil Na was increased significantly by Na treatments (Table 4.7). Gypsum had a positive effect on the leaching of sodium (Appendix 2), and although the effect was small relative to the effect of the Na treatments, it was highly significant at the 450-600 mm and 600-750 mm depths in the September 1990 samples.

Table 4.5. The effect of gypsum on exchangeable cations and on acid saturation of zero Na plots at different depths, one season after application (sampled June 1989).

Soil depth (mm)	Gypsum level (kg ha <sup>-1</sup> )			Significance of linear effect due to gypsum
	0	4000	8000	
Ca (mg L <sup>-1</sup> )				
0-150	726	1053	1165	P < 0.01
150-300	563	769	806	P < 0.05
300-450	161	269	301	P < 0.01
450-600	92	117	119	N.S.
600-750	58	74	82	P < 0.10
750-900	60	74	88	P < 0.10
Mg (mg L <sup>-1</sup> )				
0-150	223	158	136	P < 0.01
150-300	140	164	165	N.S.
300-450	42	66	81	P < 0.01
450-600	44	48	47	N.S.
600-750	62	61	59	N.S.
750-900	81	92	103	N.S.
Al+H (cmol <sub>c</sub> L <sup>-1</sup> )				
0-150	0.19	0.12	0.08	N.S.
150-300	0.79	0.60	0.56	N.S.
300-450	2.18	1.88	1.81	P < 0.10
450-600	2.57	2.43	2.47	N.S.
600-750	3.27	3.00	3.07	N.S.
750-900	3.83	3.64	3.76	N.S.
Acid saturation (%)				
0-150	3.3	1.9	1.1	P < 0.10
150-300	16.0	11.0	9.2	N.S.
300-450	62.9	48.6	45.1	P < 0.01
450-600	73.5	68.9	70.4	N.S.
600-750	78.0	75.2	75.3	N.S.
750-900	77.7	74.3	73.1	N.S.

Table 4.6. The effect of gypsum on exchangeable cations and on acid saturation of zero Na plots at different depths, two seasons after application (sampled September 1990).

Soil depth (mm)	Gypsum level (kg ha <sup>-1</sup> )			Significance of linear effect
	0	4000	8000	
<b>Ca (mg L<sup>-1</sup>)</b>				
0-150	748	935	956	P < 0.05
150-300	534	711	719	P < 0.10
300-450	159	329	356	P < 0.01
450-600	77	116	136	P < 0.01
600-750	55	79	70	N.S.
750-900	58	87	61	N.S.
<b>Mg (mg L<sup>-1</sup>)</b>				
0-150	199	173	153	P < 0.05
150-300	148	153	151	N.S.
300-450	50	83	99	P < 0.01
450-600	44	46	54	N.S.
600-750	55	54	56	N.S.
750-900	85	90	78	N.S.
<b>Al+H (cmol<sub>c</sub> L<sup>-1</sup>)</b>				
0-150	0.28	0.19	0.18	P < 0.05
150-300	0.82	0.56	0.48	P < 0.10
300-450	2.09	1.64	1.62	P < 0.01
450-600	2.53	2.34	2.32	P < 0.10
600-750	2.93	2.84	3.04	N.S.
750-900	3.80	3.60	3.24	P < 0.10
<b>Acid saturation (%)</b>				
0-150	4.6	2.9	2.7	P < 0.05
150-300	16.6	10.5	8.8	P < 0.10
300-450	60.4	40.2	37.8	P < 0.01
450-600	74.9	68.4	65.9	P < 0.05
600-750	78.1	74.1	76.9	N.S.
750-900	77.2	73.2	75.2	N.S.

Table 4.7. The effect of Na application on exchangeable Na ( $\text{mg L}^{-1}$ ) at different depths. Plots were sampled after the first and second seasons.

Sampling date & Soil depth (mm)	Na level ( $\text{kg ha}^{-1}$ )				Significance of linear effect
	0	50	100	200	
<b>June 1989</b>					
0-150	2.2a	5.1b	6.2b	12.1c	P<0.01
150-300	3.5a	12.0b	18.8c	31.1d	P<0.01
300-450	3.9a	9.3b	15.4c	23.4d	P<0.01
450-600	4.1a	4.3a	4.8a	7.9b	P<0.01
600-750	3.9a	4.5a	4.7a	6.5b	P<0.01
750-900	7.5a	8.1a	7.4a	8.7a	NS
<b>September 1990</b>					
0-150	2.6a	4.7b	5.3b	9.4c	P<0.01
150-300	3.5a	8.7b	13.2c	22.6d	P<0.01
300-450	3.6a	10.9b	16.6c	26.6d	P<0.01
450-600	3.5a	6.9b	11.9c	16.3d	P<0.01
600-750	4.0a	5.5b	6.8b	9.0c	P<0.01
750-900	5.6a	5.8a	6.0a	7.3b	P<0.01

Different letters indicate a significant difference between Na levels for comparisons at the same depth ( $P < 0.01$ ). Statistical analysis was done on log-transformed data because variance increased as level of Na treatment increased. Actual means are reported.

Significant leaching of Na to depths of greater than 600 mm had occurred by June 1989 (Table 4.7). This is deeper than any leaching due to gypsum over the same period; since there are no significant effects (at 5% probability) of gypsum at depths of greater than 450 mm (Table 4.5). The deeper leaching of Na is due both to the high solubility of the sodium salts and the mobility of the sodium ion in soils. By September 1990, there was evidence of further leaching of Na (to deeper than 750 mm) and that leaching effects due to gypsum had extended to below a depth of 450 mm. Gypsum treatments had induced leaching of Ca to a depth of greater than 450 mm and also decreased exchangeable acidity at this depth, with the nett result being a significant decrease in acid saturation in the 450-600 mm depth zone. There appears to have been little leaching of Mg to depths below 450 mm, even after the second season.



### 4.3.2 Crop yield

Both gypsum and Na had a significant effect on grain yield in the first three seasons (Table 4.8); the low yields in the 1989/90 season were due to hail at the grain-filling stage. However, a significant negative interaction between these treatments is evident i.e. there was no significant response to gypsum if Na was present, or to Na if gypsum was present. No significant Na-carrier effects were observed in any season.

As the topsoil of this trial was adequately limed (less than 11% acid saturation) and fertilized, it is believed that both the gypsum and Na effects were due to improved root penetration into the acid subsoil. Attempts were made to measure treatment effects on subsoil root growth, but in all cases there was some root development in the subsoils of the control plots. Because of high variability in subsoil root development for plots with similar treatments in different replicates, it was apparent that measurement of treatment effects on root growth would require far more intensive sampling than was practical at the time, and it was decided not to attempt to measure root growth. Improved subsoil root growth has, however, been shown to be the most likely reason for the response to gypsum at this site (Farina & Channon, 1988b), and in view of the negative interaction between the two treatments, as well as the proven effect of Na on soil solution acidity (Chapter 3), it seems likely that the Na treatments have had a similar effect.

The above explanation of the response to gypsum is supported by the data discussed above (Tables 4.5 and 4.6), which show that gypsum treatments had decreased acid saturation (which is generally associated with improved root growth) in the 300-450 mm depth zone. Acid saturation data were, however, not able to explain the Na effect, as Na treatments had no significant effect on KCl-extractable Ca, Mg, or acidity, or Ambic-2 K (Appendix 2).

The analysis of soil solutions extracted from the 300-450 mm depth samples indicated a trend of increasing pH with increasing Na, (as would be expected considering the data presented in Chapter 3), but the treatment effect was not statistically significant (using analysis of variance) due to variation in the ionic strength of the solutions extracted, and variation in the acid saturation of the ECEC. Multiple regression analysis of the soil solution data of zero-gypsum plots for the 300-450 mm depth samples (taken in June 1989) did, however, confirm that Na had a significant

effect on soil solution acidity in this trial. The analysis showed that the electrical conductivity of the soil solution (a proxy for ionic strength), Na in the soil solution, and acid saturation could together explain 85% of the variation in soil solution pH, and 79% of the variation in Al concentration (Figures 4.1 and 4.2). All three parameters made highly significant contributions ( $P < 0.01$ ) to both regression equations.

Table 4.8. The effect of Na and gypsum levels on maize grain yield. Yields shown are means of six plots.

Na level (kg ha <sup>-1</sup> )	Gypsum level (kg ha <sup>-1</sup> )		
	0	4000	8000
1988/89 yield (kg ha <sup>-1</sup> )			
0	6092	6931	7218
50	6787	7126	6949
100	6962	7339	7047
200	7017	6732	6854
LSD <sub>0.05</sub> = 674; LSD <sub>0.01</sub> = 902			
1989/90 yield (kg ha <sup>-1</sup> )			
0	1945	2514	2444
50	2195	2535	2343
100	2314	2599	2289
200	2502	2467	2308
LSD <sub>0.05</sub> = 419; LSD <sub>0.01</sub> = 560			
1990/91 yield (kg ha <sup>-1</sup> )			
0	7121	7616	7850
50	7542	7791	7673
100	7727	7766	7508
200	7716	7791	8017
LSD <sub>0.05</sub> = 436; LSD <sub>0.01</sub> = 584			
1993/94 yield (kg ha <sup>-1</sup> )			
0	7881	8045	7803
50	7340	7626	7806
100	7943	8121	7762
200	7922	8068	7952
LSD <sub>0.05</sub> = 381 (NS); LSD <sub>0.01</sub> = 509 (NS)			

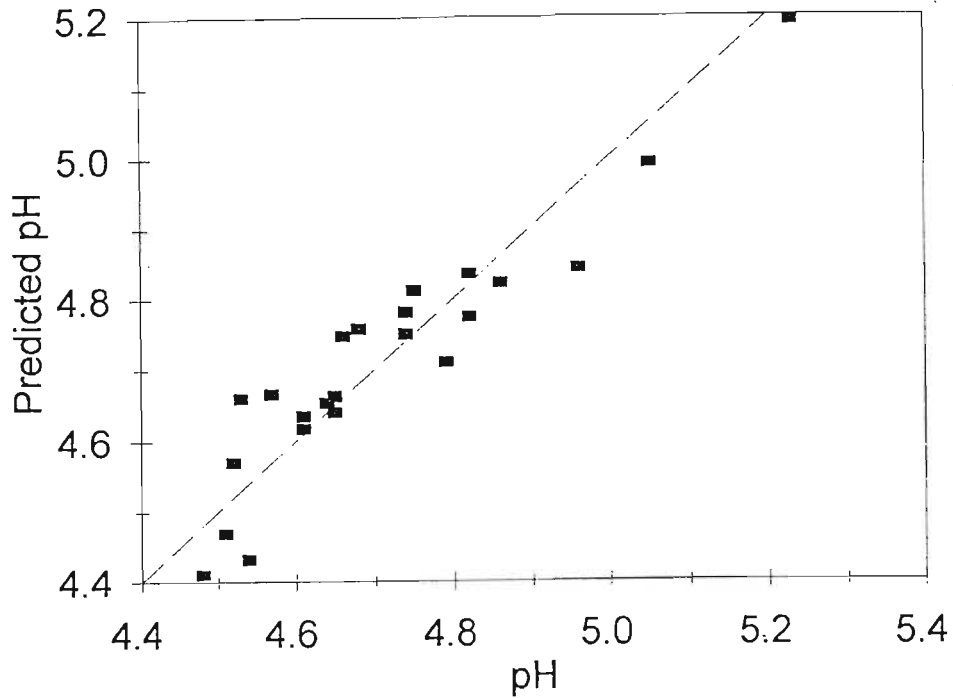


Figure 4.1. Plot of predicted pH against soil solution pH for 23 samples taken at 300-450 mm depth from the zero-gypsum plots in June 1989. Predicted pH =  $5.463 + 0.6599 \times \text{Na (mM)} - 0.03461 \times \text{EC (mS m}^{-1}) - 0.00865 \times \text{Acid saturation (\%)}$ ; ( $R^2 = 0.85$ ; s.e. of the estimated constant = 0.164; s.e.'s of the co-efficients are 0.0691 (Na), 0.00469 (EC), and 0.00254 (Acid saturation)).

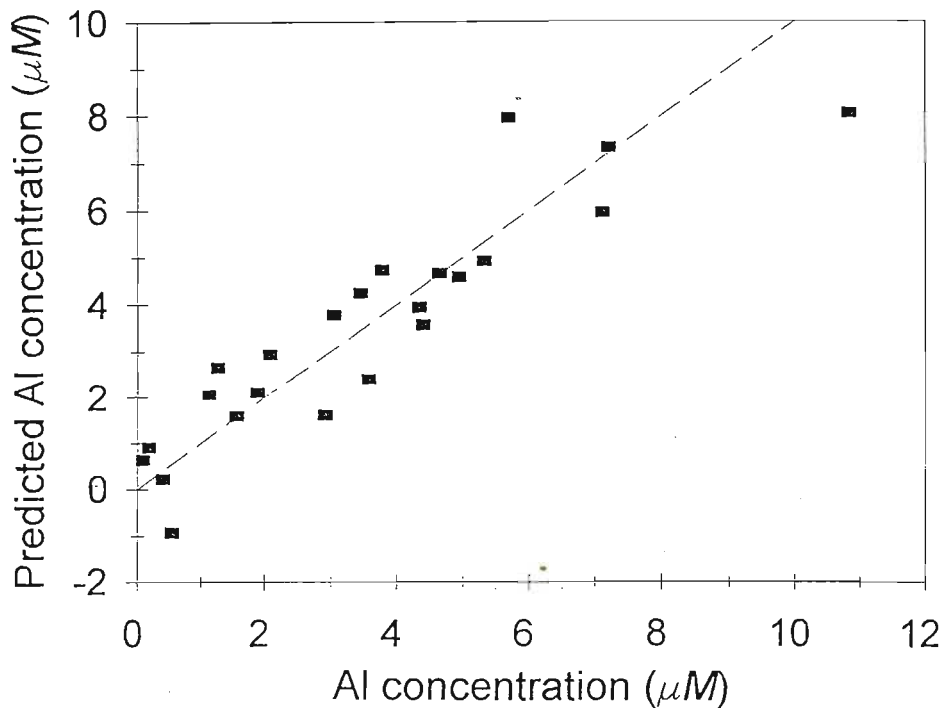


Figure 4.2. Plot of predicted Al concentration against soil solution Al concentration for 23 samples taken at 300-450 mm depth from the zero-gypsum plots in June 1989. Predicted Al concentration =  $-11.43 - 6.57 \times \text{Na (mM)} + 0.6241 \times \text{EC (mS m}^{-1}) + 0.1582 \times \text{Acid saturation (\%)}$ ; ( $R^2 = 0.79$ ; s.e. of the estimated constant = 2.77; s.e.'s of the co-efficients are 1.17 (Na), 0.6241 (EC), and 0.1582 (Acid saturation)).

Despite this effect of  $\text{Na}^+$  on soil solution acidity as a result of ion exchange phenomena, there is no conclusive evidence to link this particular effect with the improved grain yields obtained as a result of Na applications. Sodium has also been shown to alleviate the negative effects of  $\text{Al}^{3+}$  on the root growth in nutrient solution, where pH and  $\text{Al}^{3+}$  activity were maintained at constant levels (Section 2.1.3.2; Kinraide & Parker, 1987; Ryan *et al.*, 1994; Tadano & Gotoh, 1995). This more direct effect of Na on root growth may also have contributed to improved subsoil rooting and yield.

### 4.3.3 Leaf composition

The effects of Na on yield may not have been through improvements in subsoil rooting, although the interaction with gypsum would appear to indicate that this is probable. The effect of Na and gypsum on P uptake may also have contributed to the yield responses (Sections 2.2.2 and 2.2.3; Easton, 1969; Geelhoed *et al.*, 1997). In 1988/89, there was a negative interaction between the effects of Na and gypsum on both yield (Table 4.8) and leaf P (Table 4.9). This was, however, the only season that there was a significant Na x gypsum interaction for leaf P, and the only year that Na had a significant positive effect on leaf P; in 1990/91, Na had a significant negative effect on leaf P (Table 4.9). Over all four seasons, the effects on leaf P were inconsistent, and an effect on P nutrition is therefore unlikely to be the main reason for the more consistent, positive Na effects on yield.

Sodium applications at the 100 and 200 kg ha<sup>-1</sup> levels significantly depressed leaf Ca, whereas gypsum raised leaf Ca levels (Table 4.10). There was no significant interaction between the Na and gypsum effects on leaf Ca. Reuter (1986) regards Ca levels of between 2.1 and 5 g kg<sup>-1</sup> as being adequate for maximum yield, so even the lowest leaf Ca levels were probably sufficiently high to ensure optimum yields.

Sodium also resulted in a significant depression of leaf Mg (Table 4.11). Despite the leaching of Mg induced by gypsum, there was no effect of gypsum on leaf Mg in 1988/89 and 1990/91, whereas in 1989/90, gypsum actually increased leaf Mg. Again, there was no significant interaction between Na and gypsum effects, and Mg levels throughout were sufficient for maximum yield.

Table 4.9. The effect of Na and gypsum levels on leaf P. Results given are means of six plots.

Na level (kg ha <sup>-1</sup> )	Gypsum level (kg ha <sup>-1</sup> )		
	0	4000	8000
1988/89 Leaf P (g kg <sup>-1</sup> )			
0	2.81	2.98	3.12
50	3.00	2.98	3.02
100	2.88	3.15	2.98
200	3.03	2.95	3.00
LSD <sub>0.05</sub> = 0.19; LSD <sub>0.01</sub> = 0.26; Interaction significant (P<0.05); Gypsum main effect NS (P=0.081); Na main effect NS			
1989/90 Leaf P (g kg <sup>-1</sup> )			
0	2.16	2.20	2.27
50	2.23	2.20	2.43
100	2.23	2.13	2.42
200	2.23	2.23	2.48
Interaction NS; Gypsum main effect significant (P<0.01); Na main effect NS			
1990/91 Leaf P (g kg <sup>-1</sup> )			
0	2.64	2.53	2.35
50	2.38	2.38	2.30
100	2.40	2.45	2.52
200	2.28	2.13	2.15
Interaction NS; Gypsum main effect NS; Na main effect significant (P<0.05)			
1993/94 Leaf P (g kg <sup>-1</sup> )			
0	2.92	2.90	3.02
50	3.00	3.07	3.00
100	3.02	2.98	3.02
200	2.97	2.97	3.00
Interaction NS; Gypsum main effect NS; Na main effect NS			

Table 4.10. The effect of Na and gypsum treatments on leaf Ca ( $\text{g kg}^{-1}$ ). Results given are means of 18 plots for Na treatments, and 24 plots for gypsum treatments.

Na level ( $\text{kg ha}^{-1}$ )	1988/89	1989/90	1990/91	1993/94
	Leaf Ca ( $\text{g kg}^{-1}$ )			
0	4.93	4.24	4.10	6.58
50	5.21	4.14	3.51	6.04
100	4.61	4.02	3.66	5.94
200	4.71	3.81	3.30	5.36
LSD <sub>0.05</sub>	0.31	0.33	0.53	0.30
Gypsum level ( $\text{kg ha}^{-1}$ )				
0	4.42	3.65	3.39	5.64
4000	5.06	4.02	3.86	6.03
8000	5.11	4.49	3.68	6.28
LSD <sub>0.05</sub>	0.27	0.29	0.46	0.26

Table 4.11. The effect of Na and gypsum treatments on leaf Mg ( $\text{g kg}^{-1}$ ). Results given are means of 18 plots for Na treatments, and 24 plots for gypsum treatments.

Na level ( $\text{kg ha}^{-1}$ )	1988/89	1989/90	1990/91	1993/94
	Leaf Mg ( $\text{g kg}^{-1}$ )			
0	2.91	2.75	2.26	4.41
50	3.00	2.79	2.08	4.14
100	2.57	2.63	2.08	3.91
200	2.79	2.52	1.95	3.55
LSD <sub>0.05</sub>	0.20	0.21	0.14	0.26
Gypsum level ( $\text{kg ha}^{-1}$ )				
0	2.75	2.56	2.06	4.22
4000	2.91	2.67	2.16	3.96
8000	2.80	2.80	2.06	3.83
LSD <sub>0.05</sub>	NS	0.19	NS	0.22

Leaf K was higher in Na-treated plots in all seasons and the average leaf K over all four seasons for Na-treated plots was significantly higher ( $P < 0.01$ ) than that for zero-Na plots (Table 4.12). Analysis of each season separately, however, indicated that this effect was only significant ( $P < 0.05$ ) in 1993/94.

Table 4.12. The effect of Na application on leaf K. Results given for Zero-Na plots are means of 18 plots and those shown for Na-treated plots are means of 54 plots.

Season	Zero-Na plots	Na-treated plots	Significance of difference
	Leaf K (g kg <sup>-1</sup> )		
1988/89	28.4	29.2	NS
1989/90	17.1	17.8	P=0.053
1990/91	15.4	15.8	NS
1993/94	17.9	18.8	P<0.05
Mean (4 seasons)	19.7	20.4	P<0.01

Significant sodium-carrier effects on herbage composition (Appendix 2) were limited to:

- (a) a higher leaf Mn with NaCl than the other carriers in all four seasons;
- (b) a lower leaf Cu with NaCl in 1990/91 and 1993/94;
- (c) a lower leaf K and higher leaf Na with Na<sub>2</sub>CO<sub>3</sub> in 1989/90 only; and
- (d) a higher leaf P with NaNO<sub>3</sub> in 1990/91 only.

Gypsum (at 8 000 kg ha<sup>-1</sup>) resulted in marginally, but significantly higher, leaf N levels in the 1988/89 season, possibly due to a deeper rooting system which was better able to utilise N leached into the subsoil. This effect was also observed in the other maize trial at Geluksburg where it was more marked (Chapter 5). Gypsum also marginally increased leaf P in 1988/89 and 1989/90 (Table 4.9). This may be due to sulphate-phosphate ligand exchange in the soil or promotion of P uptake by Ca. Leaf Mn was raised by gypsum in the first three seasons (Table 4.13). Brazilian work has also shown that gypsum can increase plant Mn, but the mechanism is unknown (Shainberg *et al.*, 1989). The concentrations of these three nutrients in the leaf were, however, generally at levels which are unlikely to have affected grain yields (as was the case with Ca and Mg) according to the data summarised by Reuter (1986).

Table 4.13. The effect of gypsum application on leaf Mn ( $\text{mg kg}^{-1}$ ). Different letters within the same year indicate significant differences ( $P < 0.01$ ).

Season	Gypsum level ( $\text{kg ha}^{-1}$ )			Significance of linear effect
	0	4000	8000	
1988/89	112.6a	140.2b	146.2b	$P < 0.01$
1989/90	65.8a	65.9a	78.0b	$P < 0.01$
1990/91	61.1a	61.4a	65.7a	$P < 0.05$
1993/94	77.0a	73.0a	80.5a	NS

#### 4.4 CONCLUSIONS

This trial showed that grain yields of maize grown under field conditions can be increased by applications of Na salts. When considering the results of this field trial together with the soil solution and pot trial results given in Chapter 3, the most likely reason for the response to the Na treatments is that subsoil rooting was improved as a result of higher soil solution pH and Na concentration, and lower Al concentration.

Effects due to the sodium carrier were minimal. There was no carrier effect on yield, and the only consistent effect on herbage composition, was to marginally increase leaf Mn. Carrier effects on crop growth might have been expected as the ionic-strength effect of a mobile anion such as chloride would counteract the Na effect on solution Al. In this trial, however, the relatively high rates of N used ( $120 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) may have swamped Na-carrier effects on ionic strength in the zero-gypsum plots.

In 1991 it was decided to test the Na effect on maize in another field experiment. A piece of land at the same Geluksburg site, with blocks that had been limed at different rates, was used to test Na treatments at different levels of topsoil acidity. The results of this trial are presented in the next chapter.



## 5. THE RESPONSE OF MAIZE TO SODIUM AND GYPSUM AT DIFFERENT LIME RATES

### 5.1 INTRODUCTION

The first maize trial (discussed in Chapter 4) which tested the effect of Na on a soil with limed topsoil and acid subsoil, indicated that responses to Na were possible. It was decided to conduct another maize trial at a site about 200 m from the first one, in order to determine the response to Na in a situation where both topsoil and subsoil were acid.

### 5.2 MATERIALS AND METHODS

This trial used blocks previously treated with four levels of lime (with two replications) and used for cultivar evaluation trials between 1982 and 1991 (Mendes, 1985; Mendes *et al.*, 1985; M.P.W. Farina, personal communication, 1999). Rates of dolomitic lime (applied over the period May 1982 to May 1983) were 0, 2 500, 10 000, and 15 000 kg ha<sup>-1</sup>. In September 1983 and August 1984, the blocks were treated with a modified subsoiler at 90-cm intervals. This implement is described by Farina & Channon (1988a) and was used to incorporate previously limed topsoil in 0.065-m wide vertical bands to a depth of approximately 0.70 m below the soil surface. In October 1985, a further 1000 kg ha<sup>-1</sup> dolomitic lime was applied to the blocks that had previously received the 0 and 2 500 kg ha<sup>-1</sup> lime rates.

In November 1991, the limed blocks were split to compare Na and gypsum treatments with a control, at each lime level. The trial was first planted in 1991 when the gypsum (8000 kg ha<sup>-1</sup>) and first Na treatments (200 kg Na ha<sup>-1</sup> as NaCl) were applied. However, in that season the trial was abandoned as a result of drought, and it was not replanted in the following season. In 1993/94 the Na (as NaCl) treatments were reapplied. In 1994/95 and 1995/96, the Na treatments were applied as Na<sub>2</sub>SO<sub>4</sub>, with the gypsum and control plots receiving an equivalent amount of sulphur as gypsum. The basal N treatment, applied at planting as limestone ammonium nitrate, was reduced from 120 (in 1993) to 50 kg N ha<sup>-1</sup> in 1994 and 1995. A basal lime application of 1000 kg ha<sup>-1</sup> over the whole trial was made in spring 1995, as acidification over time had resulted in a linear lime response. Table 5.1 indicates the cultivars used, and planting, sampling and

harvest dates. Topsoil samples (0-150 mm) were analysed for Ca, Mg, acidity and pH (1 M KCl), and K (Ambic-2) using the methods described in Appendix 1. Leaves (below and opposite the cob) were sampled at silking and analysed for N, P, K, Ca, Mg, Na, Zn, Mn and Cu by the methods described in Appendix 1. Analysis of variance was used to compare the yields and analytical data for the different treatments.

Table 5.1. Cultivars, and planting, sampling and harvesting dates for the second maize trial.

Season	Cultivar	Planting date	Topsoil sampling	Leaf sampling	Harvest date
1993/94	PAN 6578	30 Nov	27 Dec	10 Feb	27 Jun
1994/95	TX 24	27 Dec	27 Jan	16 Mar	1 Aug
1995/96	PAN 6242	30 Nov	5 Jan	21 Feb	11 Jun

## 5.3 RESULTS

### 5.3.1 Crop yield and exchangeable cations

In both 1994/95 (drought) and 1995/96 (waterlogging) grain yields were very poor, so stover yields were measured in those seasons (rainfall data are given in Table 4.3).

A strong yield response to lime is evident in this trial, and a significant negative interaction between lime and the split-plot treatments occurred in both 1993/94 and 1994/95. There was no response to Na or gypsum at the high rates of lime, where topsoil acid saturation was less than 40% (Tables 5.2 and 5.3). However, at the lowest level of lime, both gypsum and Na treatments increased yield, and in 1993/94, the yields obtained with gypsum were significantly higher than those obtained with Na. The yield response to gypsum in 1994/95 was less marked, probably because there was less effect on topsoil acid saturation (Table 5.3) as a result of sulphate leaching. At the 3500 kg ha<sup>-1</sup> lime level, the effect of Na was only significant in 1994/95, whereas that of gypsum was significant in both 1993/94 and 1994/95.

In 1995/96, a combination of very high rainfall and low N applications resulted in very low yields. There was no response to Na, possibly as a result of leaching, and the response to gypsum was lower than in previous seasons (Table 5.2).

Table 5.2. The effects of Na and gypsum on maize grain yield or stover dry matter yield at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
<b>Grain yield (kg ha<sup>-1</sup>) in 1993/94</b>				
1000	899	1926	5283	812
3500	3274	3868	6323	812
10 000	8336	8068	8584	NS
15 000	8464	8587	8943	NS
Mean	5243	5612	7283	406
<b>Stover yield (kg ha<sup>-1</sup>) in 1994/95</b>				
1000	323	1312	1999	755
3500	2010	2881	4695	755
10 000	6556	6070	6620	NS
15 000	6664	6573	7045	NS
Mean	3888	4209	5090	377
<b>Stover yield (kg ha<sup>-1</sup>) in 1995/96</b>				
2000	1847	1943	2571	NS
4500	3687	3571	3890	NS
11000	4957	4447	5095	NS
16000	5654	5115	6331	NS
Mean	4036	3769	4472	415

LSD<sub>0.05</sub> for comparisons at different levels of lime are 1959, 755, and 2006 kg ha<sup>-1</sup> for 1993/94, 1994/95, and 1995/96 respectively.

Table 5.3. The effects of Na and gypsum on topsoil acid saturation at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Acid saturation (%) in 1993/94				
1000	79	80	54	9
3500	71	73	49	9
10 000	31	38	21	9
15 000	20	16	8	9
Mean	50	52	33	4
Acid saturation (%) in 1994/95				
1000	73	78	59	9
3500	69	71	52	9
10 000	31	42	26	9
15 000	20	18	11	9
Mean	48	53	37	5
Acid saturation (%) in 1995/96				
2000	68	70	59	7
4500	62	63	53	7
11000	22	31	22	7
16000	14	12	8	7
Mean	42	44	35	4

LSD<sub>0.05</sub> for comparisons at different levels of lime are 15%, 15%, and 10% for 1993/94, 1994/95, and 1995/96 respectively.

Data from the 1994/95 season give the clearest evidence that the yield responses to Na may be a result of the cation exchange effect suggested in Chapter 3. The positive responses to Na at lime levels of 1000 kg ha<sup>-1</sup> and 3500 kg ha<sup>-1</sup> occurred in spite of higher (although not significantly higher) average levels of acid saturation (Table 5.3). Despite the higher levels of acid saturation (on average) in the sodium-treated plots, Na had a significant positive effect on water pH in the 1994/95 season (Table 5.4). This, together with lower levels of soluble aluminium would be expected in the Na<sub>2</sub>SO<sub>4</sub> treatment relative to the control (CaSO<sub>4</sub>) treatment, as Na<sup>+</sup> ions would dominate the soluble cation suite in the former case. The yield response to gypsum can, on the other hand, be attributed to the effect of gypsum on acid saturation.

Table 5.4. The effects of Na and gypsum on topsoil pH(water) at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
pH (water) in 1993/94				
1000	3.86	3.95	4.07	0.10
3500	4.04	4.07	4.16	0.10
10 000	4.54	4.48	4.52	NS
15 000	4.79	4.76	4.82	NS
Mean	4.31	4.32	4.39	0.05
pH (water) in 1994/95				
1000	4.05	4.21	4.18	0.10
3500	4.15	4.29	4.23	0.10
10 000	4.67	4.7	4.61	NS
15 000	4.84	5.04	4.89	0.10
Mean	4.43	4.56	4.48	0.05
pH (water) in 1995/96				
2000	4.32	4.19	4.22	NS
4500	4.34	4.24	4.26	NS
11000	4.72	4.59	4.70	NS
16000	4.77	5.04	5.13	0.30
Mean	4.54	4.51	4.58	NS

LSD<sub>0.05</sub> for comparisons at different levels of lime are 0.19, 0.18, and 0.39 for 1993/94, 1994/95, and 1995/96 respectively.

Figures 5.1 and 5.2 show the results of broken-stick regression analyses of the 1994/95 data. For the yield-acid saturation relationship an initial broken-stick analysis of the data overall gave a highly significant model of the data, with a break at an acid saturation of 45%. A model allowing different plateaus for the gypsum, Na and control treatments showed no significant difference between these treatments. However, one that allowed different slopes for the portion at acid saturations of greater than 45% indicated highly significant differences between the yield-acid saturation relationships of the Na-treated plots on one hand, and the control- and gypsum-treated plots on the other (Figure 5.1). This indicates that, although differences in acid saturation can

explain the improved yields in the gypsum-treated plots, they cannot explain the higher yields obtained with the Na treatment in the more acid plots. A similar analysis of the pH(water) data (Figure 5.2) indicates, however, that there is no significant difference between the yield-pH(water) relationship for the Na-treated plots and that of the control plots, indicating that the Na effect on the water pH can explain at least part of yield response to Na.

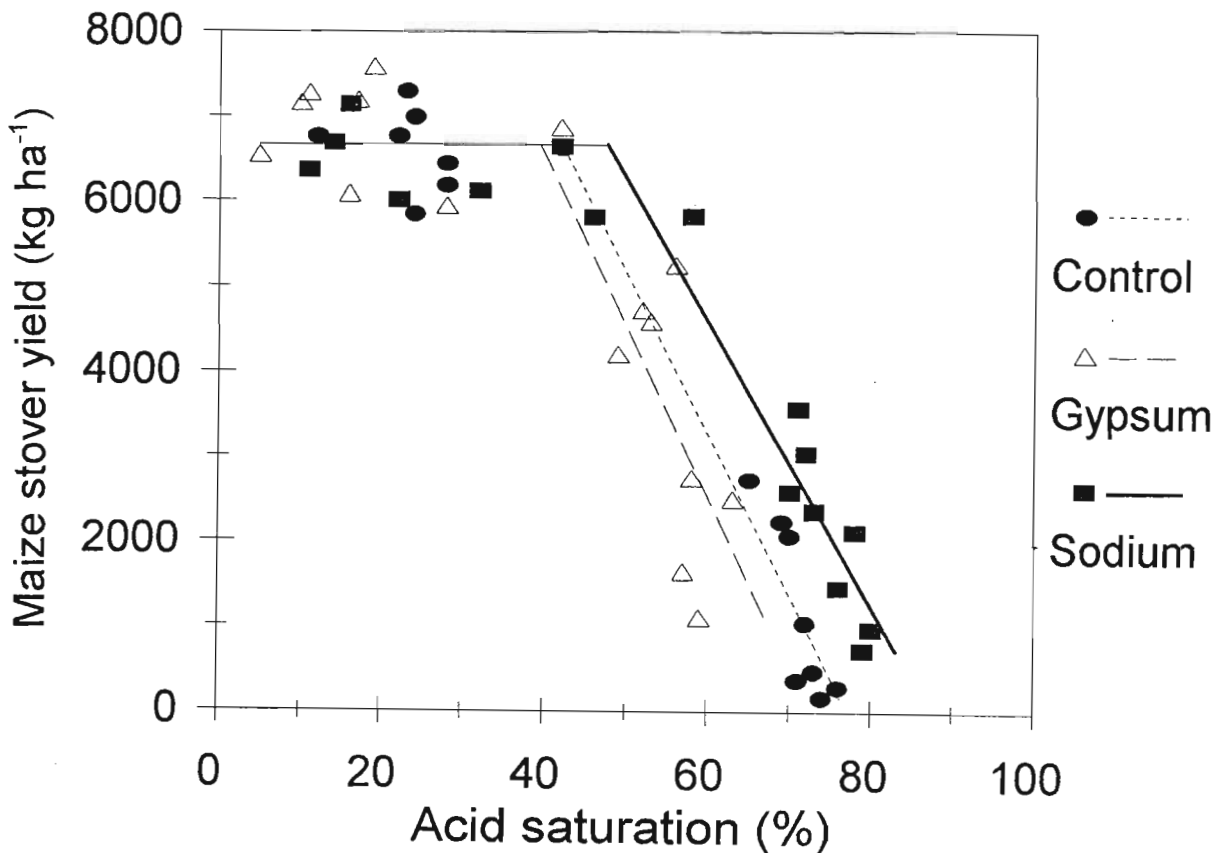


Figure 5.1. The relationship between acid saturation and maize stover yield. The broken-stick model accounts for 91.7% of the variance. The line fitted for the Na-treated plots is significantly different ( $P < 0.01$ ) to that fitted for the control and gypsum-treated plots, whereas those fitted for the control and gypsum-treated plots are not significantly different.

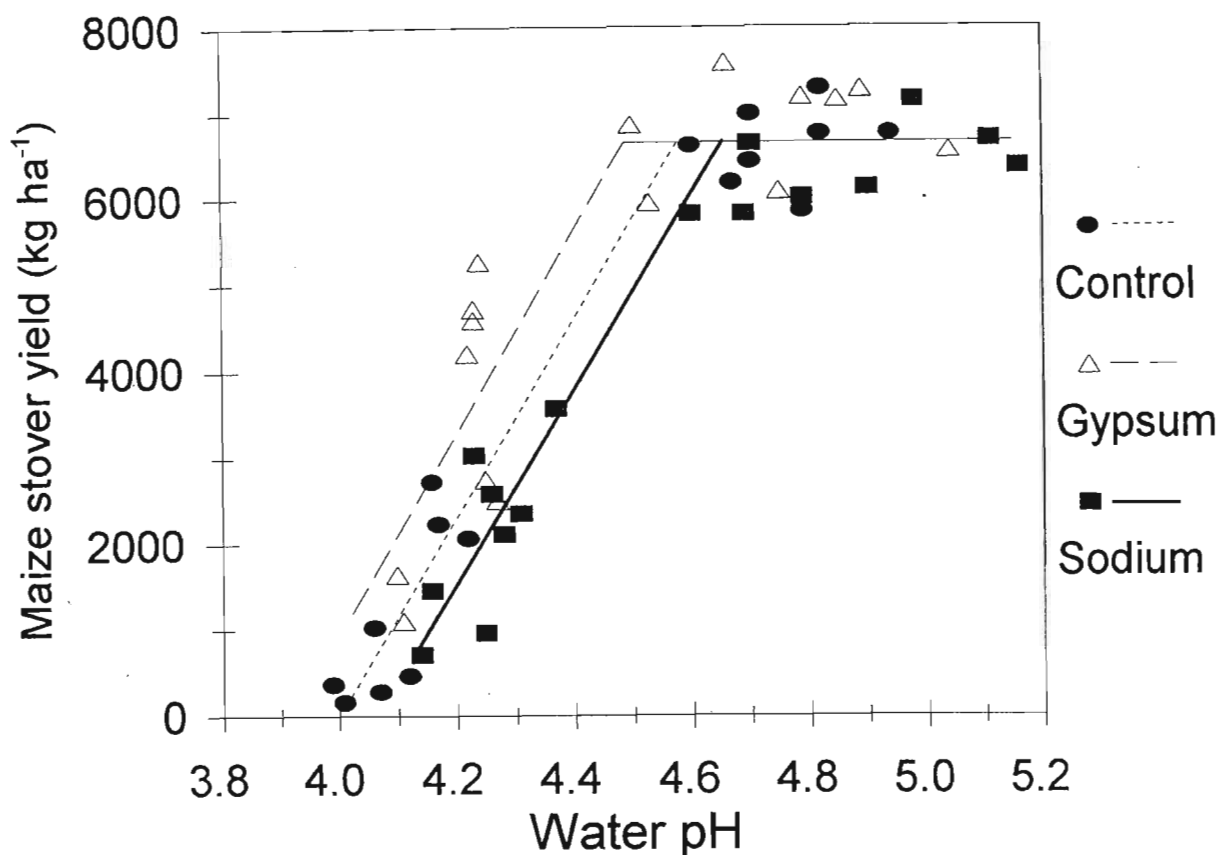


Figure 5.2. The relationship between water pH and maize stover yield. The broken-stick model accounts for 91.5% of the variance. The line fitted for the gypsum-treated plots is significantly different to the lines fitted for the control ( $P < 0.05$ ) and Na-treated ( $P < 0.01$ ) plots, whereas those fitted for the control and Na-treated plots are not significantly different.

### 5.3.2 Leaf composition

#### 5.3.2.1 Nitrogen

The treatments significantly affected leaf-N concentration (Table 5.5). Where treatment effects were significant, lime, Na and gypsum all increased leaf N. A reason for this may be improved root length achieved with lime and gypsum (and to a lesser extent Na) treatments as a consequence of the amelioration of the effects of aluminium toxicity. The effect has also been reported from gypsum-treated plots in Brazil (Souza & Ritchey, 1986, cited by Shainberg *et al.*, 1989), where a similar explanation was given. In 1993/94, trends in leaf N largely followed the trends in grain yield, and therefore probably trends in root length. In 1993/94, the gypsum main effect (higher leaf N) was significant, but the Na treatment had no effect. In 1994/95, however, both Na and gypsum increased leaf N significantly. This may be due to the change in form of Na

used; the chloride used in 1993/94 may have suppressed nitrate uptake (Marschner, 1986, p. 38). The lower leaf N in 1994/95 (despite lower rainfall and lower yields) was probably due to the large KCl dressing applied over all treatments in that season. In 1995/96, Na again had no effect on leaf N (which, along with the lack of a yield response to Na, indicates that root growth was not improved). In the third season, gypsum did again significantly increase leaf N, but the lime effect was not significant.

A higher leaf N in gypsum treatments was also observed in the first season of the first maize trial (Chapter 4), and has been recorded in other gypsum trials at the Geluksburg site (M.P.W. Farina, personal communication, 1991).

Table 5.5. The effects of Na and gypsum on leaf N at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf N (g kg <sup>-1</sup> ) in 1993/94				
1000	19.0	19.8	24.9	2.93
3500	23.1	23.8	26.8	2.93
10 000	29.5	28.2	27.7	NS
15 000	29.9	29.9	29.3	NS
Mean	25.4	25.4	27.1	1.46
Leaf N (g kg <sup>-1</sup> ) in 1994/95				
1000	19.3	20.7	18.8	NS
3500	19.4	19.7	20.8	NS
10 000	18.6	21.8	20.8	NS
15 000	16.9	21.3	19.4	3.00
Mean	18.5	20.9	20.0	1.50
Leaf N (g kg <sup>-1</sup> ) in 1995/96				
2000	7.3	7.6	8.8	NS
4500	8.0	8.7	11.1	NS
11000	11.9	12.0	13.3	NS
16000	12.6	11.7	14.5	NS
Mean	9.9	10.0	12.0	0.97

LSD<sub>0.05</sub> for comparisons at different levels of lime are 5.11, 7.78, and 5.09 g kg<sup>-1</sup> for 1993/94, 1994/95, and 1995/96 respectively.



5.3.2.2 *Calcium*

In all seasons, gypsum increased Ca uptake, but in 1993/94, gypsum increased leaf Ca more at low levels of lime than at high levels of lime (Table 5.6). The effect of gypsum is probably two-fold; aluminium-induced suppression of Ca uptake is reduced at low lime levels, and the soil Ca is increased (gypsum increased topsoil Ca by 321 mg L<sup>-1</sup>). The Na treatment decreased leaf Ca significantly in all seasons, as was shown in the earlier maize trial (Chapter 4).

Table 5.6. The effects of Na and gypsum on leaf Ca at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf Ca (g kg <sup>-1</sup> ) in 1993/94				
1000	3.30	2.08	5.00	0.75
3500	3.43	2.58	4.83	0.75
10 000	4.43	3.58	5.40	0.75
15 000	4.33	3.65	4.80	0.75
Mean	3.87	2.97	5.01	0.37
Leaf Ca (g kg <sup>-1</sup> ) in 1994/95				
1000	3.58	2.23	4.08	0.48
3500	3.55	2.20	4.63	0.48
10 000	3.48	2.90	4.38	0.48
15 000	3.40	3.03	4.18	0.48
Mean	3.50	2.59	4.31	0.24
Leaf Ca (g kg <sup>-1</sup> ) in 1995/96				
2000	2.65	1.95	2.83	0.45
4500	2.93	1.95	3.23	0.45
11000	2.88	2.30	3.40	0.45
16000	2.95	2.58	3.60	0.45
Mean	2.85	2.19	3.26	0.23

LSD<sub>0.05</sub> for comparisons at different levels of lime are 1.81, 0.71, and 0.71 g kg<sup>-1</sup> for 1993/94, 1994/95, and 1995/96 respectively.

### 5.3.2.3 *Magnesium*

Leaf Mg was decreased by gypsum in the first two seasons, but the gypsum effect was not significant in the third season (Table 5.7). The effect of Na was less consistent (Table 5.7). Sodium decreased Mg at all lime levels in 1993/94, but its effect in 1994/95 and 1995/96 was not significant. This was associated with much lower Mg uptake in the second and third seasons, probably as a result of better K nutrition (leaf K overall means of 19.4, 27.3 and 21.9 g kg<sup>-1</sup> for the first, second and third seasons respectively). Leaf symptoms indicated, and leaf-Mg levels confirmed, severe Mg-deficiency at the lowest two lime levels in 1994/95 and 1995/96 (critical leaf-Mg levels lie between 1.5 and 2.5 g kg<sup>-1</sup>). Sodium appears to have suppressed leaf Mg only when leaf K is low, an observation also made in the ryegrass trial (Chapter 6).

### 5.3.2.4 *Potassium*

In 1993/94, leaf K was significantly higher in Na-treated plots (Table 5.8), as was found in the first maize trial (Chapter 4). In 1994/95 a similar trend was observed but in that season the effect was non-significant. Aside from the atypical 1995/96 season (waterlogging), the increase in leaf K with Na treatments is consistent over both trials. This effect may be the result of K<sup>+</sup>-Na<sup>+</sup> exchange at the root cortex (Jeschke, 1984), and is consistent with other observations of Na-induced increases in leaf K discussed in Chapter 2 (ap Griffith & Walters, 1966; Lessani & Marschner, 1978; Schultz *et al.*, 1979).

Table 5.7. The effects of Na and gypsum on leaf Mg at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf Mg (g kg <sup>-1</sup> ) in 1993/94				
1000	1.48	1.20	1.18	NS
3500	1.90	1.70	1.38	0.47
10 000	3.63	2.93	3.63	0.47
15 000	4.30	3.45	3.80	0.47
Mean	2.83	2.32	2.49	0.24
Leaf Mg (g kg <sup>-1</sup> ) in 1994/95				
1000	0.70	0.78	0.63	NS
3500	0.83	0.95	0.75	0.18
10 000	1.60	1.40	1.35	0.18
15 000	1.83	1.88	1.78	NS
Mean	1.24	1.25	1.13	0.09
Leaf Mg (g kg <sup>-1</sup> ) in 1995/96				
2000	0.55	0.53	0.48	NS
4500	0.55	0.65	0.58	NS
11000	1.50	1.30	1.28	0.20
16000	1.63	1.65	1.58	NS
Mean	1.06	1.03	0.98	NS

LSD<sub>0.05</sub> for comparisons at different levels of lime are 1.48, 0.29, and 0.50 g kg<sup>-1</sup> for 1993/94, 1994/95, and 1995/96 respectively.

Table 5.8. The effect of lime and split-plot treatments (sodium and gypsum treatments) on leaf K ( $\text{g kg}^{-1}$ ).

Lime level ( $\text{kg ha}^{-1}$ )	1993/94	1994/95	1995/96
1000*	18.2	28.4	22.1
3500*	18.3	26.7	22.4
10 000*	21.3	27.7	21.7
15 000*	19.8	26.2	21.4
LSD <sub>0.05</sub>	2.4	NS	NS
<b>Split-plot treatment</b>			
Control	18.2	27.1	21.8
200 kg Na $\text{ha}^{-1}$	20.6	27.4	21.8
Gypsum	19.4	27.2	22.1
LSD <sub>0.05</sub>	1.1	NS	NS

\*Lime level increased by  $1000 \text{ kg ha}^{-1}$  in 1995/96.

#### 5.3.2.5 *Copper*

The effect of lime on leaf concentrations of Cu in the first two seasons differed markedly. Leaf Cu was significantly increased by lime in the wet 1993/94 season, but was decreased significantly in the dry 1994/95 season (Table 5.9). There was no significant effect on leaf Cu in the third season. The solubility of Cu in soils generally decreases with increasing pH (Lindsay, 1979, p.223), so the 1993/94 lime effect is surprising. Possibly the solubility of Cu in the soil in this wet season did not limit Cu uptake, and some other factor such as root growth or metabolism (which would have been adversely affected by the soil acidity in the acid plots) was limiting Cu availability. Alternatively a soil factor, such as the rate of mineralization of soil organic matter, was over-riding sorption or precipitation reactions, and controlling the short-term solubility of Cu in the soil. Gypsum had a positive effect on leaf Cu at all lime rates in the first two seasons, possibly as a result of increased solubility of Cu due to the formation of the soluble  $\text{CuSO}_4^0$  ion pair. Sodium treatments had no significant effect on leaf Cu.

Table 5.9. The effects of Na and gypsum on leaf Cu at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf Cu (mg kg <sup>-1</sup> ) in 1993/94				
1000	5.75	5.75	8.25	1.74
3500	5.75	6.25	9.00	1.74
10 000	11.75	11.00	12.00	NS
15 000	11.00	9.25	11.50	1.74
Mean	8.56	8.06	10.19	0.87
Leaf Cu (mg kg <sup>-1</sup> ) in 1994/95				
1000	9.75	9.25	8.75	NS
3500	8.25	9.00	9.75	1.11
10 000	6.25	7.25	7.50	1.11
15 000	6.00	6.50	6.50	NS
Mean	7.56	8.00	8.13	0.55
Leaf Cu (mg kg <sup>-1</sup> ) in 1995/96				
2000	4.75	4.50	4.25	NS
4500	4.75	4.25	5.50	0.87
11000	4.75	5.00	5.00	NS
16000	5.00	4.75	5.25	NS
Mean	4.81	4.63	5.00	NS

LSD<sub>0.05</sub> for comparisons at different levels of lime are 3.51, 3.03, and 1.35 mg kg<sup>-1</sup> in 1993/94, 1994/95, and 1995/96 respectively.

## 5.3.2.6 Phosphorus

Sodium and gypsum increased leaf P at the second lime level in 1995/96, but gypsum decreased leaf P at the lowest lime level in 1993/94 (Table 5.10). Gypsum increased leaf P over all lime levels in 1995/96. Leaf P levels were much lower in 1995/96 (Table 5.10), probably due to reduced root metabolism under waterlogged conditions. Low leaf P in 1995/96 occurred despite increased soil P (Table 5.11).

Table 5.10. The effects of Na and gypsum on leaf P at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf P (g kg <sup>-1</sup> ) in 1993/94				
1000	2.50	2.48	2.10	0.26
3500	2.08	2.10	2.28	NS
10 000	2.75	2.70	2.63	NS
15 000	2.55	2.70	2.58	NS
Mean	2.47	2.49	2.39	NS
Leaf P (g kg <sup>-1</sup> ) in 1994/95				
1000	2.70	2.70	2.45	NS
3500	2.48	2.38	2.70	NS
10 000	2.48	2.60	2.65	NS
15 000	2.38	2.60	2.50	NS
Mean	2.51	2.57	2.58	NS
Leaf P (g kg <sup>-1</sup> ) in 1995/96				
2000	1.25	1.25	1.25	NS
4500	1.10	1.28	1.33	0.16
11000	1.28	1.33	1.38	NS
16000	1.30	1.25	1.28	NS
Mean	1.23	1.28	1.31	0.08

LSD<sub>0.05</sub> for comparisons at different levels of lime = 0.64 in 1993/94, 0.33 in 1994/95, and 0.32 in 1995/96.

Lime reduced Ambic-2 soil P in all seasons. The lime effect on extractable P is not uncommon in highly weathered soils, especially for bicarbonate-based extractants (Haynes, 1982; Miles & Farina, 1989; Edmeades *et al.*, 1990). The reasons for the effect, as well as the implications for soil-P tests have been widely debated (Haynes, 1982; Farina *et al.*, 1989; Miles & Farina, 1989; Edmeades *et al.*, 1990; van Raij & Quaggio, 1990), and will not be dealt with here. Sodium and gypsum had no consistent effect on Ambic-2 P.

Table 5.11. The effects of Na and gypsum on soil P at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Soil P (mg L <sup>-1</sup> ) in 1993/94				
1000	23.0	22.0	20.0	NS
3500	20.3	19.0	18.3	NS
10 000	12.0	15.0	15.0	NS
15 000	11.5	10.0	11.0	NS
Mean	16.7	16.5	16.1	NS
Soil P (mg L <sup>-1</sup> ) in 1994/95				
1000	30.3	26.5	23.8	3.4
3500	22.8	22.5	22.5	NS
10 000	16.8	17.0	15.5	NS
15 000	15.5	13.8	13.3	NS
Mean	21.3	19.9	18.8	1.7
Soil P (mg L <sup>-1</sup> ) in 1995/96				
2000	30.0	32.5	29.0	NS
4500	27.5	29.3	27.0	NS
11000	18.0	22.0	18.5	NS
16000	17.3	16.5	14.5	NS
Mean	23.2	25.1	22.3	2.2

LSD<sub>0.05</sub> for comparisons at different levels of lime = 5.0 in 1993/94, 5.4 in 1994/95, and 7.1 in 1995/96.

5.3.2.7 *Manganese*

Sodium chloride increased leaf Mn in the first maize trial (Chapter 4), but not in this trial, where NaCl was used as the Na treatment in 1993/94. Table 5.12 indicates lower leaf Mn for the NaCl treatment than for the control (not significant) and for the gypsum treatment (significant). Gypsum did not have a significant effect on leaf Mn in this trial, in contrast with the effect of gypsum observed in the first maize trial. Significant quadratic effects of lime on leaf Mn were observed in 1993/94 and 1995/96 (Table 5.12). Although the effect in 1994/95 was not significant, the trend was similar; i.e. leaf Mn increased from the first level of lime to the second, but decreased from the second or third level of lime to the highest level of lime.

Table 5.12. The effects of Na and gypsum on leaf Mn at different levels of lime.

Lime (kg ha <sup>-1</sup> )	Control	Na	Gypsum	LSD <sub>0.05</sub>
Leaf Mn (mg kg <sup>-1</sup> ) in 1993/94				
1000	81	57	99	26
3500	143	107	143	26
10 000	92	97	111	NS
15 000	78	84	81	NS
Mean	99	86	108	13
Leaf Mn (mg kg <sup>-1</sup> ) in 1994/95				
1000	104	98	108	NS
3500	130	127	137	NS
10 000	101	109	120	NS
15 000	83	85	88	NS
Mean	104	104	113	NS
Leaf Mn (mg kg <sup>-1</sup> ) in 1995/96				
2000	33	33	38	NS
4500	41	38	43	NS
11000	45	43	48	NS
16000	38	34	36	NS
Mean	39	37	41	3

LSD<sub>0.05</sub> for comparisons at different levels of lime = 32 in 1993/94, 35 in 1994/95, and 8 in 1995/96. Interaction significant only in 1993/94.



## 5.4 CONCLUSIONS

The results of this maize trial indicate that Na treatment of acid soils may improve maize yields in soils with high acid saturation, although it appears that excessive leaching of Na may occur in extremely wet seasons and prevent any beneficial effect from Na. The lack of response to gypsum or Na at the higher two rates of lime is at variance with other trials conducted at the Geluksburg site (Farina & Channon, 1988b; Chapter 4), and is probably because partial amelioration of the acid subsoil had occurred with the modified subsoiler treatments applied in 1983 and 1984.

## 6. THE RESPONSE OF ITALIAN RYEGRASS TO SODIUM, LIME AND POTASSIUM ON AN ACIDIC SOIL

### 6.1 INTRODUCTION

There are many potentially beneficial effects of Na in grazed pasture systems (Chapter 2). Horn (1988) and Beringer (1988) found that sodium applications to grasses can decrease the incidence of grass tetany and infertility in cattle, and improve grass palatability. Moseley (1980) found that NaCl fertilization of perennial ryegrass increased its digestibility in sheep. Sodium uptake by certain species (such as Italian and perennial ryegrass, Rhodes grass and white clover) can also decrease their potassium requirement without affecting dry-matter yield (Nowakowski *et al.*, 1974; Smith, 1974; Schultz *et al.*, 1979; Smith *et al.*, 1980; Mundy, 1983). Yield responses to Na at suboptimal soil K levels and associated changes in the composition of perennial ryegrass pastures have been shown to increase milk yield and milk fat content of cows grazing those pastures (Chiy & Phillips, 1991). The effect of Na on soil solution acidity (Chapters 3, 4 and 5) may also have beneficial effects on pasture growth. Thus investigation of Na-K and Na-acidity interactions may indicate ways of producing pastures of improved quality through the application of relatively cheap Na fertilizers. This may be of special significance on the highly weathered, acid soils of the KwaZulu-Natal midlands which are frequently K-deficient.

Italian ryegrass (*Lolium multiflorum*) is an important pasture species in KwaZulu-Natal. It responds to Na if K is deficient (Nowakowski *et al.*, 1974) and responds to lime on acid KwaZulu-Natal soils (Miles, 1986). The feasibility of cost-effective Na applications was therefore tested for this species in a field trial employing different rates of lime, sodium and potassium.

### 6.2 MATERIALS AND METHODS

The field experiment was sited at the Tabamhlope research station near Estcourt, KwaZulu-Natal (altitude 1450 m, mean annual rainfall 1166 mm, and pan evaporation 1478 mm). The soil is a sandy clay loam (clay content 320 g kg<sup>-1</sup>) of the Inanda form, Himeville family (Soil Classification Working Group, 1991), a Typic Hapludox (Soil Survey Staff, 1990), and the clay mineralogy is

kaolinitic-sesquioxidic. The soil is extremely acid, has very low topsoil P and K levels (Table 6.1) and has a high capacity to sorb applied phosphate.

Table 6.1. Topsoil (0-150 mm) data for the site used in the ryegrass trial. Soil P and K were determined in an Ambic-2 extract, and Ca, Mg, Na and titratable acidity in a 1 M KCl extract (Appendix 1).

Sample density (g mL <sup>-1</sup> )	0.87
Organic carbon (g kg <sup>-1</sup> )	31.5
P (mg L <sup>-1</sup> )	2.3
K (mg L <sup>-1</sup> )	45
Ca (mg L <sup>-1</sup> )	105
Mg (mg L <sup>-1</sup> )	39
Na (mg L <sup>-1</sup> )	20
Al+H (cmol <sub>c</sub> L <sup>-1</sup> )	2.08
Acid saturation of ECEC (%)	66.5
pH (KCl)	4.1

The design used was an unreplicated 4<sup>3</sup> fully confounded factorial with different levels of lime, NaCl and KCl applied to Italian ryegrass (*Lolium multiflorum* cv. Midmar). The gross plots measured 10.0 m x 3.0 m and they were separated in the direction of tillage by 1-m pathways. The nett plot size (for harvesting and soil sampling) was 7.6 m x 1.2 m.

Dolomitic limestone treatments were 0, 4 000, 8 000 and 12 000 kg ha<sup>-1</sup>, incorporated to a depth of 150 mm with a rotovator six weeks before planting in the autumn of 1989. The limestone had a calcium carbonate equivalent of 92.6%, and a Ca/Mg ratio of 2.73. The KCl and NaCl treatments and basal fertilizers were applied and incorporated to the same depth as the lime on the day that the trial was seeded. Potassium was applied at rates of 0, 42.5, 85 and 170 kg K ha<sup>-1</sup> and Na at rates of 0, 25, 50, 100 kg Na ha<sup>-1</sup> (Na and K rates are equivalent on a mole basis). Basal levels of P, Mg, S, B, Cu, Zn and Mo were applied at rates of 100, 150, 198, 5, 7, 20 and 0.2 kg ha<sup>-1</sup>, respectively. The K and Na treatments were reapplied after the third cut and further maintenance K applications (0, 15, 30, and 60 kg K per ha) were applied after the fourth and sixth cuts. Nitrogen was applied at a rate of 50 kg ha<sup>-1</sup> three weeks after planting and after each cut.

The trial was replanted in autumn 1990, but with the Na treatments in the form of Na<sub>2</sub>SO<sub>4</sub> at rates

of 0, 40, 80 and 120 kg Na ha<sup>-1</sup>. Sulphate levels were balanced using gypsum applications. Phosphate (100 kg P ha<sup>-1</sup> as double superphosphate) was re-applied at planting. The Na (and gypsum) treatments were re-applied on 6 July 1990 and 24 September 1990. Potassium levels were increased to 100, 150, 200 and 250 kg ha<sup>-1</sup> at planting and 60, 90, 120 and 150 kg ha<sup>-1</sup> on 6 July 1990 and 24 September 1990. Nitrogen applications after planting and after each cut were increased to 70 kg ha<sup>-1</sup>.

The trial was harvested at intervals of four weeks, resulting in seven harvests in each season. Herbage mass was determined on-site immediately after mowing and sub-samples taken for dry matter determination and chemical analysis (N, P, Ca, Mg, K, Na, Zn, Cu, and Mn) using the methods described in Appendix 1. Topsoils (0-100 mm) were sampled after the first, third and sixth cuts in the first season and after the first, third, fifth and seventh cuts in the second season. Subsoil samples were taken after each season's growth. Ambic-2 extractable P, K and Zn, 1 M KCl extractable Ca, Mg, Na and acidity, and pH were determined on the soil samples (Appendix 1). Percent acid saturation was calculated as "extractable acidity" x 100 / (Ca + Mg + K + "extractable acidity"). Resin-extractable P was determined for the soil samples taken on 6 November 1989 and 3 May 1990, using the mixed cation and anion exchange resin membrane method of Saggar *et al.* (1990).

### 6.3 RESULTS AND DISCUSSION

Lime decreased acid saturation, and Figure 6.1 shows the relationship between the total yield for each season and the acid saturation at the beginning of the respective season, at each level of lime. It is evident that in 1989 there was a response to lime at an acid saturation as low as 15%. As previous trials have indicated a permissible acid saturation for Midmar ryegrass of 25% (Miles, 1986), the significant response to the third lime level (8000 kg ha<sup>-1</sup>) in 1989 is unlikely to have been the result of Al toxicity. This response may have been due to the stimulation of N mineralization (plant N was increased by lime [Appendix 2]). However, herbage P was also consistently increased by lime, despite depression of Ambic P soil test values by lime (Appendix 2), so the lime effect may also have been a result of improved root growth, or improved availability of soil P, possibly as a result of P mineralization.

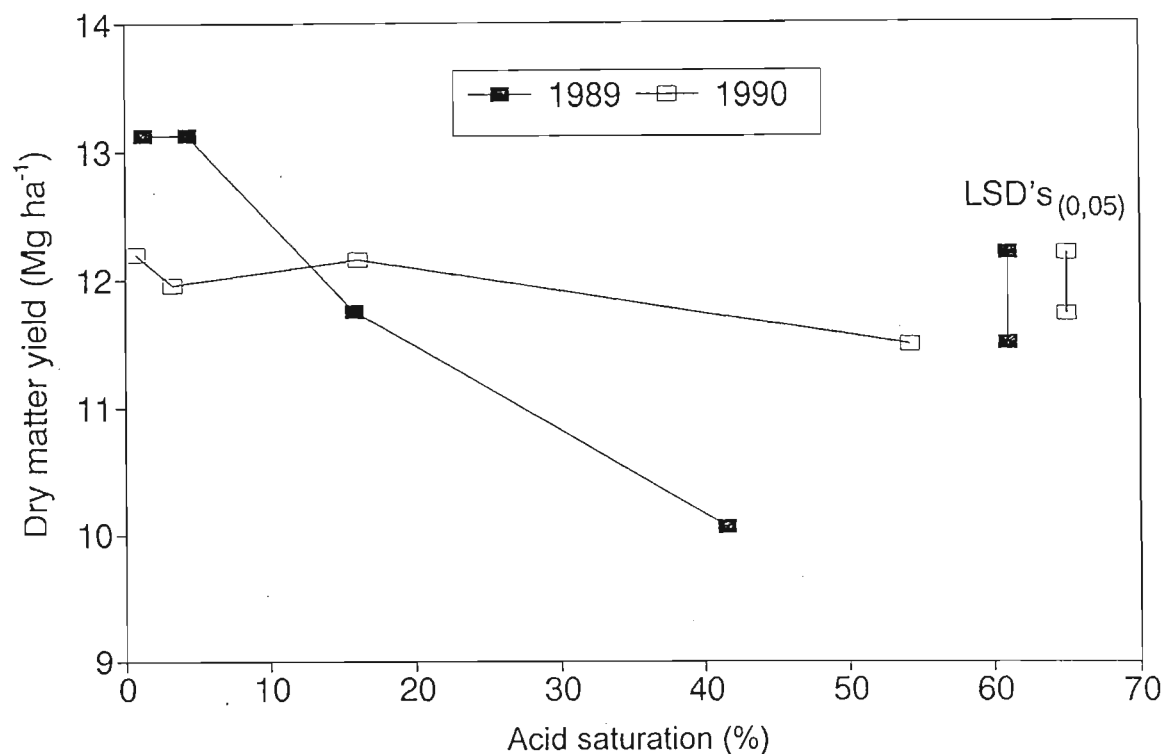


Figure 6.1. The relationship between total dry matter yield of ryegrass and acid saturation of the soil for the two seasons. The soils were sampled after the first cut in each season.

In 1990 a higher N application rate was used and 100 kg P ha<sup>-1</sup> was applied again at planting so that both the N status and the P status of the trial were higher than in 1989. This is probably why there was less response to lime in the second season (Figure 6.1 indicates only a 6% response to lime, with no significant response beyond the first lime level). Lime only increased herbage P in the first cut, which was also the only cut where there was a significant main effect due to lime on yield.

There were no significant interactions between lime and K or Na level in 1989 (results not shown), but in 1990, the sum of cuts 2, 3, and 4 (May to August), indicated a negative lime x Na interaction (Table 6.2). This may have been due to better P availability (discussed in more detail below), or to a higher soil solution pH in the Na<sub>2</sub>SO<sub>4</sub>-treated plots, both of which may have decreased the response to lime. The absence of a lime x Na interaction in 1989 may have been due to the lower P status of the soil in that year, or to a higher ionic strength (extra Cl<sup>-</sup> added as NaCl) which tends to override Na effects on solution pH (Chapter 2).

Table 6.2. Sodium and lime effects on the total yield (kg DM ha<sup>-1</sup>) from cuts 2, 3 and 4 (May to August) in 1990.

Lime level (kg ha <sup>-1</sup> )	Na level (kg ha <sup>-1</sup> )				Mean
	0	40	80	120	
0	2999	3603	3514	3396	3378
4 000	3038	3776	3451	4002	3567
8 000	2975	3389	3490	3773	3407
12 000	3323	3355	3474	3101	3313
Mean	3084	3531	3482	3568	

LSD<sub>0.05</sub> for body of table is 446 kg ha<sup>-1</sup>, and for marginal means is 223 kg ha<sup>-1</sup>.

As in the second maize trial (Chapter 5), lime applications had a significant negative effect on Ambic-2-extractable soil P (Table 6.3). It is, however, questionable whether this reflects the capacity of the soil to release P. The P extracted by mixed anion and cation membrane strips was unaffected or slightly increased by lime (Table 6.3). As methods involving the use of ion exchange resin are generally regarded as being more representative of plant-available P (Sibbesen, 1983; van Raij & Quaggio, 1990) it seems likely that the effect of lime on Ambic-2 P is an artifact of the Ambic extraction rather than an indication of the effect of lime on the ability of the soil to supply P. The lime-induced depression of bicarbonate-extractable P, possibly a result of an increase in Ca in the extracting solution, has been recognised as a problem associated with this analytical method (Miles & Farina, 1989; van Raij & Quaggio, 1990) and these data confirm the need to investigate the problem further.

Table 6.3. Effect of lime on Ambic-2 and resin-extractable P (mg L<sup>-1</sup>).

Lime rate kg ha <sup>-1</sup>	Sampled 6 Nov 1989		Sampled 3 May 1990	
	Ambic-2 P	Resin P	Ambic-2 P	Resin P
0	14.8	14.2	16.3	18.3
4 000	12.6	13.1	12.9	20.3
8 000	10.9	14.5	11.3	20.0
12 000	9.6	14.7	10.8	22.7
LSD <sub>0.05</sub>	2.8	NS	2.3	4.1

The yield response to K in 1989 was almost linear, and at every cut after the first, maximum yield was attained at the highest K level (Table 6.4). At times, even the plots receiving the highest level of K may have been deficient in K. The K application rates in 1990 were higher, and Table 6.4 indicates a plateau in yield at K rates of 440 kg ha<sup>-1</sup> and higher. Yield response to K was significant only at the second (29 May), third (6 July), and fourth (23 August) cuts; a linear response to K was evident in the second and third cuts, after appreciable K removal in the first cut; in the fourth cut a yield response was only evident at the first and second increments of K (Table 6.4).

Table 6.4. Response to K at each cut and total yield (kg DM ha<sup>-1</sup>) for each season.

Harvest date	Total K applied in season (kg ha <sup>-1</sup> )				LSD <sub>0.05</sub>
	0	115	230	460	
12 Apr 89	891	1245	1242	1223	283
10 May 89	2077	2212	2256	2587	263
7 Jun 89	1013	980	1052	1276	127
25 Aug 89	697	569	586	752	NS
2 Oct 89	2358	2867	3088	3322	301
6 Nov 89	1932	2281	2415	2473	167
4 Dec 89	1255	1635	1775	2000	167
Total	10223	11788	12414	13632	699
	Total K applied in season (kg ha <sup>-1</sup> )				
	220	330	440	550	
3 May 90	2964	2990	3203	2995	NS
29 May 90	1055	1139	1152	1323	113
6 Jul 90	575	692	741	904	128
23 Aug 90	1299	1535	1643	1607	168
24 Sep 90	1803	1675	1833	1844	NS
30 Oct 90	3063	3269	3383	3277	NS
29 Nov 90	531	427	401	479	NS
Total	11289	11729	12356	12429	476

Figure 6.2 indicates that the total yield from cuts 2 and 3 in both years showed a linear response to Ambic-extractable soil K, and it is evident from the indicated herbage K levels (given for each cut) that even the highest K treatment was probably K-deficient between the second and third cuts; the critical herbage K level for Midmar ryegrass at this stage of growth is  $30 \text{ g kg}^{-1}$  (Miles *et al.*, 1986). This highlights the difficulties associated with K fertilization of ryegrass. Increasing K applications at establishment generally increases K removal at the first cut (or grazing) by increasing herbage K to levels above that required for optimum growth, so that the application of high rates of K at planting is an inefficient way of supplying K for the second or third cut or grazing. This is recognised as a problem with pastures grazed by dairy cattle where K is removed from the pasture, but may also be a problem in beef systems where return of K is localised in dung and urine patches.

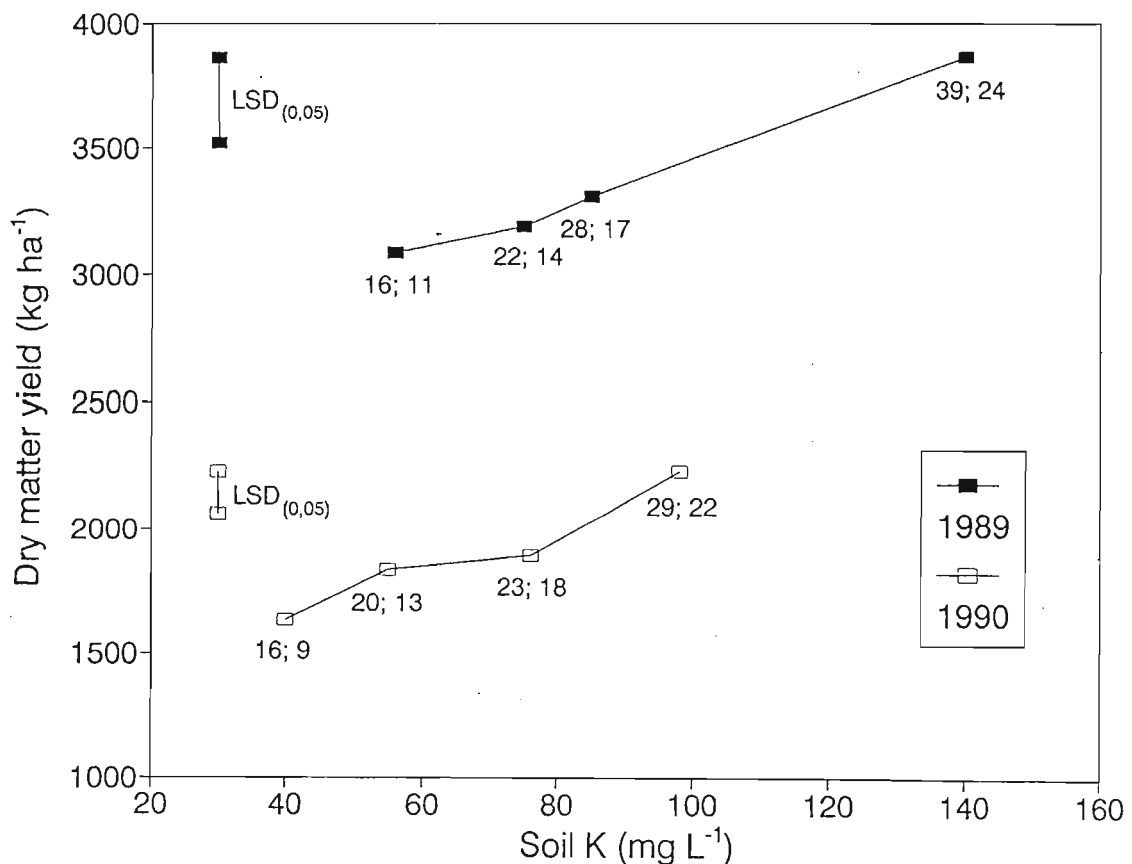


Figure 6.2. The relationship between soil K level (soils sampled at the first cut) and the dry matter yield of ryegrass from the second and third cuts in each of the two seasons. The first and second data labels for each point are herbage K level ( $\text{g kg}^{-1}$ ) at the second and third cuts, respectively.



It is evident from the 1990 data (Figure 6.3) that the August growth was more responsive to K than the October growth. In fact, the August growth of that season was more responsive to K than the September growth (Table 6.4), despite depletion of soil K over the period between K applications on 6 July 1990 and 24 September 1990, indicating that the plant may respond to higher soil K levels in the cooler part of the year. Cool soil temperatures are known to suppress K uptake by both temperate and tropical grass species (Wallace, 1957, Nielsen *et al.*, 1960, Nielsen *et al.*, 1961, Miller & Davey, 1967, Walker, 1969).

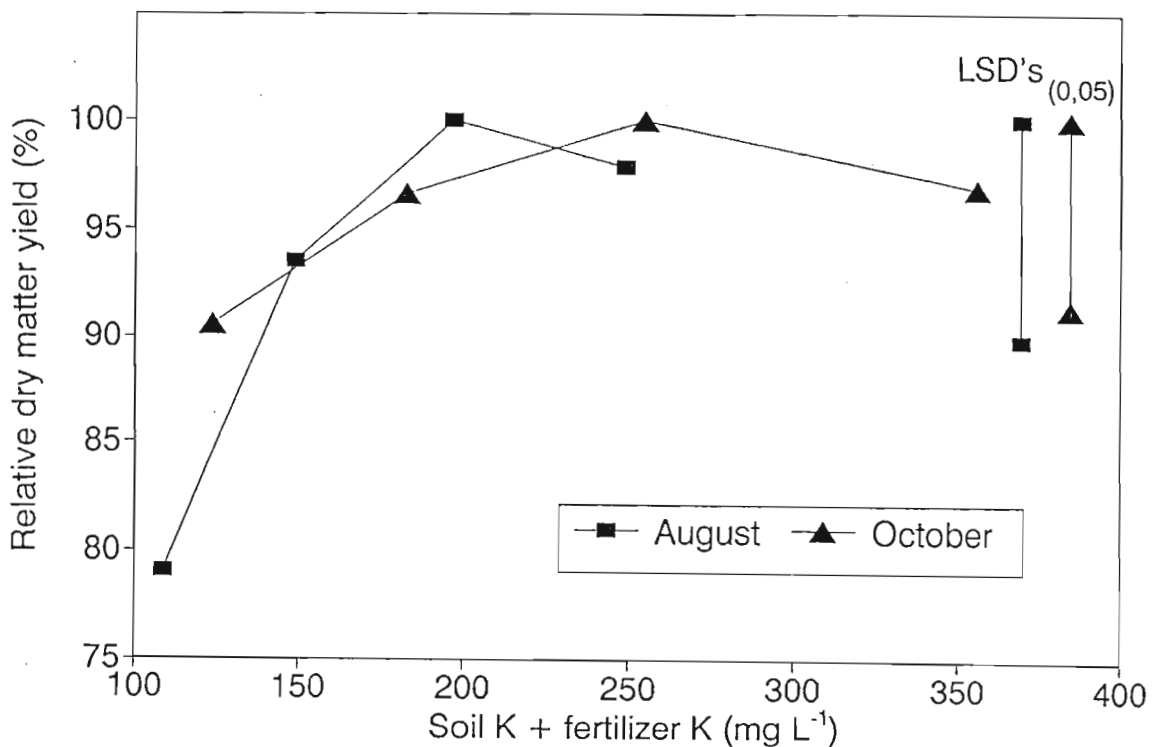


Figure 6.3. The relationship between the sum of soil K (Ambic extraction) and fertilizer K and the dry matter yield of ryegrass from the fourth (August) and the sixth (October) cuts in 1990. It was assumed that 1 kg K ha<sup>-1</sup> applied to the soil surface was equivalent to 1 mg K L<sup>-1</sup> of soil (sampling depth of 100 mm).

Figure 6.4 shows that the critical herbage K level may also decrease after establishment and the cool winter period; cuts one (12 April) and two (10 May) of 1989 and cut four (23 August) of 1990 show responses to K when herbage levels exceed 25 g kg<sup>-1</sup>, but cut six (6 November) of 1989 and cuts five (24 September) and six (30 October) of 1990 indicate that little response to

K occurs at this growth period (initiation of reproductive phase) if leaf K levels exceed  $20 \text{ g kg}^{-1}$ . This is important if leaf samples are to be taken to diagnose possible K deficiencies, as the critical leaf K would depend on the time of the year that the sample was taken.

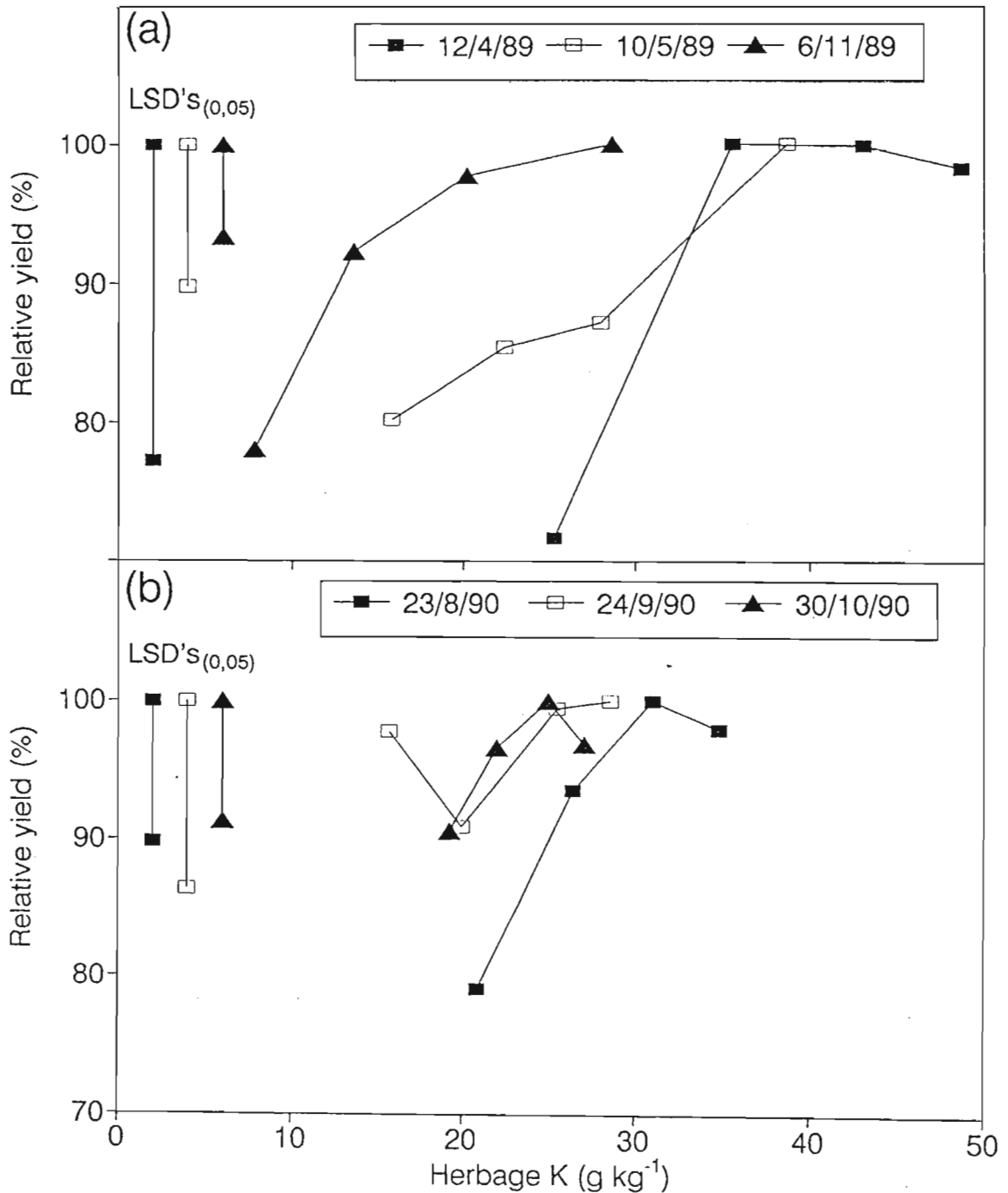


Figure 6.4. The relationship between relative dry matter yield of ryegrass (expressed as a percentage of maximum yield at each cut) and herbage K for (a) the first, second and sixth cuts in 1989 and (b) the fourth, fifth and sixth cuts in 1990.

Nowakowski *et al.* (1974) indicated that Na may modify critical herbage K levels in pot trials. In this field trial the only individual cut showing a significant K x Na interaction was the fourth cut of 1990 (Figure 6.5). Where Na responses at other cuts were significant, as was the case several times in 1989 (Table 6.5), there was generally a response to Na at the highest K level. This may have been because K was limiting yield even at that level, or because Na increased yield via a mechanism other than K substitution. Nevertheless, it is clear that a yield response to Na can be of considerable benefit. As indicated, the chance of K deficiency in parts of most pastures is high after the first or second grazing, even if initial K application rates were substantial; higher soil levels of Na during this period may decrease the sensitivity of the pasture to such a deficiency.

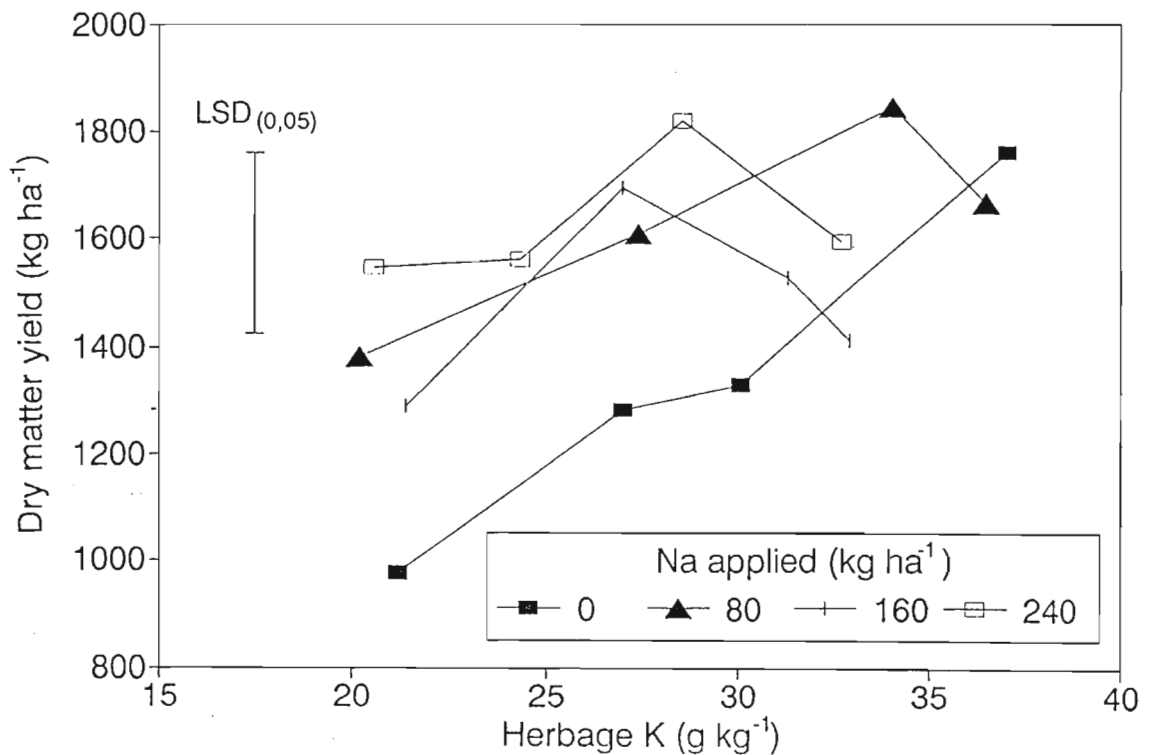


Figure 6.5. The relationship between herbage K and the dry matter yield of ryegrass from the fourth cut (23 August) of 1990, at different levels of Na application.

Table 6.5. Response to Na at each cut and total yield (kg DM ha<sup>-1</sup>) for each season.

Harvest date	Total Na applied in season (kg ha <sup>-1</sup> )				LSD <sub>0.05</sub>
	0	50	100	200	
12 Apr 89	1133	1168	1038	1261	NS
10 May 89	2029	2247	2363	2493	263
7 Jun 89	1010	992	1124	1195	127
25 Aug 89	561	691	635	716	NS
2 Oct 89	2778	2832	2947	3077	NS
6 Nov 89	2166	2313	2301	2322	NS
4 Dec 89	1612	1647	1655	1752	NS
Total	11289	11888	12065	12815	699

	Total Na applied in season (kg ha <sup>-1</sup> )				
	0	120	240	360	
3 May 90	3042	3092	3037	2981	NS
29 May 90	1087	1177	1232	1172	NS <sup>a</sup>
6 Jul 90	660	716	770	767	NS
23 Aug 90	1337	1637	1480	1630	168
24 Sep 90	1779	1855	1778	1742	NS
30 Oct 90	3287	3320	3319	3067	NS
29 Nov 90	500	461	399	479	NS
Total	11691	12259	12016	11836	NS

<sup>a</sup> The response to Na for the cut taken on 29 May 1990 was significant at the 10% level with LSD<sub>0.1</sub>=94 kg ha<sup>-1</sup>

Another mechanism whereby Na may increase plant growth is by increasing soil P solubility (Barrow & Shaw, 1979; Section 2.2.2). In a variety of soils, it has been shown that the type of cation in the soil solution and on the exchange complex, affects the solubility of soil-fixed phosphate (Lehr & van Wesemael, 1952; Ryden & Syers, 1975; Singh & Tabatabai, 1976; Barrow & Shaw, 1979; Sharpley *et al.*, 1988). In all the cases, an increased proportion of Na relative to the other common exchangeable cations increased phosphate solubility. In this trial Na had a

significant positive effect on P concentration in the herbage at the first, third, fourth, fifth and sixth harvests of 1989 (Table 6.6), and the concentrations of P were at levels where a yield response to increased P uptake would be expected (Miles, 1986).

Table 6.6. Effect of NaCl applications on P concentration in ryegrass herbage at each harvesting date in 1989. Sodium was applied at planting and after the third harvest.

Harvest date	Na applied (kg ha <sup>-1</sup> application <sup>-1</sup> )				LSD <sub>0.05</sub>
	0	25	50	100	
	g P kg <sup>-1</sup>				
12 Apr 89	3.03	3.34	3.52	3.57	0.37
10 May 89	2.78	2.76	2.98	2.91	NS
7 Jun 89	2.32	2.36	2.61	2.59	0.16
25 Aug 89	1.80	1.89	1.98	2.02	0.11
2 Oct 89	1.65	1.68	1.82	1.78	0.12
6 Nov 89	2.16	2.49	2.50	2.44	0.18
4 Dec 89	2.06	2.14	2.33	2.24	NS

In the 1990 season there was no significant response to Na at those cuts that showed no response to K, but analysis of the total yield from cuts two, three, and four (all of which showed a response to K) indicates a highly significant ( $P < 0.001$ ) response to Na, and there was a significant ( $P < 0.05$ ) interaction with K (Figure 6.6). This response to sodium may therefore be as a result of K substitution by Na. There was, however, also a significant effect of applied Na **and** K on herbage P in the samples taken on 7 July 1990 (the third cut), and a tendency towards a negative interaction between the Na and K effects on herbage P was also evident (Table 6.7). This was not observed throughout the rest of the season, indicating that the yield response to Na (and possibly also to K) over the coolest part of the season may have been at least partly due to a P-uptake effect.

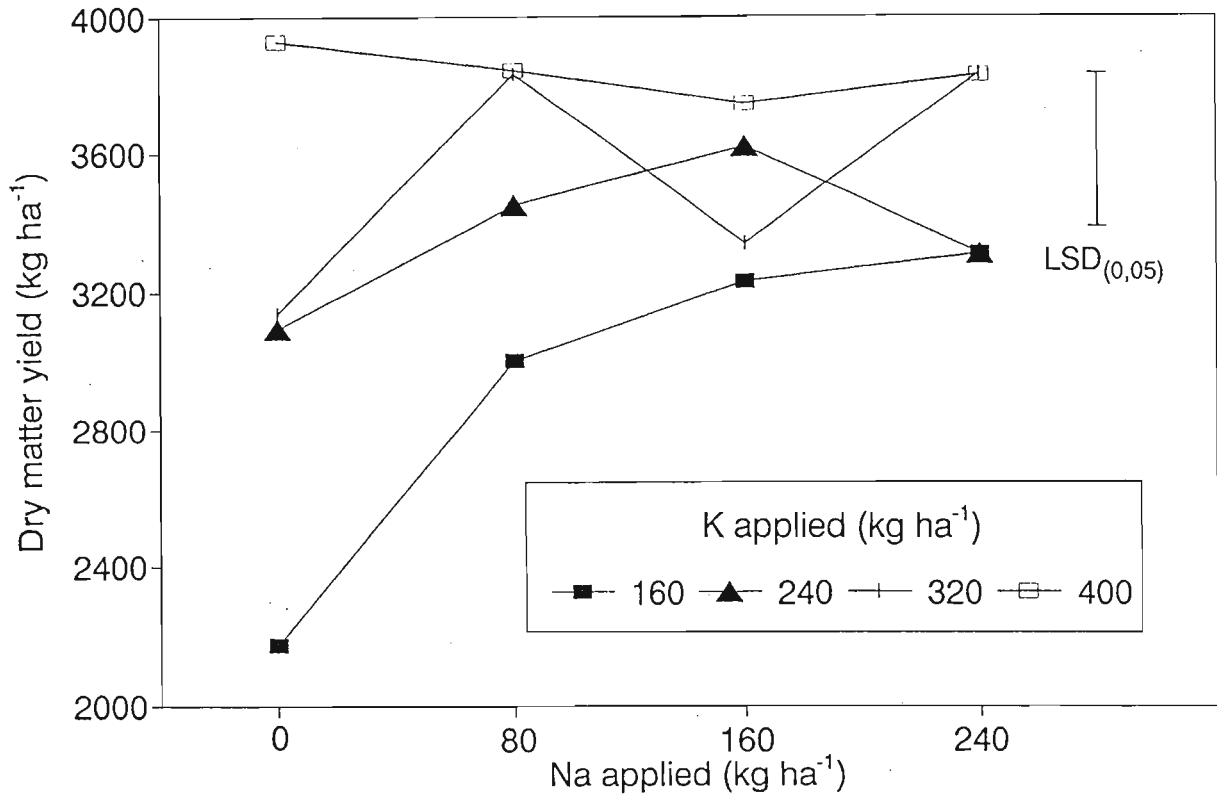


Figure 6.6. The effect of applied Na and K on the total dry matter yield of ryegrass from the second, third and fourth cuts (May to August) in 1990.

Table 6.7. Effects of Na and K applications on P concentration in ryegrass herbage sampled on 7 July 1990.

K applied (kg ha <sup>-1</sup> applic. <sup>-1</sup> )	Na applied (kg ha <sup>-1</sup> application <sup>-1</sup> )				Mean
	0	25	50	100	
	----- g P kg <sup>-1</sup> -----				
0	1.73	1.83	1.98	2.08	1.90
42.5	1.72	1.90	2.23	1.98	1.96
85	2.03	2.10	2.10	2.20	2.11
170	2.13	2.08	2.05	2.23	2.12
Mean	1.90	1.98	2.09	2.12	

LSD<sub>0.05</sub> for marginal means = 0.14 g kg<sup>-1</sup>; interaction is not significant.

The elemental composition of pasture grasses is important as it affects the quality of the herbage as a source of minerals important in animal nutrition. In this context, the effects of different treatments on the concentrations of Ca, Mg, K, and Na in the herbage are important (Mundy, 1983; Miles *et al.*, 1986). The K and Na treatments had significant effects on the cation concentrations in the ryegrass. Figure 6.7b shows that the Mg level in herbage samples taken on 2 October 1989 was depressed by K applications and that at low K, Na applications also depressed herbage Mg, although at high K, Na had little effect. This negative interaction is significant at the 95% confidence level. A similar trend is evident in the case of Ca (Figure 6.7a), although in this case the interaction is not statistically significant. In the case of herbage K (Figure 6.7c), Na applications had no effect at any level of K, but K applications did have a marked effect on level of K in the herbage. The effects of K and Na on herbage Na were, however, markedly different (Figure 6.7d). At high levels of K, very little Na was taken up, irrespective of the rate of Na application, whereas at low K, Na applications resulted in a large increase in herbage Na; this interaction is significant at the 99% confidence level. This is important because, although Italian ryegrass is a natrophile, it is unlikely that Na applications would increase herbage Na and thus animal Na uptake significantly unless herbage K levels were suboptimal for maximum yield.

#### 6.4 GENERAL DISCUSSION

Although there was a significant yield response to lime at an acid saturation of 15% in 1989, the 1990 results correspond to those expected after the work of Miles (1986), which indicates a critical acid saturation of 25% for this cultivar. This discrepancy may have been due to the correction of a yield-limiting factor other than Al toxicity, such as N or P deficiency, possibly by mineralization of organic N or P or improved availability of inorganic soil P or a combination of these mechanisms. Haynes (1982, 1984) and Edmeades *et al.* (1990) stress the importance of considering these factors when assessing responses to liming, and consideration of the stimulation of microbial breakdown of organic matter after liming is particularly pertinent in the cropping of humic (high organic matter, low base status) topsoils. Reports of positive pasture growth responses on these soils to lime, under conditions where responses would not have been expected on the basis of exchangeable acidity levels, are common, and it is likely that many of these observed responses were a result of enhanced N or P mineralization.

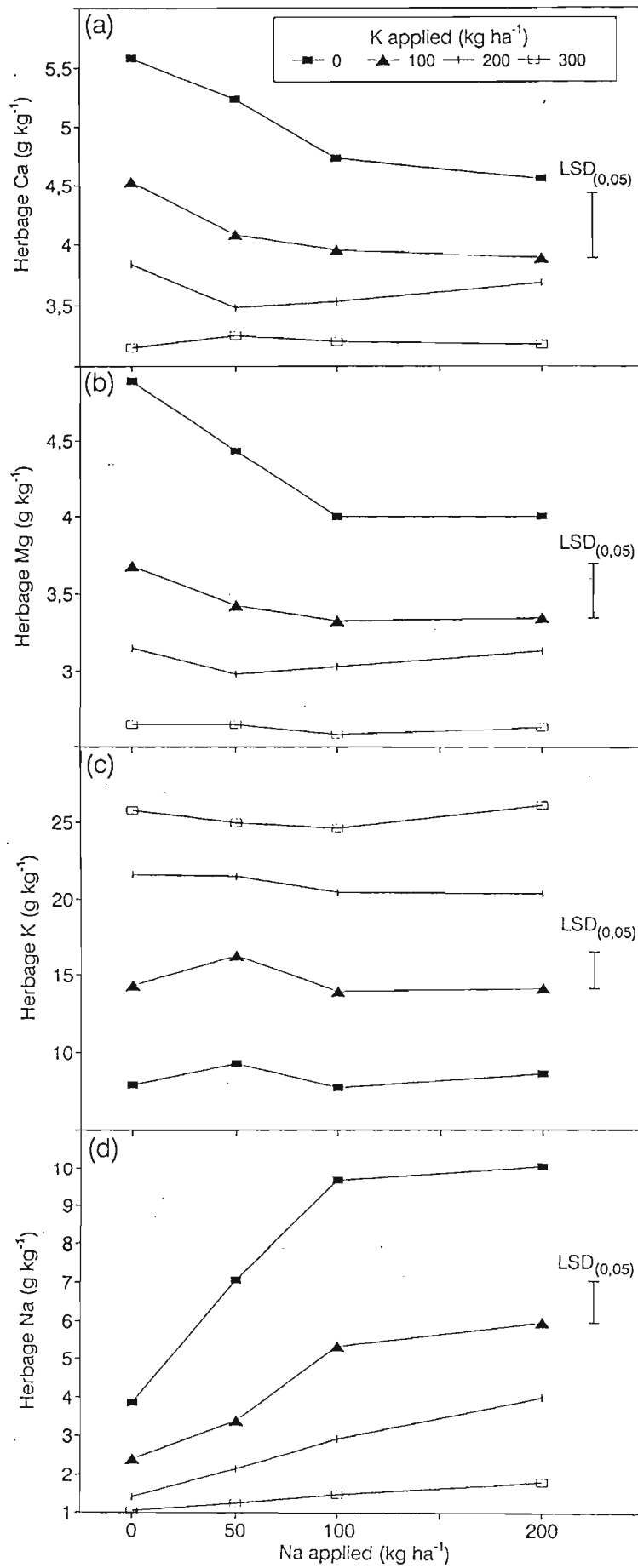


Figure 6.7. The effect of K and Na applications on (a) Ca, (b) Mg, (c) K and (d) Na concentrations in herbage samples taken on 2 October 1989.



With regard to the K responses observed in this trial, the findings of Miles *et al.* (1986) were confirmed. In autumn and winter, Italian ryegrass responds positively to K applications when soil K levels are below  $100 \text{ mg L}^{-1}$  and herbage K levels are below  $30 \text{ g kg}^{-1}$ . In addition, there are indications that Italian ryegrass may be more responsive to K, and may require higher herbage K levels early in the season and in cooler periods than in the late spring and early summer period.

Although this trial indicated that Na may modify the response of Italian ryegrass to acidity, the effect was not clearly demonstrated, and no definite conclusions in this regard can be made. On the other hand, the overall response to Na indicates that the element may be useful as a fertilizer, especially if it is recognised that Na is essential for animal nutrition. Responses to limited autumn applications of Na may occur in situations where soil K and P reserves are marginal for optimal growth in the coolest part of the growing season, when fodder production is critical. Sodium can, however, have a negative effect on soil physical properties; soil infiltration rates may decrease in situations where low infiltration rates are already a problem. To minimise this potentially negative effect, Na for the autumn should only be applied at planting, when it can be incorporated into the soil rather than surface applied. Surface-applied applications not exceeding  $100 \text{ kg ha}^{-1}$  may be considered in July to stimulate spring growth. NaCl would probably be the least harmful carrier as it would result in a high soil solution ionic strength, making the soil surface less susceptible to sealing. Applications of gypsum (surface applied) would probably completely overcome any possible surface sealing problems (Jayawardane & Chan, 1994).

## 7. DISCUSSION

### 7.1 SODIUM AND SOIL ACIDITY

The following evidence exists that Na can alleviate effects of soil acidity:

- higher pH and lower Al concentration and  $\text{Al}^{3+}$  activity at a given ionic strength (Chapter 3);
- improved penetration of maize roots into a NaCl-treated (rather than KCl-treated) acid subsoil (pot trial, Chapter 3);
- improved yield of field-grown maize with NaCl,  $\text{Na}_2\text{CO}_3$ , and  $\text{NaNO}_3$  applied to the Pinedene soil at Geluksburg (limed topsoil; Chapter 4);
- negative interaction between the effects of Na and gypsum on maize yield in a Geluksburg field trial (limed topsoil; Chapter 4);
- relationship between soil solution Na and soil solution pH and soil solution Al of a Geluksburg subsoil (multiple regression, Chapter 4);
- increased maize yields due to NaCl and  $\text{Na}_2\text{SO}_4$  in field plots with acid saturations of greater than 40% (second Geluksburg field trial, Chapter 5);
- increased water pH with  $\text{Na}_2\text{SO}_4$  treatments in Geluksburg field trial (Chapter 5);
- negative interaction between Na and lime effects on Italian ryegrass yield in Tabamhlope field trial (cuts two, three and four of 1990, Chapter 6);
- improved root growth of wheat, maize, and rice in Al-containing nutrient solutions (Section 2.1.3.2; Kinraide & Parker, 1987; Ryan *et al.*, 1994; Tadano & Gotoh, 1995); and
- correlation of the ratio of the concentration of Al to Na in 0.005 M KCl extracts with the incidence of Al toxicity in wheat over 53 field experiments in Western Australia. This index was superior to Al concentration alone when comparing responses at different sites and in different seasons (Carr *et al.*, 1991; Carr & Ritchie, 1993).

It is apparent that at least two independent mechanisms exist whereby Na may alleviate the effects of soil acidity, i.e., the cation-exchange effect, whereby increased exchangeable Na at a particular concentration of exchangeable Al and ionic strength gives higher pH and lower solution Al; and the direct effect of Na on roots growing in nutrient solutions containing Al. The work reported here cannot be used to assess the relative importance of these two effects for crops growing in

soil.

One aspect of the cation-exchange effect on solution Al worth consideration is the interaction with total solution anion concentration (closely related to ionic strength). This parameter will determine the soil concentration of exchangeable Na required to have an appreciable effect on soil solution acidity. Sodium effects will be maximal at low solution anion concentrations for two reasons. Firstly, there must be sufficient Na to dominate the cation suite in the soil solution, and secondly, cation exchange equilibrium models, simply expressed by the Ratio Law, indicate that at higher ionic concentrations Na<sup>+</sup> competes more strongly with Al<sup>3+</sup> for cation-exchange sites (Russell, 1973, p. 90).

The interacting effects of Na and total solution anion concentration compound the difficulties associated with the selection of an index of Al toxicity. For example, the 1:5 0.005 M KCl extract used by Carr *et al.* (1991) does not necessarily reflect the acidity of the soil solution at a similar ionic strength, because in some soils Na<sup>+</sup> will dominate that solution, making it significantly less acid than in the 1:5 0.005 M KCl extract. In other soils the Na<sup>+</sup> concentration will be negligible, and in these the 1:5 0.005 M KCl extract is likely to reflect the soil solution acidity more closely.

Percival *et al.* (1996) reported data from a set of soils which had high levels of 1 M KCl-extractable acidity, but had low concentrations of Al at field moisture conditions and low ionic strength. The exchangeable Na concentrations of the soils did, however, vary from 0.08 to 1.01 cmol<sub>c</sub> kg<sup>-1</sup> (ESP range was 0.4-5.8%). This variation would probably result in a range of soil acidity responses to increased ionic strength. The Na concentration should also affect the relationship between water pH and soil solution pH (the only difference between the two measures being the amount of water added). The data of Percival *et al.* (1996) do show that solution Na (expressed as an equivalent fraction of the total soluble cations) is related to this pH difference which was greater than 0.5 pH units for five of the 14 soils in that study (Section 3.3.3).

Sodium will have an effect on any measure of acidification or amelioration of acidity when pH(water) is used as an index and in many situations it would be wise to back up such an index with measurements that are not Na-sensitive (or ionic-strength sensitive). An example of such a situation is the use of buffer methods for the determination of lime requirement of soils (Aitken

& Moody, 1994; Chapter 2). As indicated in Chapter 2, Na effects on the resin method of lime assessment (Bornman *et al.*, 1988) may be significant. When using this method to compare pure  $\text{CaCO}_3$  powder with a 20:80 mixture of  $\text{Na}_2\text{CO}_3$  and  $\text{CaCO}_3$ , the mixture was assessed as having 10.4% more neutralizing power than the pure  $\text{CaCO}_3$ , i.e. the  $\text{Na}_2\text{CO}_3$  was assessed as being 61% more effective than the pure  $\text{CaCO}_3$  when compared equivalent-for-equivalent.

Manganese toxicity is not a major problem in the soils studied but Na effects on solution acidity are likely to affect the expression of this problem also. Where pH is used to identify Mn problems, the effects of Na and ionic strength on the relationship between measured water pH and actual soil solution pH may again be relevant.

Can Na be used to combat soil acidity problems? Because Na is so easily leached, and because of its potentially negative effects, effective amelioration of topsoils will generally be better accomplished with the use of lime and other amendments that actually neutralize acidity. In subsoils, too, deep incorporation of lime, or surface application of gypsum will usually give more predictable and long-term effects. The use of Na may, however, be justified in certain situations, e.g. as a low-cost, short-term ameliorant where expensive, long-term amendment of acidity is not justified (such as when land is leased). In the first maize field trial (Chapter 4),  $100 \text{ kg ha}^{-1}$  of Na as NaCl used as a subsoil ameliorant was as effective as  $4000 \text{ kg ha}^{-1}$  of gypsum at a fraction of the cost (currently R94-00  $\text{ha}^{-1}$  and R480-00  $\text{ha}^{-1}$  for the NaCl and gypsum treatments respectively). Where lime cannot be incorporated to the depth required, and gypsum applications are not effective, Na application can also be considered.

Sodium may make other approaches more effective. Maintenance of low ionic strength, together with moderate Na treatments could be useful in cases of subsoil acidity. A similar approach may be to create spatial variability e.g., applications of lime in bands could be used to neutralize zones with high salt (fertilizer) levels, while a low-salt, moderate-Na strategy in inter-rows may be sufficient to allow effective rooting in those zones.

Organic amendments are receiving a considerable amount of attention as ameliorants of soil acidity (Haynes & Moklobate, 1999) and interactions between their effects and those of Na may be of importance. Animal manures often contain appreciable amounts of Na. Gilbertson *et al.*

(1979) indicate that typical Na concentrations in manures from different species range from 3 to 7 g kg<sup>-1</sup> (dry-matter basis) and they warn that under some circumstances the proportions of Na and K in manure or feedlot runoff water may promote soil structure deterioration. In chicken litter (which has become a popular source of plant nutrients in KwaZulu-Natal) concentrations of 0.7-7.4 g Na kg<sup>-1</sup> (in moist chicken litter) are reported by Moore *et al.* (1995), and concentrations of 2.7-7.3 g Na kg<sup>-1</sup> (dry-matter basis) have been measured by the KwaZulu-Natal Department of Agriculture laboratory at Cedara. The Na content of manures and chicken litter may influence their efficacy as ameliorants through the cation exchange effect, and possibly also the solubility and mobility of organic matter. A note of caution for those researching the acid-neutralising effects of these and other materials containing Na is that one needs measurements other than water pH to assess actual neutralization of acidity, as Na on its own may have significant effects on water pH of soils without actually neutralising acidity.

## 7.2 SODIUM AND CATION EXCHANGE: OTHER POSSIBLE IMPLICATIONS

Lower soil solution Ca concentrations (as a result of the presence of Na) might enhance dissolution of gypsum (CaSO<sub>4</sub>) and rock phosphate applied to soil, as a higher level of exchangeable Ca would be required to support a particular Ca activity in the soil solution. This would make the exchange phase a larger sink for dissolved Ca, and allow higher sulphate or phosphate levels in solution before high activity products of the relevant ions retarded further dissolution. Thus Na may enhance the ability of gypsum to ameliorate subsoil acidity and increase the plant availability of rock phosphate.

Effects on K availability could include lower K in solution which may limit uptake by some plants, but in some soils may increase availability of 'non-exchangeable K' from high-energy sites (Section 2.2.1). The nett effect of Na through cation-exchange phenomena will, therefore, probably be different for different species and for different soil types, and will be confounded by the direct effect of Na on K uptake (Section 2.1.3.1), with a Na<sup>+</sup>-K<sup>+</sup> pump at the plasmalemma (Jeschke, 1984) being the most likely reason for the observed effects on K uptake by maize (Chapters 4 and 5).

### 7.3 SODIUM AND POTASSIUM IN PLANT NUTRITION

Potassium-substitution effects of Na in pasture species and other crops are likely to be of far greater importance than the K-effects discussed above. Recent work at Cedara (N. Miles, personal communication, 1999) confirms that soil-K norms for Italian ryegrass can be substantially reduced, with likely animal nutrition benefits (Section 2.1.4), especially in the light of the high variability in soil-K concentration across grazing paddocks. Even if Na fertilizers are not recommended, K recommendations can be reduced for soils with substantial concentrations of Na. Perennial ryegrass, clover, and *Cynodon* species are other important KwaZulu-Natal species which could be used more effectively if the K-Na interaction was more closely considered.

Other crops grown on acid KwaZulu-Natal soils which would likely benefit from Na fertilizer as a K substitute are the brassica crops (of which cabbage is the most important) and Japanese radish, an important winter fodder crop often grown on the acid soils of the Highland Sourveld.

### 7.4 SODIUM EFFECTS ON PHOSPHORUS-USE EFFICIENCY

Observations of Na effects on P-availability in this study were limited, but it may be significant that they were observed when P-availability was probably most limited. In the first maize trial (Chapter 4), the only positive effect of Na on leaf P was in the first season, before soil P levels had built up, and no effects were observed in the second maize trial (Chapter 5), where previous applications of P had already built up soil P levels. The most marked effects of Na on leaf P were in the first season of the Italian ryegrass trial (Chapter 6), in a site never fertilized previously. In the second season of that trial, Na effects were limited to the coolest part of the season. These observations highlight the possibility that the effects of P sorption may be lower in soils with moderate Na concentrations than in soils with more-typically low Na and that application of P together with a source of Na may limit P sorption. In the case of Na applications, relatively small amounts of Na in the fertilizer granule, or in the fertilizer band may suffice (effects are more likely to be positive if ionic strength is low in the vicinity of the applied P). The Na content of animal wastes may account for part of their effects on P sorption.

## 7.5 FORMS OF SODIUM FERTILIZER

When assessing Na as a fertilizer, attention will need to be given to the carriers of Na which might be used. The cheapest and most obvious is NaCl, but increased ionic strength due to the Cl<sup>-</sup> ion may reduce P solubility and increase Al<sup>3+</sup> solubility, possibly making the more expensive Na<sub>2</sub>CO<sub>3</sub>, Na<sub>2</sub>HPO<sub>4</sub> or NaNO<sub>3</sub> more attractive alternatives. Placement of relatively low rates of Na<sub>2</sub>SiO<sub>3</sub> or Na<sub>2</sub>CO<sub>3</sub> with phosphate in bands at planting also needs consideration, as benefits may accrue from the localized effects of those compounds on both acidity and P solubility.

Price and local availability would probably mitigate against widespread use of carriers other than NaCl in KwaZulu-Natal unless specific, cost-effective applications were demonstrated on a field scale. Recent prices (as at November 1999) quoted by a local chemical supplier were R0.49, R1.20, R1.48, R2.80, and R8.50 per kilogram for NaCl, Na<sub>2</sub>SO<sub>4</sub>, Na<sub>2</sub>CO<sub>3</sub>, NaNO<sub>3</sub>, and Na<sub>2</sub>HPO<sub>4</sub>, respectively. Cattle salt is available from agricultural suppliers at R0.37 per kilogram.

## 7.6 POSSIBLE PROBLEMS

Caution is required before widespread use of Na as a fertilizer is advocated. If high application rates are used there is a risk of long-term soil degradation as a result of decreased hydraulic conductivity (Shainberg & Letey, 1984). Reduced infiltration rates might also be significant since decreased infiltration rates are known to be associated with exchangeable Na percentages of greater than two (Shainberg & Letey, 1984), which are probable at application rates of greater than 100 kg Na ha<sup>-1</sup>.

Sodium applications are, however, least likely to have a negative effect if the soils are well-drained and have a high degree of aggregate stability (as are most dystrophic KwaZulu-Natal soils), if the co-anion applied with the Na is mobile in the soil (chloride or nitrate rather than carbonate or phosphate), and if the Na is incorporated into the soil rather than surface-applied.

## 7.7 POSSIBLE FUTURE WORK

One approach would be to look at the effect of Na and ionic strength on the relationships between soil solution pH and Al and commonly used indices (water and KCl pH, KCl-extractable acidity, Al and acid saturation) in a wider variety of soils. Can simple cation-exchange equations (eg. the Gapon equation) be used to predict these relationships reliably, or are more complex models necessary? Can data from simple routine analyses be used to predict soil solution pH and Al?

Are crops that respond to Na in nutrient solutions the only ones that respond to Na as an acid soil ameliorant? Research aimed at answering this question may lead to a better understanding of the importance of each of the two observed effects of Na, i.e. the improved rooting observed in nutrient solutions containing Al and the cation-exchange effect of Na resulting in lower  $Al^{3+}$  activity in soil solution.

Carr *et al.* (1991) found that a measure of Na could be used to develop an improved index for the prediction of Al toxicity. This thesis has shown that future work aimed at developing predictive soil acidity indices should also consider exchangeable and/or solution Na as a factor that can modify plant response to acidity.

Can techniques be developed whereby Na and ionic strength effects on soil solution acidity and root growth can be used more effectively? The possibility of maintaining spatial variability has been mentioned above (Section 7.1).

Research into the effects of Na on a wider variety of crops may lead to useful information. These include acidity effects (e.g. Na effects on lucerne), potassium-substitution effects in a wider variety of crops (cabbage, Swiss chard, red beet, Smuts finger grass, *Cynodon* species are all important in KwaZulu-Natal), and P-availability effects on crops in the field situation. In particular, investigation of the effects of Na on efficacy of banded P may lead to reduced P-inputs for field crops.



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<b>(Quattro Pro 6.0)</b>	
Ch4 Leaf data.wb2	Leaf analysis data for the first maize trial discussed in Chapter 4.
Ch4 Plot plan.wb2	Plot plan for the first maize trial discussed in Chapter 4.
Ch4 Soil data.wb2	Soil analysis data for the first maize trial discussed in Chapter 4.
Ch4 Yield data.wb2	Yield data for the first maize trial discussed in Chapter 4.
Ch5 Leaf data.wb2	Leaf analysis data for the second maize trial discussed in Chapter 5.
Ch5 Plot plan.wb2	Plot plan for the second maize trial discussed in Chapter 5.
Ch5 Soil data.wb2	Soil analysis data for the second maize trial discussed in Chapter 5.
Ch5 Yield data.wb2	Yield data for the second maize trial discussed in Chapter 5.
Ch6 Leaf data.wb2	Leaf analysis data for the Italian ryegrass trial discussed in Chapter 6.
Ch6 Plot plan.wb2	Plot plan for the Italian ryegrass trial discussed in Chapter 6.
Ch6 Soil data.wb2	Soil analysis data for the Italian ryegrass trial discussed in Chapter 6.
Ch6 Yield data.wb2	Yield data for the Italian ryegrass trial discussed in Chapter 6.

## APPENDIX 1. ANALYTICAL METHODS

### Soil analysis

The following soil analyses were performed using the rapid procedures described by Hunter (1975) and Farina (1981): Ambic-2-extractable P, K and Zn, KCl-extractable Ca, Mg and acidity, and pH (KCl and water). These procedures are those used by the Fertilizer Advisory Service of the KwaZulu-Natal Department of Agriculture at Cedara, and are described below.

### Sample preparation

Samples are air dried using air forced to flow over the samples laid out in drying trays. The air is kept at room temperature. When air-dry, the samples are milled (using a mill where the soil is crushed between rubber belts) and passed through a 1 mm sieve; material coarser than 1 mm is discarded.

### Batch handling

Samples are scooped into trays which each contain 11 PVC cups (capacity 70 mL); a tray is used for nine unknown samples, one standard soil sample (for quality control) and one blank. For operations such as dispensing and stirring, and for quality control, batches of three trays (27 samples, three unknowns, and three blanks) are used. Multiple dispensers and diluter/dispensers are used to dispense aliquots of extractant or reagent to three samples at a time.

### pH

10 mL of soil is scooped into sample cups. 25 mL of 1 M KCl solution or de-ionised water is added and the suspension is stirred at 400 r.p.m. for 5 min using a multiple stirrer. The suspension is allowed to stand for about 30 minutes, and the pH is measured using a gel-filled combination glass electrode while stirring.

**Extractable (1 M KCl) calcium, magnesium and acidity**

2.5 mL of soil is scooped into sample cups. 25 mL of 1 M KCl solution is added and the suspension is stirred at 400 r.p.m. for 10 min using a multiple stirrer. The extracts are filtered using Whatman No.1 paper. 5 mL of the filtrate is diluted with 20 mL of 0.0356 M SrCl<sub>2</sub>, and Ca and Mg determined by atomic absorption. 10 mL of the filtrate is diluted with 10 mL of de-ionised water containing 2-4 drops of phenolphthalein, and titrated with 0.005 M NaOH.

**Extractable (Ambic-2) phosphorus, potassium, zinc and manganese**

The Ambic-2 extracting solution consists of 0.25 M NH<sub>4</sub>CO<sub>3</sub> + 0.01 M Na<sub>2</sub>EDTA + 0.01 M NH<sub>4</sub>F + 0.05 g L<sup>-1</sup> Superfloc (N100), adjusted to pH 8 with a concentrated ammonia solution. 25 mL of this solution is added to 2.5 mL soil, and the suspension is stirred at 400 r.p.m. for 10 min using a multiple stirrer. The extracts are filtered using Whatman No.1 paper. Phosphorus is determined on a 2 mL aliquot of filtrate using a modification of the Murphy and Riley (1962) molybdenum blue procedure (Hunter, 1974). Potassium is determined by atomic absorption on a 5 mL aliquot of the filtrate after dilution with 20 mL de-ionised water. Zinc is determined by atomic absorption on the remaining undiluted filtrate.

**Effective CEC (ECEC) and Acid saturation**

Effective CEC is calculated as the sum of KCl-extractable Ca, Mg, and acidity and Ambic-2 extractable K. Percent acid saturation of the ECEC is calculated as "extractable acidity" x 100 / (Ca + Mg + K + "extractable acidity").

**Plant tissue analysis**

Plant material was also analysed using procedures used by the KwaZulu-Natal Department of Agriculture Fertilizer Advisory Service. The batch-handling procedures are similar to those used for the soil analyses described above. Plant material is dried at 70°C, and milled to pass through a 0.84 mm sieve. Subsamples of plant material are then dry ashed at 450°C overnight and taken up in 1 M HCl. The P concentration is determined colorimetrically by the same method used for soil extracts, and K, Na, Ca, Mg, Cu, Mn, and Zn are determined by atomic absorption. Nitrogen is determined before ashing, using near-infrared reflectance (Eckard *et al.*, 1988).