INTRODUCTION

Groundnut (*Arachis hypogaea* L.) has traditionally been one of the important crops of the smallholder-farming sector in Zimbabwe. As a protein source, it is an important component of the diet of the rural people. The demand for it by the oil expressing industry and confectioners also makes groundnut a cash crop of significance to the economy of Zimbabwe. The smallholder-farming sector produces more than 60% of the total crop (CSO, 2001). Spanish groundnut cultivars with a growing period of 100-130 days, depending on altitude, are largely grown. Some Valencia cultivars are also grown in the cooler, wetter areas (Hildebrand, 1996).

The bulk of the groundnut crop in Zimbabwe is produced on light textured soils ranging from coarse and fine sands to sandy clay loams. These soils are highly weathered, and have low Ca, Mg, P and Zn status (Grant, 1970; Mashiringwani, 1983; Tagwira *et al.,* 1993). In addition, the soils are usually acidic (Grant, 1970; Grant *et al.,* 1979, Mashiringwani, 1983), giving rise to high hydrogen ion (H^+) concentrations as well as toxicities of aluminium (Al) and manganese (Mn). Nyamangara & Mpofu (1996) reported considerable acidification rates in light textured soils in some communal areas in the high potential zones, with approximately 24% of arable soils becoming very strongly acidic over a ten-year period, and 56% of the soils needing to be limed. Recent surveys by the Chemistry and Soils Research Institute, Zimbabwe utilising the Diagnosis and Recommendation Integrated System (DRIS) programme showed that 69% of the sandy soils in eight communal areas had pH values between 4.2 and 4.5, with the majority of the soils having Al saturation levels exceeding 20% of the CEC (Mukurumbira, 1997; Dhliwayo *et al.*, 1998).

Despite the recent genetic and disease resistance improvements to the groundnut crop, its productivity has declined in the smallholder-farming sector, with pod yields averaging less than 500 kg ha^{-1} (CSO, 2001). Acid soil infertility in this farming sector could be a major contributing factor, and even if smallholder farmers are aware of the acidity status of their soils, their poor resource base is a major socioeconomic constraint that limits the extent to which they can invest in large amounts of liming materials. In view of this situation, practicable options for soil acidity amelioration are a prerequisite.

To overcome the constraints arising from acid soil infertility of the Zimbabwean sandveld soils, liming is advocated. Liming increases soil pH, neutralizes exchangeable Al and Mn toxicity, improves Ca and Mg supply, increases molybdenum (Mo) availability, decreases phosphorus (P) fixation, improves nitrogen efficiency and ensures optimal bacterial nitrogen fixation (Mendez & Kamprath, 1978; Sanchez & Uehara, 1980; Haynes, 1984). Mukurumbira & Dhliwayo (1996) showed that upon correction of soil pH through liming, a substantial increase in the N and P fertilizer use efficiency was achieved. Besides lime, other alternative ameliorants include wood ash (Clapham & Zibilske, 1992); animal wastes and green manures (Ahmad & Tan, 1986; Hue, 1992; Berek, *et al*., 1995; Materechera & Mkhabela, 2002); phosphate (Mongia *et al*., 1998) and gypsum (Shainberg *et al.,* 1989; Sumner, 1993; Carvalho & van Raij, 1997). On Zimbabwean soils, Grant (1967) observed that an annual cattle manure application of 3 to 6 t ha^{-1} progressively increased the cation exchange capacity, exchangeable bases and pH of a sandveld soil. Mugwira (1984) also documented substantial increases in soil pH due to application of cattle manure (1.29% N) at rates ranging from 10 to 80 t ha^{-1}.

Many studies have shown soil acidity amelioration to be of benefit to groundnut production (Snyman, 1972; Hartzog & Adams, 1973; Reid & Cox, 1973; Sullivan, Jones & Moore, 1974; Walker, 1975: Blamey & Chapman, 1982; Gani *et al.,* 1991). In general, results have shown that the benefit of soil amelioration, particularly with respect to kernel quality, has been due to improved calcium nutrition. Nonetheless, because of the many factors involved in acid soil infertility, coupled with the geocarpic nature of the crop, elucidation of the often unpredictable responses of groundnut to soil amelioration has been difficult (Blamey & Chapman, 1982).

SCOPE OF THESIS

The factors that constitute acid infertility and govern plant growth and yields in acid soils are complex. Low exchangeable soil Ca and Mg levels, low availability of P, K, Zn and Mo, and high H, Al and Mn levels in soil solution contribute in various degrees to the infertility problems of acid soils. The situation is further complicated by interactions of these factors with drought and with plant genotypes. At a given soil pH value, the limiting factor may vary with soil type; in a given acid soil, it may vary with plant species or cultivar (Awad *et al.,* 1976; Foy, 1984;

Fageria *et al.,* 1990; McCray & Sumner, 1990). It is therefore imperative to accurately identify the growth-limiting factor(s) in the particular soil, and then develop appropriate ameliorative strategies.

Since low soil pH stress and Ca deficiency are important components of the soil acidity constraints to groundnut growth in acid soils, the study will attempt to quantify the role of low pH *per se* and contributions of absolute Ca deficiency as well as pH x Ca interactions in regulating growth and productivity of groundnut.

Because the fruits of groundnut develop underground, they are just as vulnerable to direct effects of soil acidity as the roots are, thereby necessitating an assessment of the effects of acidity both in the podding (0 – 10 cm soil depth) and rooting (20 – 30 cm soil depth) environments of groundnut. It is reported in the literature that high Ca supply in the rooting environment inhibits Mg, P, K and Fe uptake, which may reduce these nutrients in the groundnut plant to deficiency levels. In the podding zone, high Ca also inhibits Mg, Zn and Mn uptake by the developing pods (Zharare, 1997). In addition, high Mg in the podding environment inhibits direct Ca and Zn uptake by pods, which results in poor pod filling. High concentrations of K and Mg in the pod zone can affect Ca uptake, thereby affecting groundnut fruit development, yield and quality (Alva *et al.,* 1989). The addition of different Ca-containing materials to soils not only changes various physico-chemical properties of soil, but also affects the availability of nutrients to plants. Caution is needed to avoid inducing deficiencies of other essential nutrients when applying Ca/Mg-containing materials to ameliorate soil acidity for groundnut production. This study will observe the reactions of the different types and amounts of liming materials with soils, as well as their effects on the nutrient status of the soils. There is a growing body of literature indicating that gypsum combined with lime is more effective in improving crop productivity than is lime alone when soils are acid (McLay *et al.,* 1994; Menzies *et al.*, 1994). This study will seek to elucidate the effectiveness of Ca-materials applied alone or in combination in improving groundnut performance in acid soils.

The overall goal of this study is to measure the effects of soil acidity amelioration on nutrient composition, growth, yield and quality of groundnut so as to come up with sound ameliorative

strategies that would improve groundnut yields on acid soils. The study seeks to shed light on the nutrient interactions in the podding and rooting environments of groundnut. Hypotheses to be tested in the study are:

1. Groundnut yields on acid granite sands are limited by either (i) low pH *per se*, (ii) deficiencies of essential nutrients, particularly Ca, Mg or P or (iii) combinations of low pH and deficiencies of essential nutrients, and can be ameliorated to varying degrees by different Ca sources.
2. Because of the geocarpy of the groundnut plant in which the fruits mature underground, the crop is also susceptible to soil acidity in the podding environment, in addition to the rooting environment, and the direct effects of soil acidity in the podding environment can be observed.
3. Seed priming or pelleting with Ca can improve groundnut establishment under low pH stress.

The specific hypotheses and objectives are presented in detail for each experiment in the pertinent chapters.

RESEARCH METHODOLOGY

To assess the effect of judicious use of Ca-containing materials in ameliorating acid soil infertility constraints to groundnut growth, productivity and quality, several issues were investigated.

(a) What are the effects of the Ca-source on soil pH and availability of essential nutrients (Ca, Mg, N, P and K) in the rooting and podding environment of groundnut?

(b) Which components of acid soil infertility are most limiting to groundnut productivity on the acid sandy soils in Zimbabwe?

(c) What are the effects of low pH *per se,* or the interactive effects of pH and availability of Ca on (i) germination, (ii) seedling survival, (iii) early growth and (iv) pod formation and development?

(d) Can seed priming or pelleting with Ca provide sufficient Ca to ameliorate the effects of acidification in the sensitive seedling stage?

(e) Do groundnut genotypes differ in their tolerance to acid soil infertility?

A three-year field experiment was conducted to determine the ameliorative effects of four Ca-sources on soil acidity, soil nutrient availability and plant nutrient composition, and on the vegetative and reproductive performance of groundnut on acid light textured soils of Zimbabwe. Residual effects of the ameliorants were assessed in seasons two and three. Pot experiments were also conducted for two seasons under glasshouse conditions at Harare Research station to examine the effects of Ca-source and Ca-rate on uptake of nutrients by groundnut in relation to both vegetative and reproductive performance in acid, light textured soils collected from communal areas. Soils were analysed for essential nutrients at the peak flower and physiological maturity stages from the pod zone (0 - 10 cm soil depth) and the root zone (20 - 30 cm soil depth). Samples of the youngest fully expanded leaves were also taken at peak flower and at physiological maturity stages, and analysed for essential nutrients. At maturity, samples of the groundnut shells and kernels were digested for chemical analysis. The four Ca-sources used in the study are calcitic lime (23% Ca), dolomitic lime (18% Ca), gypsum (20% Ca) and single superphosphate (12% Ca).

To investigate genotypic differences in tolerance to acid soil infertility, yield, soil and leaf nutrient composition, data was collected for fifteen groundnut cultivars and lines grown in a breeding experiment in the 1999/2000 season at Makoholi Experiment Station, Zimbabwe.

Greenhouse and growth chamber experiments were conducted at the Hatfield Experimental Farm, University of Pretoria to derive a better understanding of the relative importance of low pH *per se*, and Ca deficiency in limiting groundnut growth and productivity. The experiments investigated the effects of low pH *per se* and availability of Ca on germination, seedling survival, and vegetative and reproductive growth of groundnut. Studies on the effects of low pH and Ca on pod formation and development were conducted using a split medium technique whereby the roots were grown in sand culture and the pods in solution culture. Effects of seed priming and pelleting with Ca on germination and early seedling growth were investigated in growth chambers and in the field at the Hatfield Experimental Farm, University of Pretoria.

CHAPTER 1

LITERATURE REVIEW

1.1 THE GROUNDNUT CROP

1.1.1 ORIGIN, DISTRIBUTION AND STATISTICS

The cultivated groundnut (*Arachis hypogaea* L.) is an ancient crop of the New World, which originated in South America (southern Bolivia/north west Argentina region) where it was cultivated as early as 1000 B.C. Dissemination of the crop to Africa, Asia, Europe and the Pacific Islands occurred presumably in the sixteenth and seventeenth centuries with the discovery voyages of the Spanish, Portuguese, British and Dutch (Krapovickas, 1969, 1973; Gregory *et al.*, 1980; Hammons, 1982; Isleib *et al.*, 1994). Today, it is grown in areas between 40 degrees South and 40 degrees North of the equator, where average rainfall is 500 to 1200 mm and mean daily temperatures are higher than 20^{o}C. The groundnut crop is cultivated in 108 countries on about 22.2 million hectares, of which 13.69 million ha are in Asia (India 8 million ha; China 3.84 million ha), 7.39 million ha in Sub-Saharan Africa, and 0.7 million ha in Central and South America. Average pod yields on a global scale increased slightly from 1.08 Mt ha^{-1} in the 1980's to 1.15 Mt ha^{-1} in the 1990's (Carley & Fletcher, 1995), and the global production is 29 million tonnes of pods. India, China, and the United States are the leading producers and grow about 70% of the world's groundnuts (FAO, 1995-2001; CGIAR Research, 2000).

1.1.2 UTILISATION

The uses of groundnut are diverse; all parts of the plant can be used. The nut (kernel) is a rich source of edible oil, containing 36 to 54% oil and 25 to 32% protein (Knauft & Ozias-Akins, 1995). About two thirds of world production is crushed for oil, which makes it an important oilseed crop (Woodroof, 1983). The oil is used primarily for cooking, manufacture of margarine, shortening and soaps. Seeds are consumed directly either raw or roasted, chopped in confectioneries, or ground into peanut butter. Young pods may be consumed as a vegetable,

while young leaves and tips are utilized as a cooked green vegetable (Martin & Ruberte, 1975). Scorched seeds may serve as a coffee substitute (Duke, 1981).

Nonfood products such as soaps, medicines, cosmetics, pharmaceuticals, emulsions for insect control, lubricants and fuel for diesel engines can be made from groundnut. The oil cake, a high-protein livestock feed, may be used for human consumption. The haulms are excellent high protein hay for horses and ruminant livestock. Groundnut shells may be used for fuel (fireplace "logs"), as a soil conditioner, for sweeping compounds, as a filler in cattle feed, as a raw source of organic chemicals, as an extender of resin, as a cork substitute, and in the building trade as blocks or hardboard (Gibbons, 1980).

In folk medicine, groundnut is used for aphrodisiac purposes, inflammation, cholecystosis, nephritis and decoagulant. In China, the oil is taken with milk for gonorrhea, and used externally for rheumatism, while in Zimbabwe the groundnut is used in folk remedies for plantar warts (Duke & Wain, 1981; Duke & Ayensu, 1985).

1.1.3 BOTANY

The groundnut belongs to the family *Leguminosae,* subfamily *Papilionoidae,* tribe *Aeschnomeneae,* sub-tribe *Stylosanthinae,* genus *Arachis* and species *hypogaea* (Isleib *et al.*, 1994). The genus name *Arachis* stems from a-rachis (Greek, meaning without spine) in reference to the absence of erect branches. The species name *hypogaea* stems from hupo-gè (Greek, meaning below earth) and relates to the gynophore (flower stalk or peg) that grows downward into the earth so that the pod develops underground. Remarkably *A. hypogaea,* the only cultivated species, is not known in its wild state. Subspecific and varietal classifications are mostly based on location of flowers on the plant, patterns of reproductive nodes on branches, number of trichomes and pod morphology (Krapovickas & Gregory, 1994). There are two major subspecies of *A.hypogaea* that mainly differ in their branching pattern (Gibbons *et al.,* 1972): ssp. *hypogaea* with alternate branching and subspecies *fastigiata* with sequential branching (Table 1.1). Within the *hypogaea* ssp.are two botanical varieties; var. *hypogaea* (Virginia and runner types) and var. *hirsuta* (Peruvian humpback and Chinese dragon). Subspecies *fastigiata* is also

divided into botanical varieties *fastigiata* (Valencia type) and *vulgaris* (Spanish type) (Chapman, 1990; Singh & Simpson, 1994).

Table 1.1 Subspecies of Arachis hypogaea

Subspecies	Site of flowering and pod production	Growth habit	Botanical variety and market type	Seed dormancy	Maturation time
Hypogaea	Lateral branches	Spreading	*Hypogaea* runner	Present	Long 145-165 days
		Bunching	*Hypogaea* Virginia *Hirsuta*	Present	
Fastigiata	Main stem	Erect	*Fastigiata* Valencia	Low or absent	Short 90-120 days
			Vulgaris Spanish	Low or absent	

Source: Singh & Simpson, 1994; Shokes & Melouk, 1995

1.1.4 MORPHOLOGY AND DEVELOPMENT

Groundnut seed consists of two cotyledons, stem axis and leaf primordia, hypocotyls and primary root. The function of the hypocotyl is to push the seed to the soil surface during germination, and its length is determined by planting depth. The hypocotyl stops elongating as soon as light strikes the emerging cotyledon. Thus, groundnut emergence is intermediate between the epigeal (hypocotyl elongates and cotyledons emerge above ground) and hypogeal (cotyledons remain below ground) types. The taproot grows very fast, reaching a mean length of 10 – 12 cm within four to five days. Lateral roots appear about three days after germination (Gregory *et al.,* 1973). Initial plant growth is slow, with more rapid growth being observed between 40 and 100 days after emergence (Ramanatha Rao, 1988).

Groundnut is a self-pollinating, annual, herbaceous legume growing upright or prostate, and has an indeterminate growth habit. Natural cross pollination occurs at rates of less than 1% to greater

than 6% due to atypical flowers or action of bees (Duke, 1981; Coffelt, 1989). The plant is sparsely hairy and generally grows 12 to 65 cm high. Plants develop three major stems; the main stem develops from the terminal bud on the epicotyl while the two lateral stems equal in size to the central stem develop from the cotyledonary auxiliary buds. Groundnut produces a well-developed taproot with many lateral roots. The taproot has four series of spirally arranged lateral roots with abundant branching and usually with a large number of nodules. Roots do not have conventional root hairs; clumps of hairs are formed in the axils of lateral roots (Moss & Ramanatha Rao, 1995).

Groundnut plants start flowering about 30 to 40 days after planting and maximum flower production occurs 6 to 10 weeks after planting. The flowers are self-pollinated around sunrise, and wither within 5-6 hours. Within one week of fertilization, the tip of the ovary bearing from 1–5 ovules, grows out from between the floral bracts, bearing with it the dried petals, calyx lobes and hypanthia; creating a unique floral structure - the carpophore, commonly known as a peg or gynophore (Ramanatha Rao, 1988). The peg quickly elongates, and growth is positively geotropic until it penetrates several centimeters (5-10 cm) into the soil when the tip becomes diageotropic, and the ovary starts developing into a pod (Ramanatha Rao, 1988). Because flowering continues over a long period, and because of the relationship between the number of pods per plant and rainfall pattern, pods are in all stages of development at harvest. Pegs near the taproot that enter the soil early in the season require a longer period of time to reach maturity than pegs located farther away from the plant (Ramanatha Rao, 1988; Stalker, 1997).

The pod is an elongated sphere with different reticulation on the surface and /or constriction between the seeds, and contains one to five seeds (Gregory *et al*., 1973; Ramanatha Rao, 1988; Stalker, 1997). Pods reach maximum size after 2 to 3 weeks in the soil, maximum oil content in 6 to 7 weeks, and maximum protein content after 5 to 8 weeks (Ramanatha Rao & Murty, 1994).

Considerable variability exists in groundnut morphological traits: seed size, (0.15 to more than 1.3 g seed^{-1}), seed color (white, light rose, rose, red, purple, white blotched with purple red), number of seeds pod^{-1} (1-5), pod length (11-83 mm) and pod breadth (9-27 mm) (Krapovickas & Gregory, 1994; Ramanatha Rao & Murty, 1994; Retamal *et al*., 1990; Stalker & Simpson, 1995).

1.1.5 ECOLOGY AND FERTILITY REQUIREMENTS

Groundnut requires abundant sunshine and warmth for normal development, but does not appear to be especially sensitive to day-length, though it generally produces more flowers under long day conditions (Stalker, 1997). Temperature significantly influences the rate of development and growth of groundnut, the optimum range for vegetative and reproductive growth being between 25 and 30^{o}C (Cox, 1979; Leong & Ong, 1983). Groundnut grows in regions with an average annual rainfall of 500 – 1200 mm; thrives best when more than 500 mm of rain is evenly distributed during the growing season (Sellschop, 1967). Moisture stress during reproductive development causes embryo abortion, reduces seed development by restricting calcium uptake by the pods, and increases aflatoxin contamination of the seeds (Stalker, 1997).

Groundnut is grown mostly on light-textured soils ranging from coarse and fine sands to sandy clay loams with moderately low amounts of organic matter (1 – 2 %) and good drainage (Henning *et al.,* 1982). The well-drained soils provide good aeration for the roots and nitrifying bacteria. Groundnut does not grow well in soils with a high water retention capacity (Stalker, 1997), and grows best in slightly acidic soils with optimum pH ranging from 5.5 to 6.2 (Gibbons, 1980).

Groundnut requires considerable amounts of nutrients for high yields, however, responses to applied fertilizers have been observed to be very erratic, justifying the name of "the unpredictable legume". It has often been accepted that groundnut has the ability to utilize soil nutrients that are relatively unavailable to other crops, and can therefore make good use of residual fertility (Sellschop, 1967; Reid & Fox, 1973; Cox *et al*., 1983). An effective fertilization programme should take into cognizance the levels of nutrient removal. Thus, the estimated amounts of nutrients removed by the groundnut crop, the partitioning of total uptake of macronutrients by growth stage and sufficiency ranges of the nutrients are given in Tables 1.2, 1.3 and 1.4, respectively.

Table 1.2 Nutrient uptake/removal in groundnuts (kg ha^{-1})

Plant Part	Yield	N	P	K	Ca	Mg	S
Pods	*3 t ha^{-1}*	120	11	18	13	9	7
Haulms	*5 t ha^{-1}*	72	11	48	64	16	8
	Total	192	22	66	77	25	15

Source: Gascho, 1992

Table 1.3 Partitioning of total uptake of macronutrients by growth stage

Growth stage	Percentages (%) of total uptake				
	N	P	K	Ca	Mg
Vegetative	10	10	19	10	11
Reproductive	42	39	28	53	48
Ripening	48	51	53	37	41

Source: Longanathan & Krishnamoorthy, 1977

Table 1.4 Sufficiency levels of nutrients in groundnut leaf dry matter

Macronutrients	**% of dry matter**					
Sampling period	**N**	**P**	**K**	**Mg**	**Ca**	**S**
7th leaf at 40 days after planting	3.3-3.9	0.15-0.25	1.0-1.5	0.30	2.0	0.19-0.25
Upper mature leaves at bloom	3.0-4.5	0.2-0.5	1.7-3.0	0.3-0.8	1.25-2.0	0.20-0.35
Micronutrients	**mg kg^{-1} dry matter**					
	Mn	**Fe**	**B**	**Cu**	**Zn**	**Al**	**Mo**
Upper mature leaves at bloom	20-350	50-300	20-60	5-20	20-60	<200	0.1-5.0

Source: Plank, 1989

Calcium

The most critical element in the production of groundnuts is calcium, and in many regions of the world, it is a major limiting factor to groundnut production. The developing pods require adequate Ca in the surrounding soil for proper pod development and production of high quality seed (Cox *et al.,* 1982; Gascho & Davis, 1994). Because root-absorbed Ca is not translocated to the developing pods after the groundnut peg has entered the soil (Brady, 1947), the Ca required for pod development must be absorbed directly from the soil solution, thereby necessitating high Ca levels in the podding environment (Skelton & Shear, 1971). Soil Ca levels in the range 600 to 800 mg kg^{-1} in the fruiting zone (0-10 cm) are considered adequate for the production of good quality groundnut kernels (Kvien *et al*., 1988; Sumner *et al*., 1988).

The most important morphological attributes that influence Ca uptake by the pods are pod surface area, pod volume, number of days to maturation of a pod, shell thickness and specific shell weight (Boote *et al.,* 1983; Kvien *et al.,* 1988). Smaller-seeded cultivars, because of their larger surface to volume ratio, require lower soil Ca levels than the large seeded types. The soil factors that affect Ca nutrition of groundnut include soil water content, water soluble Ca, exchangeable Ca and the type of soil minerals present (Keisling *et al.,* 1982).

Calcium deficiency results in lower yield, darkened plumules in the seed, empty pods (pops), reduced percentage of sound mature kernels and sometimes plants that stay green and continue to produce flowers and pegs, many of which may be infertile (Cox & Reid, 1964; Sullivan *et al*., 1974). To avoid Ca deficiency in the pod zone a soluble source of Ca like gypsum can be applied over the row at early flowering stage (Smal *et al.,* 1989), though groundnut cultivars do not always respond to such Ca supplements (Walker, 1975). In acid soils, lime incorporation into the pod zone before planting can correct soil acidity and simultaneously supply adequate Ca for maximum yield of small-seeded cultivars (Gascho & Kidder, 1993).

Magnesium

Magnesium deficiency rarely limits plant growth, however, its necessity for groundnut stems from its role as a carrier of phosphorus in oil formation, and its effect on seed viability (Smith *et al,* 1994). The supply of Mg to the developing pod is partly from the roots via long distance

transport and partly from direct uptake by pods. Because of this complementarity, Mg supply may be omitted from the pod zone without adverse effects on pod development of some cultivars, provided adequate Mg is supplied in the root zone (Zharare *et al.,* 1993). Because of that, little response to Mg application has been recorded for groundnut, except on excessively drained soils where cations are easily leached, and in acid soils with very low Mg levels (Gascho & Davis, 1994; Smith *et al,* 1994). When Mg deficiency occurs in acid sandy soils, the deficiency can be corrected by applying dolomitic limestone, which will correct the acidity and supply both Mg and Ca (Sanchez, 1976; Foster, 1981).

Nitrogen, Phosphorus and Potassium

When inoculated with effective strains of Rhizobia, the groundnut is independent of nitrogenous fertilizers because enough N is fixed through symbiotic relations with *Bradyrhizobium* spp. It has been shown that uptake of nitrogen is most intensive during the period between flowering and pod formation. During the reproductive stages, there is continual mobilization of N from leaves to the developing fruit, and this sometimes results in appearance of N deficiency symptoms (Kvien *et al*., 1986; Cox & Sholar, 1995). On soils in which effective Rhizobia are absent, application of nitrogenous fertilizers increases groundnut yield. In most growing areas of the world application of N to groundnut in order to avoid deficiency is common, and responses to N fertilization have been observed on deep sandy soils (Gascho, 1992).

Groundnut is often grown on P deficient soils in many areas of the world (Cox *et al.,* 1982; Survanvesh & Morrill, 1986). The P deficiency can be easily corrected by application of P fertilizers, since groundnut is normally grown on sandy soils with low amounts of clay and P fixation is generally not a problem. Also, P requirements and removal by groundnut is low, and very little P leaches (Gascho & Davis, 1994). Although groundnut is largely unresponsive to P application, large responses have been observed in soils with high P fixation, particularly under low fertility conditions.

Generally, it is believed that groundnut requires very little K for its growth and reproduction. The crop removes small amounts of potassium and will only respond to K application when the soil K levels are very low. Although variable effects of K fertilizer on groundnut pod yield have been

reported in literature, the consensus is that there is no advantage in applying K fertilizer directly to the groundnut crop. Consequently, it is usually grown on residual fertility, following a well-fertilized crop (Cox *et al.,* 1982). This is because groundnut roots are efficient in obtaining K from low available levels in the soil. Because of this efficiency in utilization of soil K from soils that are low in available K, groundnut response to K fertilizers is rare (Weiss, 1983).

High levels of soil K in the pod zone are undesirable as they result in pod rot and interfere with the uptake of Ca by pegs and pods, which results in a higher percentage of pops and Ca deficiency in the seeds (Hallock & Garren, 1968; Csinos & Gaines, 1986). The most efficient way to apply K is to the preceding crop, or incorporate it well before planting to allow enough time for K to leach into the root zone before pegging (Walker *et al.*, 1979).

Micronutrients

Availability of micronutrient in soils is governed by soil pH, cation and anion exchange capacity, nutrient interactions, soil physical and chemical properties. Groundnut requires the seven micronutrients known to be essential for plants: boron (B), chlorine (Cl), Copper (Cu), Iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn). The potential for symbiotic assimilation of dinitrogen by groundnut creates special demands not only for molybdenum and cobalt, but also for boron, copper and zinc nutrition. The micronutrient most often limiting for groundnut production is B, because of its role in kernel quality and flavor. Boron deficiency results in "hollow-heart" in groundnut kernels. The inner surfaces of the cotyledons are depressed and darkened, and the kernels are graded as damaged. Zinc and Mn deficiencies can be expected in soils with high lime content, especially when high levels of P have been applied. At low soil pH the availability of Mn and Zn may increase to toxic levels, and liming very acidic soils to pH 5.5 decreases the solubility and uptake of Mn sufficiently to eliminate the toxicity. Molybdenum is an essential element in biological nitrogen fixation, and can be limiting at low soil pH (Gascho & Davis, 1994; Smith *et al.,* 1994; Jordan, 2001).

1.1.6 GROUNDNUT PRODUCTION CONSTRAINTS

Among abiotic stresses drought, low pH, and low temperature are important, and these occur in various combinations in Africa, Asia and the Americas (Duke, 1981). Although the groundnut plant is drought tolerant, inadequate moisture coupled with unreliable and poorly distributed rainfall is the most critical abiotic factor limiting yield in the semi-arid regions (Virmani & Singh, 1985; Stalker, 1997). Low pH and Ca deficiency can be important limiting factors in groundnut productivity, especially on the highly weathered soils of the tropics (Edwards *et al.,* 1981; Cox, *et al.,* 1982; Foy, 1984). Calcium availability may be limited by leaching from sandy soils and by limited moisture availability during pod filling (Stalker, 1997).

Considerable yield losses are caused by pests and diseases and by use of cultivars that are not adapted to local conditions (Cummins, 1985). On a global scale, the leaf spots caused by *Cercospora arachidicola* and *Cercospora personatum* and rust caused by *Puccinia arachidis* are the most destructive pathogens of groundnut, accounting for up to 70% yield losses (Subrahmanyam *et al.,* 1984). The most important pre- and post-harvest insect pests that cause significant economic losses in groundnut include aphids, thrips, jassids and *Spodoptera* (Isleib, *et al.,* 1994). Weeds cause great yield reductions when not controlled early in the growing season; therefore, cultivars that quickly establish full canopy are desirable in order to suppress the weeds (Stalker, 1997).

1.2 SOIL ACIDITY

The concept of an acid soil considers pH (a measure of the activity of H^+ ions in the soil solution) which is strongly (pH 5.5- 4.5) to extremely acid (pH<4.5), the degree of acid aluminium saturation of the cation exchange capacity (CEC), characteristics such as low concentrations or availability of Ca, Mg, P, B and Mo and high solubility of aluminium (Al) and Mn. Soil acidity is influenced by edaphic, climatic and biological factors of natural occurrence. The association between amounts of basic cations [Ca, Mg, K and sodium (Na)] and the Al species on the cation exchange complex also influences the acidity of a soil (Foy, 1984; Thomas & Hargrove, 1984: Barnard & Folscher, 1988; Ritchie, 1989; Fageria *et al.*, 1991; Carver & Ownby, 1995).

Generally, the total acidity of a soil is equated to the sum of the active (actual) and the potential (or buffer pH) acidity. Active acidity (or soil-water pH) is due to the presence of H^+ ions in the soil solution, whereas the potential acidity (measured in me/100 g soil) is due to H^+ and Al^{3+} ions adsorbed on the exchangers and this becomes active acidity when H^+ and Al^{3+} ions are exchanged to the solution. Active acidity is often used to indicate the need of liming, but it is the potential acidity that determines the amount of agricultural limestone required to neutralize soil acidity (Adams, 1990; Tisdale *et al.*, 1993; USDA Agronomy Technical Note No. 8, 1999).

On a universal scale, soils that are naturally acid or have become acid through agricultural activities comprise about 30% of the arable land (Von Uexkull & Mutert, 1995). In the tropics, approximately 43% of the land is classified as acidic, comprising about 68% of tropical America, 38% of tropical Asia, and 27% of tropical Africa. On the whole, acid soils cover a total of 1660 million hectares in the developing countries (Pandey *et al.,* 1994). The formation and nature of acid soils vary considerably due to different factors in soil formation, especially differences in climate, parent material, topography, vegetation and time of soil formation. Acid soils pose major complexities for agricultural use since they may adversely affect plant growth, but can be very productive if lime and nutrients are constantly applied and appropriate soil management is practiced (Van Wambeke, 1986).

1.2.1 CAUSES OF SOIL ACIDITY

Acidification is a natural soil-forming process caused by the production of H^+ ions. According to generalized views, acidity in soils has several sources: humus or organic matter, aluminosilicate clays, hydrous oxides of iron or aluminium, exchangeable aluminium, soluble salts and carbon dioxide. Naturally occurring elements that contribute in varying degrees to soil acidity include high rainfall which results in leaching of basic cations, low evaporation, and high oxidative biological activity that produces acids (Rowell, 1987; Carver & Ownby, 1995). Human activities such as intensive agriculture and industrialisation can accelerate the rate of acidification (Helyar & Porter, 1989).

Soil acidity may result from parent materials that were acid and naturally low in basic cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) or because these elements have been leached from the soil profile by

heavy rains. For example, soils that develop from granite parent materials acidify at a faster rate than soils derived from calcareous parent materials. Sandy soils with relatively few clay particles acidify more rapidly due to their smaller reservoir of alkaline cations (buffering capacity) and higher leaching potential. In highly leached soils only Fe^{3+} and Al^{3+} oxides and some of the trace metal oxides, which are highly resistant to weathering, remain from the original parent material (Brady, 1990).

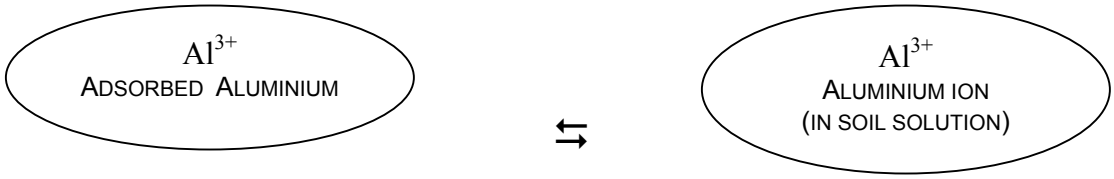
In alkaline or neutral soils, the negatively charged cation exchange complex is dominated by basic cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) whereas in acid mineral soils, this complex is usually dominated by aluminium ion species [Al^{3+} and Al $(OH)^{2+}$] formed by the dissolution of soil minerals in acid systems (Reuss & Johnson, 1986; Ritchie, 1989). In acid organic systems, H^{+} may be the dominant exchange cation. Each H^{+} in the soil competes with other cations to be bonded to the negative exchange surfaces of the soil colloids. As H^{+} ions displace the other cations, they are leached from the soil (Singer & Munns, 1996). Processes that would tend to acidify a soil include those that increase the number of negative charges, such as organic matter accumulation or clay formation, or those that remove basic cations, such as leaching of bases in association with an acid anion (Reuss & Johnson, 1986; Ritchie, 1989; Ulrich & Sumner, 1990).

Excessive rainfall influences the rate of soil acidification depending on the rate of water percolation through the soil profile. Water passing through the soil leaches basic cations such as Ca^{2+}, Mg^{2+} and K^{+}, which are then replaced by acidic cations such as Al^{3+} and H^{+} (Reuss & Johnson, 1986; Ulrich & Sumner, 1990). In addition, the leaching action of CO_2-charged water percolating through the profile of a base-saturated soil removes free salts very quickly and exchangeable basic cations more slowly. Eventually a soil becomes quite acid, unless bases are replaced by man or nature. For this reason, soils formed under high rainfall conditions are more acid than those formed under arid conditions (Brady, 1990).

Hydrolysis is a molecular phenomenon that is very important to soil acidity. Aluminium and iron as trivalent ions (M^{3+}) take part in hydrolytic reactions, a result of their high ratio of charge to ionic size (Hodges & Zelazny, 1983; Ritchie, 1989). Monomeric aluminium ions (Al^{3+}) can be displaced from clay minerals by other cations and hydrolyze in solution; the hydrolysis products are re-adsorbed on clay, causing increased hydrolysis (Ritchie, 1989). The H^{+} ions initially

adsorbed to the cation exchange sites eventually become sufficiently concentrated to attack the clay crystal releasing Si^{4+} and Al^{3+}. The released Al ions partially neutralized as $AlOH^{2+}$ or Al $(OH)^{2+}$ polymerise in the inter-layers of the clay fraction or become complexed with organic materials, while the Si^{4+} leaches to lower levels in the profile. As the soil becomes still more acid, more Al and Fe are released from the clay minerals, and Al^{3+} remains the dominant exchangeable cation (Hodges & Zelazny, 1983; Lindsay & Walthall, 1989; Zelazny & Jardine, 1989; Brady, 1990).

According to Brady (1990), the mechanisms by which adsorbed H^+ and Al^{3+} ions exert their influence on soil acidity depend on the degree of soil acidity and on the source and nature of the soil colloids. Adsorbed Al^{3+} ions contribute to soil acidity through their tendency to hydrolyse as shown in the following simplified equations:-



The aluminum ions in soil solution are then hydrolysed: $Al^{3+} + H_2O \rightarrow Al(OH)^{2+} + H^+$.

The H^+ ions released lower the pH of the soil solution and are the main source of H^+ in most very acid soils. In moderately acid soils (with high percentage of base saturation), the Al can no longer exist as ions, but is converted to aluminum hydroxy ions, some of which are adsorbed and act as exchangeable cations. In the soil solution they produce H^+ ions by the following hydrolysis reactions:-

1. $Al(OH)^{2+} + H_2O \rightarrow Al(OH)^{2+} + H^+$
2. $Al(OH)^{2+} + H_2O \rightarrow Al(OH)^3 + H^+$ (Brady, 1990).

In soils under agricultural production, acidity is often accelerated in the surface layer by certain cropping practices and events.

Fertilizer use

Acidification of soil resulting from the use of commercial fertilizers is claimed to be one of the major reasons for deterioration of soils on a global basis (Stammer, 1992). Both chemical and

organic fertilizers may eventually make the soil more acid because H^+ is added in the form of ammonia-based fertilizers ($NH4^+$), urea-based fertilizers [CO $(NH_2)_2$], and as proteins (amino acids) in organic fertilizers. Transformations of these sources of N into nitrate (NO_3^-) release H^+ to create soil acidity. Repeated applications of NH_4 fertilizers in excess of crop uptake, especially on slightly buffered soils, results in net production of H^+ by natural processes (Tisdale & Nelson, 1975; Helyar & Porter, 1989), including nitrification of ammoniacal N:

$$2NH_4 + 2H^+ \rightarrow 2NH_4^+$$

$$2NH_4 + 3O_2 \rightarrow 2NO_2 + 4H^+ + 2H_2O$$

$$2NO_2 + O_2 \rightarrow 2NO_3$$

The resultant pH values can be less than pH 4.0 and rapid loss of exchangeable Ca and Mg can occur. Some of this acidity is neutralized by NO_3^- uptake and the subsequent release of OH. Other compromising factors are the denitrification of NO_3^-, NH_4^+ volatilization or NH_4^+ uptake by the plant. Management practices that increase N-use efficiency and decrease the amount of NO_3^- lost by leaching could slow the rate of acidification (Robson, 1989).

If superphosphate is added to water, an acidic pH is developed as a result of a hydrolysis leading to formation of insoluble calcium monohydrogenphosphate:

$$Ca\,(H_2PO_4)_2 + H_2O \rightarrow CaHPO_4 + H^+ + H_2PO_4^-.$$

The effect is dramatic when the fertilizer is band-applied, but will gradually disappear as diffusion and neutralizing reactions occur (Kennedy, 1986). Superphosphate fertilisers also indirectly add to soil acidity by improving plant growth, which in turn increases the amount of produce that can be removed and also the amount of legume nitrogen available to leach.

Applications of elemental sulphur, especially the reduced forms, also have a soil acidification effect as a result of reactions analogous to those of nitrification, and are catalysed by similar aerobic autotrophs. The oxidation and mineralization of organic matter from biota in ecosystems involves a component of sulphuric acid production from reduced organic sulphur (Kennedy, 1986).

Plant uptake

Uptake by plants of more base cations such as K^+, Ca^{2+}, and Mg^{2+} than of mineral anions results in increased acidity in the soil due to the release of H^+ ions by plant roots in exchange for base

cations or of OH^- (or HCO_3^-) ions in exchange for anions taken up (Wallace *et al.,* 1976; Haynes 1990). This proton efflux can have greater consequences than the differential cation-anion uptake. When legumes and other plants obtain nitrogen through symbiotic fixation of N_2, there is less base release into the soil than when nitrate is the N source, with the net result of increased release of H^+ ions to the soil (Chesseman & Enkoji, 1984).

Repeated cultivation and harvest removal

The acidification of soils due to cultivation is a consequence of a number of processes. Improved aeration promotes rapid bacterial oxidation of soil organic matter, resulting in net production of organic acids (Beukes, 1987). Soil organic matter derived from the lignin of plants contains a significant number of reactive carboxyl, phenolic, and amino groups that are capable of bonding H^+ ions (Tisdale & Nelson, 1975). Such H^+-saturated groups behave as weak acids and the covalently bound H^+ will dissociate. When soil organic matter is mineralized, the nitrogen is released as NH_4OH or equivalent, which means that soil acidification can result. The NH_4OH can be oxidized to HNO_3 (Mengel & Kirkby, 1982). Any conditions that affect the quantity of organic matter in soil will affect the degree of acidification (Tisdale & Nelson, 1975).

Soil acidification in the surface layer is also accelerated by the removal of basic cations (Ca, Mg, K and Na) in the harvested product. Removal of straw depletes basic cations to the greatest extent and actually enhances acidification by nitrification (Wallace, 1989). The severity of soil acidity increases as yields of vegetative or grain dry matter increase (Carver & Ownby, 1995).

1.2.2 ACID SOIL INFERTILITY

It is now realised that acid soil infertility problems are not only restricted to low pH and high solution Al and Mn levels *per se.* High soil acidity reduces the availability of P to plants via fixation by a number of processes (Sample *et al.,* 1980; Sanchez & Uehara, 1980; Fageria *et al.,* 1990; Sanyal & de Datta, 1991) and reduces Mo availability to plants due to reduced solubility (Barnard & Folscher, 1988; Brady *et al*., 1994). On soils with low pH values, the levels of exchangeable Ca and Mg in relation to Al and Mn activities in the soil solution strongly affect toxicities of Al (Ca and Mg) or Mn (Ca) to plants.

Unlike some of the more obvious forms of land degradation such as erosion, soil acidification is viewed as a hidden problem with the potential to greatly affect yields and to increase the risk of other forms of land degradation (Van Wambeke, 1986). The major factors that constitute acid infertility and adversely affect sensitive plants in acid soils include direct and indirect effects of H^+ ions. The indirect effects of H^+ ions on plant growth include the following:

a) impaired absorption of several elements, especially Ca, Mg, K and P;
b) increased soil availability of Mn, Al, sometimes Fe, and possibly heavy metals including Cu and Ni, leading to uptake of toxic quantities;
c) reduced availability of P when fixed by Al or Fe before or after absorption; reduced solubility of Mo and Zn;
d) low actual concentration or inhibition in the uptake of Ca, Mg, K, B and sometimes Cu or other micronutrients as a result of prolonged leaching of the soil profile at low pH;
e) unfavourable biotic conditions such as impaired N fixation, reduced activity and survival of beneficial soil micro-organisms (e.g. rhizobia and mycorrhizae) and increased infection by some soil pathogens;
f) water and nutrient deficiencies as a result of reduced root growth;
g) accumulation of organic acids and failure of micro-organisms to decompose toxic residues and production of unfavourable redox balance resulting in reducing conditions; and
h) increased plant uptake of the toxic heavy metal cadmium, to the extent that this may accumulate to harmful levels in the kidneys of some classes of grazing animals (Hewitt & Smith, 1975; Clark, 1984; Marschner, 1995).

Each of these factors is of different comparative importance depending upon soil pH, soil type and horizon, aeration, clay mineral types and amounts, organic matter contents and kinds, levels of salts, plant species and genotype (Clark, 1984; Marschner, 1995). Acid soil infertility factors may act somewhat independently, or more often together, to affect the growth of plants (Foy *et al.,* 1978; Kamprath & Foy, 1984).

1.2.3 TOXICITY PROBLEMS IN ACID SOILS

Acid soil toxicity is not a single factor but a complex of factors that may affect growth of different plants through different physiological and biochemical pathways (Foy, 1983). Toxicity in acid soils is attributed to enhanced solubility of certain metal cations, particularly Al and Mn. In most acid soils (pH<4.0), Al and Mn toxicities are probably more important than H^+ ion toxicity in limiting the growth of higher plants, particularly the non-legumes (Moore, 1974; Kamprath & Foy, 1985).

Hydrogen ion (H^+) toxicity

Solution pH in acid soils is the result of the distribution of H^+ ions between soil surfaces and the soil solution. In the presence of a given number of H^+ ions, the pH buffering capacity is the major soil property that determines the soil solution pH and the possibility to manipulate the pH of acid soils economically (Ritchie, 1989). The soil solution not only contains a certain quantity of H^+ ions, but also has the ability to resist pH changes (pH buffering): the greater the ability of an element to repel H (hydrolyse), the stronger its acidity. Buffering of pH by the solid phase may arise from the dissolution of minerals such as kaolinite or calcite, and buffering will depend on the type and concentration of the ions on the surface and in solution as well as the type, structural characteristics and relative affinity of the surface for different ions (Adams & Moore, 1983).

The direct effects of the H^+ ion on plant growth are difficult to determine in acid soils because of the varying interrelationships that occur between pH, Al, Mn and other mineral elements that may be soluble in toxic concentrations (Kennedy, 1986). Additionally, the availability of essential elements particularly Ca, Mg, P and Mo may be sub-optimal (Fageria *et al.,* 1990).

Excess H^+ ions have marked effects on root membrane permeability. They compete with other cations for absorption sites, interfere with ion transport, and cause root membranes to become leaky. Roots may lose previously absorbed cations as well as organic substances, and prolonged exposure to low pH may reduce their capacities for subsequent absorption of nutrients. Because of their effect on nutrient uptake and retention by plant roots, excess H^+ ions can increase plant requirements for Ca, and perhaps other nutrients in a growth medium (Foy, 1992).

Aluminum toxicity

The chemistry of soil Al is fundamental to the fertility of highly weathered acid soils since in many such soils the concentrations of Al in soil solution are known to be toxic to crops (Kamprath, 1978). Because Al is tightly held to exchange sites, the total soluble Al (Al_T) in the soil solution is usually quite low, ranging between 10-350 μM, and levels >1000 μM occur only in exceptional circumstances such as in acid sulphate soils (Kamprath, 1978; Adams & Moore, 1983; Curtin & Smillie, 1983). The level of soluble species of Al is influenced by competition between Al and other cation species. Cations that form weaker complexes with the ligand than Al (e.g. Ca and Mg) can only compete effectively with Al at Al: cation ratios<1. On the other hand, cations such as Fe^{3+} that form stronger complexes with the ligand can compete even when Al: cation ratios are >1. The hydrogen ion may also compete with Al for a ligand (Ritchie, 1989).

Soluble Al species in soil solutions may be broadly divided into two groups: monomers and polymers. The total concentration of monomeric Al in acid soils is the sum of the concentrations of the various monomeric species, i.e., Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^{+}$ and $Al(OH)_3$. With sulfate in solution, an additional species (i.e. $AlSO_4^{+}$) is also present, while complex ions of Al with SO_4^{2-} and F^{-} also occur when these anions are present in soil solution (Fageria *et al.*, 1990; Kinraide, 1991). The monomeric hydrolysis of Al is significant at pH 4.0, and more than 80% of total soluble Al is hydrolysed by pH 4.9. In the soil solution, the extent of hydrolysis may be reduced by the presence of other anions, particularly nitrate, chloride and sulphate (Curtin & Smillie, 1983). Aluminium can also form soluble polymers with hydroxyl ions alone or in conjunction with phosphate or silicon ions.

The concentration of soluble Al in acid soils may be controlled (i.e. buffered) by the dissolution of inorganic compounds, adsorption onto inorganic minerals or by reactions with solid organic matter. The effect of Al adsorption on pH depends on the type of clay, the hydroxyl: Al ratio in solution and the time of ageing. Removal of hydrolysed Al species from solution induces further hydrolysis of Al and consequently a lowering of the pH. If Al^{3+} were the major species adsorbed then a pH increase would be expected, although the pH increase may be temporary and will decrease with time because of buffering by surface reaction with H^{+} and OH^{-} till a new

equilibrium is established. In some cases, pH increases due to proton uptake are counterbalanced by the adsorption of Al-hydroxyl species and so only a small change may be observed (Hoyt, 1977).

Soluble monomeric Al complexes with organic anions depending on the type and concentration of organic ligand, the proportion of charged sites that are dissociated, pH, ionic strength and the presence of competing ions (Ritchie, 1989). Evidence is mounting that the toxicity of Al is reduced in the presence of inorganic and organic complexing anions and that the activity of Al^{3+} and/or the Al-hydroxyl species are the forms of Al that are most correlated with depressed yields of several plant species (Helyar, 1978; Blamey *et al.,* 1983; Ahmad & Tan, 1986; Wright, 1989; Hue, 1992; Haynes & Mokolobate, 2001).

Aluminium may form soluble or insoluble complexes with organic matter (OM) or it may be non-specifically adsorbed onto exchange sites. Aluminium in a form complexed to soluble OM is not toxic to plants (Kinraide, 1991) and this complexation seems to be a vital mechanism of detoxifying solution Al (Kochian, 1995). The addition of organic matter to a soil or solution can decrease or increase the level of soluble Al depending on the concomitant changes in pH (Haynes & Mokolobate, 2001). Increases in soluble Al could be explained by the high pH of the soil causing some dissociation of H^+ from the organic matter that lowers the soil pH and results in the dissolution or release of Al. The reactions of Al with soluble organic material can also increase the level of Al in the soil by retarding precipitation of Al oxides (Hoyt, 1977; Adams & Moore, 1983). On the other hand, the addition of organic matter can decrease soluble Al because the extent of Al binding by the OM more than counterbalances any increased Al dissolution caused by pH decreases (Hargrove & Thomas, 1981; Hue *et al.,* 1986).

The removal of Al from solution by organic matter adsorption and a concomitant increase in pH buffering capacity can have a confounding effect by increasing exchangeable acidity. Hoyt (1977) observed that even though the addition of organic matter reduced concentrations of soluble and exchangeable Al, there was an increase in exchangeable acidity (i.e. buffer capacity). In some cases, therefore, the benefits from reducing Al toxicity may be counter-balanced by an increase in the lime requirement of the soil.

Since most plants are sensitive to micromolar concentrations of Al, its toxicity is the major limiting factor for plant productivity on many acid soils (Kinraide, 1991). In the tropics, Al toxicity has been identified as a major constraint for the production of maize (*Zea mays* L.), sorghum (*Sorghum bicolor*.) and rice (*Oryza sativa)* (De La Fuente-Martinez & Herrera-Estrella, 1999). The most easily recognised symptom of Al toxicity is the inhibition of root growth, and this has become a widely accepted measure of Al stress in plants. The root system of plants severely affected by Al toxicity is often collaroid in appearance, with many stubby lateral roots and no fine branching (Kamprath & Foy, 1984; Delhaize & Ryan, 1995; Kochian, 1995). The toxic effect of Al on roots has a clear effect on plant metabolism by decreasing mineral nutrition and water absorption. Aluminium has been shown to interfere with cell division in plant roots; inhibit the respiratory activity of mitochondria; increase pectin, hemicellulose and cellulose contents of root cell walls; reduce DNA replication; decrease cell permeability by coagulating protein and inhibiting cell division; reduce root respiration; precipitate nucleic acid by forming strong complexes; inhibit cation transport across the plasma membrane; block K^+ uptake in root hairs; interfere with uptake, transport, and use of several nutrients (P, K, Ca, Mg, Zn and Fe) and water by plants (Kamprath & Foy, 1984; Keltjens, 1990; Keltjens & Djikstra, 1990; Baligar *et al*., 1993; Delhaize & Ryan, 1995; Kochian, 1995). Therefore, crop production in acid soils is largely affected by limited water and nutrient uptake caused by the inhibition of root growth and function that result from the toxic effects of Al. In addition to direct effects on plants, Al complexes with some nutrients such as P, reducing their availability for root uptake (Haynes & Mokolobate, 2001).

Manganese toxicity

Manganese in soils may be adsorbed onto the surface of hydrous oxides, clay particles and organic matter, or exists as discrete Mn compounds. Although it may exist in more than one oxidation state under conditions naturally found in soils (Graham *et al.,* 1988), Mn^{2+} is the only oxidation state that has been identified in the soil solution, and it may react with several inorganic and organic ligands to form soluble complexes. In contrast to Al, it forms much weaker complexes, with hydrolysis becoming significant only at pH>9. For that reason the inorganic complexes in acid soils will not be major forms of Mn unless if extremely high levels of sulphate or chloride are present (Graham *et al.,* 1988; Ritchie, 1989).

Mn^{2+} is weakly adsorbed onto clay minerals, and this is attributed to its inability to hydrolyse under acidic conditions. The amount of Mn available to plants in a soil depends on Mn distribution between the soil surfaces and the soil solution and how that is modified by the difference in the rates of oxidation and reduction, which are governed by environmental conditions, soil properties and microbial activity. Thus, soluble Mn levels are ultimately controlled by buffering from the solid phase, and only modified by redox reactions. Oxidation and reduction of Mn can be by both chemical and microbial pathways. Reduction, both microbial and chemical, may be enhanced by an increase in readily oxidisable organic matter, moisture content or temperature and a decrease in redox potential. Oxidation is also affected by the same factors (Nelson, 1977; Curtin & Smillie, 1983; Graham *et al.,* 1988; Ritchie, 1989).

In soils high in Mn minerals, dissolution of Mn at low pH may result in Mn toxicity. Manganese toxicity is perhaps the second major growth-limiting factor after Al toxicity in acid soils (Sanchez & Salinas, 1981). Plants absorb Mn primarily as the Mn^{2+} ion. Decreasing soil pH below 5.5 increases the concentration of Mn^{2+} ions in the soil solution and, consequently, increases the likelihood of Mn toxicity (Kamprath & Foy, 1985). Manganese toxicity can also occur at higher soil pH values (up to 6.0) in poorly drained or compacted soils where reducing conditions favour the production of divalent Mn which plants absorb. The solubility and potential toxicity of Mn to a given crop depends on many soil properties, including total Mn content, pH, organic matter level, aeration and microbial activity (Foy, 1984; 1992; Foth & Ellis, 1997).

Excess Mn seems to affect plant tops more directly than roots. Manganese produces more definitive symptoms in plant tops than Al does, and for a given plant, Mn accumulates in proportion to plant injury. Plant symptoms of Mn toxicity include marginal chlorosis and necrosis of leaves, and leaf puckering (Foy, 1984; 1992). In severe cases of Mn toxicity, plant roots turn brown, usually after the tops have been severely injured. Plant symptoms of Mn toxicity are often detectable at stress levels that produce little or no reduction in vegetative growth (Foy *et al*, 1978).

Manganese toxicity alters the activities of enzymes and hormones in plants; causes the destruction of indole-3-acetic acid (IAA) through increasing the activity of IAA oxidase, amino

acid imbalance, lower respiration rate, reversal of growth inhibition of roots caused by enhanced auxin production (Robson, 1988). Manganese toxicity is often associated with a decrease in Ca concentration of plants, and supplying additional Ca to the growth medium sometimes reduces Mn accumulation, decreases the severity of Mn-induced chlorosis and alleviates growth reductions (Smith, 1979).

Manganese toxicity is frequently induced or exacerbated by N fertilization, which lowers soil pH (Nelson, 1977). The addition of organic matter can reduce Mn toxicity, probably by chelating excess divalent Mn that plants absorb, and also because microorganisms can oxidise the soluble and toxic divalent Mn to the tetravalent, non-toxic form (Graham *et al.* 1988). Manganese has been reported to interact with Fe, Mo, P, Ca and Si in affecting toxicity symptoms and plant growth (Borkert & Cox, 1999). It appears, therefore, that the toxicity of a given level of soluble Mn in the growth medium, or even within the plant, depends on interactions between Mn and several other mineral elements, particularly Fe and Si (Foy *et al.,* 1978; Foy 1984; 1992).

1.2.4 DEFICIENCIES OF ESSENTIAL NUTRIENTS

Calcium and magnesium

Calcium and Mg deficiencies are key limitations to plant growth in many acid soils, especially in highly leached, sandy soils. With increasing soil acidity, Al and/or Mn replace exchangeable Ca and Mg, and in soils with low CEC the resultant low levels of Ca and Mg may cause deficiency problems with some crops (Foy, 1984; Fageria *et al.,* 1991). Crops remove between 20 and 150 kg ha^{-1} Ca and 10 to 80 kg ha^{-1} Mg (Sanchez, 1976). The availability of Ca and Mg to plants is influenced by the percentage Ca and Mg saturation, the total Ca and Mg supply, the concentration of Ca and Mg in the soil solution, and by the presence of ions such as Al^{3+} and Mn^{2+}, which inhibit Ca^{2+} and Mg^{2+} absorption. While inadequate soil Ca levels in the topsoil are noticeably manifested on plant growth, inadequate Ca levels in the subsoil may be invisible (Adams, 1984). For root growth, Ca deficiency is discernible by the death of the meristematic root tissue. Because of the incapability of plants to translocate Ca within the phloem tissue, roots cannot grow in a soil zone that is Ca deficient (Adams, 1984).

Absolute Ca deficiency is difficult to identify within the acid soil complex except in the most highly leached acid soils with low CEC (Foy, 1984; Kamprath & Foy, 1985). This is because the levels of Ca required for essential growth functions are so low as to approach those of micronutrients (Wallace *et al.,* 1966), therefore the majority of the Ca in soils and in plants serves as an excluder or detoxifier of other elements, such as Al and heavy metals that might otherwise be toxic (Foy, 1992). While absolute deficiencies of Ca have been attributed to possible Al-Ca antagonism rather than to low Ca supply *per se,* recent evidence suggests that Ca deficiency can be a worse growth-limiting factor than Al toxicity (Foy, 1992). This is because some of the acid soils can be particularly low in exchangeable Ca without a concurrent phytotoxic level of soluble Al (Spain *et al.,* 1975).

Magnesium deficiency may limit plant growth on acid, sandy, highly leached soils having low CEC values and possibly high Al saturations. The uptake of Mg is antagonized by high Al saturations, and because Mg is a poor competitor with Al and Ca for exchange sites, it is often deficient in the topsoil because of acidification, or because of application of large quantities of soluble Ca. Thus, liming to near neutrality with calcitic lime in acid soils low in available Mg can exacerbate Mg deficiency, so can application of high levels of K (Kamprath & Foy, 1985). The critical Mg saturation levels have been reported as 5 to 10% of CEC, with a Mg/K ratio of at least 0.5 (Mayland & Grunes, 1979).

Nitrogen, Phosphorus and Potassium

Nitrogen deficiency is more widespread than the deficiency of any other nutrient mainly because plants take up relatively large amounts of N while soils contain relatively small amounts of N. Thus in acid soils of the tropics, N deficiency is a major limitation to plant growth, and is exacerbated by lower rates of N application *vis a vis* the amount removed in harvested crops or lost by other processes, and the decreases in organic matter content with successive harvests. A decline in organic matter content results in a decrease in effective CEC and the capacity of the soil to retain plant-available nutrients (Fageria *et al.,* 1990).

In low fertility acid soils, P deficiency is a major limiting factor to plant growth. The occurrence of P deficiency in acid soils is attributed to low native soil P content and high P fixation capacity (Marschner, 1995). In acid soils the major inorganic P fractions include phosphate ions adsorbed

to Al- and Fe-oxyhydroxides and P precipitated as amorphous and crystalline Al and Fe minerals, and these transform with time from sparingly soluble into increasingly insoluble crystalline forms such as variscite (Al-P) and strengite (Fe-P) from which the P is unavailable for uptake by the plants (Sample *et al.,* 1980). Consequently, plant available P is insufficient in most acid soils even though the total amount of P may greatly exceed crop requirements. In the soil solution of most acid soils the concentrations of inorganic P are low, ranging between 1-5 mmol m^{-3} (Bieleski, 1973). As a result, fertilizer P has to be applied to most acid soils in order to provide soluble P close to the roots to meet plant requirements.

Potassium deficiency in acid soils is not as widespread as P deficiency (Fageria *et al.,* 1991). However, the more acid a soil becomes, the less K is retained on exchange sites, thereby subjecting K to downward movement by leaching. In addition, increased levels of soluble Al would stunt the roots, further exacerbating the reduced K supply to the plants (Barnard, 1986; Sumner *et al.,* 1991). Because high-yielding crops remove large amounts of K, failure to replace the K removed in the harvested crop results in K deficiency becoming a limiting factor in crop production (Sanchez, 1976). The increased incidence of K deficiency in Australia has been attributed to improved P status of the soils and increased yields (Leach & Easton, 1991). Management practices to alleviate K deficiency in crops include application of K fertilizers at judicious rates that replace K lost through crop removal and leaching, incorporation of crop residues or use of K-efficient cultivars (Fageria *et al.,* 1991).

Micronutrients

While the solubility of other micronutrients generally increases with increasing acidity, the availability of molybdenum is reduced with decreasing pH. Molybdenum is required in greater quantities by legumes for the process of nitrogen fixation. The problem of Mo availability to plants growing in acid soils is compounded by the fact that it is a trace element, and is highly insoluble in acid soils (Fageria *et al.,* 1990). Liming, or treating seeds with Mo can rectify the problem. Deficiencies of other micronutrients on acid soils can occur because of leaching losses (Spencer, 1966; Fageria *et al.,* 1990)

1.2.5 SOIL ACIDITY CONSTRAINTS TO GROUNDNUT PRODUCTION

Although soil acidity can affect groundnut growth indirectly by creating nutrient toxicities and deficiencies (see sections 1.2.3 and 1.2.4) the high H^+ activity at low pH can directly affect legume growth in a number of ways. Tang & Thomson (1996) found that root elongation and shoot growth of a number of grain legumes supplied with mineral N declined at pH below 5.0 in the nutrient solution. The depressions in root elongation and shoot growth associated with high concentrations of H^+ were related to decreased proton extrusion from roots which in turn caused limited nutrient uptake and disturbed cytoplasmic pH regulation (Schubert *et al,* 1990a; Marschner, 1995). The H^+ ion can also adversely affect the growth of legumes grown without N-fertilizer application through its detrimental effects nodulation (Schubert *et al,* 1990; Schubert *et al,* 1990b; Tang & Thomson, 1996). High H^+ concentration impairs rhizobial survival and multiplication in soils, root infection, nodule initiation and legume rhizobial efficiency (Andrew, 1978) that can lead to reduced plant growth as a result of nitrogen deficiency. These effects of the H^+ ion are, however, complex and often overshadowed by Al toxicity, Mn toxicity and deficiencies of Ca, Mg and P (Foy, 1984). Helyar (1978) categorized the toxic effects of Al on legume growth in terms of toxic substrate levels, ion uptake and transport, and toxicity and tolerance mechanisms. At substrate levels of Al sufficient to cause some toxic effects, growth declines in a logarithmic fashion. Studies with soybean have shown that toxic levels of Al inhibit root elongation and decrease the adsorption and translocation of nutrients to plant tops (Sanzonowicz *et al.,* 1998). Inhibition of cell division by high concentrations of Al^{3+} is the prime cause for restricted root elongation in some grain legumes. The symptoms of Al toxicity indicate that the toxic effect is mainly through interference in the P metabolism of the plant, and the plant tops in general appear typically P deficient. Reduced growth of legumes in the presence of Al is not only due to toxicity *per se* but also because of the inhibitory effect of Al on uptake and translocation of Ca. Therefore, one of the primary reasons for response of legumes to liming of acid soils is the neutralization of exchangeable Al (Kamprath, 1978). In the pod environment of groundnut Al toxicity may inhibit Ca uptake by developing groundnut pods leading to an increase in pod rot and in the production of empty pods (pops).

The common symptoms of Mn toxicity in grain legumes are inter-veinal chlorosis and crinkle leaf in young leaves (e.g. soybean) and formation of brown speckles in mature leaves. Some of these symptoms are probably related to induced deficiencies of Ca and Mg (Marschner, 1995). Apart from the interferences with Ca and Mg nutrition, excess Mn disrupts phytohormone balance, certain enzyme activities and membrane functions in leaf tissues. For groundnut, shoot Mn concentrations in the region of 600 - 700 mg kg^{-1} are sufficient to cause toxicity symptoms or a small (about 10 percent) yield decline (Helyar, 1978).

Deficiencies of Ca, Mg and Mo, and decreased P uptake are important limitations to groundnut growth in many acid soils. In soils with low CEC, low Ca levels may cause deficiency problems with groundnuts. The sensitivity of groundnut to low Ca levels is attributed to its unusual fruiting habit, as more Ca is needed for the pod-filling process (Adams, 1984). Mo deficiency may particularly affect growth of legumes because of the high requirements for it by plants dependent on biological nitrogen fixation (Coventry & Evans, 1989). Hafner *et al.,* (1992) observed large improvements in groundnut response to application of Mo in acidic soils deficient in Mo.

1.2.6 MANAGEMENT OF ACID SOILS

Knowledge of why soil acidity increases, and how acid soils affect plant growth is crucial in devising management options to remedy the acid soil infertility barrier to productivity of crops on acid soils. Accurate identification of the extent and severity of the soil acidity problem would assist in deciding on the best management option. Factors taken into account when choosing the best management option include rainfall availability, rate of acidification, type of land use, capability of the land and soil, and cost of the management option. Thus, within the agricultural context, a number of management options to deal with acid soils are commonly advocated.

Curbing soil acidification by using less acidifying management practices

The use of management practices and cropping systems that aim to reduce the acidifying effects of the carbon and nitrogen will ultimately reduce the rate of soil acidification. In this respect, the ideal management practices include (i) use of less acidifying nitrogen and elemental sulphur

fertilizers (ii) split applications of nitrogenous fertilizers to reduce leaching of N (iii) use of deep-rooted crops to utilise N leached into the lower horizons (iv) inclusion of fewer legumes in rotation, (v) returning of crop residues to avoid major cation removal. While these practices can reduce the rate of acidification, ultimately they will not stop it (Van Wambeke, 1976; Helyar & Conyers, 1997).

Cultivation of acid-tolerant species

The basis of this option is that plant species have widely differing tolerances to acidity and nutritional requirements; therefore crops that are adapted to acid conditions (calcifuges) can be used for cultivation on acid soils in order to avoid yield losses from soil acidity. For example, acid tolerant crops such as buckwheat, cassava, cotton, pineapples, sugarcane, and sweet potatoes can be used to increase returns while acidity is being corrected (Kellogg, 1966). Since the pH will continue to decline if unchecked, eventually all plant species will be affected by soil acidity, thus rendering this option a short-term solution.

Use of more nutrients

In an effort to maintain productivity levels, higher rates of fertiliser can be applied to compensate for a retarded root system and fewer available nutrients. With a continued decline in pH levels, more fertiliser will need to be applied to avoid nutrient deficiencies. This option increases production costs, and is not sustainable.

Neutralising soil acidity

Addition of acid reducing (liming) materials offers a longer-term control of soil acidity. Lime materials containing various proportions of carbonates, hydroxides, and oxides of Ca and Mg, have been used for centuries to increase the pH of agricultural soils (Adams, 1980). Liming acid soils is known to improve crop growth by reducing the harmful effects of low pH, decreasing the amount of exchangeable Al or Mn, and increasing the supply of nutrients such as Ca, Mg, Mo (Ahmad & Tan, 1986)

1.2.7 AMELIORATION OF SOIL ACIDITY BY LIMING MATERIALS

On soils with a low buffering capacity, routine application of lime is a basic principle of good farming. The lime programme is usually determined by the neutralizing value of the liming material, current and target soil pH, the pH-buffering capacity of the soil, plans for future production and anticipated fertiliser use. The application method of the liming material will depend on whether the aim is to maintain or lift the pH in the topsoil (0-10 cm) or subsoil (10-20 cm). The species of plant to be grown and the soil type largely determine the target pH (Adams, 1980).

Amelioration of acid soils has generally been accomplished by the application of agricultural limestone ($CaCO_3$) or dolomitic limestone ($MgCO_3.CaCO_3$). Other ameliorants that have been used include dusts from cement works, lime kilns and marble works, residues from water and sewage treatment plants, crushed shellfish shells, spent lime from ammonia works, blast furnace slags, wood stove or fireplace ashes (Adams, 1980; Clapham & Zibilske, 1992). In addition, it has been shown that gypsum can improve acid soils that have subsoil acidity problems (Shainberg *et al.,* 1989; Sumner, 1993; Carvalho & van Raij, 1997).

The effectiveness of applied lime depends on the quality of the material, the amount applied, the soil pH, the uniformity of spread, and the extent of soil-lime mixing. The chemical potential of liming materials for neutralizing soil acidity is determined in terms of the $CaCO_3$ equivalence, i.e. grams of $CaCO_3$ required to equal the reactiveness of 100 g of material (Adams, 1980). Generally, the neutralizing capacity of a liming material is related to its effectiveness in removing H^+ and Al^+ off exchange sites (potential acidity) and neutralizing H^+ in solution (active acidity). The effectiveness of the lime material also depends on the size distribution of lime particles, whose rate of dissolution is dependent upon the amount of contact between lime-particle surface and the acid soil solution. The extent of soil-lime mixing also affects the rate at which lime reacts in the soil; ideally, each lime particle should be surrounded by soil particles (Adams, 1980; Tisdale *et al.,* 1993).

The amount of lime needed to achieve a certain pH depends on (a) the pH of the soil and (b) the buffering capacity of the soil, which is related to the cation exchange capacity (CEC). The higher the CEC, the more exchangeable acidity (hydrogen and aluminum) is held by the soil colloids. As with CEC, buffering capacity increases with the amounts of clay and organic matter in the soil, and soils with a high buffering capacity require larger amounts of lime to increase the pH than soils with a lower buffering capacity (Adams, 1980; Tisdale *et al.*,1993).

Gypsum (Ca SO_4) can be a valuable soil amendment, as it supplies a large amount of Ca ions deep into the soil where increased concentrations of this nutrient are needed. The dissociated sulfates (SO_4^{2-}) from gypsum combine with the detrimental Al^{3+} ions to form aluminium sulfate, which is less phytotoxic than Al^{3+} (Evanylo, 1989; Ismail *et al*., 1993; Sumner, 1993).

Surface-applied gypsum is an effective ameliorant of soils with acid subsoils since the dissolved gypsum is leached into the subsoil where various chemical reactions take place (Shainberg *et al.,* 1989, Sumner, 1993). Gypsum can increase the pH of some acid soils by hydroxyl replacement from clay by sulfate (Sumner *et al.* 1986; Farina & Channon, 1988; Shainberg *et al.* 1989; Alva *et al.* 1990; Sumner 1993 & 1994). Even though the change in the pH is usually very small, the effect on crop yields is often large because of the decrease in levels of soluble Al^{3+} ions and increase in soluble Ca. Significant yield responses (7-200%) to applications of gypsum on the soil surface or incorporated into the plow layer have been obtained in experiments conducted in Brazil, South Africa, and the United States on maize, soybeans, alfalfa, wheat, rice, beans and cotton (Sumner 1993). Evanylo (1989) reported the beneficial effects of gypsum to be increased rooting proliferation and alleviation of drought stress in deep-rooted crops.

Soil characteristics affecting response to liming in acid soils

McLean (1971) has summarized the most important soil properties that determine the liming effects in acid soils (Table 1.5).

Table 1.5 Soil attributes pertinent to liming effects (source: *McLean, 1971*)

Attribute	Description
Permanent charge form of acidity	A change in net CEC of a soil occurs when the negative charge on the surfaces of the clay crystals is partially neutralized by AlOH ions. These ions vary in positive charge depending on whether they adsorb additional OH ions from lime, or lose them by neutralization with H^+. Continued leaching and greater concentration of H ions results in the neutralisation of OH ions associated with the Al ions, leaving Al^{3+} as the predominant form of exchangeable acidity.
Type and crystallinity of clays	Continued weathering causes the gradual removal of K from crystalline clay materials, exposes the interlayers to further weathering and removal of silica, which causes destruction of the 2:1 type clays, eventually leaving hydrous oxides of Fe and Al, with some residual kaolinite as the predominant forms of clay.
Potassium release tendency	Large quantities of non-exchangeable K can be released from parent materials containing micaceous clays during the weathering process, but as smaller amounts of micaceous clays remain, less K of this type can be released. However, with increases in the H ion concentration, relatively more K is weathered from primary minerals, and a more rapid turnover of that in the plant residues also helps replenish the soil supply.
Phosphate fixing tendency	Al and Fe released from mineral crystals by weathering are accessible in soil solution, on exchange sites, or as constituents of exposed surfaces. Each ion reacts with soluble phosphate forming relatively insoluble compounds. Once the Al and Fe are released in large quantities and coat most of the exposed surfaces of individual particles and granules, lime may not favourably affect the availability of P that they retain.
Ionic exchange capacity	Because the total CEC of soils is roughly proportional to concentrations of OM and of clay, the CEC of soils increases as K is weathered from micaceous clays, and as plants grow, producing OM in the soil. However, as OH-Al accumulates and polymerises on clay surfaces or is complexed by the COOH groups of OM, the effective CEC decreases. Conversely, the gradual increase in hydrous oxide clays concomitantly increases the anion exchange capacity (AEC). The dependence of a higher proportion of the total CEC on pH is a result of a high pH-dependence of the negative charges on both OM and hydrous oxide clays.

Table 1.5 contd. Soil attributes pertinent to liming effects (source: *McLean, 1971*)

Base saturation (Ca).	There exists an inverse relationship between exchangeable Ca, Mg or total bases, and exchangeable Al. Ca and other basic cations are removed from the soil by weathering process, resulting in decreased saturation of the CEC with bases, thereby causing the soil to become progressively more acid.
Natural stability of structure	In highly weathered soils, solubilization of Al and Fe results in the formation of Fe- and Al-complexes and oxide or hydrous oxide coatings that stabilize the soil aggregates. In less weathered soils, the structure of the surface horizon is stabilized by Ca- and OM- stabilized aggregates, which can only be destroyed by excessive cultivation, erosion, leaching or residue removal.

Benefits from lime application

In general, liming acid soils increases yields because of the increase in soil pH to the crop's most favorable range for growth. The other beneficial effects of liming are mainly a reversal of the processes associated with the chemistry of acid soils, namely:

a) an increase in soil pH that affects the solubility of various compounds;
b) acid weathering of primary and secondary minerals is curtailed by the decreased concentration of H^+;
c) inactivation or neutralisation of toxic concentrations of Mn^{2+}, Al^{3+} (the major limiting factors on acid soils) and other substances;
d) alteration in ratios of basic cations adsorbed and in solution: base saturation, particularly Ca increases ;
e) an increase in pH-dependent CEC, and a decrease in pH-dependent AEC;
f) improvement of the environment for beneficial soil microorganisms, thereby increasing microbial activity;
g) encouragement of a more rapid breakdown of organic materials in the soil, releasing nutrients for growing plants;
h) improvement of nitrogen mineralization and symbiotic N-fixation by legumes; this can improve palatability of forages;
i) provision of an inexpensive source of Ca^{2+} and Mg^{2+} when these nutrients are deficient at lower pH;
j) an increase in electrolyte concentration due to dissolution of lime; and

k) may improve the activity of some herbicides (Adams, 1981b; Ahmad & Tan, 1986; Tisdale *et al.,* 1993; Foth & Ellis, 1997).

Benefits from gypsum application

Application of gypsum on acid soils has a broad range of benefits for plant nutrition and yield, and for soil improvement. Some of the major benefits as documented by Carvalho *et al.* (1986), Farina & Channon (1988), Shainberg *et al.* (1989), Wallace (1989), de Silva & van Raij (1992), Sumner (1993) and Rengasamy *et al*., (1993) are summarized below.

a) Corrects subsoil acidity by increasing exchangeable Ca and decreasing Al^{3+} and H^{+}, resulting in deeper root penetration and improved plant use of water and nutrients in the subsoil. Crops can better withstand periodic droughts during the season, which translates into increased yield.
b) Decreases toxicity of Al by formation of $(AlSO_4)^{+}$ complex or by releasing hydroxyl ions from clay as replaced by sulfate. Decreases H^{+} toxicity by replacing H^{+} on clay surfaces that can then be leached away, thereby increasing the pH.
c) Supplies electrolytes that are needed to stabilize soil structure. In highly dispersive clays gypsum application promotes flocculation, thereby increasing infiltration and decreasing runoff.
d) Provides soluble Ca needed to prevent physiological disorders such as bitter pit, scald internal breakdown, and cork spot in fruit; pod rot and empty pods in groundnut.
e) Provides Ca to improve stability of soil organic matter.
f) Can improve S and Ca nutrition in acid soils, especially in highly weathered soils where they can be limiting factors for legume crops.
g) Gypsum application on acid soils can decrease acid stress on nodulating bacteria.

Harmful effects of liming

Too much lime may curtail acid weathering or compound solubility so as to cause deficiencies of Mn, Z, Cu or B. These deficiencies are mainly a result of excessive raising of the soil pH. Other negative effects of liming can include reduced phosphate availability, and suppressed availability of Mg and K. Thus, injury to crops due to overliming results primarily from changes in the availability of these nutrients, and to Mo toxicity at times. Overliming can be a problem when

soils have a low CEC and a small buffer capacity, and the pH can be increased easily. This is most likely on sandy soils with permanent charge clays. Adverse effects may result from applying more than 2 t ha^{-1} on light-textured soils (Foy, 1984; Ahmad & Tan, 1986; Tisdale et al., 1993; Foth & Ellis, 1997).

CHAPTER 2

FIELD AMELIORATION OF ACID SOIL INFERTILITY IN SANDY SOILS OF ZIMBABWE USING LIME, GYPSUM AND SUPER PHOSPHATE

2.1 INTRODUCTION

Various authors have emphasized acid soil infertility as a constraint to crop productivity on Zimbabwean soils (Grant, 1970, 1981; Grant *et al.,* 1973; Tanner, 1976; Mashiringwani, 1983; Mukurumbira, 1997; Dhliwayo *et al*., 1998). High acidification rates of light textured sandy soils under crop production in the smallholder areas of Zimbabwe have been reported by Nyamangara & Mpofu (1996). Dhliwayo *et al.* (1998) observed that more than 60% of the sandy soils in the smallholder sector were in the extremely acidic to very strongly acidic range (pH 4.15 to 4.5). Thus, soil acidity is a major crop production constraint in the smallholder sector of Zimbabwe. A majority of the smallholder farmers are aware of the acidity status of their soils, but their poor-resource base is a major socio-economic constraint that limits the extent to which they can invest in large amounts of liming materials. In view of this situation, practical and cheap options for soil acidity amelioration are a prerequisite.

Groundnut (*Arachis hypogaea* L.) is one of the most important crops in the smallholder-farming sector of Zimbabwe. In this sector, Spanish cultivars with a growing period of 100-130 days are largely grown. As a protein source, groundnut is an important component in the diet of the rural population, and the demand for it by the oil expressing industry and for confectioneries makes it a cash crop of significance to the economy of Zimbabwe. The bulk of the crop is produced on light textured soils ranging from coarse and fine sands to sandy clay loams. These soils are highly weathered, and have low Ca, Mg, P and Zn status (Grant, 1971; Mashiringwani, 1983; Tagwira *et al*., 1993). In addition, the soils are usually acidic (Grant, 1971; Mashiringwani, 1983), resulting in high hydrogen ion (H^+) concentrations as well as toxicities of aluminum (Al) and manganese (Mn) (Mukurumbira, 1997). Consequently, productivity of groundnut on these soils has declined

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despite the recent genetic and disease resistance improvements to the crop, with pod yields averaging only 0.5 t ha^{-1} (CSO, 2001).

Acid soil infertility in highly weathered tropical soils is in general a major constraint for cultivation of legume crops whose nodulation, growth and yield are reduced (Munns, 1978; Lie, 1981; Marziah *et al.,* 1995). As mentioned in Chapter 1 (section 1.2), the infertility problems of acid soil are associated with proton toxicity, nutrient deficiencies (Ca, Mg, Mo and P) and the presence of phytotoxic concentrations of Al and Mn (Awad *et al.,* 1976; Coventry & Evans, 1989). Liming may ameliorate some of these factors (Haynes, 1984; Foy, 1992), but the maximization of the benefits of liming acid soils requires a thorough knowledge of lime reactions with soil and of crop responses to lime application. Furthermore, because of the complexity of acid soil infertility, it is imperative to firstly identify the factors that are reducing plant growth in order to select the most effective measures of correcting acid soil infertility (Dolling *et al.,* 1991).

Amelioration of acid soils is generally accomplished by the application of calcitic or dolomitic limes. In addition to alleviating toxicities (Haynes, 1984), these two liming materials also supply Ca (calcitic and dolomitic limes) and Mg (dolomitic lime). The levels of these two nutrients, together with that of P, are usually low in acid soils of the tropics (Sanchez, 1976). Alternative ameliorants that supply calcium include superphosphate (Mongia *et al,* 1998) and gypsum (Shainberg, *et al,* 1989; Sumner, 1993; Carvalho & van Raij, 1997). Studies have shown that liming benefits groundnut productivity on acid soils mainly because of improved Ca nutrition (Snyman, 1972; Reid & Cox, 1973; Walker, 1975; Blamey & Chapman, 1982; Blamey, 1983; Gani *et al*., 1992; Rosolem & Caires, 1998; Macció, 2002). However, because of the many factors involved in acid soil infertility and because of the often-inconsistent response of the crop to lime application on different soils, interpretation of liming benefits of acid soils with respect to groundnut has been difficult (Blamey & Chapman, 1982).

The major goals of this study were to elucidate the cause(s) of poor groundnut yields on acid light textured soils of Zimbabwe and to identify a practical soil acidity amelioration option conducive to improved groundnut productivity in the smallholder-farming sector. The specific objectives of the study were to assess the effects of lime, gypsum and phosphate application on (1) soil pH and

nutrient status (2) plant nutrient composition and (3) vegetative and reproductive performance of Spanish groundnut cultivar *Falcon* on acid light textured soils of Zimbabwe.

2.2 MATERIALS AND METHODS

Field experiments with groundnut (Spanish type *cv. Falcon*) were established for three consecutive cropping seasons (1999/2000 to 2001/02) on acid sandy soils at the Horticulture Research Centre (HRC) located in agro-ecological region II (750 – 1000 mm rainfall), and at Makoholi Experiment Station (MES) located in agro-ecological region IV (450 – 600 mm rainfall) of Zimbabwe. The soils at both sites are derived from granite and belong to the 5G (Fersiallitic order). They are moderately shallow, grayish brown, coarse-grained sands (particle size >0.02mm; silt + clay <15%), with low pH, low cation exchange capacity (CEC) and low amounts of several cations (Thompson & Purves, 1981).

The four Ca materials evaluated in the experiments were calcitic lime (CL), dolomitic lime (DL), gypsum (G) and single superphosphate (SSP). Samples of the Ca materials were analysed by the Chemistry and Soils Research Institute in Harare to determine their chemical nature (Table 2.1).

Table 2.1 Characteristics of the Ca sources used in the experiments

Source	% Ca	% Mg	Neutralizing value (%)
Calcitic lime ($CaCO_3$) Finely ground limestone passed through a 200-mesh (0.074mm) screen.	23	7.2	107
Dolomitic lime ($CaCO_3.MgCO_3$) Finely ground dolomite passed through a 200-mesh screen	18	11	102
Gypsum ($CaSO_4$) In powder form - passed through a 200-mesh sieve.	20	0.5	25
Single Superphosphate [$Ca(H_2PO_4)_2.CaSO_4$] In granular form and contains 18.2% P_2O_5.	12	4.3	Not determined

In the 1999/2000 cropping season the treatments were calcitic lime (CL) applied at 2000 and 4000 kg ha^{-1}, dolomitic lime (DL) applied at 2000 and 4000 kg ha^{-1}, gypsum (G) applied at 200 kg ha^{-1} single superphosphate (SSP) applied at 250 kg ha^{-1}. These materials were applied either alone or in combinations, thus totaling ten soil amelioration treatments (Table 2.2). In the

2000/01 and 2001/02 cropping seasons, the experiment was repeated with minor changes; the treatments with low rates of Ca (Treatments 1, 5 and 7) were repeated each year, whereas residual effects of the other treatments were observed.

Table 2.2 Treatments applied at Horticulture Research Centre (HRC) and Makoholi Experiment Station (MES) in the 1999/2000 cropping season

Trt. No.	Treatment (kg ha^{-1})	Code
1.	Gypsum (200)	G-200
2.	Calcitic or Dolomitic lime (2000)	L-2000 †
3.	Calcitic lime (4000)	CL-4000
4.	Dolomitic lime (4000)	DL-4000
5.	Single super phosphate (250)	SSP-250
6.	Gypsum (200) + Calcitic Lime (2000)	G + CL
7.	Gypsum (200) + SSP (250)	G + SSP
8.	SSP (250) + Calcitic Lime (2000)	SSP + CL
9.	SSP (250) + Gypsum (200) + CL (2000)	SSP + G + CL
10.	Control (no amendment)	Control

†Due to the low exchangeable Mg status of the MES soil, CL was replaced with DL in the case of treatment 2. Thus, L-2000 = CL at HRC, DL at MES.

The lime was broadcast by hand and disced into the soil a month before planting while super phosphate and gypsum were banded in the row at planting. The treatments were in four replicates arranged in a randomized complete block design. The plots were maintained for the duration of the experiments. Gross plot size was eight rows of groundnut spaced at 0.45m apart and 5m long ($18m^2$), while the net plot comprised of four rows spaced at 0.45 m apart and 4m long ($7.2m^2$).

In the first and third seasons, the groundnut was planted immediately after the first effective rains in November at both sites. In the second season, the trials had to be established with irrigation at both sites due to lateness of the rains. In all three seasons, the rainfall amount was typical for the respective ecological zones, but distribution in all three seasons was poor. As is the practice with smallholder farmers, the groundnut seed was not inoculated with *Rhizobium*. All plots received a

starter nitrogen application of 20 kg N ha^{-1} as NH_4NO_3. Fungicides (Mancozeb and Benomyl) were applied as required to minimize *Cercospora* infection. No groundnut disease or pest problems were observed in all the three seasons. The crop was kept weed-free by hand hoeing throughout the growing season.

Soil samples (one from the middle of each plot in 1999/2000; four cores per plot, mixed and subsampled in 2000/01) were taken from the pod zone (0-10 cm depth) and from the root zone (20-30 cm depth) at peak flowering and at harvest. The soils were air dried, sieved to <2mm and stored for subsequent chemical analysis. Soil pH was determined in calcium chloride ($CaCl_2$) solution while phosphorus was extracted with bicarbonate using the Olsen method, and measured by the method of Murphy & Riley (1962). Exchangeable cations (K, Ca, and Mg) were extracted with 1*M*- ammonium acetate; K was determined by flame photometry while Ca and Mg were analysed by atomic absorption spectrophotometry. Mineral N (NO_3^- + NH_4^+) was determined by the semi-micro Kjeldal procedure followed by steam distillation (Bremner & Mulvaney, 1982). In the third season, the soils were analyzed for pH only, due to budget constraints. The Soil Productivity Research Laboratory (SPRL) and the Chemistry & Soils Research Institute, Department of Research and Specialist Services, Zimbabwe conducted all the analyses.

The plants were separated into pods (if present), shoots, roots and nodules, and the fresh weight of these plant parts and the number of nodules per plant were determined before they were dried in an oven at 80^o C for 48 hrs to determine dry mass. At peak flowering stage quadrants were thrown onto each plot and ten representative plants per plot were harvested to determine the effects of the treatments on leaf nutrient composition in relation to vegetative growth of the groundnut. The same procedure was repeated at physiological maturity. The youngest fully expanded leaves (YFEL) inclusive of petioles were sampled to determine uptake of N, P, K, Ca, and Mg. The plant shoots were oven-dried at 80^o C for 48 hrs to determine dry mass. The total number of nodules per plant was recorded, and the dry weight of nodules determined. At physiological maturity all plants in the net plot were harvested by hand, the nuts were hand picked, placed in mesh bags and dried to 10% moisture. Haulm, pod and kernel yields as well as quality characteristics were determined. Nutrient concentrations in the kernels were also

determined. A nitric perchloric acid (HNO_3:$HClO_4$) digestion of the plant material was used to prepare all the plant samples for analysis.

Data were analyzed as randomized complete block designs with four replicates using the General Linear Models (GLM) procedure of the Statistical Analysis System (SAS Institute Inc. Cary, NC, USA 1996 Copyright). Duncan's least significant difference (LSD) test was used to separate treatment means, and differences at the $P \leq 0.05$ level of significance are reported. In addition, data on kernel yield and some of its parameters were subjected to regression analysis. Emulating the methodology used by Blamey (1983) to investigate the mutual associations between kernel yield and yield components, simple correlation coefficients between kernel yield, yield components and soil parameters were computed.

2.3 RESULTS AND DISCUSSION

Before the application of the ameliorants, the soil pH ($CaCl_2$) values ranged from medium acid (pH 4.8 – 5.1) at HRC to strongly acid (<4.4) at MES, but the Al^{3+} levels were very low (Table 2.3). The pH was generally higher in the pod zone (0 - 10 cm depth) than in the root zone (20-30 cm depth). The soils at both sites were low in N, and in the basic cations (Ca, Mg and K) in both the pod zone and the root zone.

Table 2.3 Soil analyses before application of amendments to acid soils at HRC and MES

Site	Soil depth (cm)	pH ($CaCl_2$)	Al^{3+} (mg kg^{-1})	Mineral N (mg kg^{-1})	P (mg kg^{-1})	Exchangeable cations (mg kg^{-1})		
						K	Ca	Mg
HRC	0 – 10	5.1	0.00	11	25.1	23.5	105	22.5
	20 - 30	4.8	0.002	13	26.6	27.4	100	29.8
MES	0 - 10	4.4	0.001	14	25.0	19.5	46	12.2
	20 - 30	4.3	0.003	18	27.9	19.5	52	12.8

2.3.1 EFFECT OF AMENDMENTS ON SOIL CHEMICAL PROPERTIES

Pod zone pH changes in the 1999/2000 cropping season

At the peak flowering period of groundnut the mean pH values in the pod zone were 4.6 in the control plots at HRC (Figure 2.1) and 4.1 at MES (Figure 2.2). Application of 2000 kg ha^{-1} lime increased the pH to 5.6 at HRC, and to 5.7 at MES, while application of 4000 kg ha^{-1} CL or DL increased the pH to values >6.0 at both sites. Combining gypsum and/or SSP with 2000 kg ha^{-1} CL did not affect soil pH differently than applying the lime alone. By contrast, gypsum and SSP alone or in combination had very little effect on soil pH. The response trends at the end of the cropping season were similar to those observed at peak flowering, but with gypsum and SSP inducing some increase in soil pH (Appendix Table A2.1).

Root zone pH changes in the 1999/2000 cropping season

In the root zone (20-30 cm soil depth layer), mean pH values in the 1999/2000 cropping season were 4.7 in the control plots at HRC (Figure 2.1) and 4.0 at MES (Figure 2.2). At both sites, the largest increases in pH were recorded from plots on which 4000 kg ha^{-1} CL was applied, with mean pH values for this treatment being 5.2 at HRC and 5.6 at MES. Dolomitic lime applied at the same rate achieved similar increases at HRC (pH 5.2) and at MES (pH 5.1). Relatively small pH increases (up to 0.4 and 0.6 units at HRC and MES, respectively) were obtained when limestone was applied at 2000 kg ha^{-1} alone, or in combination with SSP and/or gypsum. Similar treatments effects were observed at physiological maturity (Appendix Table A2.1).

In the 1999/2000 season, application of lime significantly increased soil pH at both sampling periods, and the higher the lime rate, the greater the increase in soil pH. The increases in pH when equal rates of CL and DL were applied were higher with calcitic lime. Although this effect was observed on both soils, it was more pronounced on the MES soil that initially had lower pH values than the HRC soil. At both sites, lime treatments raised pH more in the pod zone than the root zone. These differences can be attributed to the generally slow movement of lime through the soil profile because of the low dissolution rate, compared to gypsum (McCray & Sumner, 1990). At both sites, there were notable decreases in pH values in the root zone at physiological maturity, compared to the flowering period. A probable explanation is that since the groundnut

plants obtain most of their nitrogen through N_2-fixation, and therefore take up more cations than anions, extrusion of H^+ from their roots acidifies the root zone (McLay *et al*., 1997). In a split pod / root solution culture experiment, Zharare (1997) observed that a massive K uptake by groundnut in the root environment that started at peak podding was accompanied by an intense acidification of the root's culture solution.

In contrast to the effect of lime, application of gypsum alone did not have any effect on soil pH. The low rate of gypsum application (200 kg ha^{-1}) as well as the fact that it was banded in the row at planting explains this. In addition, it is known that increases in pH after gypsum application are due to ligand exchange, and are regulated by zero point charge on the colloidal surface (Sumner, 1993). Thus SO_4^{2-} adsorption on soil surfaces neutralizes the positive charge present in the acid soils, and generates a negative charge until the surface reaches a new zero point charge, where no further adsorption of this anion takes place. That is why the effect of gypsum may be a decrease, increase or no change in the soil pH, depending on how close the soil pH was to zero point charge when gypsum was applied (Mora *et al.,* 1999). In this study, the lack of alteration in soil pH due to gypsum application may imply that a low positive charge was initially present in the soil. Therefore, with the small amount of gypsum applied, there was limited exchange between the SO_4^{2-} and (OH^-) ions, hence the small effect on pH.

Pod zone pH changes in the 2000/01 and 2001/02 cropping seasons

In the second and third cropping seasons, the pH in the pod zone at peak flowering generally decreased successively with time, with slight changes being observed in the gypsum and SSP plots where the ameliorants were applied annually. Mean pod zone pH values in the plots treated with both rates of CL at HRC had decreased by up to 0.54 pH units in the second cropping season; in the DL-4000 treatment the pH had decreased by 0.32 units (Figure 2.1). In the SSP and gypsum plots, there was no change in the pod zone pH as the seasons progressed. The trends observed in the second season were generally maintained in the third season. At MES, the decline in soil pH in the second season was of a lesser magnitude than that observed at HRC (Figure 2.2). Like at HRC, there were hardly any changes in soil pH in the gypsum and SSP plots. In the third season, large decreases in soil pH were observed in all the plots in which residual effects of lime were being monitored, especially the CL-4000 and DL-4000 treatments.

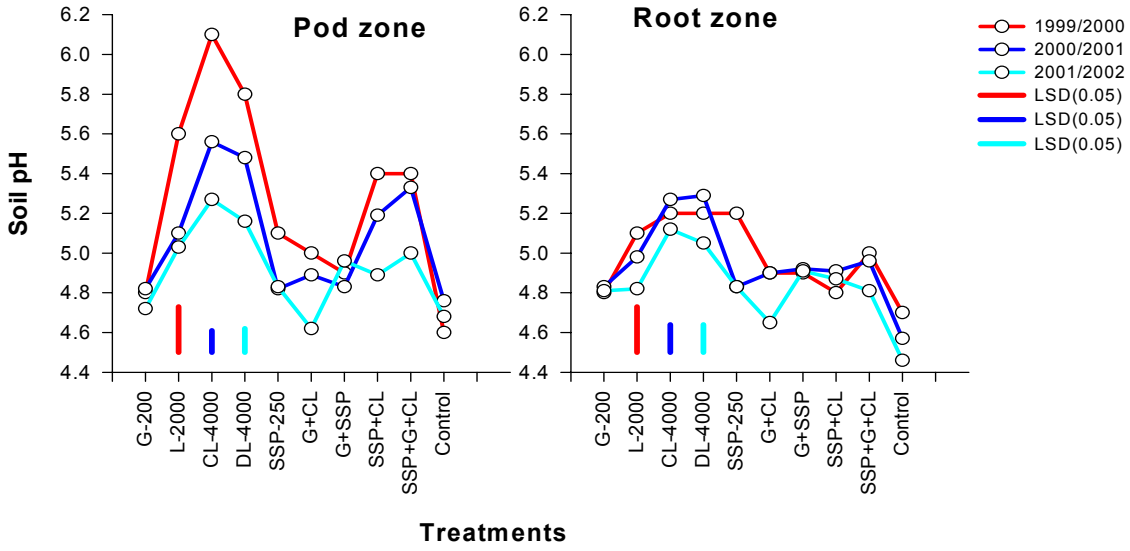


Figure 2.1 **Changes in soil pH at peak flowering in 1999/2000, 2000/01 and 2001/02 cropping seasons after application of Ca materials at HRC**

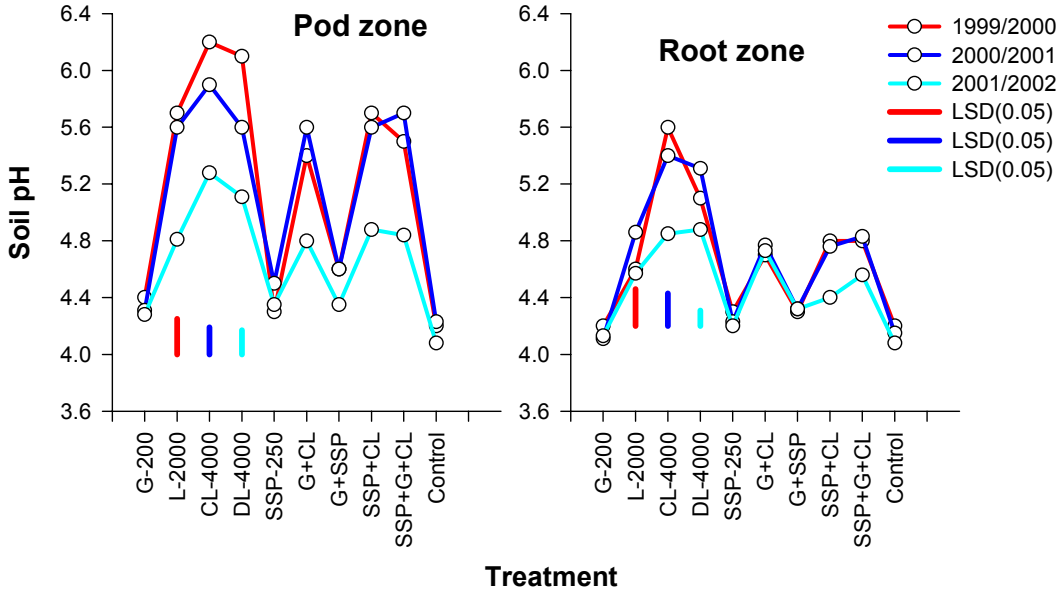


Figure 2.2 **Changes in soil pH at peak flowering in 1999/2000, 2000/01 and 2001/02 cropping seasons after application of Ca materials at MES**

Changes in the soil pH of the control treatments can be attributed to seasonal variations in the reactions that neutralize H^+ as well as produce H^+ (Conyers *et al.,* 1995). Soil pH undergoes cycles of decrease and increase (Friesen, *et al.,* 1985; Skyllberg, 1991) because of alkali-producing reactions (ammonification, reduction of Mn-oxides, oxidation of organic anions, SO_4^- adsorption) or acid-producing reactions such as nitrification, oxidation of Mn^{2+}, oxidation of organic S (Conyers *et al.,* 1995).

Root zone pH changes in the 2000/01 and 20001/02 cropping seasons

In the 2000/01 cropping season, the pH values in the root zone at both sites tended to be similar to those observed in the 1999/2000 cropping season (Figures 2.1 & 2.2). Plots treated with 4000 kg ha^{-1} CL or DL maintained the highest soil pH levels in the 2000/01 cropping season at both sites. In the 2001/02 cropping season, the soil pH values decreased considerably, resulting in soil pH levels similar to those observed in the first cropping season. The soil pH levels remained highest in plots treated with 4000 kg ha^{-1} lime.

While the pH decreased with time at both sites, soil pH levels in the pod and root zones in plots treated with 4000 kg ha^{-1} lime were still above pH 5.0 in the third season. At the HRC site, the plots treated with either 2000 kg ha^{-1} lime alone or in combination with gypsum and SSP also had soil pH levels above 5.0 in the third season. In the rest of the treatments, the soil pH was slightly higher, but not significantly different from that of the original unlimed soil. Even when gypsum and SSP were added annually, they did not improve soil pH with time. Scott *et al.* (1999) found that the rate of pH decline in the 0-10 cm soil depth depended on the pH increase achieved one year after lime application; the higher the pH increase, the faster the rate of decline and *vice versa.* Similarly in the present study a considerable decline in pH was observed in treatments that attained the highest soil pH values, and this was more pronounced at MES where initial increases in pH of >2.0 units had been observed, followed by a decline of 0.99 units in the third season.

CHANGES IN EXCHANGEABLE SOIL CA LEVELS

Pod zone Ca levels in the 1999/2000 cropping season

Concomitant with the observed increases in soil pH in the 1999/2000 cropping season, exchangeable Ca levels in the soil were also improved. Mean Ca levels in the pod zone of the control plots at HRC were 125 mg kg^{-1} at peak flowering, and application of CL was the most efficient in increasing soil Ca level by 92% to 125% (Figure 2.3). In the plots with 4000 kg ha^{-1} DL, increases in Ca levels were 51%, whereas gypsum or SSP applied alone increased Ca levels by 26% and 9% respectively. Combining gypsum or SSP with 2000 kg ha^{-1} lime did not increase Ca levels more than applying lime alone. At the MES site, the mean exchangeable Ca levels in the control plots were 43 mg kg^{-1} at peak flowering, and application of calcium materials increased the Ca levels up to 418 mg kg^{-1} with 4000 kg ha^{-1} CL (Figure 2.3). Overall, the responses were similar to those observed at HRC, and the treatment effects were highly significant.

At the physiological maturity stage of the groundnut, the pod zone Ca levels in the CL and DL treatments and their combinations tended to be higher than at the flowering stage at HRC (Appendix Table A2.2). Application of CL had increased Ca levels from the initial 167 to 233 mg kg^{-1} with 2000 kg ha^{-1}, and up to 332 mg kg^{-1} with 4000 kg ha^{-1} at HRC. Dolomitic lime applied at 4000 kg ha^{-1} increased Ca levels up to 282 mg kg^{-1}, while combinations of lime with SSP or gypsum did not result in higher Ca levels than lime alone. Similar response trends were observed at MES (Appendix Table A2.3), although the Ca levels were somewhat lower at physiological maturity than at peak flowering for most of the treatments. The Ca levels in plots treated with 4000 kg ha^{-1} CL had increased from 64 to 277 mg kg^{-1}.

Root zone Ca levels in the 1999/2000 cropping season

In the root zone at HRC, the Ca content at peak flowering and at physiological maturity was less affected by application of Ca-materials than in the pod zone, but the response trend was similar (Figure 2.3; Appendix Table 2.2). At MES, the Ca content at peak flowering was significantly increased from the initial 48 up to 209 mg kg^{-1} with application of 4000 kg ha^{-1} CL. Combining lime with gypsum and/or SSP also significantly improved the root zone Ca levels. At

physiological maturity, the root zone Ca levels were less affected by treatments than in the pod zone, but the response trend was similar (Appendix Table A2.3). Contrary to the observations made at HRC, the Ca levels in the root zone at MES were somewhat lower at physiological maturity than at peak flowering for most of the treatments. Overall, the increases in Ca levels due to application of ameliorants were higher (up to 335%) at MES than at HRC (up to 77%) with application of CL.

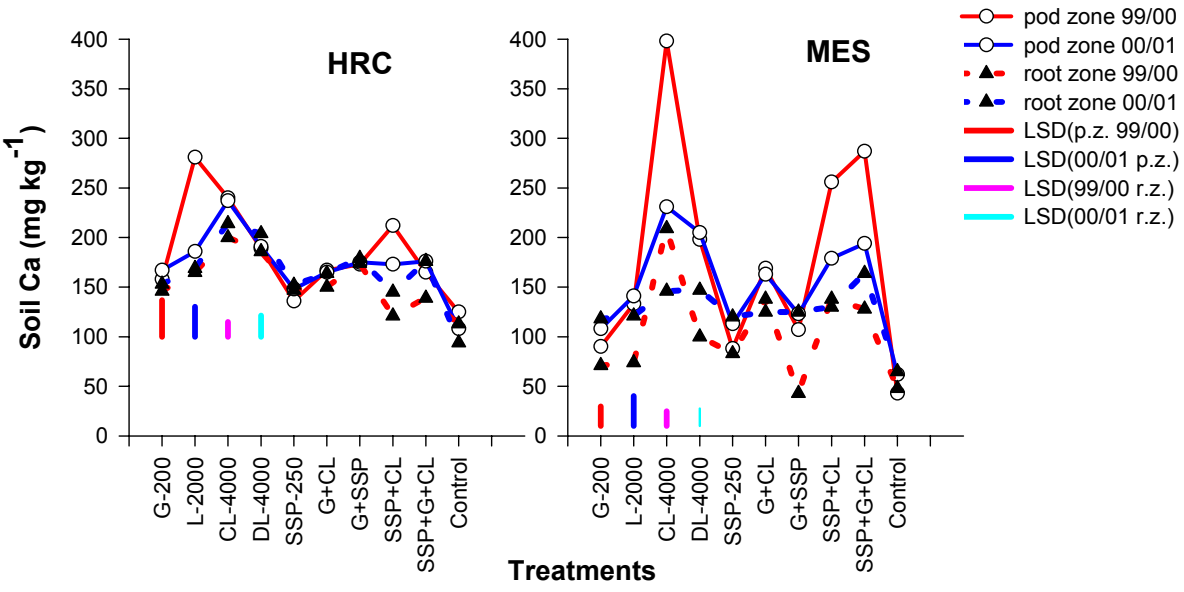


Figure2.3 Changes in soil exchangeable Ca levels at peak flowering in 1999/2000 and 2000/01 seasons after application of Ca materials at HRC and MES.

When equal rates of lime were applied, Ca levels in the pod and root zones were highest in plots where CL was applied probably due to the higher Ca concentration in CL (23%) than in DL (18%). The pod zone Ca levels in the CL and DL treatments, and their combinations, at HRC tended to be higher at the physiological maturity stage of groundnut than at the flowering stage, which could be an indication that lime may provide more Ca in solution late in the season, as a result of the low solubility and/or slow mobility. The different observation made at MES could be ascribed to uncontrollable variations due to sampling and analytical procedures. Observations that the Ca content in the root zone was less affected by treatments than the pod zone could

probably be ascribed to the depth of incorporation, and to the solubility and/or mobility of the materials.

Pod zone Ca levels in the 2000/01 cropping season

In the 2000/01 cropping season, the exchangeable Ca levels in the pod zone at HRC were either similar or slightly lower than those observed in the previous season for most treatments (Figure 2.3). The Ca levels in the control plots had declined to 108 mg kg^{-1}, and remained highest (221-237 mg kg^{-1}) in plots treated with 4000 kg ha^{-1} CL or DL. At MES, the Ca levels in the pod zone also tended to be similar or lower than those observed in the previous season (Figure 2.3). Overall, the highest Ca levels were observed in the plots with 4000 kg ha^{-1} lime and in plots treated with lime in combination with SSP and gypsum. At both sites, the response trend at peak flowering was similar to that observed at physiological maturity. Data for the physiological maturity sampling dates are presented in Appendix Tables A2.2 & A2.3.

Root zone Ca levels in the 2000/01 cropping season

In the root zone, the exchangeable Ca levels at both sites generally showed slight increases compared to those observed in the previous season (Figure 2.3). The mean Ca values in the control plots at peak flowering were 94 mg kg^{-1} at HRC and 48 mg kg^{-1} at MES, and residual effects of 4000 kg ha^{-1} CL increased the levels to 244 mg kg^{-1} at HRC, whereas at MES residual effects of lime in combination with SSP and gypsum increased the levels to 164 mg kg^{-1}. Like in the pod zone, the highest Ca levels were observed in the plots with 4000 kg ha^{-1} lime and in plots treated with lime in combination with SSP and gypsum. At both sites the response trends at physiological maturity were similar to those observed at peak flowering (Appendix Tables A2.2 & A2.3).

The movement of Ca below the depth of initial incorporation could explain the observed higher levels of Ca in the second season in the root zone. Similar interpretations were made by Scott *et al.* (1999) who detected significant increases in Ca in the 10-15 and 15-20 cm soil layers after application of 1000 kg ha^{-1} lime in the previous year. However, the Ca increases could be overestimated if undissolved lime remained in the soil and the extraction of exchangeable cations resulted in the dissolution of some undissolved lime (Aitken *et al.,* 1998).

CHANGES IN EXCHANGEABLE SOIL MG LEVELS

Pod zone Mg levels in the 1999/2000 cropping season

At both sites the exchangeable Mg levels in the pod zone at the peak flowering period of groundnut were increased due to application of CL and DL. At HRC, the exchangeable Mg increased by 183% to 68 mg kg^{-1} in the plots treated with 4000 kg ha^{-1} DL (Figure 2.4). Gypsum and SSP applied alone or in combination did not affect exchangeable Mg levels. At the MES site, the treatments had a similar effect on Mg levels as that observed at HRC (Figure 2.4). Application of 4000 kg ha^{-1} DL increased the Mg content from an initial 11 mg kg^{-1} to 63 mg kg^{-1}, an increase of 473%. Reactions in soil exchangeable Mg levels at physiological maturity of groundnut were similar to those observed at peak flowering at both sites (Appendix Tables A2.2 & A2.3). Generally, significant increases in the levels of exchangeable Mg were found on limed plots. The exchangeable Mg levels at both sites were generally lower at physiological maturity than at peak flowering, the only exception being the DL 4000 kg ha^{-1} treatment at HRC that registered a 34% increase in exchangeable Mg levels.

Root zone Mg levels in the 1999/2000 cropping season

In the root zone, the treatment effects on exchangeable Mg were similar to those observed in the pod zone at both sites, though less prominent (Figure 2.4). At both sites, the gypsum and SSP treatments had no effect on the Mg content of the soil. When they were applied in combination with lime, non-significant increases in Mg content were observed. As expected, plots treated with DL were higher in soil Mg levels than other plots throughout the groundnut growing season, and the higher the application rate, the larger the increase in soil Mg content. This is attributable to the higher Mg content of dolomite (10.9%) compared to that of CL (7.2%), SSP (4.2%) and gypsum (0.5%).

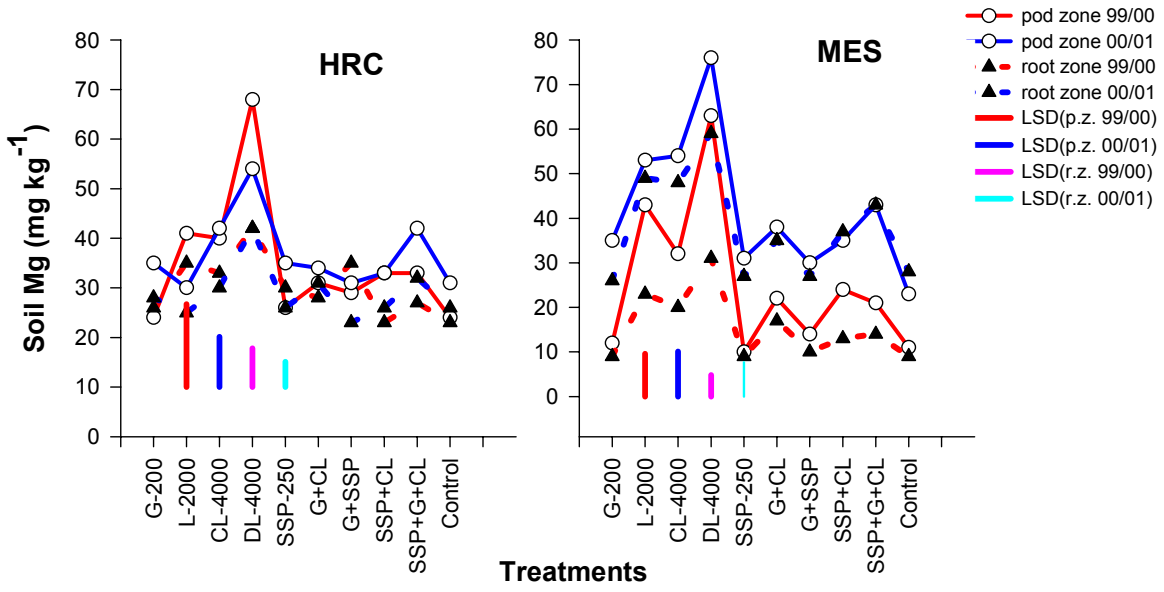


Figure2. 4 Changes in soil exchangeable Mg levels at peak flowering in 1999/2000 and 2000/01 seasons after application of Ca materials at HRC and MES

Pod zone Mg levels in the 2000/01 cropping season

Levels of exchangeable Mg in the pod zone at HRC were similar to those observed in the previous season for all treatments (Figure 2.4). The lowest Mg levels were in the control plots (31 mg kg^{-1}) while the highest (54 mg kg^{-1}) were in plots treated with 4000 kg ha^{-1} DL. Mg levels considerably higher than the control were also observed in plots treated with 4000 kg ha^{-1} CL and where lime was combined with gypsum and SSP. At MES, the Mg levels in the pod zone tended to be higher than those observed in the previous season (Figure 2.4). The Mg levels ranged from 23 mg kg^{-1} in the control treatment to 76 mg kg^{-1} in plots treated with 4000 kg ha^{-1} DL. While the response trends observed at peak flowering were maintained at physiological maturity at both sites, somewhat lower Mg levels were observed at the latter stage (Appendix Tables A2.2 & A2.3).

Root zone Mg levels in the 2000/01 cropping season

In the root zone, the exchangeable Mg levels at HRC were not different from those observed in the 1999/2000 cropping season (Figure 2.4), whereas at MES the Mg levels were considerably higher than those observed in the previous season (Figure 2.4). The highest mean Mg values were observed in the plots with 4000 kg ha^{-1} DL at both sites, whereas annual applications of SSP

and gypsum did not increase the soil Mg levels. Overall, the residual effects of the applied ameliorants on soil Mg content were more prominent at MES than at HRC.

At physiological maturity of groundnut, the residual effects of the ameliorants on soil Mg content were similar to those observed at peak flowering at both sites (Appendix Tables A2.2 & A2.3). High levels of exchangeable Mg were found on limed plots whereas gypsum and superphosphate had no effect on the Mg status of the soil. At both sites, the Mg levels were generally lower at physiological maturity compared to the peak flowering period.

CHANGES IN SOIL N, P AND K LEVELS

Pod and root zone N levels in the 1999/2000 and 2000/01 cropping seasons

At both sampling periods in the first season (Table 2.4; Appendix Table A2.4), considerable variation in the N status of the pod zone was observed over the plots of the experiment, especially at the peak flowering period, where the levels ranged from 7 to 17 and 5 to 22 mg kg^{-1} at HRC and MES, respectively. Similar variations were observed in the root zone at both sites. While statistically there were significant differences between the N levels observed, no clear explanation for the variations in N-analysis can be offered. Rosolem & Caires (1998) attributed the low N levels observed in their limed plots to increased N uptake, resulting in the depletion in soil N levels.

In the second cropping season, the mineral N levels in the pod zone at the peak flowering period of groundnut were generally improved at both sites, especially in the limed plots (Table 2.5). As observed in the previous season, the treatment effects were in general not significant, but the higher mineral N levels in the lime treatments may be a reflection of the treatment effects on groundnut productivity during the previous season, resulting in more crop residues on some plots. The trends observed in the pod zone were repeated in the root zone. Overall, the soil N levels remained low during the two cropping seasons. Divergent results on the effects of lime on N mineralization have been documented; with some reporters observing improved N mineralization following lime application (Black, 1968; Lyngstad, 1992), while Nyborg & Hoyt (1978) found no correlation between soil pH and the N mineralized per unit of organic N. Lyngstad (1992)

observed that the release of N caused by liming was short-lived, and that the direct as well as residual effects of lime on amounts of N mineralized varied among soils.

Pod and root zone P levels in the 1999/2000 and 2000/01 cropping seasons

In the first season, the mean pod zone P levels in the control plots at peak flowering were 39 mg kg^{-1} at HRC, and increased to 46 mg kg^{-1} with application of SSP in combination with gypsum and lime (Table 2.4). At MES, the mean pod zone P levels in the control plots were 20 mg kg^{-1}, and application of 4000 kg ha^{-1} DL resulted in the highest P content of 41 mg kg^{-1} (Table 2.4). Similar treatment effects were observed at the physiological maturity stage (Appendix Table A2.4). In the root zone at HRC, the P levels ranged from 35 mg kg^{-1} in the control plot to 47 mg kg^{-1} in the plot treated with 250 kg ha^{-1} SSP (Table 2.4). At physiological maturity, the P levels were generally lower, ranging from 19 to 29 mg kg^{-1} (Appendix Table A2.4). This trend was also observed at the MES site where high soil P levels were observed even in the control plots (Table 2.4; Appendix Table A2.4).

The pod and root zone P levels at both sampling periods in the second season were similar to those observed in the first season (Table 2.5; Appendix Table A2.5). The soil analysis in this study clearly shows that there were adequate amounts of plant available P present in the soils at both sites. The absence of any treatment effects on soil P content indicates that any observed differences in plant growth could not be related to differences in P nutrition.

Table 2.4 Soil N, P and K levels in the 0-10 cm and 20-30 cm soil depth layers at peak flowering period of groundnut at HRC and MES, 1999/2000 season

Treatment	HRC						MES					
	Soil nutrient level (mg kg^{-1})						Soil nutrient level (mg kg^{-1})					
	N		P		K		N		P		K	
	Soil depth layer (cm)						Soil depth layer (cm)					
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	12	10	37	37	23	26	9	23	26	37	11	12
L-2000	8	9	38	37	25	27	11	5	30	36	8	8
CL-4000	10	6	33	37	15	23	7	7	26	51	8	8
DL-4000	17	8	44	40	37	29	6	4	41	49	10	11
SSP-250	7	7	36	47	22	23	5	5	19	41	9	13
G + CL	16	10	36	36	17	22	10	10	20	40	11	18
G + SSP	8	13	35	39	14	23	10	22	27	63	9	9
SSP + CL	11	7	34	37	21	20	9	7	24	47	8	8
SSP + G + CL	11	10	46	41	19	25	5	3	34	22	8	9
Control	8	18	39	35	20	22	22	11	20	61	12	14
Mean	11	10	38	39	21	24	9	10	27	45	9	11
LSD $_{(0.05)}$	3.2	2.8	3.01	4.18	4.57	3.44	4.46	7.68	7.63	10.0	2.08	2.66

Table 2.5 Soil N, P and K levels in the 0-10 cm and 20-30 cm soil depth layers at peak flowering period of groundnut at HRC and MES, 2000/01 season

Treatment	HRC						MES					
	Soil nutrient level (mg kg^{-1})						Soil nutrient level (mg kg^{-1})					
	N		P		K		N		P		K	
	Soil depth layer (cm)						Soil depth layer (cm)					
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	12	13	23	15	23	19	13	11	20	34	21	20
L-2000	17	11	24	18	21	14	14	14	20	38	18	17
CL-4000	14	13	27	20	27	18	15	10	26	35	19	15
DL-4000	12	10	25	19	21	13	20	12	27	34	20	14
SSP-250	12	14	29	18	17	14	13	9	21	33	16	14
G + CL	18	15	18	15	27	18	22	14	19	33	22	15
G + SSP	12	13	34	20	17	14	16	10	20	34	17	14
SSP + CL	18	13	27	26	21	14	16	11	23	34	19	16
SSP + G + CL	16	13	35	29	25	15	19	10	25	39	16	13
Control	14	15	18	13	23	16	11	10	17	32	14	16
Mean	**14**	**13**	**26**	**19**	**22**	**15**	**16**	**14**	**22**	**20**	**18**	**15**
LSD $_{(0.05)}$	**5.182**	**2.87**	**5.52**	**5.24**	**6.99**	**5.18**	**3.23**	**2.89**	**5.16**	**5.93**	**3.31**	**2.23**

Pod and root zone K levels in the 1999/2000 and 2000/01 cropping seasons

Potassium levels in the pod zone at HRC ranged from 14 to 37 mg kg^{-1} at peak flowering (Table 2.4) and 12 to 20 mg kg^{-1} at physiological maturity (Appendix Table A2.4). At the MES site, K levels in the pod zone ranged from 8 to 12 mg kg^{-1} at peak flowering (Table 2.4) and 14 to 25 mg kg^{-1} at physiological maturity (Appendix Table A2.4). At both sites, there were no clear soil K responses to application of the Ca-materials. Some plots had lower K levels compared to the control plots, and this may be explained in terms of loss from the soil as a result of consumption by the better growing plants in these plots. In the root zone at HRC, the K values at peak flowering were generally higher than those observed in the pod zone, but were not significantly affected by treatments (Table 2.4). At physiological maturity, the K values in the root zone were similar to those in the pod zone at HRC (Appendix Table A2.4), and lower than those in the pod zone at the MES site (Table 2.4). The high K levels in the pod zone at MES were observed only in plots treated with CL or DL.

In the second season, the K levels were affected by treatments at both sites, and there were no clear response trends (Table 2.5; Appendix Table A2.5). The tendency for lower K levels in some plots compared to the control plots was repeated in the second season. Aitken *et al.* (1998) observed that lime application in acidic soils of south-east Queensland generally did not affect exchangeable K levels, but where the lime effects were significant, the K levels were significantly reduced with application of <4000 kg ha^{-1} lime, and attributed this to the relative ease of displacement of K from the cation complex by Ca. The propensity for generally higher K values in the root zone than in the pod zone at peak flowering, and *vice versa* at physiological maturity, was also repeated in the second season at both sites.

Overall, the soil K levels in this study at both sites are considered too low for production of groundnut, which requires not less than 80 mg kg^{-1} K (Swanevelder, 1998). Therefore, fertilization may be necessary to improve plant available K in the soils used in this study. The observed K levels in the root and pod zones corroborate the observations by Zharare (1997) that at Ca levels that are optimal for pod growth, groundnut plants excrete K through the pods after absorption by the roots, hence the increase in the nutrient in the pod zone, especially at peak pegging and early pod formation stage. More K in the pod zone was observed in plots that

generally had high Ca levels. This transfer of K from the root zone to the pod zone has valuable economic implications on the K-fertilization program in cropping systems including groundnut, as groundnut can be sequenced with shallow-rooted crops so that they can utilize subsoil K that would have been recycled to the topsoil by groundnut.

2.3.2 EFFECT OF AMENDMENTS ON PLANT STAND, NODULATION, LEAF NUTRIENT COMPOSITION AND YIELD OF GROUNDNUT

Plant stand

Plant density is an important factor affecting groundnut yield. An assessment of this parameter over the three seasons showed that application of ameliorants significantly improved plant stand at both sites (Figure 2.5). In the first season, the mean plant stand in the control plots at HRC was 77%, and application of lime combined with gypsum and SSP increased the plant population to 94%. Application of 4000 kg ha^{-1} CL or DL achieved a plant stand of 88%. Gypsum and SSP alone or in combination also improved the plant stand compared to the control treatment. Combining lime with gypsum and/or SSP did not influence plant stand differently than applying the lime alone. Similar treatment effects were observed in seasons two and three. Overall, better plant stands were observed in season two, and this can be attributed to better rainfall distribution in that season, coupled with favorable soil pH levels and improved nutrient status.

At MES, the mean plant stand in the control plots in the first season was 71%, and application of lime increased the plant stand to 86% with 2000 kg ha^{-1} CL, and to 90% with 4000 kg ha^{-1} CL. Application of 4000 kg ha^{-1} DL achieved a plant stand of 85%. Unlike at HRC, gypsum and SSP alone did not improve the plant stand, but when applied in combination resulted in a plant stand of 81%. Combining 2000 kg ha^{-1} CL with gypsum and/or SSP did not influence plant stand differently than applying the lime alone. These trends were observed over the three seasons. At this site, plant establishment in the respective treatments was almost similar across the three seasons, despite the improvements in soil pH and soil nutrient status.

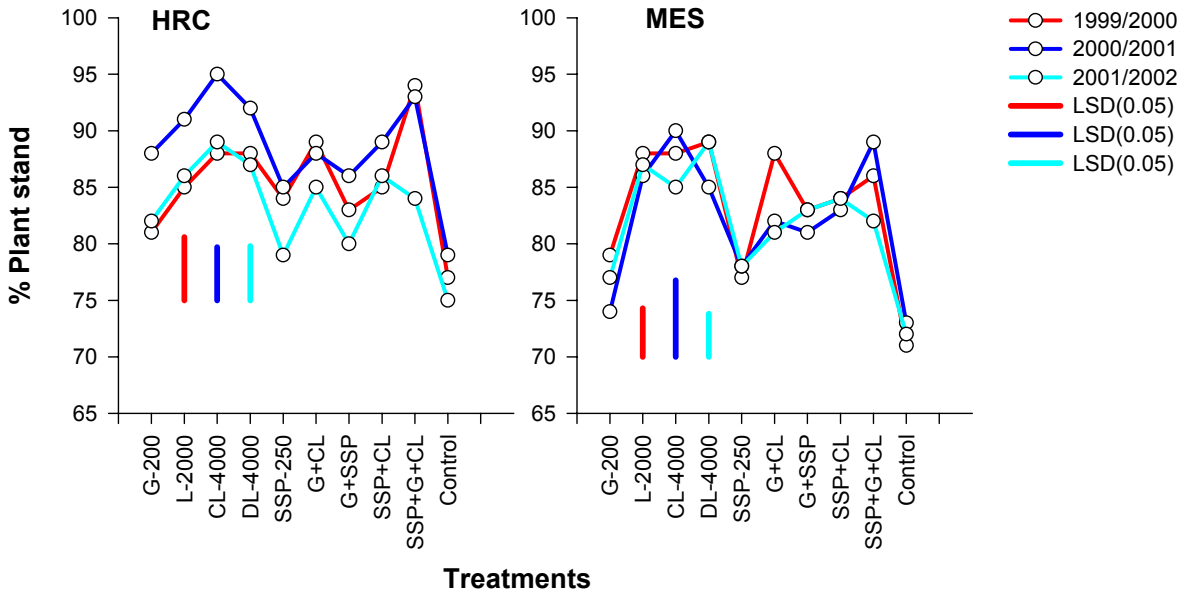


Figure 2.5 Plant stand (%) at HRC and MES as affected by application of Ca materials

Nodule number and mass

At HRC, the number of nodules per plant was significantly influenced by application of ameliorants, with an average of 104 nodules per plant being produced with 4000 kg ha^{-1} CL, compared to 32 in the control treatment in the 1999/2000 season (Table 2.6). Nodulation in the gypsum and SSP treatments was not significantly different from the control treatment. Nodule numbers were higher in the DL-4000 treatment than in the CL-2000 treatment. Similar response trends were observed in 2000/01 and 2001/02 seasons, though nodulation was less prolific compared to the 1999/2000 season. Nodule number per plant increased from 32 in the control treatment to 104 following the application of 4000 kg ha^{-1} CL in the 1999/00 season, and similar trends were observed in the second and third seasons. The response of nodule dry mass to ameliorants reflected that of nodule number (Table 2.6). The highest nodule dry mass (0.25 g $plant^{-1}$) in 1999/2000 season was observed in plots treated with 4000 kg ha^{-1} lime while the lowest (0.07 g $plant^{-1}$) was in the control plots. A similar effect was observed in the following seasons.

Although nodule number was influenced by application of ameliorants at MES, nodulation was less profuse than at HRC (Table 2.7). The mean number of nodules per plant in the control plots

was 10, 35 and 31 in the 1999/2000, 2000/01 and 2001/02 seasons respectively. Application of 4000 kg ha^{-1} lime increased the nodule number per plant to 35 in 1999/2000, 75 in 2000/01 and 56 in 2001/02. The same response trends were observed for nodule dry mass (Table 2.7).

The poor nodulation in the control and gypsum treated plots could be attributed to low pH or low Ca levels, since the process is inhibited by pH levels below 5.0 for most legumes (Jayasundara *et al.*, 1998) and by Mo and Ca deficiency (Munns, 1978). Nodule initiation has been found to be highly sensitive to acidity (Evans *et al.,* 1980), while excess H^+ ions and deficiencies of Ca and P are the acidity factors most detrimental to the nodulation process (Vargas & Graham, 1988; Coventry & Evans, 1989). The pH in the control and gypsum plots was below pH 5.0 in the three seasons while the Ca content in the root zone was low. Hohenberg & Munns (1984) in their work with cowpeas, observed that pH <4.5 reduced early nodule number by as much as 80% compared to nodulation at pH 5.5, and also caused delays in nodulation at low Ca levels. Alva *et al.* (1990) observed that low Ca or pH levels significantly influenced the time to appearance of first nodules, nodule number and nodule dry mass of cowpeas.

Depressed nodulation with gypsum application has been ascribed to probable increased activity of Al-ions in an Al-toxic soil (Blamey & Chapman, 1982), or reduced Mo availability due to the antagonistic effect of sulphate on Mo availability (Reisenauer, 1963). Mengel & Kamprath (1978) observed that in addition to increasing the number of nodules on soybean roots, liming also changed the location and size. Nodules were large and located mainly on the taproot at low pH, and were initiated on the lateral roots as the pH increased, and the mean nodule weight decreased.

Table 2.6 Nodule number and nodule dry mass at HRC as affected by application of Ca materials

Treatment	Nodule number (nodules plant^{-1})			Nodule dry mass (g plant^{-1})		
	1999/00	2000/01	2001/02	1999/00	2000/01	2001/02
G-200	44	43	51	0.079	0.083	0.103
L-2000	68	68	67	0.205	0.173	0.163
CL-4000	104	76	69	0.245	0.128	0.12
DL-4000	96	71	77	0.210	0.105	0.118
SSP-250	38	30	28	0.170	0.083	0.08
G + CL	50	53	88	0.187	0.120	0.133
G + SSP	58	44	48	0.153	0.105	0.095
SSP + CL	39	39	52	0.200	0.083	0.094
SSP + G + CL	73	56	52	0.210	0.123	0.123
Control	32	20	37	0.074	0.048	0.098
Mean	**60**	**50**	**57**	**0.180**	**0.102**	**0.113**
LSD $_{(0.05)}$	**21.33**	**16.377**	**25.177**	**0.043**	**0.025**	**0.031**

Table 2.7 Nodule number and nodule dry mass at MES as affected by application of Ca materials

Treatment	Nodule number (nodules plant^{-1})			Nodule dry mass (g plant^{-1})		
	1999/00	2000/01	2001/02	1999/00	2000/01	2001/02
G-200	15	30	34	0.073	0.095	0.085
L-2000	16	72	43	0.105	0.110	0.143
CL-4000	35	75	56	0.158	0.115	0.105
DL-4000	29	41	47	0.146	0.088	0.123
SSP-250	24	51	41	0.045	0.103	0.085
G + CL	25	45	42	0.143	0.113	0.098
G + SSP	25	55	37	0.100	0.113	0.078
SSP + CL	32	45	48	0.125	0.078	0.098
SSP + G + CL	33	48	49	0.146	0.155	0.110
Control	10	35	31	0.033	0.070	0.058
Mean	**24**	**50**	**43**	**0.107**	**0.110**	**0.101**
LSD $_{(0.05)}$	**8.278**	**14.953**	**14.467**	**0.020**	**0.029**	**0.027**

Leaf nutrient composition

The mean leaf Ca concentrations for the control treatment at HRC were 0.59% in the first season and 0.75% in the second season (Table 2.8). Application of CL at 2000 and 4000 kg ha^{-1} produced a two-fold increase in Ca concentrations in the 1999/2000 season. The other ameliorants also significantly increased the leaf Ca concentrations. However, these increases did not attain the leaf Ca levels of 1.25 – 2.0% indicated to be adequate for good growth of Spanish-type groundnut (Reuter & Robinson, 1986; Gascho & Davis, 1994), indicating the marginal Ca status of the plants. In the 2000/01 season, the treatment effects were similar to those observed in the first season, but the Ca concentrations were higher than in the previous season, probably reflecting the improved availability of Ca.

At MES the effect of lime on leaf Ca concentrations was similar to that observed at HRC (Table 2.9). However, the mean leaf Ca concentrations were higher than at HRC, ranging from 0.76 to 1.47% in 1999/2000 season, and from 0.85 to 1.93% in 2000/01 season. The higher concentrations could be a concentration effect due to relatively poor plant growth at this site, rather than the effects of the amendments *per se.* Stunted plants contain higher tissue concentrations of several nutrients because either the nutrients are not efficiently utilized, resulting in their accumulation in leaf tissue (Ali, 1998), or because of lower dry mass accumulation in relation to their uptake rates (Inskeep & Bloom, 1987). Only plants growing in plots treated with 2000 or 4000 kg ha^{-1} lime had adequate leaf Ca concentrations in the 1999/2000 season, whereas in the 2000/01 season, only plants growing in the control treatment and in plots treated with SSP or gypsum were Ca deficient.

In general, increased Ca concentrations were observed in treatments with higher soil Ca concentrations. Bell *et al.* (1989) made similar observations on a number of tropical legumes (cowpeas, groundnut, guar, pigeonpea and soybean) when he noted that leaf Ca concentrations increased with increasing solution Ca concentrations. Rechcigl *et al.* (1986) and Alva *et al.* (1991) also observed increases in leaf Ca content of legumes as solution Ca concentration increased.

Table 2.8 Ca, Mg, N, P and K concentrations in groundnut leaves (YFEL) sampled at peak flowering at HRC

Treatment	1999/00					2000/01				
	Leaf nutrient concentrations (%)					Leaf nutrient concentrations (%)				
	Ca	Mg	N	P	K	Ca	Mg	N	P	K
G-200	0.96	0.38	3.29	0.37	1.54	1.26	0.80	3.55	0.44	1.31
L-2000	1.20	0.43	3.78	0.32	1.48	1.30	0.77	3.56	0.37	1.27
CL-4000	1.25	0.44	3.88	0.28	1.27	2.02	0.79	3.72	0.34	1.24
DL-4000	1.08	0.45	3.88	0.29	1.12	1.73	0.88	3.79	0.37	1.49
SSP-250	1.00	0.39	3.28	0.33	1.34	1.14	0.70	3.63	0.39	1.29
G + CL	1.12	0.39	3.15	0.30	1.53	1.48	0.67	3.64	0.43	1.01
G + SSP	1.05	0.39	3.46	0.33	1.33	1.26	0.66	3.68	0.41	1.46
SSP + CL	1.09	0.40	3.67	0.33	1.41	1.32	0.69	3.65	0.41	1.27
SSP+G+CL	1.13	0.40	3.65	0.25	1.16	1.57	0.77	3.85	0.35	1.11
Control	0.59	0.33	3.07	0.26	0.94	0.75	0.49	3.46	0.45	1.37
Mean	**1.02**	**0.40**	**3.51**	**0.30**	**1.28**	**1.38**	**0.72**	**3.65**	**0.40**	**1.28**
LSD $_{(0.05)}$	**0.232**	**0.019**	**0.211**	**0.03**	**0.124**	**0.115**	**0.082**	**0.121**	**0.033**	**0.155**

Table 2.9 Ca, Mg, N, P and K concentrations in groundnut leaves (YFEL) sampled at peak flowering at MES

Treatment	1999/00					2000/01				
	Leaf nutrient concentrations (%)									
	Ca	Mg	N	P	K	Ca	Mg	N	P	K
G-200	0.78	0.45	2.34	0.38	2.015	0.94	0.33	3.21	0.4	1.37
L-2000	0.71	0.55	3.05	0.27	1.14	1.27	0.52	3.38	0.38	1.015
CL-4000	1.47	0.56	3.34	0.27	0.67	1.45	0.63	3.82	0.36	1.315
DL-4000	1.1	0.42	3.39	0.28	1.08	1.33	0.39	3.4	0.39	1.255
SSP-250	0.76	0.43	2.92	0.385	1.61	0.93	0.35	3.46	0.39	1.135
G + CL	1.11	0.33	2.9	0.26	1.335	1.15	0.57	3.55	0.44	1.015
G + SSP	0.81	0.36	2.46	0.32	1.575	1.1	0.34	3.65	0.37	0.895
SSP + CL	1.18	0.42	2.89	0.315	1.475	1.45	0.46	3.6	0.44	1.225
SSP + G + CL	1.23	0.49	3.06	0.42	1.845	1.93	0.38	3.41	0.38	0.9
Control	0.79	0.3	2.54	0.285	1.615	0.85	0.32	3.52	0.42	1.42
Mean	**0.994**	**0.431**	**2.889**	**0.3185**	**1.436**	**1.24**	**0.429**	**3.50**	**0.397**	**1.155**
LSD $_{(0.05)}$	**0.223**	**0.020**	**0.174**	**0.032**	**0.139**	**0.103**	**0.049**	**0.116**	**0.033**	**0.140**

The ameliorants significantly increased Mg concentrations at HRC in the both seasons (Table 2.8). The highest Mg concentrations were observed in plants from plots treated with 4000 kg ha^{-1} DL. In both years, plants in all treatments exhibited Mg concentrations within the established sufficiency ranges of 0.3 to 0.8% (Jones, 1974), and the concentrations were inexplicably higher in the second season. At MES, the ameliorants significantly affected leaf Mg concentrations in both seasons (Table 2.9). The Mg levels in the control treatment were 0.3% in both seasons, and were doubled with application of 4000 kg ha^{-1} DL. Application of 2000 kg ha^{-1} DL achieved similar increases. Gani *et al. (*1990) observed similar trends, with the direct and residual effects of lime increasing leaf Mg concentrations of groundnut.

The observed high Mg concentrations in treatments with high soil Ca levels are at variance with observations made by other researchers. Alva *et al. (*1991) noted that an increase in solution Ca decreased the Mg concentrations in soybean and cowpea tops. Bell *et al. (*1989) also reported negative effects of increased solution Ca concentrations on the leaf Mg content of five tropical grain legumes. However, Aitken *et al. (*1998) found no consistent trends with respect to the effect of lime on leaf Mg concentrations of maize.

Leaf N concentrations were significantly improved by application of liming materials in the first season at HRC (Table 2.8), with application of 4000 kg ha^{-1} attaining the highest N concentrations of 3.9%. In the second season, there were no differences in the N concentrations between the treatments, with N concentrations above sufficiency levels (3.0 – 4.5 %) according to Jones (1974). Shamsuddin *et al. (*1992) in their study on effects of Ca and Al on nodulation, N-fixation and growth of groundnut in solution culture observed that the leaf N concentrations were little affected by solution Ca concentration. At MES, the lowest N concentrations (2.34 and 3.21%) were in the gypsum treatment whereas the highest were in plots treated with 4000 kg ha^{-1} CL or DL (Table 2.9). The N concentrations were generally below sufficiency ranges in the 1999/2000 season, but adequate in the 2000/01 season.

In general, the P concentration of the leaves was not affected by application of ameliorants at both sites and in both seasons (Tables 2.8 & 2.9). The P concentrations were adequate in all

treatments at both sites, and tended to be lower at the high lime rates. The adequate P concentrations of the leaves are a reflection of the soil P status.

The K concentrations were generally deficient in both seasons and at both sites (Tables 2.8 & 2.9). Values for leaf K concentrations were slightly lower in lime treatments at both sites. Bartlett & McIntosh (1969) observed lower soil K and reduced plant uptake of the nutrient on limed soils and attributed it to the reduction in percentage K saturation of the cation exchange complex because of a lime-induced increase in cation exchange capacity. Soils at both HRC and MES experimental sites have an inherently low K status (Table 2.3).

The response trends of the leaf nutrient concentrations generally reflected the soil nutrient status. Soil Ca and Mg levels were improved by application of ameliorants, so were the leaf Ca and Mg levels. The direct as well as residual effects of the applied ameliorants on soil N, P and K were not significant, neither were they significant for leaf N, P and K concentrations with the exception of N levels at HRC in the first season. Bell *et al. (*1989) found that more Ca in solution produced varied effects on leaf concentrations of N, P and K in groundnut and other tropical food legumes.

Haulm, pod and kernel yields

Haulm yields were determined in the first and third seasons only. At HRC, the haulm yields from the control plots were 1857 kg ha^{-1} in the 1999/2000 season, and 1734 kg ha^{-1} in the 2001/02 season (Table 2.10). Overall, application of ameliorants increased the haulm yields, but there were no consistent trends. In the 1999/2000 season, the highest haulm yields (3750 kg ha^{-1}) were from plots treated with 2000 kg ha^{-1} CL combined with gypsum and SSP, whereas the residual effect of 4000 kg ha^{-1} DL resulted in the highest haulm yields (3719 kg ha^{-1}) in the 2001/02 season. The least yield increases were in plots treated with gypsum or SSP alone. In the experiment at MES, the yields were very low in the first season, a result of the poor plant growth caused by acid soil infertility coupled with water stress in the early vegetative stages of the crop. In spite of the water stress, all the lime treatments produced significant increases in haulm yields (Table 2.10). The yields ranged from 957 kg ha^{-1} in the control plots to 2021 in plots treated with 2000 kg ha^{-1} CL combined with gypsum, and in plots treated with 4000 kg ha^{-1} CL. The yields in

the third season were highest (2393 kg ha^{-1}) in the treatment in which CL was combined with SSP and gypsum, an increase of 85% compared to the control treatment.

Table 2.10 Haulm and pod yields at HRC and MES as affected by application of Ca materials

Treatment	HRC					MES				
	Haulm yields		Pod yields			Haulm yields		Pod yields		
	1999/00	2001/02	1999/00	2000/01	2001/02	1999/00	2001/02	1999/00	2000/01	2001/02
G-200	1852	2435	1756	1433	1296	1019	1623	80	838	803
L-2000	2401	2790	2708	2062	1672	1620	2585	236	1530	1499
CL-4000	2963	3226	2741	2663	1888	2021	2904	286	2226	1594
DL-4000	2315	3719	2523	2306	1896	1805	2649	262	2306	1543
SSP-250	2847	2097	1978	1389	1200	1095	1854	86	1061	865
G + CL	3425	2727	2263	2058	1798	2022	3111	264	1852	1529
G + SSP	2384	2775	2004	1650	1552	1250	2486	171	1105	1007
SSP + CL	2963	2766	2364	2046	1814	1698	2524	200	1924	1728
SSP+G+CL	3750	3164	2580	2138	1978	1497	2789	164	2365	2017
Control	1857	1734	1846	1150	941	957	1680	69	631	571
Mean	**2676**	**2743**	**2276**	**1890**	**1604**	**1498**	**2521**	**182**	**1584**	**1316**
LSD $_{(0.05)}$	**673**	**431**	**548**	**599**	**449**	**104**	**944**	**34**	**714**	**645**

Pod yields from the control plots were 1846, 1150 and 941 kg ha^{-1} for the three seasons at HRC (Table 2.10). Application of ameliorants significantly increased the pod yields by up to 48% in the first season, and the highest yields were achieved by 4000 kg ha^{-1} CL. In the second season, the residual effects of the applied ameliorants increased the pod yields by 79% with 2000 kg ha^{-1} CL, and by 132% with 4000 kg ha^{-1} CL. Dolomotic lime applied at 4000 kg ha^{-1} increased the yield by 101%. The lowest increase (21%) was attained with application of 250 kg ha^{-1} SSP. Similar treatment effects were observed in the third season, though the yield increases were of a lesser magnitude, ranging from 28% with 250 kg ha^{-1} SSP to 101% with 4000 kg ha^{-1} DL.

Pod yields at MES were 69, 631 and 571 kg ha^{-1} across the three seasons in the control plots (Table 2.10). Application of ameliorants significantly increased the yields in all three seasons, with the highest yield increases of 314% in 1999/2000 and 334% in 2000/01 attained with 4000 kg ha^{-1} CL or DL. In the third season, the highest yield increase of 253% was attained with lime combined with SSP and gypsum. Gypsum or SSP applications did not influence pod yields in the 1999/2000 season, but increased yields by 33% and 68%, respectively, in the 2000/01 season,

and by 41% and 51%, respectively, in the 2001/02 season. Combining gypsum with SSP achieved higher yields than applying each ameliorant alone.

Kernel yields in the first season at HRC were 1 247 kg ha^{-1} in the control plots, and application of 4000 kg ha^{-1} CL resulted in the highest kernel yield increase of 78% (Figure 2.6). In the plots treated with gypsum or SSP, the kernel yields were not significantly different from the control treatment. At MES, the mean kernel yield in the control plots was only 43 kg ha^{-1} in the 1999/2000 season, and application of ameliorants increased the kernel yield by 142% to 362. The kernel yield was highest with application of 4000 kg ha^{-1} CL or DL. The kernel yield response to gypsum or SSP was not significantly different from that of the control treatment.

In the second and third seasons, the kernel yield was significantly increased by residual effects of the 4000 kg ha^{-1} CL or DL treatments, and by the treatments that combined lime with gypsum and/or SSP at both sites. By the third season at HRC, the cumulative kernel yield for the control treatment was 2630 kg/ha, and the application of 4000 kg ha^{-1} CL more than doubled the cumulative kernel yield to 5520 kg/ha. By comparison, applying 2000 kg ha^{-1} CL produced a cumulative kernel yield of 4420 kg/ha over the three seaons, a difference of 25% from the 4000 kg ha^{-1} CL treatment. Application of lime combined with gypsum and SSP increased the cumulative kernel yield by 75%, whereas gypsum application resulted in the least increase (23%). Kernel yield increases due to application of lime at MES were of a much higher magnitude compared those at HRC. The cumulative kernel yield of the control treatment was only 819 kg/ha, and application of 4000 kg ha^{-1} DL resulted in the highest cumulative kernel yield of 3374 kg/ha, an increase of 312%. The cumulative kernel yield attained with application of 4000 kg ha^{-1} CL, or with 2000 kg ha^{-1} CL combined with gypsum and SSP was also considerably high, whereas application of 200 kg ha^{-1} gypsum achieved the least cumulative yield increase of 20%.

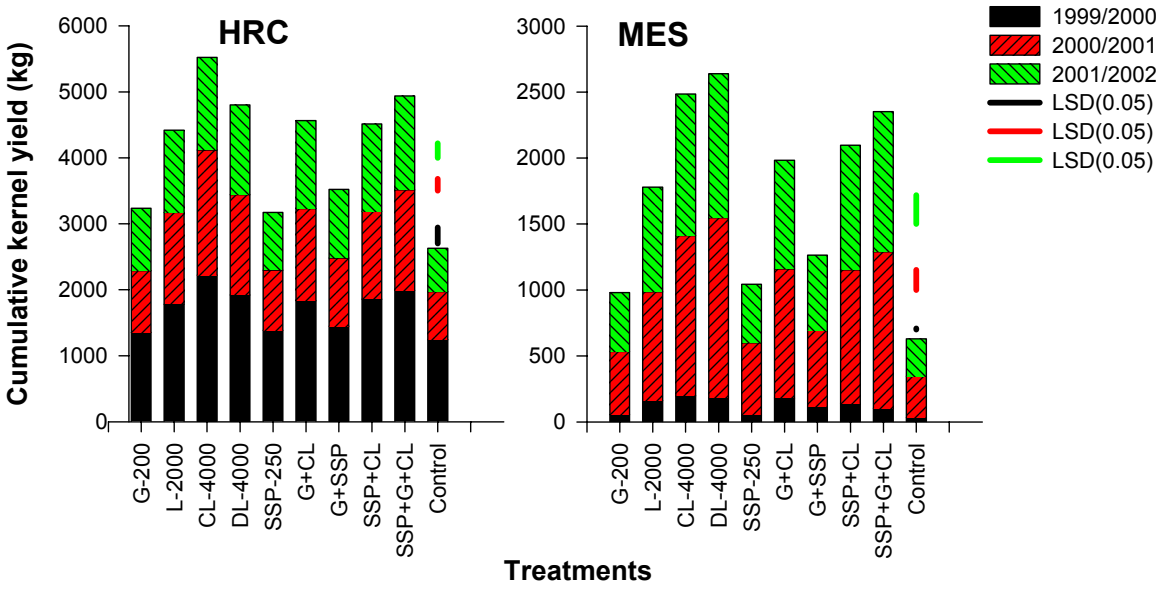


Figure 2.6 Cumulative kernel yields at HRC and MES in 1999/2000, 2000/01 & 2001/02 seasons

The poor kernel yield response to SSP and to gypsum is contrary to the expectation that groundnut production can be improved by SSP and gypsum application through enhanced Ca availability, and through enhanced S availability in the case of gypsum. This poor response is probably a reflection of the lack of effect of the two ameliorants on soil pH, which was not significantly different from the control plots, and the low rates of application. Gypsum application has been observed to have a greater effect on kernel yield in relatively dry seasons (Snyman, 1972; Rajendrudu & Williams, 1987), the reason being that because of its high solubility, it can ensure a continuous supply of available Ca with small amounts of moisture in the pod zone.

Increases in yield due to application of ameliorants were generally higher in the second and third seasons compared to the first, despite the decline in soil pH levels. Reasons for this are not clear, but it is possible that there were additional benefits from application of the ameliorants, and that these benefits would only manifest themselves after some time. For instance, there may be benefits from Mo and P availability or cycling, soil structure, microbial breakdown of organic

matter and other spin-offs from application of ameliorants (Scott *et al.,* 1999). In addition to subjection to water stress, the other possible explanation for the small yield increases in the first season at MES could be the sharp increase in soil pH, especially in the high lime treatments. Excessive raising of pH in some highly weathered soils to pH values >6.0 has been known to cause deficiencies of essential nutrients like P, B, Mn, and Zn (Kamprath, 1971; Sanchez, 1976), and to the deterioration of soil structure, thereby leading to yield reductions.

Yields were influenced by application of the ameliorants in a similar manner at both sites, though the magnitude of the effects was not the same. The variations in rainfall amount and distribution could in part explain the differences. Over the three seasons, the kernel yield responses to the applied ameliorants were consistent, with high yields being obtained from the CL or DL treatments and low yields from the gypsum and SSP treatments. It was observed at HRC that applying 2000 kg ha^{-1} CL alone or in combination with gypsum and/or SSP resulted in yields which were statistically on par with the 4000 kg ha^{-1} DL treatment, suggesting that the low lime rate was adequate to reduce the negative effects of soil acidity on kernel yield of groundnut. The residual effects of both rates of lime were still observed in the third season as evidenced by the yield increases over the control treatment. The higher the original application rate, the more effective were the residual effects. The decline in the magnitude of the yield increases by the third season is an indication that another application of the ameliorants was required to boost the yields.

At the time of the experiments, lime at 2000 and 4000 kg ha^{-1} cost Z$29 700 and 59 400 respectively, while 200 kg of gypsum and 250 kg of SSP cost Z$998 and 2 493 respectively. At a grain marketing board producer price of Z$96 000 t^{-1} shelled groundnuts, the cumulative increases in kernel yield due to use of these amendments at HRC represent gross benefits of Z$ 142 140 for lime at 2000 kg ha^{-1}, 218 040 for lime at 4000 kg ha^{-1}, 55 278 for gypsum, and 134 697 for SSP. At MES, the gross benefits were Z$ 80 700 for lime at 2000 kg ha^{-1}, 133 368 for lime at 4000 kg ha^{-1}, 30 702 for gypsum, and 32 265 for SSP. These results show that use of Ca-containing materials, particularly lime, to improve groundnut productivity on acid soils is profitable. The benefits can be substantially higher if consideration is given to premiums paid for superior quality, since the ameliorants improved kernel quality. Consequently, farmers can be persuaded to adopt the liming technology to improve productivity and income on acid soils.

2.3.3 EFFECT OF AMENDMENTS ON KERNEL NUTRIENT COMPOSITION, POD AND KERNEL QUALITY

KERNEL NUTRIENT COMPOSITION

Calcium

In the first season, the kernel Ca concentrations at both sites were significantly influenced by application of ameliorants (Tables 2.11 & 2.12). At HRC, the kernel Ca concentrations were lowest (0.02%) in the control treatment, and were increased to 0.05% with application of either 2000 kg ha^{-1} CL combined with gypsum and SSP, or with 4000 kg ha^{-1} CL. Similarly, at MES, the kernel Ca concentrations were increased from 0.02% to 0.04% with application of 4000 kg ha^{-1} CL. The kernel Ca concentrations in the control, G-200, SSP-250 treatments and their combinations were below the sufficiency ranges of 0.04 – 0.08% (Gascho & Davis, 1994).

In the second season, the mean Ca concentrations in the control treatment were 0.02%, and were increased to 0.06% in the 4000 kg ha^{-1} CL treatment at HRC (Table 2.11). Concomitant with the improved soil Ca levels in the pod zone in the second season, the Ca concentrations were generally improved in the kernels. The kernel Ca concentrations were still below sufficiency levels in the control treatment, and in the G-200 and SSP-250 treatments and their combinations. Similar treatment effects were observed at MES (Table 2.12).

Notwithstanding the significant effects of applied ameliorants on the exchangeable Ca content of the soil, the kernel Ca concentration was not influenced to the same extent, especially at MES. No significant correlations were observed between kernel Ca concentration and soil Ca content (Appendix Table A2.6). Snyman (1972) obtained similar results, and concluded that the shell Ca content was a better indicator of soil Ca status than kernel Ca concentration. Possible reasons for the observed results in this study could be the influence of factors such as variable moisture regimes, or the low (2 – 3%) Ca-fertilizer uptake efficiency of the pods (Keisling *et al.,* 1982). Reduced kernel Ca concentrations have been observed in situations where pod development took place under inadequate moisture conditions (Skelton & Shear, 1971; Cox *et al.,* 1976; Wright, 1989), and attributed to limited solubility and impeded movement of Ca to the pods by mass flow (Gascho & Davis, 1994).

Table 2.11. Effects of ameliorants on Ca, Mg, N, P and K concentrations in groundnut kernels at HRC

Treatment	1999/2000					2000/01				
	Kernel nutrient concentrations (%)					Kernel nutrient concentrations (%)				
	Ca	Mg	N	P	K	Ca	Mg	N	P	K
G-200	0.038	0.19	4.34	0.29	0.70	0.026	0.15	3.45	0.19	0.69
L-2000	0.040	0.24	4.31	0.37	0.70	0.045	0.17	3.37	0.23	0.69
CL-4000	0.043	0.24	4.56	0.35	0.63	0.060	0.16	3.33	0.23	0.55
DL-4000	0.039	0.21	4.51	0.32	0.64	0.040	0.19	3.35	0.21	0.50
SSP-250	0.041	0.19	4.72	0.40	0.70	0.029	0.15	3.66	0.25	0.62
G + CL	0.040	0.20	4.23	0.32	0.69	0.027	0.15	3.42	0.21	0.62
G + SSP	0.036	0.19	4.44	0.40	0.70	0.032	0.14	3.55	0.25	0.60
SSP + CL	0.037	0.19	4.55	0.33	0.63	0.043	0.14	3.69	0.22	0.58
SSP + G+CL	0.046	0.20	4.48	0.41	0.65	0.048	0.15	3.44	0.25	0.58
Control	0.024	0.18	4.06	0.41	0.73	0.017	0.14	3.27	0.26	0.62
Mean	**0.039**	**0.20**	**4.43**	**0.36**	**0.67**	**0.038**	**0.15**	**3.46**	**0.23**	**0.60**
LSD $_{(0.05)}$	**0.006**	**0.01**	**0.11**	**0.04**	**0.02**	**0.007**	**0.01**	**0.10**	**0.03**	**0.01**

Table 2.12. Effects of ameliorants on Ca, Mg, N, P and K concentrations in groundnut kernels at MES

Treatment	1999/2000					2000/01				
	Kernel nutrient concentrations (%)					Kernel nutrient concentrations (%)				
	Ca	Mg	N	P	K	Ca	Mg	N	P	K
G-200	0.028	0.18	3.92	0.36	0.91	0.029	0.12	2.57	0.23	0.65
L-2000	0.039	0.20	4.08	0.38	0.74	0.040	0.15	2.54	0.24	0.48
L-2000	0.043	0.28	3.80	0.41	0.75	0.055	0.13	2.11	0.26	0.49
DL-4000	0.036	0.22	3.96	0.49	0.77	0.049	0.17	2.20	0.29	0.50
SSP-250	0.029	0.19	4.00	0.43	0.88	0.023	0.12	2.78	0.27	0.57
G + CL	0.028	0.17	4.04	0.48	0.78	0.035	0.10	2.55	0.28	0.51
G + SSP	0.035	0.18	3.98	0.47	0.90	0.021	0.11	2.65	0.28	0.58
SSP + CL	0.031	0.18	3.87	0.50	0.74	0.033	0.13	2.83	0.30	0.48
SSP+G+CL	0.035	0.17	3.92	0.40	0.70	0.036	0.12	2.39	0.24	0.46
Control	0.022	0.11	3.85	0.40	0.95	0.020	0.12	2.47	0.26	0.47
Mean	**0.033**	**0.19**	**3.94**	**0.43**	**0.81**	**0.033**	**0.13**	**2.50**	**0.27**	**0.52**
LSD $_{(0.05)}$	**0.003**	**0.033**	**0.117**	**0.036**	**0.023**	**0.005**	**0.008**	**0.140**	**0.018**	**0.038**

Magnesium

The kernel Mg concentration was significantly altered by application of ameliorants at both sites and in both seasons (Tables 2.11 & 2.12). At HRC, the kernel Mg concentration ranged from 0.18% in the control treatment to 0.24% in the CL-4000 treatment in the 1999/2000 season. The kernel Mg levels were adequate in all treatments. The sufficiency ranges are 0.16 – 0.2% (Gascho & Davis, 1994). At MES, the kernel Mg concentration ranged from 0.11% in the control treatment to 0.28% in the CL-4000 treatment, and was adequate in all but the control treatment in the 1999/2000 season.

In the second season, the Mg levels in the kernels were lower at both sites, ranging from 0.14% to 0.19% at HRC, and from 0.10% to 0.17% at MES (Tables 2.11 & 2.12). With the exception of the CL-2000, CL-4000 and DL-4000 treatments, the Mg levels in the kernels were below sufficiency at HRC. Despite the slightly improved soil Mg levels in the second season, the kernel Mg concentrations at MES were inadequate in all but the DL-4000 treatment. No significant correlation between exchangeable soil Mg and kernel Mg concentrations was observed, (Appendix Table A2.6), and no explanation for the seasonal variations in kernel Mg levels can be offered.

Nitrogen, Phosphorus and Potassium

Application of the ameliorants had no effect on the N concentrations of the kernels at both sites (Tables 2.11 & 2.12). The ranges of the N concentrations in the first season were 4.1% to 4.7% at HRC, and 3.8% to 4.1% at MES, respectively. In the second season, the N concentrations were much lower at both sites, and the response to the ameliorants was varied. The N concentrations ranged from 3.3% to 3.7% at HRC, and from 2.1% to 2.8% at MES, and reasons for the variations are not clear.

The effects of ameliorants on P concentration in the kernels were not significant at both sites, and this could partly be attributed to the inherent high P levels in the soils, and the fact that the ameliorants did not influence the soil P levels (Tables 2.11 & 2.12). The mean P concentrations in all the treatments were, however, within the sufficiency ranges of 0.17– 0.47% (Gascho & Davis, 1994) at both sites and in both seasons.

The Ca sources had no effect on K concentration in the kernels, which tended to be higher in the control and gypsum treatments at both sites in the first season (Tables 2.11 & 2.12). The trend was observed again in the second season at MES. At HRC, the 2000 kg ha^{-1} lime treatment had the highest kernel K concentrations. Snyman (1972) observed significant increases in kernel K concentrations due to applications of lower rates of Ca, but a considerable decrease in kernel K concentrations as the Ca application rate increased. The overall insignificant effect of applied ameliorants on kernel N, K and Mg can be ascribed to the preferential absorption of Ca over Mg, K and N as proposed by Csinos & Gaines (1986).

PROPORTION OF MATURE PODS

At HRC the proportion of mature pods was significantly affected by the ameliorant treatments (Figure 2.7). In the first season, the control treatment had a low proportion of mature pods (65%), whereas the application of 4000 kg ha^{-1} CL increased the proportion of mature pods to 74%, the highest among the treatments for the season. Combining lime with gypsum and/or SSP also increased the proportion of mature pods to more than 70%. The proportion of mature pods was low (64 %) in plots treated with 250 kg ha^{-1} SSP. Similar treatment effects were observed in the third season where the proportion of mature pods in the control plots was quite low (51%). In the other treatments, the proportion of mature pods generally improved compared to the first season, with the highest value of 79% being achieved with application of 4000 kg ha^{-1} CL. The same response trends were observed at MES (Appendix Table A2.7).

PRODUCTION OF EMPTY PODS (POPS)

The proportion of pops was significantly reduced to 5.3% by application of 4000 kg ha^{-1} CL, from 23.5% in the control treatment (Figure 2.7). The incidence of pops was also greatly reduced in plots treated with gypsum alone or in combination with SSP. Snyman (1972) also observed a highly significant decrease in percentage empty fruit where gypsum was applied, compared to lime application. Overall, application of the ameliorants was beneficial in reducing the percentage of pops, and this trend continued in the third season. Data from the MES site (Appendix Table A2.7) also exhibit response trends were similar to those observed at HRC.

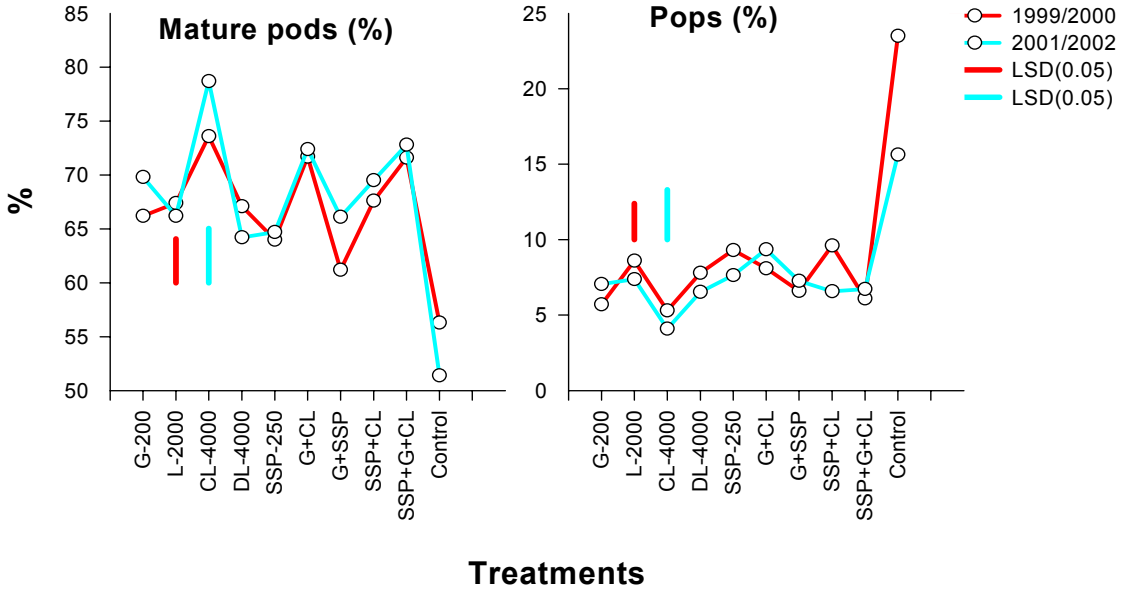


Figure 2.7 Percentage mature pods and pops at HRC as affected by application of Ca materials

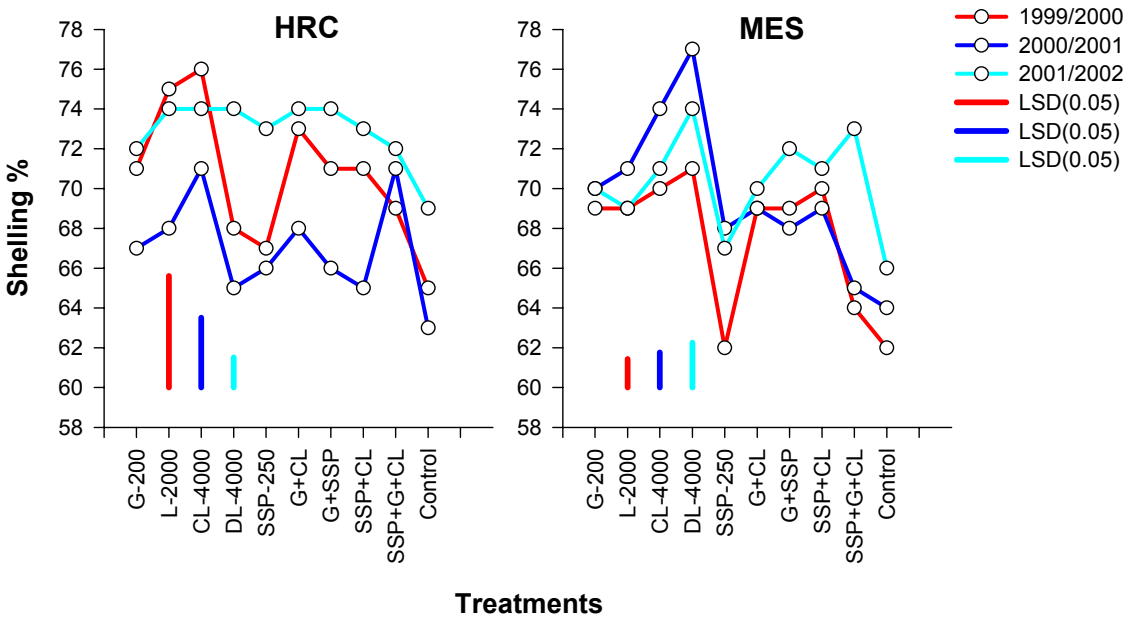


Figure 2.8 Effects of Ca materials on shelling % at HRC and MES

SHELLING PERCENTAGE

At HRC, the shelling percentage values were generally highest in the third season, intermediate in the first season and lowest in the second season, whereas at MES they tended to improve as the seasons progressed from 1999/2000 to 2001/02 (Figure 2.8). The response trends were however similar, with the lowest values being observed in the control treatment, and in the SSP treatment. The shelling percentage values were highest with application of 4000 kg ha^{-1} CL at HRC, and with application of 4000 kg ha^{-1} DL at MES. Combining lime with gypsum and/or SSP also increased the shelling percentage. Shelling percentage provides the most readily available index of Ca deficiency according to Hartmond *et al.* (1994). The significant correlations between the shelling % and exchangeable Ca in the soil (Tables 2.13 and 2.14) support this assertion.

PERCENTAGE OF SOUND MATURE KERNELS

The percentage of sound mature kernels (SMK%) was significantly influenced by application of ameliorants at both sites (Figure 2.9). As with shelling percentage, the magnitude of the treatment effects over the seasons was erratic, and the SMK at HRC tended to decrease as the seasons progressed, whereas a prominent reverse trend was observed at MES. The SMK% in the control plots at HRC ranged from 69% to 74% across the seasons. The highest %SMK values were in the 4000 kg ha^{-1} CL treatment, and averaged 89%. Gypsum application also increased SMK values to 87% on average, while the lowest values (83%) were attained with application of 250 kg ha^{-1} SSP. At MES, the SMK in the control plots averaged 72%, and was highest (80%) with application of 2000 kg ha^{-1} lime. In general, application of ameliorants had similar effects on the proportion of sound mature kernels as on kernel yields.

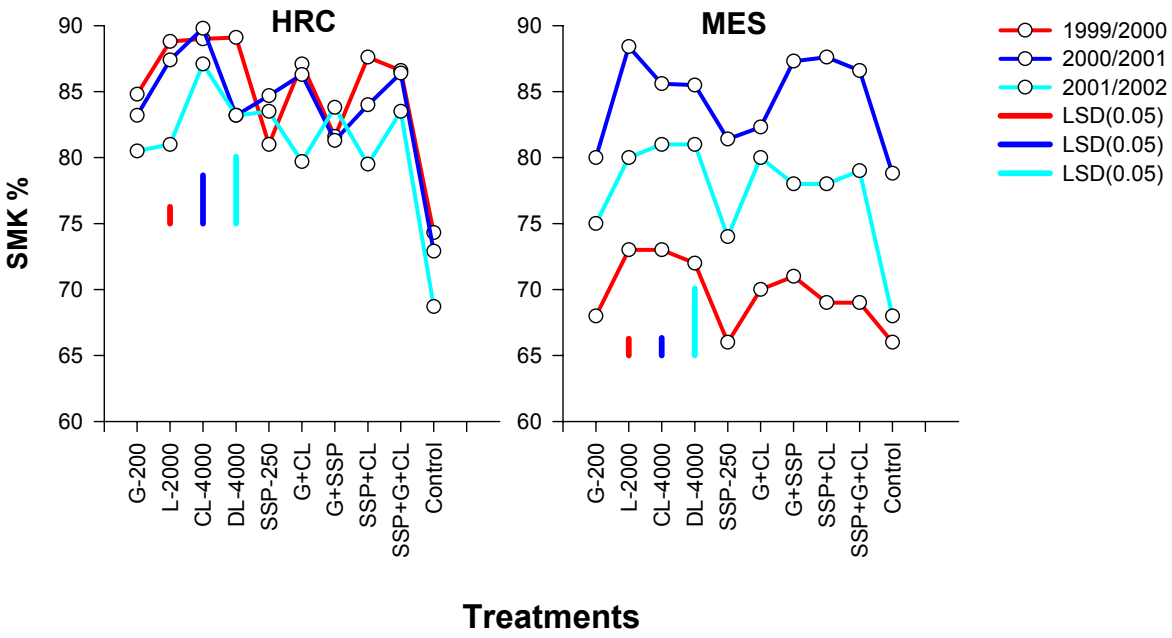


Figure 2.9 Effects of Ca materials on percentage sound mature kernels (SMK) at HRC and MES

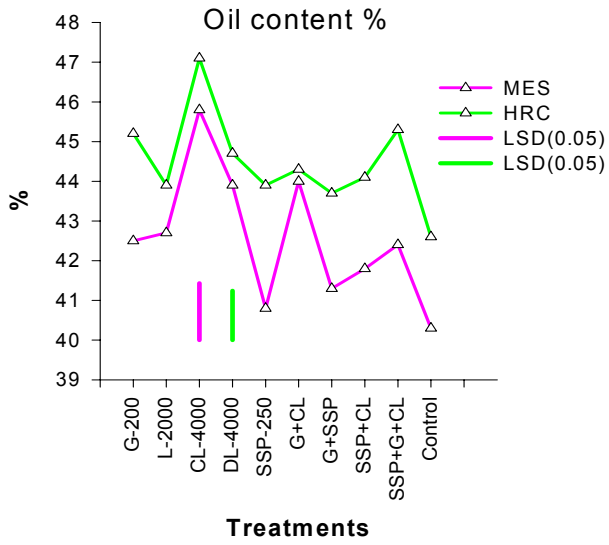


Figure 2.10 Effects of Ca materials on oil content (%) at HRC and MES

OIL CONTENT

The kernel oil content was determined at both sites in the 2000/01 season only. The mean kernel oil content from the control plots was 42.6% at HRC, and 40.3% at MES (Figure 2.10). At both sites, the oil content was significantly increased with application of 4000 kg ha^{-1} CL to 47.1% at HRC and 45.8% at MES. Gypsum and lime applied at 2000 kg ha^{-1} similarly increased oil content, whereas SSP application resulted in smaller increases in oil content. Snyman (1972) observed that kernel oil content was affected more by the source of Ca than by the amount of Ca applied, with CL and DL generally decreasing oil content at high rates of application, whereas gypsum tended to increase the oil content. Taking cognizance of the fact that kernel mass was similarly influenced by application of ameliorants, i.e. higher kernel mass with application of lime and gypsum, then the changes in kernel oil content can be ascribed to treatment effects *per se.*

2.3.4 RELATIONSHIPS OF KERNEL YIELD WITH SOIL PARAMETERS AND OTHER YIELD COMPONENTS

Very often, the elucidation of acid soil amelioration effects on groundnut is confounded by the erratic responses of groundnut to application of ameliorants. In addition, many soil parameters are changed when ameliorating acid soils, thereby making it difficult to isolate the exact cause of the yield responses (Blamey, 1983). In order to overcome the problem, correlation analyses were conducted to examine the interactions between groundnut yield components and soil parameters. At both sites, weak correlations ($r \leq 0.09$) were detected between kernel yield and soil N, P or K levels. At HRC, soil Mg was also weakly correlated ($r = 0.107$) with kernel yield. The soil parameters observed to be highly correlated with kernel yield were pH and Ca at HRC and pH, Ca and Mg at MES. Most of the plant parameters were significantly correlated with kernel yield.

The factors influencing kernel yield were divided into first order (yield parameters) and second order (soil parameters). The first order factors were plant density, number of pods per unit area, mean kernel mass, shelling percentage and proportion of pops. Soil pH and levels of exchangeable Ca were regarded as the second order factors since they strongly affected kernel yield at HRC. At MES exchangeable Mg was also included because of its strong correlation with

kernel yield. Significant correlations were then subjected to path coefficient analysis to identify the causes of poor kernel yield in the acid soils in question.

CORRELATIONS AT HRC

Correlations of kernel yield with the first order-factors were generally positive, but not always significant. At HRC, highly significant and positive correlations were found between kernel yield and the first- and second-order factors that influenced the kernel yield (Table 2.13). Pod number was the most important determinant of kernel yield among the first-order factors at HRC, since it achieved a positive correlation of the highest magnitude with kernel yield (r=0.960). By contrast, shelling percentage was the least important determinant of kernel yield (r=0.293). As expected, the proportion of pops was negatively correlated with kernel yield. The proportion of pops was negatively correlated with all the first-order factors, this being more so with kernel mass than with kernel yield. Blamey (1983) found highly significant positive correlations between kernel yield and the first-order factors, which he explained as implying that kernel development was not limited by available photosynthate, as competition for the latter would lead to some negative correlations. It, however, appears that the first-order factors do not always assume the same importance in influencing kernel yield. For example, Tarimo & Blamey (1999) observed that the most important components associated with maximum economic yield in groundnut were pod harvest index, kernel harvest index and the ratio of pod number to peg + pod number; the other parameters like pod number, kernel number per pod, kernel size being less important.

Since the kernel yield correlation was positively stronger with exchangeable Ca than with soil pH among the second-order factors at HRC (Table 2.13), it implies that the kernel yield increases in responses to application of ameliorants can be mainly attributed to improved Ca supply. Nonetheless, the significant and positive correlation between soil pH and kernel yield indicates that the soil pH had a major influence on kernel yield, also. These results, therefore, suggest that soil levels of the two parameters can be used to predict kernel yield responses to application of the ameliorants at HRC.

Table 2.13 Total correlation coefficients between groundnut kernel yield, yield components and soil parameters at HRC

	Kernel yield	Pod No.	Kernel mass	Shelling %	% Plant stand	% SMK	% Pops	pH	Exch. Ca
Kernel yield	1.000								
Pod No.	0.960**	1.000							
Kernel mass	0.648**	0.604**	1.000						
Shelling %	0.293**	0.115ns	0.288**	1.000					
% Plant stand	0.514**	0.529***	0.074ns	0.010ns	1.000				
% SMK	0.414**	0.409**	0.720**	0.245*	0.023ns	1.000			
% Pops	-0.306**	-0.246*	-0.575**	-0.217*	-0.001ns	-0.415**	1.000		
PH	0.274**	0.245*	0.086ns	0.093ns	0.283**	0.042ns	-0.010ns	1.000	
Exch. Ca	0.346**	0.296**	0.254*	0.242*	0.138ns	0.161ns	-0.204*	0.659	1.000

Table 2.14 Total correlation coefficients between groundnut kernel yield, yield components and soil parameters at MES

	Kernel yield	Pod No.	Kernel mass	Shelling %	% Plant stand	% SMK	% Pops	pH	Exch. Ca	Exch. Mg
Kernel yield	1.000									
Pod No.	0.996**	1.000								
Kernel mass	0.288**	0.284**	1.000							
Shelling %	0.371**	0.316**	0.209*	1.000						
% Plant stand	0.254*	0.262*	0.271**	-0.036ns	1.000					
% SMK	0.632**	0.627**	-0.269*	0.285**	0.012ns	1.000				
% Pops	-0.425**	-0.417**	-0.323**	-0.168ns	0.007ns	-0.415**	1.000			
PH	0.534**	0.542**	0.097ns	-0.234*	-0.026ns	-0.628**	0.451**	1.000		
Exch. Ca	0.524**	0.534**	0.135ns	0.222*	0.074ns	0.395**	0.369**	0.599**	1.000	
Exch. Mg	0.689**	0.695**	0.042ns	0.239*	-0.038ns	0.629**	0.446**	0.724**	0.627**	1.000

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

CORRELATIONS AT MES

At MES, significant correlations were found between kernel yield and the yield determining factors (Table 2.14). Among the first-order factors, the kernel yield had the highest positive correlation with pod number (r=0.996) and lowest correlation with plant stand (r=0.254). As at HCR, the proportion of pops was also negatively correlated with kernel yield, being much stronger than that between kernel yield and either shelling percent or kernel mass.

With soil factors, correlation with kernel yield was highest with Mg (r=0.689), followed by pH (r=0.534) and lastly Ca (Table 2.14). The three soil parameters were also significantly correlated between themselves, with Mg being more strongly correlated with soil pH than with Ca. Overall, the observed correlations indicate that the three soil parameters affected kernel yield to varying degrees, and soil levels of the three parameters can be used to predict kernel yield responses to application of the ameliorants at this site.

Path coefficients at HRC and MES

The path coefficient analysis showed that at HRC the direct effects (path coefficients - β) of pod number on kernel yield were much greater than those of any other plant parameter (Figure 2.11). Variation in pod number explained 88% of the variation in kernel yield. Shelling percentage and kernel mass also played a significant role in determining kernel yield, whereas the direct effects of plant stand and the proportion of pops were not significant. In the experiment at MES similar effects of first order yield parameters on kernel yield were observed, with plant stand and the proportion of pops having a non-significant direct influence on kernel yield (Figure 2.12).

At HRC the path coefficients relating Ca to the plant parameters were highest for kernel mass and the proportion of pops, and least for plant stand (Figure 2.11). These results concur with the assertion that Ca has an influence on kernel mass and on pops. At MES, Ca had the largest effect on shelling percentage, but similar effects on pod number and pops (Figure 2.12). As at HRC, the path coefficients relating Ca to plant stand were the lowest, but significant. The positive and significant effects of Ca on the kernel yield components suggest that Ca *per se* influenced kernel yield; the direct effect of exchangeable Ca on kernel yield was high (β = 0.292), whereas that of soil pH was lower (β = 0.082), but significant. A regression analysis with kernel yield as the

dependent variable and soil pH and Ca as independents showed that variation in the two soil components accounted for 57% of the kernel yield variation observed at HRC.

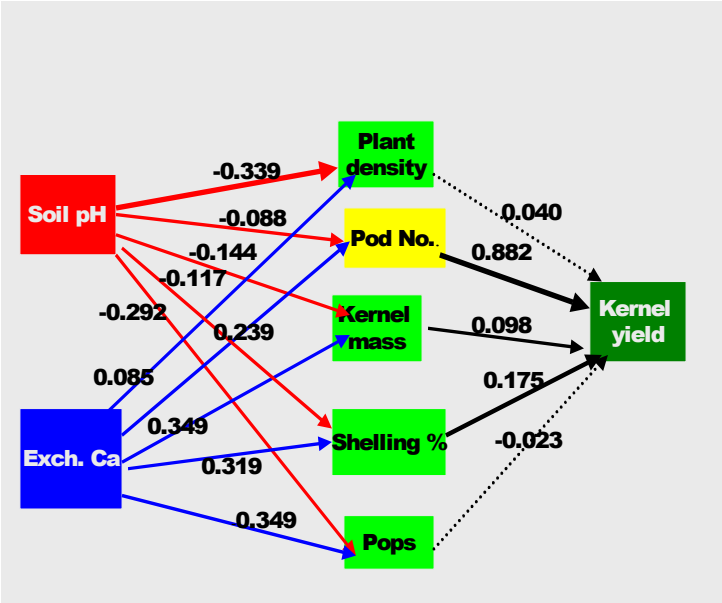


Figure 2.11 Direct effects of the yield components on kernel yield at HRC

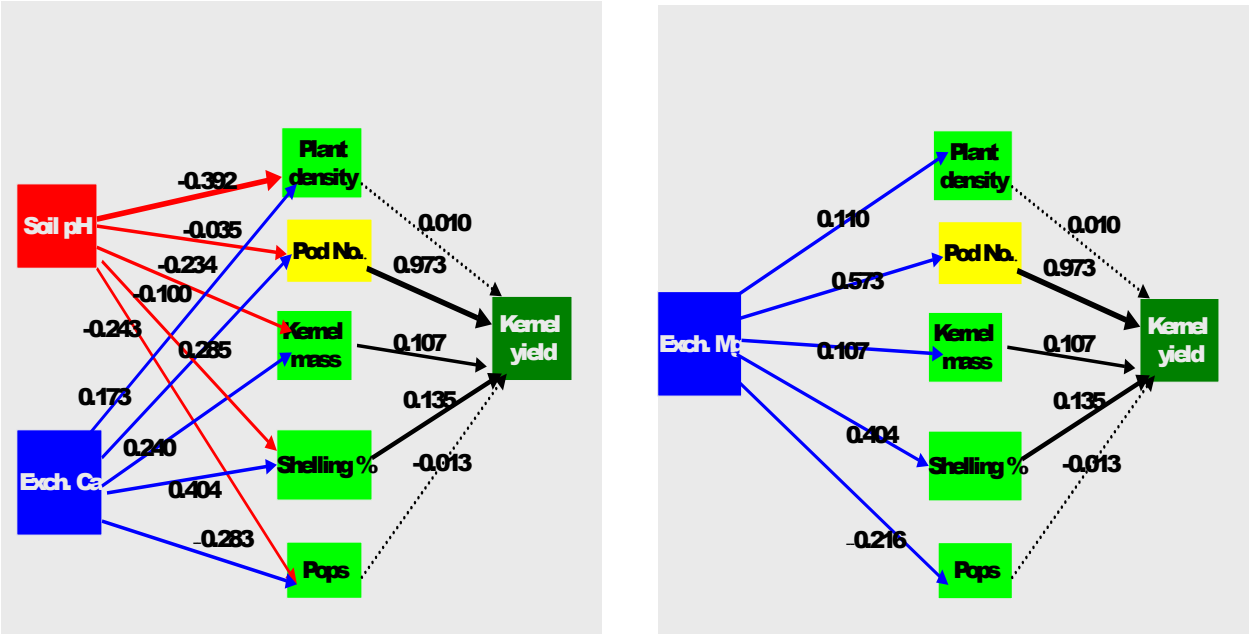


Figure 2.12 Direct effects of the yield components on kernel yield at MES

The direct effects of Mg on the first order yield parameters at MES were greatest on pod number and on shelling percentage (Figure 2.12). Kernel mass was the least affected. At this site,

exchangeable Mg appeared to exert a greater influence on kernel yield parameters than exchangeable Ca. Exchangeable Mg also had the greatest effect on the plant parameter that influenced kernel yield most, namely pod number. Given that significant kernel yield increases due to application of dolomite lime were observed at this site, it can be inferred that Mg *per se* directly improved yield. A regression analysis with kernel yield as the dependent variable and soil pH, Ca and Mg as independents showed that variation in the three soil components accounted for 76% of the kernel yield variation. The direct effects of exchangeable Mg on kernel yield were high ($\beta = 0.578$), whereas those of Ca and soil pH were $\beta = 0.245$ and $\beta = 0.129$ respectively.

Path coefficients relating soil pH to the plant parameters showed that the greatest influence of soil pH was on plant stand, and on pops. This observation was made at both sites (Figures 2.11 and 2.12). The direct effects of soil pH on pod number were of a low magnitude at both sites, and non-significant at MES. Since pod number was the plant parameter observed to influence kernel yield most, this result implies that the observed kernel yield responses to application of Ameliorants cannot be attributed to improved soil pH *per se*, but to its indirect effects on other parameters influencing yield. For example, soil pH had a significant direct effect on plant stand, and in turn, the indirect effects of plant stand via pod number on kernel yield were significant (r=0.249), in fact higher than the direct effects.

2.4 CONCLUSIONS

The major effects of applying the ameliorants were to increase soil pH and exchangeable Ca and Mg levels. The ameliorants had little effect on the soil N, P and exchangeable K content. In general, application of CL or DL was more beneficial compared to gypsum or SSP and their combinations. Clear increases in yields due to lime application at 2000 and 4000 kg ha^{-1} were observed in the year of application as well as with residual effects. The increases were higher with the higher application rate. Application of lime at 2000 kg ha^{-1} was as effective as combining the same rate with either gypsum or SSP, implying that the combinations would impose an unnecessary cost burden to resource poor farmers, as no additional benefits can be expected. Annual applications of gypsum and SSP were not as effective as the traditional liming materials in overcoming soil acidity, but resulted in slight yield improvements over the control.

The residual benefits of application of lime (improved plant stands, better growth, nodulation, productivity and quality) lasted for the duration of the experiments, despite the dissipation of the lime effect on soil pH. After three cropping seasons the soil pH was either lower than or not significantly different from that of the original unlimed soil, except in the high lime treatment. It was concluded that amendments other than lime have no potential for ameliorating acid soils in which nutrient deficiencies and low pH *per se* are limiting groundnut growth and productivity. It is recommended that researchers and extension agents conscientize the smallholder farmers on the benefits of liming, and encourage them to invest in the technology, while policymakers should ensure that the issue of lime availability to the resource-poor farmers is adequately addressed.

Notwithstanding the various significant correlations between kernel yield, yield components and soil parameters, path coefficient analysis proved an effective tool for isolating the specific causes of poor groundnut growth on acid sandy soils. It showed that pod number was the most influential determinant of kernel yield, implying that management strategies that increase number of pods per ha should be adopted. Because the kernel yield parameters were more directly influenced by soil exchangeable Ca and Mg than with pH, it was concluded that poor groundnut yields on the acid soils at HRC and MES are caused by deficiencies of Ca and Mg primarily, and by low pH *per se*. With the magnitude of the lime responses demonstrated in this study, it is clear that the only practical solution to poor groundnut productivity on acid sandy soils is to apply lime.

CHAPTER 3

EFFECT OF CALCIUM SOURCE AND APPLICATION RATE ON SOIL CHEMISTRY, GROWTH, NUTRIENT COMPOSITION AND YIELD OF GROUNDNUT IN AN ACID SANDY SOIL

3.1 INTRODUCTION

The economic constraints to the use of liming materials in the smallholder-sector make it necessary to know their effect on crop yields as well as their potential benefits to the soil resource, namely the changes in soil properties that are expected to result from various rates of application. Studies have shown that the addition of Ca-containing materials to soil not only changes the chemical and physical properties of the soil, but also affects the availability of nutrients to plants (Simard *et al.,* 1988; McLay & Ritchie, 1993; Mora *et al,* 1999). The effects of these materials on the chemical composition of the soil solution, and on availability of both macro- and micronutrients differ with the material, and also with the soil type. Consequently, it is necessary to understand, and be able to predict the effects of Ca-containing materials on soil solution composition of the soils, and the resultant effects on plant growth.

Commercial liming materials containing various proportions of carbonates, hydroxides, and oxides of Ca and Mg, have been used for centuries to increase the pH of agricultural soils (Adams, 1980). **C**alcitic limestone ($CaCO_3$) or dolomitic limestone ($MgCO_3.CaCO_3$) are the most common amendments used to ameliorate acid soil infertility. Application of these materials to a soil results in a number of direct effects (increased Ca and Mg content in the soil; increased soil pH) and indirect effects as a result of improved pH like improved P and Mo availability, decreased Al concentration in soil solution, decreased availability of Mn, Cu, Fe and Zn (Ahmad & Tan, 1986; Fageria *et al.,* 1990). While liming is largely done to neutralize the acidity of the plough layer, it can simultaneously provide adequate Ca for maximum yield of groundnut when incorporated into the pegging zone before planting (Hodges *et al.,* 1993).

Gypsum (Ca SO_4), although not an inherently acid-neutralizing compound like limestone, has been shown to be a valuable soil amendment that can increase Ca and decrease Al activity in acid soils. While gypsum does not change the soil pH much, the dissociated sulfates (SO_4^{2-}) from gypsum combine with detrimental Al^{3+} ions to form aluminum sulfate that is less phytotoxic (Evanylo, 1989**;** Ismail *et al.,* 1993; Sumner, 1993). When applied to the soil surface, gypsum was shown to be more effective than surface applied limestone in improving crop yields on soils with acidic subsoils in Brazil, South Africa, and the United States (Shainberg *et al.,* 1989; Sumner 1993). In groundnut, the use of gypsum has been widespread because of its ability to supply readily available Ca to the developing pods (Snyman, 1972; Walker, 1975; Cox *et al.,* 1982; Hodges *et al.,* 1993).

A simultaneous increase in soil pH, Ca and Mg levels can be achieved by the use of lime. Though not liming materials *per se*, gypsum ($CaSO_4$) and single superphosphate [$Ca(H_2PO_4)_2.CaSO_4$] are compounds that can be applied to raise the status of Ca and Mg in soils, but their effects on soil pH depend on the soil type. Considering that the beneficial effect of gypsum and SSP application in acid soils is in part due to the increase of soil Ca, one way to evaluate this benefit in soil acidity amelioration is to compare them with limestone applied in equivalent amounts of Ca.

Differential effects of liming on nutrient availability in highly weathered soils have been reported (Haynes, 1984). This study hypothesised that applications of Ca-containing materials to groundnut may introduce imbalances of other nutrients in the soil because of either reduced solubility in the soil solution due to increases in pH, or uptake inhibition by Ca and/or Mg. Caution is needed to avoid inducing deficiencies of other essential nutrients when applying Ca/Mg-containing materials to ameliorate soil acidity for groundnut production.

The objective of this study was to apply various rates of calcitic lime, dolomitic lime, gypsum and single superphosphate to an acid sandy soil and observe (a) changes in soil pH and chemical composition and (b) subsequent growth and productivity of groundnut.

3.2 MATERIALS AND METHODS

A greenhouse experiment to study the effects of different Ca sources on an acid soil was set up at Harare Research Station during the summer period in 1999 and repeated in the summer of 2000. Soil was collected from the top 0 - 30 cm of an acid medium-grained sandy soil from a previously cultivated but unlimed field in the Mhondoro Communal Area in Natural Region II of Zimbabwe. Mean annual rainfall in this region is 750 to 1000 mm. The farmer articulated that groundnut yields had steadily declined over the past ten years, and attributed the decline to droughts and the fact that the soil is exhausted.

Four sources of calcium namely, calcitic lime, dolomitic lime, gypsum and superphosphate were used as liming materials. A brief description of the Ca sources is given in Chapter 2.

3.2.1 INCUBATION EXPERIMENT

To determine the influence of Ca sources on availability of soil nutrients, an incubation test was conducted on the soil collected from Mhondoro Communal Area during the summer period in 1999. The soil was air-dried and sieved through a 2 mm stainless steel sieve prior to being weighed in 3 kg samples that were placed into polythene bags. Four levels each of calcitic lime (CL), dolomitic lime (DL) and gypsum (G) to supply the equivalent of 115, 209, 380 and 690 kg ha^{-1} Ca were thoroughly mixed with the soil. Other treatments were single superphosphate (SSP) applied at 53 kg ha^{-1} Ca (a higher Ca equivalence required application of very high rates of SSP, which would result in toxic levels of P) or combined with CL, DL or gypsum. This resulted in a total of 17 treatments, including a control treatment in which no Ca-material was applied (Table 3.1). The amounts of ameliorants to be applied were calculated on the basis of application per ha to a depth of 30 cm. The statistical design for the experiment was a completely randomised design, with four replicates.

The soil was incubated at field capacity in the polythene bags for one week at 22^{o} C. Distilled water passed through a deioniser was added as and when required to keep the soil at field capacity. After incubation, samples (300 g) of soil from 0 to 5cm and 7 to 12cm depths from

each bag were combined to make a composite sample. The samples were air dried and stored for subsequent chemical analysis. Soil pH was determined in calcium chloride ($CaCl_2$) solution, while phosphorus was extracted with bicarbonate using the Olsen method, and measured by the method of Murphy and Riley (1962). Exchangeable cations (K, Ca, and Mg) were extracted with 1*M* ammonium acetate; K was determined by flame photometry, while Ca and Mg were analysed by atomic absorption spectrophotometry. Mineral N was determined by the semi-micro Kjeldal procedure followed by steam distillation (Bremner & Mulvaney, 1982).

Table 3.1 Treatments applied in the incubation experiment and greenhouse experiment in 1999/2000 and 2000/01.

TREATMENTS IN 1999/2000			**TREATMENTS IN 2000/01**		
Treatment		**Ca rate Kg ha^{-1}**	**Treatment**		**Ca rate kg ha^{-1}**
1.	Calcitic lime	115	1.	Calcitic lime	115
2.	Calcitic lime	209	2.	Calcitic lime	403
3.	Calcitic lime	380	3.	Calcitic lime	690
4.	Calcitic lime	690	4.	Dolomitic lime	115
5.	Dolomitic lime	115	5.	Dolomitic lime	403
6.	Dolomitic lime	209	6.	Dolomitic lime	690
7.	Dolomitic lime	380	7.	Gypsum	115
8.	Dolomitic lime	690	8.	Gypsum	403
9.	Gypsum	115	9.	Gypsum	690
10.	Gypsum	209	10.	SSP	53
11.	Gypsum	380	11.	SSP + Calcitic lime	743
12.	Gypsum	690	12.	SSP + Gypsum	743
13.	SSP + Calcitic lime	743	13.	Control	0
14.	SSP + Dolomitic lime	743			
15.	SSP + Gypsum	743			
16.	SSP	53			
17.	Control	0			

3.2.2 GREENHOUSE EXPERIMENT

The experiment was conducted between November 1999 and April 2000, and repeated during the same period in the 2000/01 season. Ten kilogrammes of the same soil as that used in the incubation experiment was placed in each pot after being air-dried and passed through a 2 mm stainless steel sieve. In the 1999/2000 season the soil was treated with the same Ca sources and rates (17 treatments) as in the incubation experiment. In 2000/01, three levels each of calcitic lime, dolomitic lime and gypsum were applied to supply an equivalent of 115, 403 and 690 kg ha^{-1} Ca. Other treatments were single superphosphate applied at 53 kg ha^{-1} Ca or combined with CL or gypsum. This resulted in a total of 13 treatments, including a control treatment in which no Ca-material was applied (Table 3.1). Each pot received initial starter nitrogen equivalent to 20 kg ha^{-1} N as ammonium nitrate, and pre-planting applications of P, K, Zn, and Fe as per soil analysis.

Three uniform sized seeds of Spanish groundnut cv. *Falcon* were sown in each pot at a depth of 25 mm. The seeds were not inoculated with *Bradyrhizobium* spp. Ten days after emergence, the seedlings were thinned to one per pot. Throughout the duration of the experiment, the plants were watered using distilled water passed through a deioniser.

At peak flowering stage plants from three replicates were harvested to determine the effects of the treatments on leaf nutrient composition and vegetative growth of the groundnut. The youngest fully expanded leaves (YFEL) were sampled to determine uptake of N, P, K, Ca, and Mg. Each plant was separated into shoots (stem and leaves) and roots. The roots from each pot were washed over a 500µm sieve to ensure retrieval of most roots. The shoots and roots were oven-dried at 80^{o} C for 48 hrs to determine dry mass. The total number of nodules per plant was recorded, and the dry weight of nodules determined. In the 1999/2000 season the plants were harvested before physiological maturity, so only pod dry mass was determined. In 2000/01, in addition to pod yields, kernel yields as well as quality characteristics were also determined. Nutrient concentrations in the shells and kernels were determined. A nitric perchloric acid (HNO_3:$HClO_4$) digestion of the plant material was used to prepare all the plant samples for analysis.

Soil samples were taken at peak flowering from 0 - 5cm and 7 - 12cm depths in each pot, and mixed to make a composite sample. The samples were air dried and stored for subsequent chemical analysis. The chemical analyses were similar to those described for the incubation experiment.

The statistical configuration for the experiment was a completely randomised design with seven replicates. All data were subjected to analysis of variance or regression analysis using the General Linear Models procedure on SAS statistical software (SAS, 1996). The Duncan's least significant difference (LSD) test was used to separate treatment means.

3.3 RESULTS AND DISCUSSION

The initial chemical properties of the soil used in the experiments are shown in Table 3.2.

Table 3.2 Initial properties of the soil used in the experiments

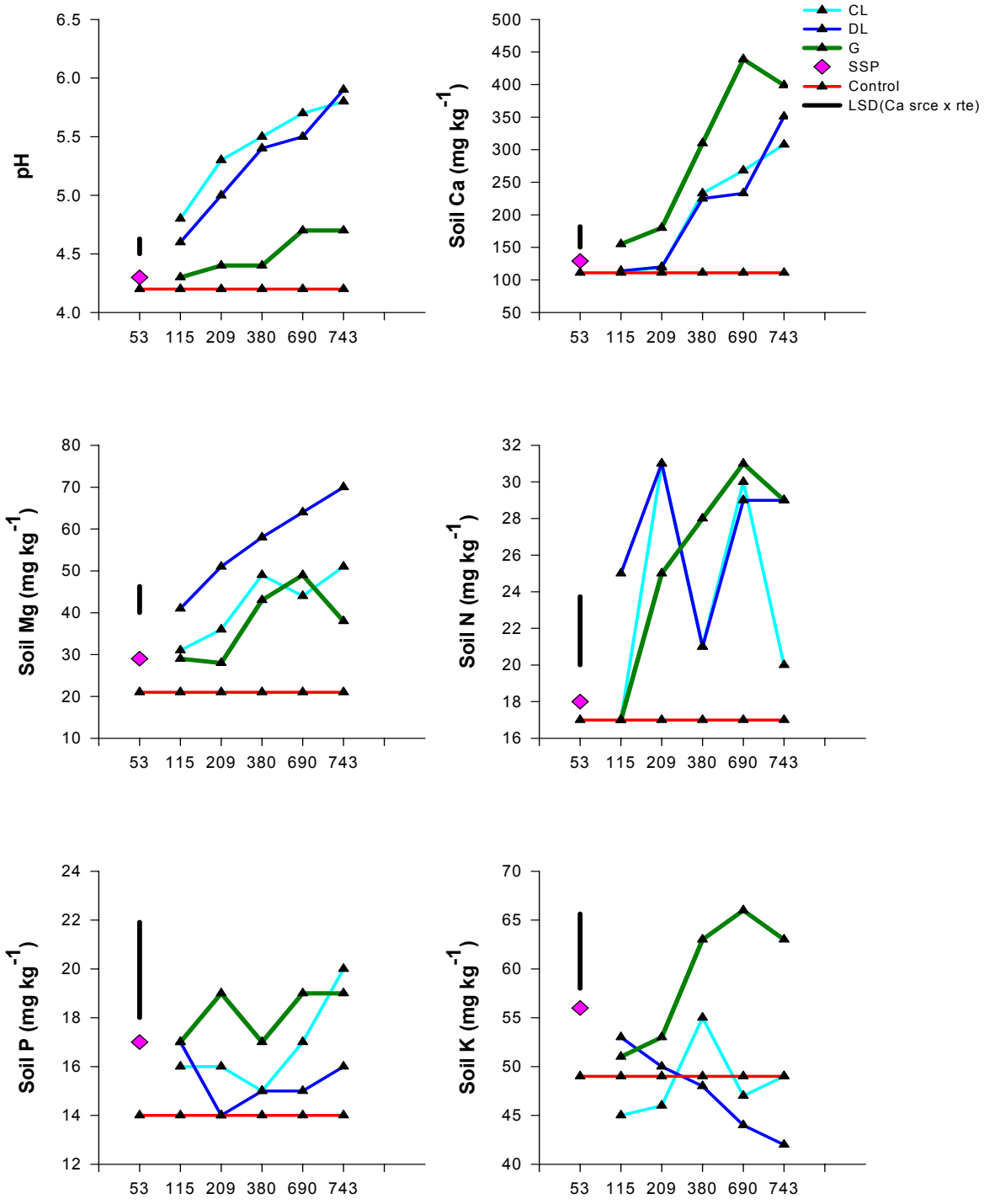
pH($CaCl_2$)	Soil nutrient level (mg kg^{-1})					Al^{3+}	Clay	Silt	Sand
	Ca	Mg	N	P	K	(mg kg^{-1})	(%)	(%)	(%)
4.1	92	25.6	18	14.4	44.7	0.044	4	3	93

The soil was extremely acid and low in N, P and the basic elements (Ca, Mg and K). At this pH level bacteria grow poorly while fungi thrive, and organic matter does not readily accumulate (DR&SS, 1974). The low soil pH value is probably a consequence of low levels of bases in the soil, since soil pH is largely determined by the amount of these bases in the soil (Adams, 1984). The nutrient status of this soil implies that macronutrient deficiency would be the major growth-limiting factor.

3.3.1 EFFECT OF THE CA SOURCES ON SOIL CHEMICAL PROPERTIES

a. Incubation experiment

Results of the chemical analysis after incubation are shown in Figure 3.1. Application of gypsum had the least effect on pH, whereas application of CL and DL significantly increased the soil pH.



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or DL or G @ 690 kg ha^{-1}.

Figure 3.1 **Effect of Ca source and rate on soil pH, Ca, Mg, N, P and K after a 7-day incubation period**

Gypsum application increased the soil pH by 0.08 to 0.48 units, whereas CL increased the soil pH by 0.61 to 1.28 units, and DL by 0.34 to 1.48 units. Similar effects were observed when the Ca materials were applied in combination with SSP. Single superphosphate on its own did not increase soil pH owing to its low Ca content together with low application rate (53 kg ha^{-1} Ca). For all the Ca materials increasing the application rate from 115 to 690 kg ha^{-1} Ca significantly increased the soil pH. Overall, application of CL or DL showed a rapid influence on the soil pH after one week of incubation. This could be attributed to the fineness of the liming material and the thorough mixing of the lime with the soil, which would ensure swift reaction with the soil.

Application of the different Ca sources resulted in significantly increased concentrations of Ca as the rate of applied Ca increased from 115 to 690 kg ha^{-1}. The increase in Ca concentration was highest with gypsum, despite similar Ca application rates of the three Ca sources. This could be explained by the high solubility of gypsum compared to the other Ca sources. The combination of SSP with lime increased the soil Ca levels more compared to application of lime alone. This could be attributed to the higher rate of Ca application (743 kg $ha^{-1)}$ in the treatment combinations compared to 690 kg ha^{-1} when the sources were applied individually. Soil Mg concentration was highest with application of DL, and increased with increase in the rate of DL applied. Mineral N and available P content were improved by application of the amendments, whereas exchangeable K levels were significantly affected by application of higher gypsum rates.

b. Greenhouse Experiment

1999/2000 and 2000/01 seasons

In the 1999/2000 season the soil pH values at the peak flowering period of the groundnuts ranged from 4.1 in the control treatment to 6.0 when SSP was combined with CL (Figure 3.2). With the exception of the SSP and the gypsum treatments, there was generally an improvement in pH for most of the treatments compared to the control. The largest pH increases were recorded from treatments in which either CL or DL was applied in combination with SSP. When similar rates of Ca were applied, DL and CL had similar effects on soil pH, although the values were slightly higher for the latter. Gypsum applied on its own did not have an effect on soil pH at all application rates. Similar treatment effects were observed in the 2000/01 season, with the largest pH increases recorded from treatments in which either CL or DL was applied either alone or in combination with SSP (Appendix Table A3.1).

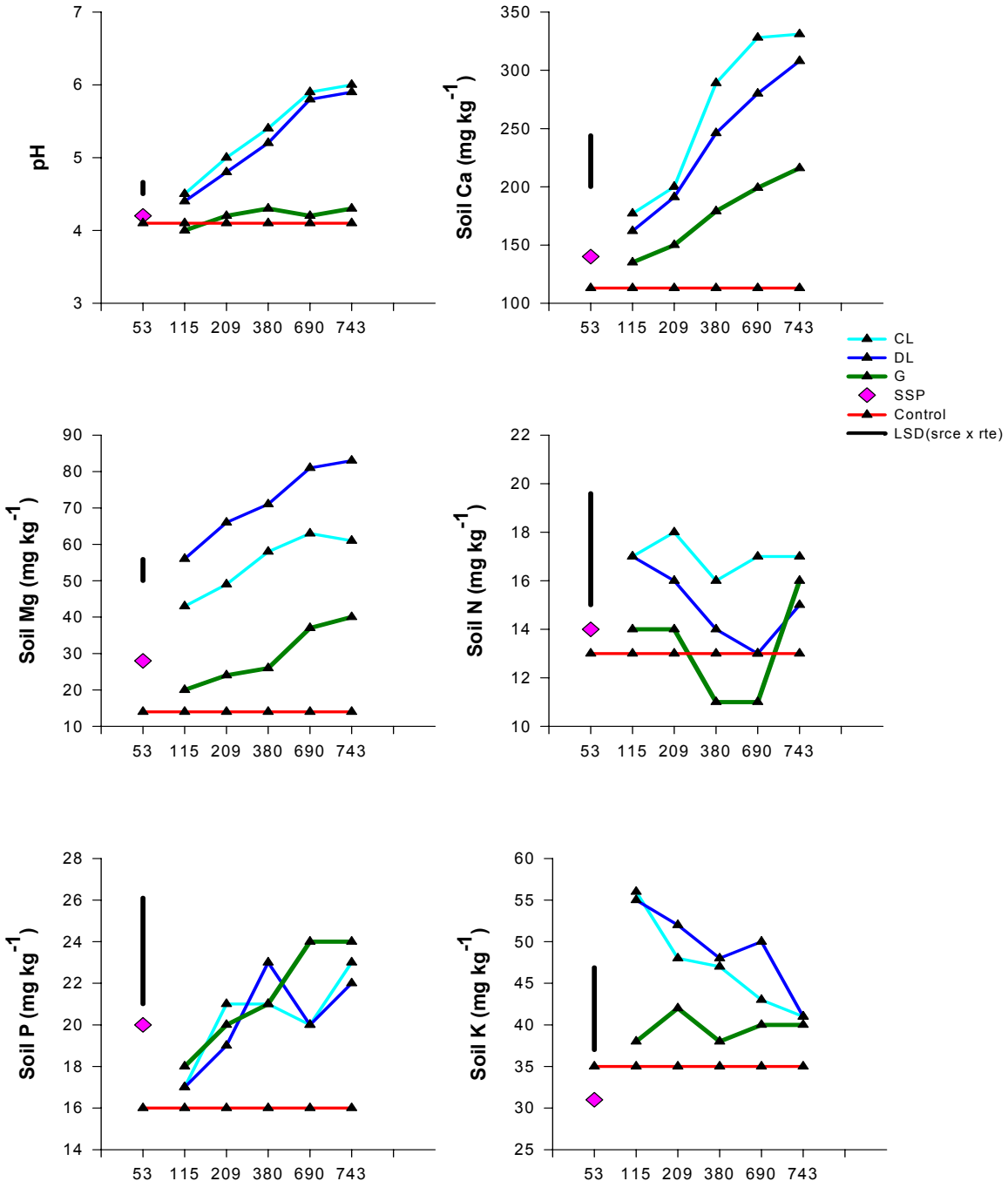


Figure 3.2 **Effect of Ca source and rate on soil pH, Ca, Mg, N, P and K at peak flowering period of groundnut in 1999/2000 season**

Varied effects of gypsum on soil pH have been documented. Sullivan *et al.* (1974) observed a decrease in soil pH by 0.4 units after application of 673 to 1346 kg ha^{-1} gypsum. Other studies have observed increases in soil pH after gypsum application, and attributed the phenomenon to a self-liming effect resulting from the dislocation of OH^- by SO_4^{2-} on the surface of soil particles, or if the H^+ originating from the hydrolysis of Al^{3+} does not exceed the release of OH^- (Alva *et al.*, 1988; Noble *et al.,* 1988; Alva *et al.*, 1991; Carvalho & van Raij, 1997). Mora *et al.* (1999) state that gypsum application may decrease, increase or not affect soil pH depending on how close the soil pH is to zero point charge. The latter regulates pH changes produced by ligand exchange when SO_4^{2-} displaces OH^- on the surface of soil particles. Carvalho & van Raij (1997) explain that beside the ligand exchange reaction, Ca^{2+} displaces H^+ and Al^{3+} (which suffer hydrolysis, liberating H^+). Therefore, the effect of gypsum on soil pH will depend on the magnitude of occurrence of these reactions. The effect of pH on pod development is examined in Chapter 5.

The mean exchangeable Ca content of the soil in the control plot was 113 mg kg^{-1} in the 1999/2000 season (Figure 3.2), and 104 mg kg^{-1} in the 2000/01 season (Appendix Table A3.1). In both seasons, a significant increase in exchangeable soil Ca levels was obtained by increasing the application rate of CL and DL, and the increases were higher with the former. The higher Ca content of the CL treated soil could be expected since CL contains 23% Ca compared to 18% in DL. Gypsum application also significantly increased the levels of exchangeable Ca, but the increases were of a lower magnitude compared to CL and DL. This result is at variance with the earlier observations in the incubation experiment, and can be attributed to Ca leaching because of the higher solubility of gypsum than lime. It could also be due to increased uptake of Ca by the plants because (a) gypsum is more efficient than lime in providing Ca and (b) gypsum does not produce additional cation exchange sites that make Ca inaccessible to the plants (Evanylo, 1989). These phenomena would result in faster depletion of Ca in the gypsum plots.

In the 1999/2000 season, the level of exchangeable Mg in the control treatment was 14 mg kg^{-1}, and was increased up to 27 mg kg^{-1} in the gypsum treatment, 63 mg kg^{-1} in the CL treatment and 81 mg kg^{-1} in the DL treatment (Figure 3.2). Application of the Ca sources in 2000/01 season increased the exchangeable Mg content from 21 mg kg^{-1} in the control treatment to 82 mg kg^{-1} in

the DL treatment (Appendix Table A3.1). In both seasons, significant increases in the soil Mg levels were observed as the application rate of CL and DL increased from 115 to 690 kg ha^{-1} Ca, and the increases were higher for DL. Increasing the gypsum application rate did not result in significant increases in the soil Mg levels. The lower Mg status in the CL and gypsum treated soil could be expected, since application of 690 kg ha^{-1} Ca as CL supplied 216 kg ha^{-1} Mg, while gypsum applied at the same rate supplied only 35 kg ha^{-1} Mg, compared to 414 kg ha^{-1} supplied with DL. The SSP treatment increased the Mg levels of the soil, whether applied alone or in combination with lime and gypsum.

The nitrogen levels of the soil were affected by application of CL and DL at lowerCa application rates in both seasons (Figure 3.2, Appendix Table A3.1). Gypsum application tended to result in lower N levels than the other Ca sources. The overall low N levels could have been influenced by the initial low soil N content of the soil, or by the low soil P levels triggering the plants to have a lower $N\text{-}_2$ fixing ability and probably take up more nitrates from the soil relative to $N\text{-}_2$ fixation (Marschner, 1995). Phosphorus is essential in nodulation and N fixation (de Mooy & Pesek, 1966). The phosphate levels of the soil were increased by application of all three Ca sources. The P levels were generally higher in treatments where SSP was combined with either type of lime. Reports on the effects of lime on P availability have been varied, partly because of the confounding effects of Ca, Mg and other elements affected by pH changes which have been shown to interact with P (Sumner & Farina, 1986). In situations where increases in soil extractable P have been observed after liming, the effect has been related to intense mineralisation of organic P at a rate which may sometimes exceed that of plant uptake (Häussling & Marschner, 1989).

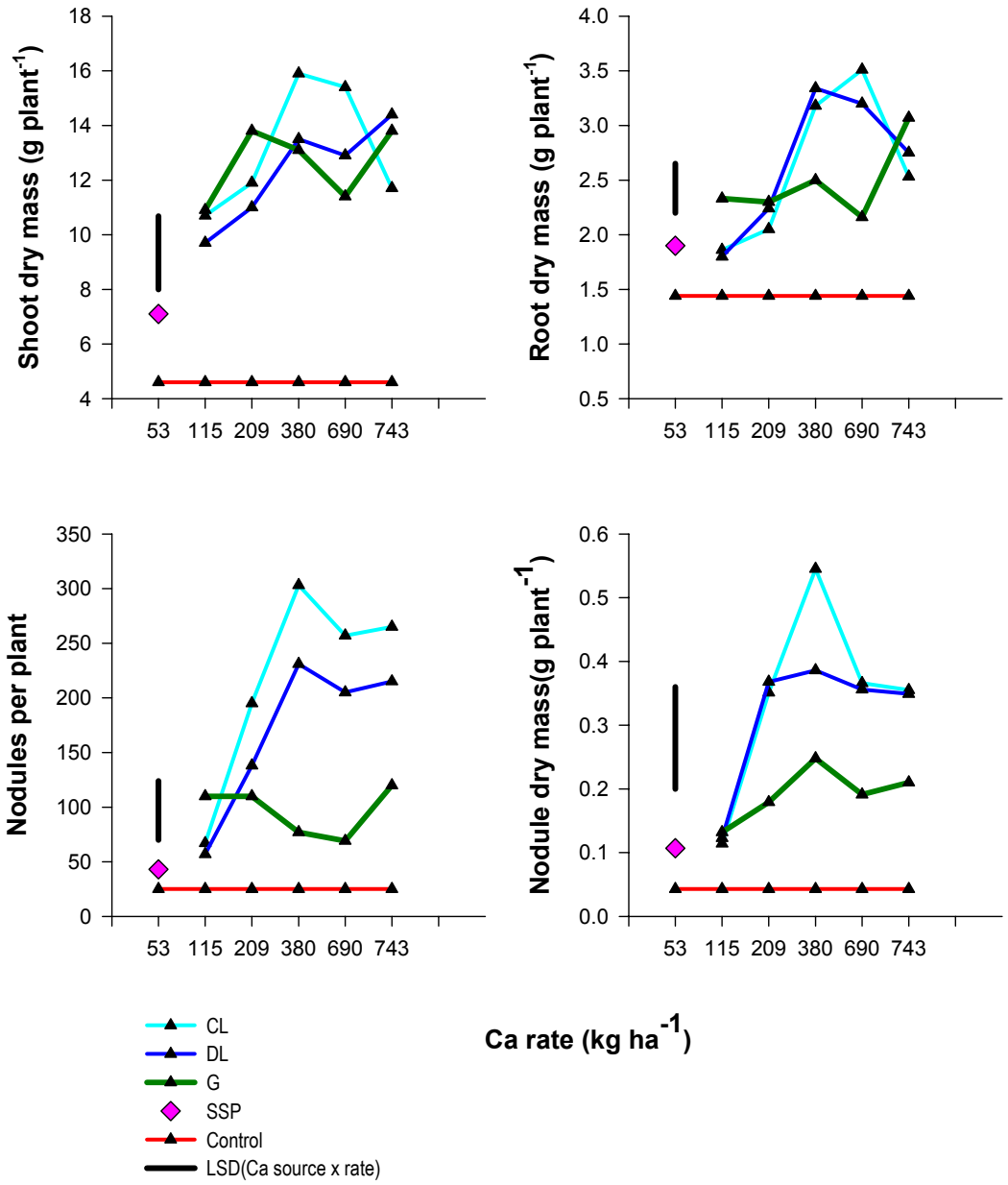
Whilst application of the Ca materials had a significant effect on exchangeable K content, increasing the rate of application did not increase the soil K levels (Figure 3.2, Appendix Table A3.1). Rather, the K levels tended to decrease at the higher Ca application rates. Snyman (1972) observed the same trend, and ascribed it to either increased leaching of the nutrient from the gypsum treated plots, or a loss from the soil as a result of increased K uptake by higher-yielding plants in the gypsum plots. Mora *et al.* (1997) also observed reduced soil K in lime and gypsum-treated plots and in the control treatment and described the phenomenon as an

illustration of the poor buffering capacity of the soil to removal of exchangeable K by plants. The observed effect of Ca sources on soil K implies that in soils where available K is marginal, the lime or gypsum induced reduction in K may have a negative impact on plant growth.

3.3.2 PLANT GROWTH

1999/2000 and 2000/01 seasons

Shoot and root dry mass data from the 1999/2000 and 2000/01 seasons are shown in Figure 3.3 and Appendix Table A3.2 respectively. Application of the Ca sources produced significant increases in shoot dry mass production, and the largest increases were recorded in the CL and DL treatments. Overall, increases in shoot dry mass relative to the control ranged from 111 to 246% in the 1999/2000 season, and 72 to 163% in the 2000/01 season. The best growth was produced at the intermediate lime rates (209 - 403 kg ha^{-1} Ca), and no further response was observed at 690 kg ha^{-1} Ca. Blamey & Chapman (1982) also observed that haulm yields increased significantly with lime rates of up to 1600 kg ha^{-1}, whereas liming above this rate was of no further significant benefit. Gani *et al.* (1991) reported that shoot dry mass was generally maximized at 500 to 1000 kg ha^{-1} lime, with no further benefit from increasing the lime application rate. In the present study, the decline in dry mass production at the highest Ca application rates alludes to a potential for nutritional problems if overliming occurs in these soils. Application of SSP alone increased the shoot dry mass by 37 to 54%, while significantly higher dry mass values were observed when SSP was applied together with lime or gypsum. Gypsum also increased shoot dry mass, with the best growth being observed at the intermediate application rate. Retarded groundnut growth in gypsum-treated plots compared to the control or lime treatments has been observed by Mann (1935) and by Blamey & Chapman (1982).



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or DL or G @ 690 kg ha^{-1}.

Figure 3.3 **Effect of Ca source and rate on shoot dry mass, root dry mass, nodule number and nodule dry mass in 1999/2000 season**

All the Ca sources produced significant increases in root dry mass (Figure 3.3; Appendix Table A3.2). The response of root dry mass to application of Ca sources was similar to that of shoot dry mass, with no further increases in growth at the highest Ca application rate. The addition of lime combined with SSP did not result in larger root dry mass than the application of lime alone. Although gypsum application significantly increased root dry mass relative to the control treatment, there was a tendency for the root dry mass to decrease as the rate of gypsum increased. However, the general improvement in root dry mass due to gypsum application compared to the control is an indication that gypsum was effective in reducing the negative effect of the H^+ ion on root growth. The significant root dry mass response to application of Ca sources was reflected in the good shoot growth observed.

3.3.3 NODULATION

1999/2000 season

Although inoculation was not performed on the seeds, the soils contain reasonable populations of indigenous rhizobia for nodulation to occur. In pot experiments conducted using similar acid soils at Marondera, Zimbabwe, van Rossum *et al.* (1994) observed better nodulation with indigenous *Bradyrhizobium* spp. at low soil pH compared to neutral pH, with nodule numbers increasing by 21% at pH 5.0 compared to pH 6.5. Assessment of nodulation in the present study showed that numbers of nodules per plant were significantly influenced by Ca sources (Figure 3.3). In the control treatment an average of 25 nodules per plant were found as compared to 303 in treatments receiving 380 kg ha^{-1} Ca as CL. Nodule numbers were highest in the CL treatments, followed by the DL treatments and least in gypsum treatments. Application of SSP alone (Ca rate 53 kg ha^{-1}) did not influence nodulation.

The propensity for gypsum to reduce nodulation of groundnut has been noted by Mann (1935) and by Blamey & Chapman (1982), who suggested the possibility of an increase in activity of Al-ions due to gypsum application as a cause, or reduced Mo availability due to the antagonistic effect of SO_4^{2+} on Mo availability as observed by Reisenauer (1963). There was a tendency towards higher numbers of nodules at the intermediate Ca application rate (380 kg ha^{-1} Ca). Reasons for the decreased nodulation at higher Ca application rates were not clear. However,

depressed nodulation at high lime application rates has been attributed to decreased P availability, since P is essential in nodulation and N fixation (de Mooy & Pesek, 1966).

Nodule dry mass per plant was significantly influenced by application of Ca (Figure 3.3). The lowest nodule dry mass was observed in the control and SSP treatments (0.04 – 0.11 g plant^{-1}), and the highest (0.545 g plant^{-1}) in the CL treatment.

The largest nodules were formed at the lowest Ca application rate and *vice versa* (Appendix Table A3.2). Overall, fewer but larger nodules were formed at low pH. In the control or 115 kg ha^{-1} Ca treatments with less than 75 nodules per plant, the mean size per nodule ranged from 5.81 to 11.18 mg, while in the high Ca treatments with more than 200 nodules per plant, the nodule size decreased to less than 5.0 mg nodule^{-1}. Mengel & Kamprath (1978) documented similar results with soybean. They observed that nodules formed at low pH were large and concentrated mainly on the taproot, and as the pH increased, nodules were initiated on the lateral roots, but the nodule size decreased. These observations support the assertion that soil acidity has little effect on nodule development and activity once the infection process and nodule initiation has occurred (Evans *et al.,* 1980).

3.3.4 LEAF NUTRIENT COMPOSITION

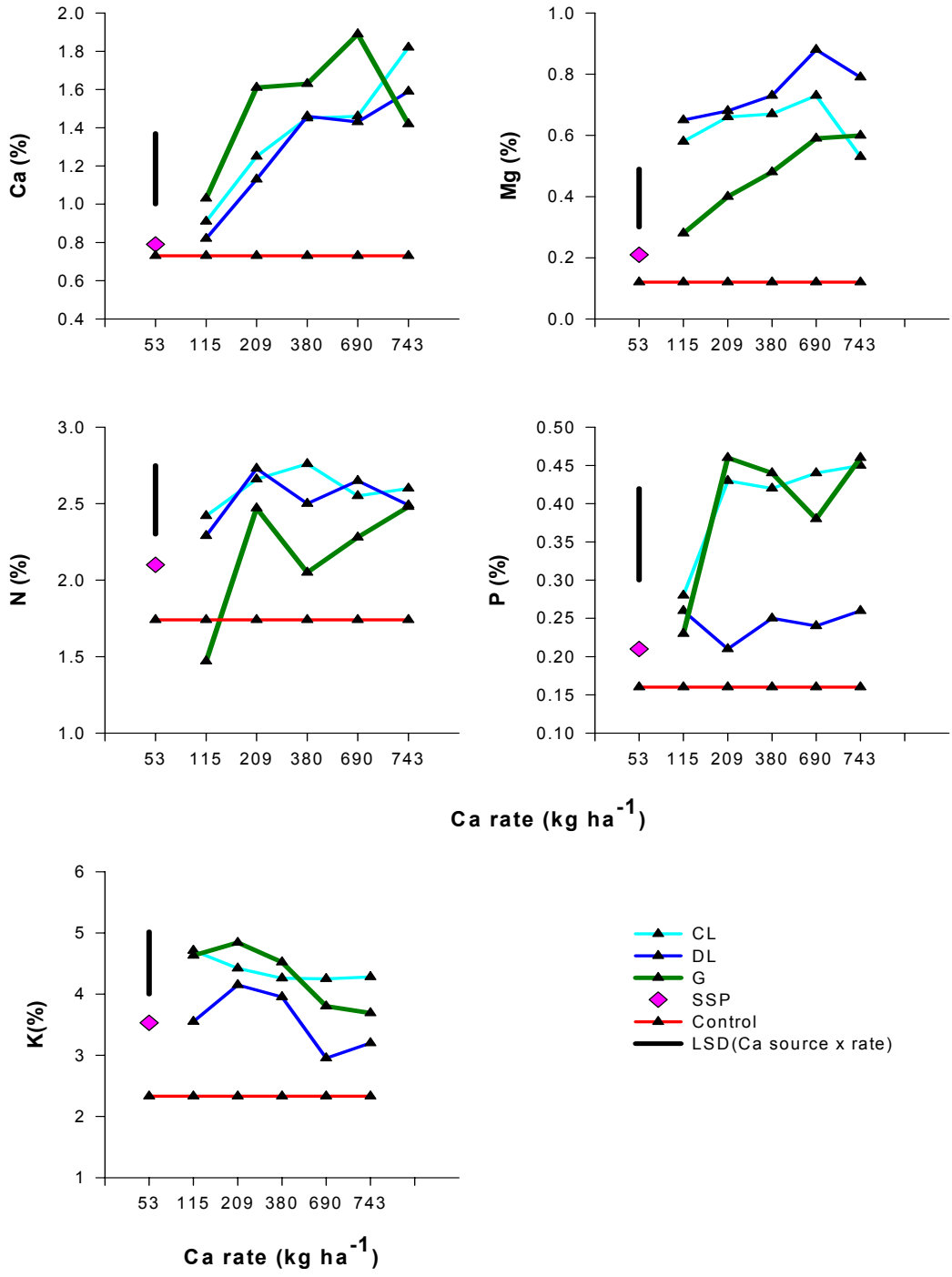
1999/2000 and 2000/01 seasons

Tissue concentrations of all the elements analyzed in 1999/2000 season are shown in Figure 3.4. The mean leaf Ca concentration in the control treatment was 0.8 %, and it increased up to 1.9% with application of gypsum at 690 kg ha^{-1} Ca. In 2000/01 season the Ca concentration in the control treatment was 0.76%, and was increased up to 2.1% in the gypsum treatment, and 1.5% in the CL and DL treatments (Appendix Table A3.3). In both seasons, all the Ca sources generally increased leaf Ca concentration, but the increases were highest with gypsum application at the intermediate application rates. Snyman (1972) also recorded significantly higher Ca concentration in groundnut vegetative material from gypsum-treated plots compared to the plots treated with calcitic or dolomitic lime. He further noted that the response of the Ca content of the vegetative material to gypsum was quadratic, with peak Ca concentrations being observed at the

intermediate application rates. Overall, leaf Ca concentrations in the CL and DL treatments were not significantly different, but when combined with SSP the Ca concentration was significantly higher in the SSP + DL treatment. For all the Ca sources, the lowest level of Ca did not have any effect on leaf Ca concentration, but application of the intermediate rates significantly increased the leaf Ca levels. The low Ca application rate did not increase the leaf Ca content to the levels indicated to be adequate for good growth of Spanish-type groundnuts, which are 1.25 to 2.0% according to Gascho & Davis (1994.

Leaf Mg levels in the control and SSP treatments were 0.12% and 0.21% respectively in the 1999/2000 season (Figure 3.4), while the critical leaf Mg level for Spanish-type groundnuts is 0.3% (Gascho & Davis, 1994). In the 2000/01 season the leaf Mg levels ranged from 0.25% in the control treatment to 0.79% in the DL treatment (Appendix Table A3.3). The highest Mg levels were recorded in plants sampled from the DL treatment, and lowest in plants sampled from the gypsum treatment. Magnesium levels in the CL treatment were intermediate. Increasing the Ca application rate from 115 to 690 kg ha^{-1} significantly increased the leaf Mg concentration only in the DL treatment. Depressions in leaf Mg concentration were observed when lime or gypsum were combined with SSP.

Leaf N concentrations ranged from 1.7% in the control treatment to 2.8% in plants grown in the CL treatment at 380 kg ha^{-1} Ca in the 1999/2000 season (Figure 3.4). In all the treatments, the N levels were below sufficiency levels for groundnut, which range from 3.0 to 4.5% according to Gascho & Davis (1994). Similar treatment effects were observed in 2000/01 season, with the N levels below sufficiency levels in all the treatments (Appendix Table A3.3). No symptoms of N deficiency were observed on plants in the CL and DL treatments even though they had <3% N, whereas plants in the control and gypsum treatments exhibited a yellowish colour associated with N deficiency. The low N content of the control and gypsum treatments could be attributable to the low soil pH that affects the efficacy of rhizobium bacteria (Sullivan *et al.,* 1974). Another explanation offered for low N content in gypsum plots is the possibility of increased translocation of N from the leaves to fruits created by the heavier fruiting (Sullivan *et al.,* 1974), but since in my experiment the plants were sampled at peak flower, the explanation could not be verified.



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or DL or G @ 690 kg ha^{-1}.

Figure 3.4 **Effect of Ca source and rate on leaf Ca, Mg, N, P and K concentrations at peak flowering of groundnut in 1999/2000 season**

Phosphorus concentrations in the leaves sampled in 1999/2000 ranged from 0.16% in the control treatment to 0.46% in the gypsum treatment (Figure 3.4). Similar leaf P concentrations were observed in the 2000/01 season, with values ranging from 0.15% in the control treatment to 0.48% in plants grown in the CL+SSP treatment (Appendix Table A3.3). The critical leaf P content for groundnut is 0.25% (Gascho & Davis, 1994), and plants grown at 115 kg ha^{-1} Ca in the DL and gypsum treatments were deficient in P. Leaf P content was generally high with application of intermediate Ca rates irrespective of the Ca source, but the DL treatment resulted in lower P concentrations than the CL and gypsum treatments.

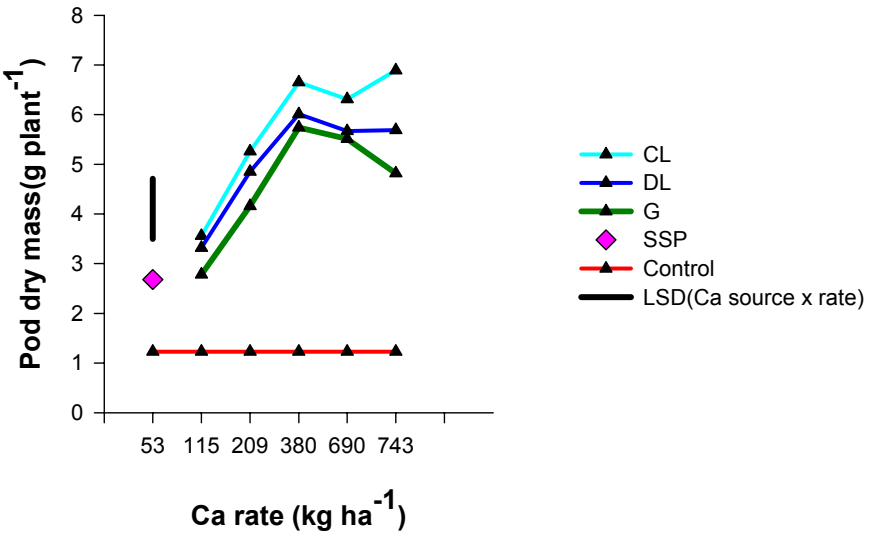
In both seasons the K concentrations were adequate in all treatments, the sufficiency values being 1.7 to 3.0% as suggested by Gascho & Davis (1994). Values for leaf K concentrations were high in plants grown in the ameliorated soils compared to the control, and ranged from 2.33% in the control treatment to 4.84% in plants grown at 209 kg ha^{-1} Ca in the gypsum treatment (Figure 3.4). In the 2000/01 season the leaf K concentrations ranged from 2.21% in the control treatment to 4.52% in plants grown in the gypsum treatment at 403 kg ha^{-1} Ca (Appendix Table A3.3). In both seasons, the leaf K concentrations tended to decrease at the higher Ca application rates. The observed leaf K values were much higher than those observed in the field experiments, and this could be attributed to higher soil K levels (44.7 mg kg^{-1}) in the soil used in the greenhouse experiment compared to 19.5 – 27.4 mg kg^{-1} K in the field experiments. Bartlett & McIntosh (1969) observed reduced plant uptake of K on limed soils and attributed it to the reduction in percentage K saturation of the cation exchange complex because of lime-induced increase in cation exchange capacity.

3.3.5 POD AND KERNEL YIELDS

1999/2000 season

Mean pod yield per plant in the control treatment was 1.23 g, and application of CL at 380 kg ha^{-1} Ca increased the pod yield to 6.7 g $plant^{-1}$ (Figure 3.5). Pod yield response to SSP alone was significantly better than in the control treatment. For all Ca sources, increasing the application rate from 115 to 380 kg ha^{-1} Ca significantly increased the pod yields. However, increasing the application rate to 690 kg ha^{-1} Ca did not result in a further increase in pod yields.

Notwithstanding the low pH in the gypsum treatments, the yields were not significantly different from those in the CL or DL treatments. This indicates that changes in the Ca status of the soil are the major reason for improved kernel yield and not improved pH *per se*.



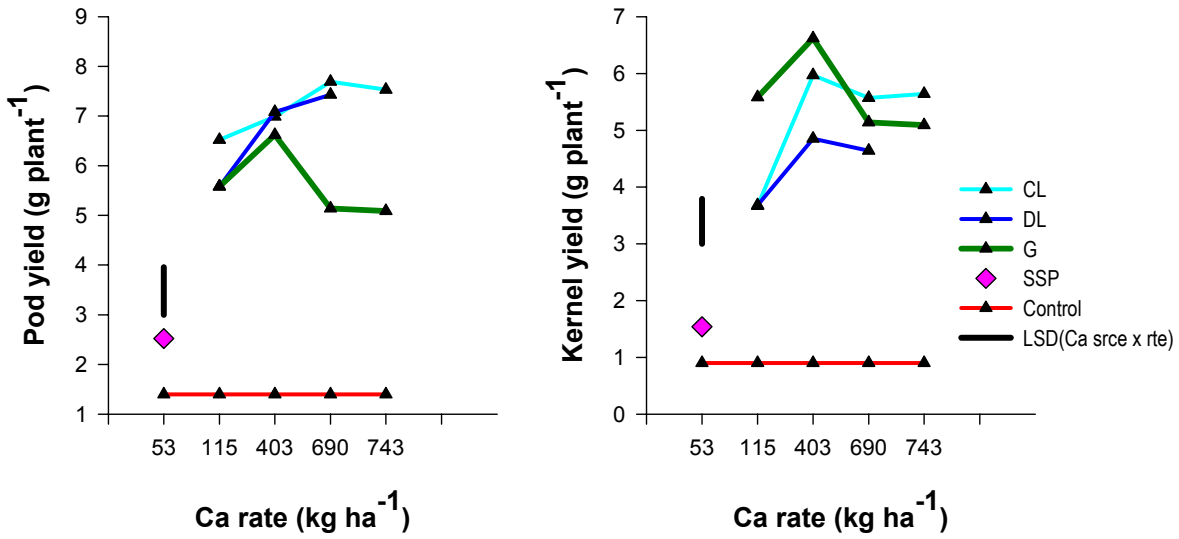
** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or DL or G @ 690 kg ha^{-1}.

Figure 3.5 Effect of Ca source and rate on pod yield in 1999/2000 season

2000/01 season

The pod yield response to application of CL and DL in 2000/01 was analogous to that observed in the 1999/2000 trial, while application of higher gypsum rates tended to depress yield (Figure 3.6). The pod yield response to SSP was not significantly different from the control treatment. When equal rates of Ca were applied as either CL or gypsum, similar yields were produced.

The total kernel yield per plant was significantly increased by all Ca treatments (Figure 3.6). The mean kernel yield in the control treatment was 0.91 g plant^{-1}, and application of Ca increased the yield up to 5.97 g plant^{-1}. On average, the differences in kernel yields obtained from the different Ca sources were not statistically significant at the lowest and highest Ca application rates. With application of 403 kg ha^{-1} Ca, CL had higher yields than gypsum. Combining CL or gypsum with SSP did not result in significant yield increases compared to applying the materials individually; neither did kernel yield response to SSP alone significantly differ from the control treatment.



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or G @ 690 kg ha^{-1}.

Figure 3.6 Effect of Ca source and rate on pod and kernel yield in 2000/01 season

Significant increases in kernel yield were obtained when the Ca rate was increased from 115 to 403 kg ha^{-1} Ca in the CL treatment, but not in the gypsum and DL treatments. For all the Ca sources, there was no yield advantage due to application of 690 kg ha^{-1} Ca. Studies by Zharare (1997) on Ca requirements for pod growth of a Spanish type cultivar showed a wide range of optimal Ca concentrations in the pod zone, suggesting that varied yield responses to Ca application might be expected. Decreases in kernel yield due to application of high rates of DL have been attributed to an imbalance of the K: Mg ratio, especially in soils with high Ca levels and a high K: Mg ratio (Strauss & Grizzard, 1948). The soil in the present study was not high in exchangeable Ca, but the significant increases in Mg content due to application of Ca materials, coupled with the tendency for K levels to decrease at the higher Ca application rate caused an imbalance in the K: Mg ratio, resulting in the decreased yields.

Partitioning of the total kernel yield into basal and apical kernel yields showed that the response of the two to application of Ca sources was similar to that of total kernel yield per plant (Appendix Table 3.4). Because the basal cavities have a higher percentage seed-set than the

apical cavities, the basal kernel yields were higher than apical kernel yields in all treatments. The ratio of basal to apical kernels was lower in the gypsum treatment, an indication of better seed-set in the apical ovarian cavities of the two-compartmented pods of this cultivar. The better seed-set in the gypsum treatment is probably an indication of the superiority of this Ca source in supplying adequate Ca for fruit production.

3.3.6 PROPORTION OF MATURE PODS AND EMPTY PODS (POPS)

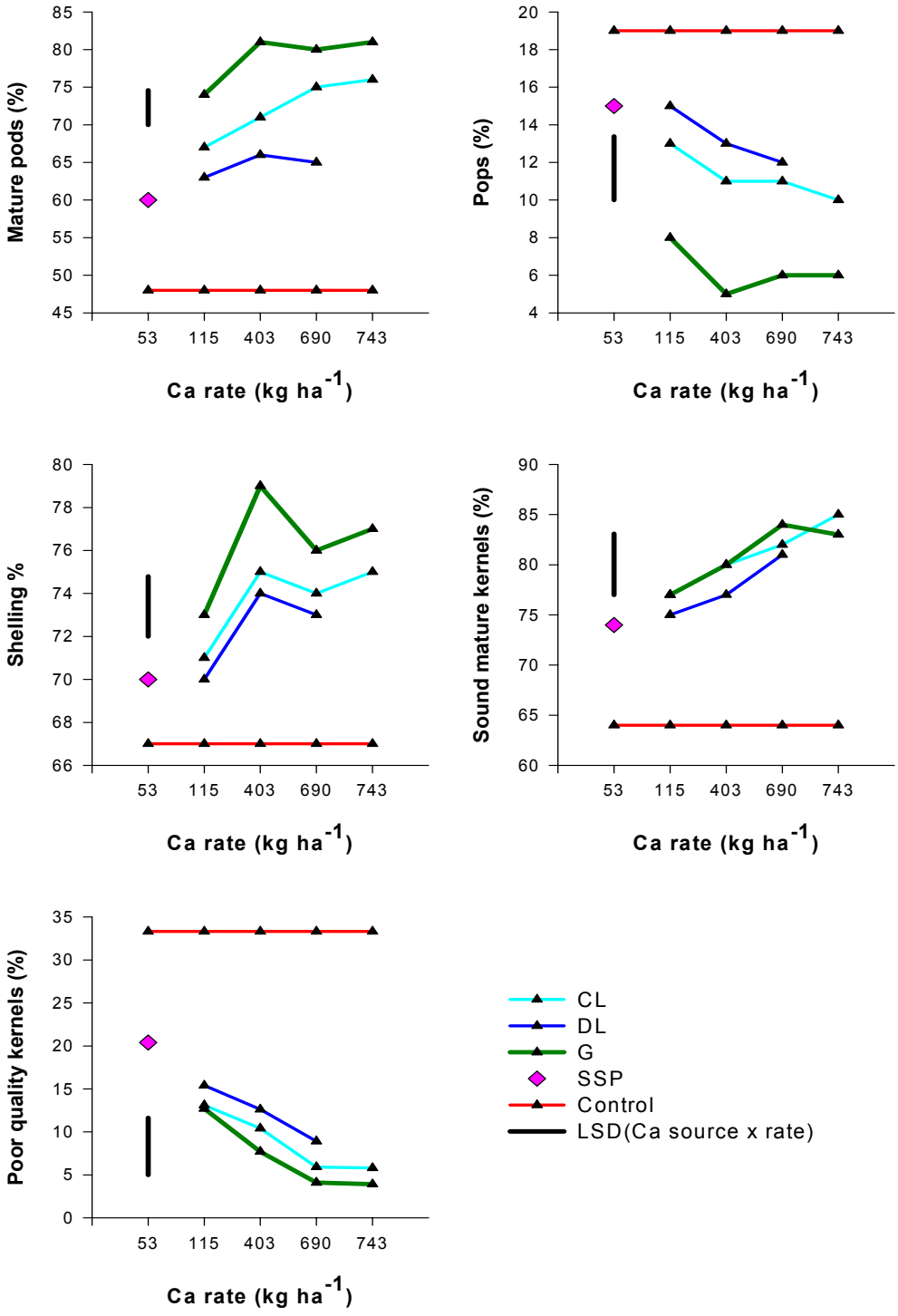
2000/01 season

The percentage of mature pods per plant was significantly higher on plants grown in lime or gypsum treated soils relative to the control treatment, and the higher the application rate the higher the number of mature pods per plant (Figure 3.7). The proportions of immature pods and pops were highest in the control plots (Figure 3.7), and application of Ca sources, especially the gypsum treatment reduced their proportions. The mean percentage of pops in the gypsum treatment was 6.3%, compared to 11.7% in the CL treatment, 13.7% in the DL treatment and 19% in the control. Blamey & Chapman (1982) also observed a significant reduction in pops by both lime and gypsum. Snyman (1972) observed that gypsum was the only Ca source having a marked influence in decreasing the percentage of unfilled pods compared to CL and DL.

3.3.7 KERNEL QUALITY

2000/01 season

Application of the Ca sources resulted in highly significant effects on some of the kernel quality parameters measured (Figure 3.7). Shelling percentage was significantly increased by application of the Ca sources, and ranged from 67% in the control plot to 79% with application of 403 kg ha^{-1} Ca as CL. Shelling percentage in the gypsum treatment was better than in the CL and DL treatments. Application of SSP on its own had no effect on shelling percentage, but combining it with CL or gypsum increased the shelling percentage. For all Ca sources, increasing the application rate from 115 to 690 kg ha^{-1} Ca did not result in significant improvements in the shelling percentage.



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or G @ 690 kg ha^{-1}.

Figure 3.7 Effect of Ca source and rate on pod and kernel quality in 2000/2001 season

The effects of Ca sources on the proportion of sound mature kernels (SMK) were highly significant (Figure 3.7). Mean percent SMK in the control treatment was 64%, and application of 690 kg ha^{-1} Ca as gypsum increased it to 84%. With all Ca sources, increasing the Ca application rate increased the proportion of sound mature kernels. Combining SSP with CL improved the percent SMK, whereas combining SSP with gypsum did not. Overall, the proportion of sound mature kernels in the gypsum treatment was higher than in the CL and DL treatments. Application of SSP on its own did not increase the proportion of sound mature kernels.

Total poor quality kernels (shriveled, rotted and discolored) were affected by the Ca source used, with gypsum reducing the proportion of poor quality kernels by a greater magnitude compared to CL and DL (Figure 3.7). While the number of rotted and discolored kernels was not significantly influenced by application of Ca sources, shriveled kernels were (Appendix Table A3.4). A high percentage of shriveled kernels were recorded in the control and SSP treatments, and when Ca was applied at 115 kg ha^{-1}. For all Ca sources, increasing the rate of Ca application significantly reduced the number of poor quality kernels. Since a high percentage of poor quality kernels results in the downgrading of groundnut on the market, application of the Ca sources would be beneficial in ensuring that a high proportion of high quality nuts are produced.

3.3.8 SHELL AND KERNEL CA, MG AND K CONTENT

2000/01 season

Calcium

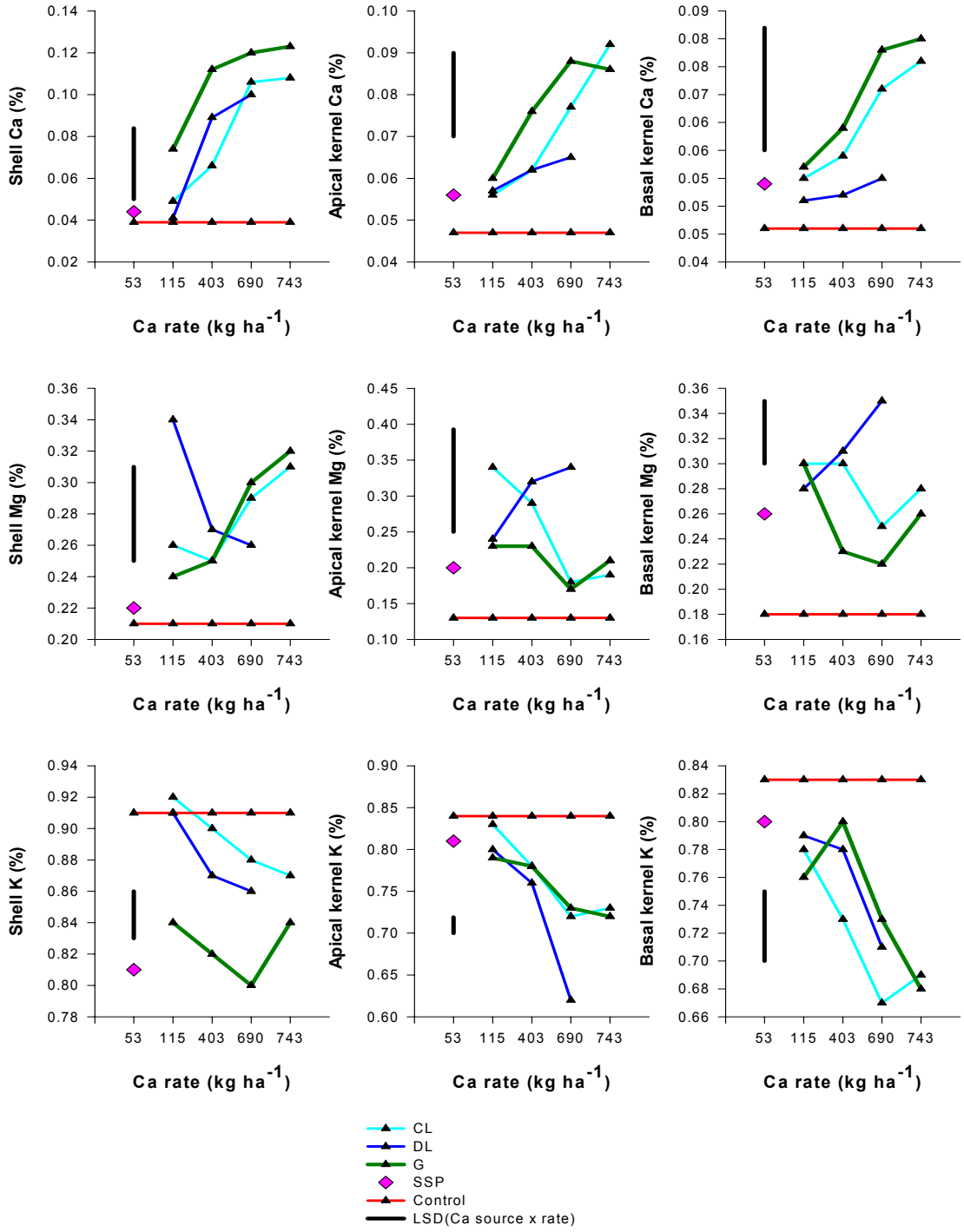
The shell Ca concentrations were significantly influenced by Ca source and rate of application (Figure 3.8). For all Ca sources, significant increases in shell Ca content were observed as the application rate was increased from 115 to 690 kg ha^{-1} Ca. On average, the Ca content was highest in the gypsum treatment, whereas CL and DL treatments had similar shell Ca content. Combining gypsum or CL with SSP was of no benefit in increasing the shell Ca content.

The kernel Ca concentrations in all treatments were adequate (Figure 3.8), the sufficiency values being 0.04 to 0.08% as suggested by Gascho & Davis (1994). The mean Ca concentration in the control treatment was 0.05% in both the basal and apical kernels. Application of gypsum at 690 kg ha^{-1} Ca significantly increased the Ca content to 0.08% in the basal kernels, and to 0.09% in the apical kernels. Combining SSP with CL similarly increased the Ca content in the basal and apical kernels. Increasing the Ca application rate increased the concentration of Ca in basal and apical kernels. Application of SSP also increased the kernel Ca concentration. Overall, the kernel Ca concentrations tended to be higher in the gypsum treatment than in the CL and DL treatments. Slightly higher Ca concentrations in the apical kernels than in the basal kernels were observed, and the reasons for this phenomenon, also observed by Zharare (1997), are not clear.

Magnesium

The shell Mg concentrations increased as the application levels of CL and gypsum increased, but decreased as the DL application rate increased from 115 to 403 kg ha^{-1} Ca (Figure 3.8). Nevertheless, application of 115 and 403 kg ha^{-1} Ca as DL resulted in shell Mg concentrations that were higher than in the CL and gypsum treatments. In the study by Snyman (1972), a significant increase in the Mg content of the shells was observed with increasing levels of CL and DL, whereas gypsum application generally decreased the Mg content.

Application of Ca sources had a significant though varied effect on kernel Mg content (Figure 3.8). Whereas application of DL increased the Mg content as the rate of application increased, the reverse trend was observed with application of CL and gypsum. This trend was observed in apical and in basal kernels. Overall, the kernel Mg content in the apical kernels ranged from 0.13% in the control treatment to 0.34% in the DL treatment. In the basal kernels, Mg content ranged from 0.18% in the control treatment to 0.35% in the DL treatment. Thus, the kernel Mg levels were generally adequate in all but the basal kernels in the control treatment, the sufficiency values being 0.16 – 0.2% as suggested by Gascho & Davis (1994).



** Ca rate of 743 = SSP @ 53 kg ha^{-1} + CL or G @ 690 kg ha^{-1}.

Figure 3.8 Effect of Ca source and rate on shell and kernel Ca, Mg, and K concentrations in 2000/2001 season

Potassium

The K content of the shells tended to be slightly better under conditions of low Ca (control and 115 kg ha^{-1} Ca treatments). Shells in the gypsum treatment generally had the lowest K levels (up to 0.83%) while those in the control treatment had a mean K content of 0.91% (Figure 3.8).

The K concentration in the basal and apical kernels was influenced by application of Ca sources (Figure 3.8). Like in the shells, the K concentrations were highest at the lowest Ca application rate, and in the control treatment. The trend was observed in both basal and apical kernels. Snyman (1972) observed a quadratic response of kernel K to increases in Ca application rate, with significant decreases in K content being recorded at the lower Ca application rates, but insignificant decreases being observed at the higher application rates. Kernels in the gypsum treatment generally had the lowest K levels compared to the CL and DL treatments, and in all the treatments, apical kernels tended to have slightly higher K concentrations compared to basal kernels.

The tendency for the K concentrations in the shells and kernels to decline as the Ca application rate was increased concurs with the assertion that Ca inhibits K uptake. Nevertheless, the K concentrations removal, within the sufficiency levels of 0.62 to 0.89% as suggested by Gascho & Davis (1994) in all treatments impy that the applied Ca rates were not detrimentally antagonistic to K uptake by the pods. However, it may be noted that K may enter the pods via long distance transport in the xylem sap from the roots. Hence, provided that sufficient amounts of K exist in the root zone, deficiencies in the pod tissues may not be experienced.

3.4 CONCLUSIONS

Although a different soil was used, the results of this study concur with those from the field experiments. Application of various rates of calcitic and dolomitic lime produced significant changes in soil pH, whereas gypsum did not, even when equal rates of Ca were applied. Application of single superphosphate at 53 kg ha^{-1} Ca did not influence the soil pH. Following increases in solution pH, concomitant increases in soil exchangeable Ca and Mg levels were observed after application of CL or DL. Gypsum application increased exchangeable Ca levels, but not Mg. The Ca sources had little effect on the soil N, P and exchangeable K content. An

increase in soil pH significantly increased concentrations of Ca and Mg in the leaves, kernels and shells of groundnut, but had small or variable effects on N, P and K concentrations. However, the concentrations of N, P and K in the shoots appeared to be adequate for unrestricted growth of groundnut.

Increasing the Ca application rates increased the pH of the soil solution, thereby eliciting positive effects on growth and productivity of groundnut. The observed better yields with intermediate Ca application rates particularly in the CL and DL treatments appear to be consistent with the pH and calcium levels in the soil. Ca application rates above 400 kg ha^{-1} seem detrimental to yield in the sandy soil under consideration.

Even though gypsum application did not change soil pH, the observed plant growth and productivity in that treatment was as good as that obtained with application of CL and DL. Combining SSP with gypsum or CL was generally not beneficial, probably due to the resultant high Ca application rate, which might have induced nutrient imbalances. The magnitude of response to application of Ca sources was generally of the order CL>DL>G for most of the measured parameters. Overall, both lime types were superior to gypsum in improving the vegetative and reproductive growth of groundnut, but when it came to improving pod and kernel quality, gypsum was superior. The similarity of these results to those observed in the field experiments (Chapter 2) implies that pot experiments, which have the advantage of testing as many treatments combinations as possible, can be used to screen a range of soil acidity amelioration treatments before they are tested in the field.

CHAPTER 4

TOLERANCE OF GROUNDNUT GENOTYPES TO ACID SOILS

4.1 INTRODUCTION

The predominantly granitic sandy soils on which most of the groundnut crop in Zimbabwe is grown are highly leached, depleted of base nutrients and contain very low reserves of minerals that have the potential to weather and release the elements that are essential for plant growth (Vincent & Thomas, 1962; Nyamapfene, 1989). Most of the soils are acidic, and deficient in organic matter, calcium, magnesium, phosphorus and zinc (Grant, 1970, 1981; Mashiringwani, 1983; Tagwira *et al*., 1993). Thus, nearly all nutrients and lime have to be added in order to maintain fertility in these soils. Improved groundnut varieties with high yielding potential produce as little as 0.5 t ha^{-1} of kernels on these soils compared with 4.0 t ha^{-1} obtained on the heavier loamy and clayey soils (Hildebrand, 1996). These yield gaps are attributed mainly to limitations imposed by acid soil infertility, and to a lesser extent to limited water supply and to production constraints such as lack of disease and pest control. Nutrient stresses (both deficiencies and toxicities) are largely responsible for poor plant growth and lower nutrient use efficiency in acid soils (Foy, 1984; Fageria *et al*., 1990; Sumner *et al*., 1991; Foy, 1992; Baligar & Fageria, 1997; Baligar *et al*., 2001). Groundnut genotypes that are able to grow and produce well on acid soils can contribute towards improved crop productivity on acid soils of the resource poor farmers in the smallholder sector.

Since acid-soil infertility can involve both nutrient deficiencies (Ca, Mg, M, K S and N) and toxicities (Al and Mn), the tolerance of plants to soil acidity could be a function of an efficient uptake and utilisation of those nutrients that are deficient under acid-soil conditions and/or tolerance to Al and Mn toxicities. In this respect, tolerance can be defined as the ability of a plant to grow better, produce more dry matter, and develop fewer deficiency symptoms than another plant when grown at low or toxic levels of a mineral element (Clark, 1976). Alternatively, it can be defined as the ability of a genotype to produce a high yield in a soil that has a deficiency or

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toxicity of a particular element compared to a standard genotype (Graham, 1984). Other definitions of nutrient efficiency include efficiency of acquisition (plant nutrient content per available nutrient) or the efficiency with which a nutrient is used to produce biomass (plant biomass per plant nutrient content) or grain (grain yield per plant nutrient content). A nutrient-efficient genotype is also defined as one that is able to acquire nutrients from the growth medium and /or to incorporate or utilise them in the production of shoot and root biomass or seed, grain, fruit or forage (Blair, 1993; Baligar & Fageria, 1997; Baligar *et al.,* 2001).

The efficiency of nutrient utilisation (nutrient efficiency ratio - NER) is defined as the amount of dry mass produced per unit of mineral element present in the dry mass (Siddiqi & Glass, 1981; Glass, 1989). This parameter is a quantitative measurement of the efficiency with which plants convert primary resources (CO_2, H_2O and inorganic nutrients) into dry mass (Glass, 1989). Scientists have used the parameter to compare the efficiencies of nutrient utilisation among several crop species (Giordano, *et al.,* 1982; Woodend *et al.,* 1989; Behling *et al.,* 1989; Li & Gableman, 1990). Review papers, notably by Siddiqi & Glass (1981), Blair (1993), Gourley *et al.,* (1994) argue that the nutrient efficiency ratio might not have a sufficiently strong relationship to absolute yield. Siddiqi & Glass (1981) and Glass (1989) recommended that expression of utilisation efficiency should consider tissue concentration of the element rather than the absolute amount, and should be expressed as biomass per unit of tissue concentration. Accordingly, they deemed nutrient utilisation efficiency (NUE) a more appropriate measure of nutrient utilisation since growth depends on tissue nutrient concentration, and NUE takes into consideration tissue concentration rather than absolute amount. In that context, NUE is the amount of biomass produced per unit of tissue nutrient concentration, or in other words, a product of the efficiency ratio (NER) and biomass produced per plant (Siddiqi & Glass, 1981; Glass, 1989).

Given the prevalence of nutrient deficiency stresses in the low CEC sandy soils of Zimbabwe and the fact that the correction of nutrient deficiencies is a particular problem in the low-input cropping systems, groundnut genotypes tolerant to nutrient stress can be introduced to alleviate the limitations associated with nutrient deficiency. It is envisaged that productivity of groundnut in these soils can be improved by a combination of liming plus screening of genotypes for tolerance to acid stress. It should however be realised that the identification of a more efficient

genotype is at its best a temporary solution. As acidification continues, liming will ultimately be essential. Likewise, low soil fertility will need to be addressed in a sustainable manner.

The study objective was to examine genetic differences in groundnut for growth, productivity and efficiency of nutrient uptake and utilisation in an acid soil.

4.2 MATERIALS AND METHODS

Twelve advanced breeding lines of groundnut and three check lines (commercial cultivars Falcon, Jesa and Teal) were sown in separate plots on acid sandy soils during the 1999/2000 cropping season at Makoholi Experiment Station (MES) located in natural region IV (450 -600 mm rainfall) of Zimbabwe. The soils at MES are derived from granite and belong to the 5G (Fersiallitic order). They are moderately shallow greyish brown coarse-grained sands (particle size >0.02mm; silt + clay <15%), with low pH, low cation exchange capacity (CEC) and low amounts of cations (Thompson & Purves, 1981). Soil tests done before planting showed that the plots were uniform, and no differences were detected in soil pH, P, K, Ca or Mg among the plots. The chemical characteristics of the soil were pH ($CaCl_2$) 4.3, Al^{3+} 0.047 mg kg^{-1}, available P (Olsen) 11.9 mg kg^{-1}, available K 14 mg kg^{-1}, extractable Ca 72 mg kg^{-1}, extractable Mg 18 mg kg^{-1} and mineral N 11 mg kg^{-1}.

Dolomitic limestone at a rate of 600 kg ha^{-1} was disced into the soil a month before planting. A basal dressing of compound M (N_{10}:P_{10}:K_{10}) fertilizer at a rate of 360 kg ha^{-1} was applied prior to planting, while gypsum was broadcast on the row at 300 kg ha^{-1} at flowering. The 15 genotypes were in four replicates arranged in a randomised complete block design. Net plot size was seven rows of groundnut spaced 0.45m apart and 3m long. The groundnut genotypes were planted at 120 kg seed ha^{-1} on 24 November 1999. Fungicides (Mancozeb and Benomyl) were applied as required to minimise *Cercospora* infection. The crop was kept weed-free by hand hoeing throughout the growing season.

At peak flowering stage, soil and plant samples were taken for chemical analysis. Soil samples were taken from the middle of each plot and analysed for pH, Ca, Mg, K, P and N. Exchangeable cations were extracted with 1M ammonium acetate, and were analysed by atomic absorption

spectrometry (AAS). Phosphorus was extracted with bicarbonate using the Olsen method while soil pH was measured in calcium chloride. Samples of the youngest fully expanded leaves (YFEL) inclusive of blades and petioles were taken randomly from the inner seven rows of each plot for chemical analysis. The leaves were washed with distilled water and dried. The plant tissue samples (15g) were digested in 5:1 nitric acid:perchloric acid and nutrient concentrations (N, P, K, Ca, Mg, Fe, Zn, Mn and Cu) in the digest analysed using AAS. The Soil Productivity Research Laboratory (SPRL), Department of Research and Specialist Services, Zimbabwe conducted all chemical analyses.

At physiological maturity, all groundnut plants in the net plot were counted and harvested by hand and separated into aboveground plant parts and pods. The aboveground parts were dried in the oven at 60^0C for 48 hours and the dry weight recorded. The pods were sun-dried to 10% moisture and the dry weight recorded. Genotype performance was evaluated in terms of production of aboveground biomass, pod and kernel yield, kernel nutrient composition and efficiency of nutrient uptake and utilisation. The measures of nutrient efficiency used in this study to assess differences between genotypes were shoot dry mass (SDM), kernel yield, nutrient efficiency ratio (NER) and nutrient use efficiency (NUE). The NER was defined as production of shoot dry mass or harvestable product (kernels) per unit of nutrient absorbed (nutrient accumulation), that is, the amount of dry mass (g) produced for each 1g of a nutrient absorbed and accumulated in the dry mass (Siddiqi & Glass, 1981; Gerloff & Gableman, 1983; Gourley *et al.,* 1994). The total amount of nutrient absorbed (nutrient accumulation) was obtained by multiplying dry mass by nutrient concentration in the tissue. Nutrient efficiency ratio was calculated as dry mass yield divided by the amount of nutrient accumulation. In this context the ratio defines the efficiency with which plants recover nutrients from the soil. The NUE was defined as production of shoot dry mass or kernels per nutrient concentration, i.e. units of dry mass produced per unit nutrient concentration in the dry mass (Siddiqi & Glass, 1981; Glass, 1989). Since nutrient concentration is the inverse of the NER, then NUE is the product of NER and dry mass produced per plant. It quantifies dry mass production by plants at a given nutrient concentration.

The results were analysed as randomized complete block designs with four replicates using the General Linear Models (GLM) procedure of the Statistical System (SAS Institute Inc. Cary, NC, USA 1996 Copyright). Differences among treatments were determined with Duncan's multiple range test, and differences at the $P \leqq 0.05$ level of significance are reported. In addition, data on kernel yield and some of its parameters were subjected to regression analysis.

4.3 RESULTS AND DISCUSSION

Soil tests at peak flowering showed that the pH ($CaCl_2$) was 4.9, available P (Olsen) 18.4 mg kg^{-1}, available K 20 mg kg^{-1}, extractable Ca 103 mg kg^{-1}, extractable Mg 25 mg kg^{-1} and mineral N 14 mg kg^{-1}. Total rainfall received for the season was 826.6 mm, with 51.5 mm received in November, 144.5 mm in December, 171 mm in January, 400.5 mm in February, and 59.1 mm in March.

4.3.1 YIELD AND YIELD COMPONENTS

Differences in shoot dry mass were highly significant among the genotypes (Table 4.1). The advanced breeding line 106/96 produced the highest shoot dry mass (12.69 g $plant^{-1}$), while the lowest (7.70 g $plant^{-1}$) was produced by line 316/5/3. Shoot dry mass of the three check cultivars was generally high, ranging from 10.69 to 11.25 g $plant^{-1.}$

In terms of yield potential, at least six of the breeding lines performed as good as the check cultivars (Table 4.1). The highest kernel yield of 1124 kg ha^{-1} produced by line 106/96 was 85.2% higher than that produced by the lowest yielder (line 262/8/2). Line 106/96 was also characterised by the highest shelling percentage (76.7%) and the largest seed size (0.52 g). Genotypes with the highest yields tended to have larger seeds, and *vice versa*. This denotes a positive relationship between seed size and kernel yield, and the correlation analysis showed a highly significant correlation between the two parameters (Table 4.8).

Table 4.1 Pod and kernel yield, shelling %, shoot dry mass and seed size of groundnut genotypes

Genotype	Pod yield (kg ha^{-1})	Kernel yield (kg ha^{-1})	Shelling %	Shoot dry mass (g plant^{-1})	Kernel size (g seed^{-1})
262/8/2	939	607	64.6	9.06	0.295
297/7/16	1 366	877	64.2	8.75	0.432
303B/7/5	1 197	738	61.7	9.34	0.318
309/8/2	1 163	722	62.0	9.58	0.299
316/5/3	1 107	675	61.0	7.70	0.300
328/5/7	965	658	68.2	9.13	0.393
328/5/12	1 309	834	63.7	9.03	0.298
338/5/2	1 289	886	68.7	10.52	0.321
19/82	1 006	649	64.5	8.54	0.325
418/93	1 351	923	68.4	11.20	0.464
95/96	1 383	930	67.2	12.46	0.363
106/96	1 466	1124	76.7	12.69	0.521
TEAL	1 214	796	65.6	10.69	0.344
JESA	1 174	733	62.4	11.25	0.314
FALCON	1 017	717	70.5	10.97	0.321
Mean	**1 196**	**791**	**66.0**	**10.06**	**0.354**
LSD$_{(0.05)}$	**119**	**90.4**	**5.93**	**2.06**	**0.03**

The four lines with the highest shoot dry mass (106/96, 95/96, 418/93 and 338/5/2) also produced the highest pod and kernel yields. This suggests a positive relationship between vegetative growth and kernel yield, which is contrary to the contention that abundant vegetative growth is detrimental to groundnut fruit load. The correlation analysis, in fact, showed no significant correlation between kernel or pod yield with shoot dry mass (Table 4.8). It has, however, been established in other legumes and cereals that grain yield is positively correlated with dry mass yield (Snyder & Carlson, 1984). Fageria *et al.* (2001) also established a positive relationship between biomass yield and grain yield in common bean, where they observed a highly significant and positive correlation between the two parameters.

4.3.2 N, P, K, CA AND MG CONCENTRATIONS IN THE LEAVES

Leaf analysis is important for determining the nutritional health of plants. For groundnut, chemical analyses of the leaves (YFEL) performed at flowering are considered suitable for judging the nutrient status of the plants during vegetative growth (Smith *et al.,* 1994). In this respect, the established nutrient sufficiency levels in groundnut YFEL are 3 to 4.5% N, 0.2 to 0.5% P, 1.7 to 3.0% K, 1.25 to 2.0% Ca and 0.3 to 0.8% Mg (Gascho & Davis, 1994). The elemental concentrations in groundnut YFEL sampled in this study are given in Table 4.2. Leaf N concentrations of 3.0% to 3.9% were in sufficient quantities in all genotypes, and no significant differences in N content were detected among the genotypes. The highest N concentrations were observed in the YFEL of line 338/5/2 whereas the N concentrations of the check cultivars were intermediate. Phosphorus concentrations in the YFEL of all the lines were also within the range considered sufficient for optimal vegetative growth of groundnut and varied among the lines from 0.28 to 0.48% (Table 4.2). Six of the lines had significantly higher P concentrations than line 328/5/12, which had the lowest P content (0.28%).

Values for K concentrations were not significantly different among genotypes, and ranged from 0.87 to 1.33%, while those for Ca concentrations ranged from 0.81 to 1.32%. Potassium was severely deficient in all genotypes while Ca was deficient in all but three genotypes, suggesting possible yield limitations due to deficiency of the two elements. Overall, the three check cultivars had lower K and Ca concentrations compared to the breeding lines, and cultivar Jesa had the lowest K and Ca concentrations among all the genotypes. Magnesium concentrations ranged from deficiency (0.23%) in line 309/8/2 to sufficiency (0.40%) in lines 95/96 and 328/517, and were adequate in most genotypes. Lines 95/96 and 328/5/7 had significantly higher Mg concentrations (0.40%) than the other genotypes.

The deficient Ca and K levels in the leaves could be a reflection of the low concentrations of these nutrients in the soil solution. Foy (1974) classified the problems associated with Ca deficiency into two categories namely, (a) inability to absorb Ca from soils low in Ca levels or with low ratios of Ca opposed to other cations and (b) inadequate distribution of Ca to actively growing tissues after absorption. Thus the low Ca levels in leaf tissue could be a result of either

(a) or (b) or a combination of both. Calcium translocation, rather than uptake, is usually the primary determining factor in the final Ca content of plant tissue according to Kirkby & Pilbeam (1984).

Table 4.2 Nutrient concentrations (%) in groundnut leaf dry mass (YFEL sampled at peak flowering)

Genotype	N	P	K	Ca	Mg
268/8/2	3.7	0.42	1.19	1.32	0.33
297/7/16	3.4	0.34	0.98	1.03	0.28
303B/7/5	3.6	0.42	1.02	1.01	0.29
309/8/2	3.7	0.31	0.85	1.03	0.23
316/5/3	3.0	0.36	1.11	1.06	0.35
328/5/7	3.2	0.40	1.16	1.26	0.40
328/5/12	3.7	0.28	0.95	1.03	0.29
338/5/2	3.9	0.48	1.07	0.99	0.32
19/82	3.5	0.44	1.08	0.94	0.31
418/93	3.4	0.36	1.06	0.95	0.32
95/96	3.7	0.46	1.33	1.28	0.40
106/96	3.7	0.42	1.10	0.96	0.28
TEAL	3.3	0.37	0.91	1.00	0.26
JESA	3.7	0.33	0.87	0.81	0.27
FALCON	3.5	0.39	1.18	0.90	0.34
Mean	**3.5**	**0.39**	**1.06**	**1.04**	**0.31**
LSD $_{(0.05)}$	**0.56**	**0.13**	**0.34**	**0.36**	**0.09**

4.3.3 N, P, K, CA AND MG CONCENTRATIONS IN KERNELS

Healthy, mature groundnut kernels typically contain 0.14 to 0.47 % P, 0.62 to 0.89% K, 0.038 to 0.088% Ca, and 0.16 to 0.20% Mg (Adams *et al.,* 1993; Savage & Keenan, 1994). The kernel nutrient concentrations observed in our study are given in Table 4.3. Significant differences were observed for kernel N concentration among the genotypes. Two of the lines had N concentrations higher than the cultivar Jesa (4.12% N) while seven of the lines had N concentrations higher than the cultivar Falcon (3.70% N). The P concentrations were in the

sufficient ranges for all genotypes, with significant differences in the P concentrations that ranged from 0.27 to 0.45%. The K concentrations were in the sufficient ranges in all the genotypes, and ranged from 0.6% to 0.96%. There were no significant differences in the K concentrations between the genotypes. The kernel Ca concentrations, which ranged between 0.019 – 0.038 % among the lines, were extremely low, with the highest concentration of 0.038 % falling within the lower end of the range 0.038-0.041% found to be adequate for maximum germination of four groundnut cultivars by Adams *et al.* (1993). The Ca concentrations differed among genotypes, and were highest in the check cultivars (0.028 - 0.038%). Magnesium content was generally adequate in all genotypes, but differed significantly between genotypes, and was highest in line 95/96 (0.21%) and lowest in line 303B/7/5 (0.14%).

Even though the concentrations of K and Mg appeared deficient in the leaves in most of the lines, the concentrations of these two nutrients, as well as those for P and N in the kernels were generally within the normal ranges expected for groundnut. Thus, Ca was the only deficient nutrient in the kernels. It has been observed that groundnut pods appear to be poor absorbers of Ca (Cox *et al.,* 1982); hence the unusually high soil Ca requirements within the pod environment (Cox *et al,* 1982; Hodges *et al.,* 1993). The Ca deficient status of the kernels in the present study could be a reflection of the low Ca status of the soil, as well as the antagonistic relationship between Ca and Mg or K. The variability in kernel Ca concentration could be a direct consequence of differences in Ca uptake by the pods, or differences in Ca amounts that can be imported from the roots (Beringer & Taha, 1976). Since Ca in the xylem sap is translocated upward in the transport system and is neither mobile in the phloem nor redistributed within the plant (because of formation of ion complexes as oxalate or other insoluble forms or binding to the cell wall), it is unavailable for transport (Ferguson, 1979). Variability in pod Ca concentration in snap beans was attributed to differences in transport of Ca via root pressure (Quintana *et al.,* 1997), or to differences in direct Ca uptake (Quintana *et al.,* 1999).

Table 4.3 Nutrient concentrations (% DM) in groundnut kernels

Genotype	N	P	K	Ca	Mg
262/8/2	3.53	0.269	0.658	0.026	0.148
297/7/16	4.12	0.374	0.819	0.028	0.188
303B/7/5	3.84	0.294	0.630	0.024	0.140
309/8/2	4.01	0.341	0.600	0.023	0.149
316/5/3	4.05	0.397	0.735	0.028	0.170
328/5/7	3.83	0.356	0.750	0.029	0.164
328/5/12	3.70	0.302	0.655	0.024	0.153
338/5/2	4.46	0.452	0.705	0.019	0.159
19/82	4.20	0.365	0.793	0.028	0.183
418/93	3.37	0.348	0.815	0.024	0.176
95/96	5.02	0.361	0.833	0.029	0.214
106/96	4.32	0.302	0.956	0.022	0.178
TEAL	3.96	0.324	0.636	0.028	0.175
JESA	4.12	0.357	0.739	0.038	0.184
FALCON	3.70	0.445	0.739	0.032	0.175
Mean	**4.02**	**0.353**	**0.737**	**0.027**	**0.170**
$LSD_{(5\%)}$	**0.06**	**0.12**	**0.031**	**0.015**	**0.02**

4.3.4 NUTRIENT RELATIONSHIPS IN THE LEAVES AND KERNELS

Correlation analysis data for leaf and kernel nutrient relationships are presented in Table 4.4. The leaf nutrient relationships show that the N concentrations were negatively correlated with Ca, Mg and K concentrations. A negative correlation between N and Ca was observed by Kawasaki (1995) who reported that N from NH_4 inhibited Ca absorption by barley, maize and tomato. There were positive and significant correlation coefficients between the P, Ca, Mg, and K concentrations in the leaves, suggesting synergistic uptake interactions among these nutrients. The synergism between nutrients could be explained by interdependence of the nutrients in plant metabolism. Nonetheless, synergistic relationships among nutrients (e.g. Ca, Mg and K) are usually a common phenomenon when the nutrients are present at low concentrations (Marschner, 1995; Fageria, 2001), as was the case with the soils being investigated. In this study, the correlations between Ca and other nutrients were stronger with K and Mg than with P.

Unlike in the leaves, correlations between the nutrient concentrations in the kernels were generally weak (Table 4.4). Only those correlations between the concentrations of Ca and P, and between Mg and the concentrations of N, K and P in the kernels were significant. Negative but non-significant correlations were observed between Ca concentration and those of N and K, and between N and K concentrations. Antagonistic interactions between Ca^{2+}, $Mg^{2+,}$ K^{+} and N^{+} were expected, because of competitive inhibition in the uptake of these nutrients that occurs because of having ions with similar sizes, geometry of coordination, and electronic configuration (Fageria, 2001). Nevertheless, other factors could be involved in determining the interactions between these nutrients since there were differences in the interactions of the same nutrients between the leaves and the kernels.

Table 4.4 Nutrient relationships in leaves and kernels of groundnut

Relationship	Correlation coefficient (r)	
	Leaves	**Kernels**
N vs Ca	-0.266***	-0.022ns
P vs Ca	0.417***	0.721***
K vs Ca	0.692***	-0.204ns
Mg vs Ca	0.721***	0.020ns
N vs Mg	-0.360***	0.320***
P vs Mg	0.429***	0.242*
K vs Mg	0.852***	0.393***
N vs P	-0.085ns	0.193ns
N vs K	-0.403***	-0.131ns
P vs K	0.565***	0.172ns

4.3.5 NUTRIENT UPTAKE BY LEAVES AND KERNELS

In order to evaluate genotypic variation in nutrient accumulation, the uptake (content) of nutrients was calculated as nutrient concentration in tissue x dry mass. This was used as an estimate of nutrient removal from the soil. Nutrient uptake has been advocated as a valuable index of nutrient efficiency since it is closely related to growth and nutrient concentration (Glass, 1989). Considerable variation in uptake of N, P, K, Ca and Mg by the genotypes was observed (Table 4.5). In the leaves, uptake of the five nutrients was highest in lines 106/96 and 95/96, which were

the highest producers of shoot dry mass. Despite the better shoot growth in the check cultivars, their nutrient uptake levels were not significantly better than some of the breeding lines with poorer shoot growth. The lines that produced the lowest shoot DM did not necessarily remove the least amount of nutrients from the soil. This can be attributed to differences in nutrient concentrations and dry mass production. Line 316/5/3 with the lowest shoot dry mass had higher concentrations of P, K, Ca and Mg compared to the mean concentrations of these nutrients in the check cultivars.

In the kernels, significant differences in uptake of N, P, K, Ca and Mg by the genotypes were observed (Table 4.5). Overall, nutrient removal was highest in the line with the highest kernel yield (line 106/96) and lowest in line 262/8/2 - the line with the lowest kernel yield. With the exception of N, nutrient uptake by the check lines was higher than in at least five of the breeding lines for each of the nutrients.

Table 4.5 Nutrient uptake (kg ha^{-1}) in shoots and kernels of groundnut genotypes.

Genotype	Uptake in shoots					Uptake in kernels				
	N	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
262/8/2	100	11	31	35	9	21	1.61	3.49	0.16	0.89
297/7/16	89	9	25	26	7	36	3.39	7.05	0.25	1.62
303B/7/5	99	12	29	28	8	29	2.12	4.51	0.15	1.02
309/8/2	104	8	24	29	6	29	2.51	4.33	0.15	1.08
316/5/3	69	8	25	24	8	27	2.68	4.98	0.18	1.15
328/5/7	87	11	31	34	11	25	2.49	4.94	0.19	1.07
328/5/12	97	8	28	30	8	32	2.65	5.31	0.22	1.27
338/5/2	121	15	33	31	10	39	3.92	6.28	0.17	1.41
19/82	88	11	27	23	8	27	2.24	5.13	0.16	1.18
418/93	113	12	34	30	10	31	3.22	7.49	0.23	1.63
95/96	135	17	49	47	15	48	3.10	6.52	0.30	1.98
106/96	139	16	42	36	11	49	3.30	9.61	0.25	2.04
TEAL	105	12	29	32	8	31	2.54	5.07	0.22	1.38
JESA	122	11	30	28	9	30	2.65	5.33	0.29	1.33
FALCON	111	13	39	29	11	27	3.29	5.14	0.25	1.23
MEAN	**105**	**12**	**32**	**31**	**9**	**32**	**2.78**	**5.67**	**0.20**	**1.35**
LSD $_{(5\%)}$	**8.05**	**1.28**	**3.31**	**3.39**	**0.94**	**5.94**	**0.15**	**1.31**	**0.02**	**0.07**

4.3.6 RELATIONSHIPS BETWEEN NUTRIENT UPTAKE, NUTRIENT CONCENTRATIONS, YIELD AND YIELD PARAMETERS

Nutrient concentrations (N, P, K, Ca and Mg) in the leaves were generally not correlated with pod or kernel yield, seed size or shoot dry mass (Table 4.6). In the kernels, Ca and P concentrations were not correlated with yield and shoot dry mass, whereas N and K showed significant correlations with pod and kernel yields. Magnesium and K concentrations showed significant correlations with seed size and shoot dry mass. The lack of correlations between leaf nutrient concentrations and yield support the observation by Gascho & Davis (1994) that the final groundnut kernel yield and quality do not generally relate well to leaf composition during growth due to restricted downward phloem movement of nutrients from the above-ground plant parts to the developing pods. Both leaf and kernel Ca concentrations were weakly correlated with pod or kernel yield, suggesting that factors other than Ca nutrition were also involved. The poor correlation between leaf Ca and kernel yield was expected, since root-absorbed Ca is of little value to underground developing pods of groundnut, owing to the limited translocation of root-absorbed Ca to the pods (Bledsoe *et al.,* 1949; Skelton & Shear, 1971; Chahal & Virmani, 1973). The lack of correlations between leaf and kernel Ca concentrations appears to support this point.

Nutrient uptake (N, P, K, Ca and Mg) in the leaves was positively and significantly correlated with shoot dry mass, whereas only N uptake was significantly correlated with pod and kernel yield (Table 4.6). Only the uptake of N and P were significantly correlated with seed size. Correlations between nutrient uptake in the kernels and yield, shoot dry mass and seed size were generally significant (Table 4.6). With the exception of N and Mg, nutrient uptake in the kernels was not correlated with shoot dry mass. In a solution culture study, Fageria & Baligar (1989) noted that the shoot nutrient concentrations in five crop species were negatively correlated with dry mass, whereas uptake was significantly and positively correlated, implying that nutrient uptake can be used as a reliable indicator of nutrient use efficiency of genotypes.

Table 4.6 Correlation coefficients between yields, nutrient concentration and uptake in leaves and kernels of groundnut genotypes.

	POD YIELD	KERNEL YIELD	SEED SIZE	SDM	POD YIELD	KERNEL YIELD	SEED SIZE	SDM
	NUTRIENT CONCENTRATION							
	IN THE LEAVES				IN THE KERNELS			
Ca	0.037ns	0.022ns	0.044ns	0.007ns	-0.012ns	-0.012ns	-0.118	-0.051ns
Mg	0.003ns	0.026ns	0.072ns	0.037ns	0.010ns	0.100ns	0.265**	0.307**
N	0.296**	0.300**	0.031ns	0.041ns	0.281**	0.266**	0.015ns	0.174ns
P	-0.182ns	-0.160ns	0.135ns	0.076ns	-0.046ns	-0.033ns	-0.124ns	0.047ns
K	-0.113ns	-0.057ns	0.082ns	0.081ns	-0.308**	-0.244*	0.226*	0.269**
	NUTRIENT UPTAKE							
Ca	0.106ns	0.131ns	0.142ns	0.593***	0.606***	0.616***	0.213*	0.137ns
Mg	0.106ns	0.157ns	0.188ns	0.665***	0.858***	0.935***	0.504***	0.284**
N	0.281**	0.341***	0.218*	0.877***	0.897***	0.937***	0.394***	0.231*
P	-0.064ns	-0.013ns	0.238*	0.626***	0.746***	0.770***	0.293**	0.152ns
K	0.011ns	0.091ns	0.199ns	0.690***	-0.100ns	-0.104ns	-0.082ns	-0.108ns

*** Correlation is significant at the 0.01 level (2-tailed). ** Correlation is significant at the 0.05 level

* Correlation is significant at the 0.10 level ns - Correlation is not significant.

4.3.7 NUTRIENT EFFICIENCY RATIO AND NUTRIENT USE EFFICIENCY IN SHOOT PRODUCTION

Differences in nutrient efficiency ratio (NER) were significant for all nutrients (Table 4. 7). For vegetative growth, the highest Ca efficiency ratio (CaER) of 138 g shoot dry mass per g Ca was recorded for cultivar Jesa whereas the lowest (77) was recorded for line 262/8/2. Line 106/96 that produced the highest shoot dry mass had a CaER of 105. The efficiency ratio of Mg (MgER) varied between 251 and 475 g shoot dry mass per g Mg. The N efficiency ratio (N-ER) ranged from 26 to 33 g shoot dry mass per g N, while the P efficiency ratio (PER) ranged from 219 to 399 g shoot dry mass per g P. Variations in the efficiency ratio of K (KER) ranged from 77 to 129 g shoot dry mass per g K. The highest or lowest nutrient efficiency ratios were not confined to specific genotypes.

Nutrient use efficiency (NUE) in vegetative growth significantly differed among genotypes

(Table 4.7). The Ca use efficiency (CaUE) values were highest (1521 g shoot dry mass per g Ca concentration) for cultivar Jesa and lowest (699) for line 262/8/2. The Mg use efficiency (MgUE) values ranged between 2266 and 4538 g shoot dry mass per g Mg concentration, while those in N (N-UE) ranged between 247 and 346 g shoot dry mass per g N concentration. Phosphorus use efficiency (PUE) ranged from 2040 to 3715 g shoot dry mass per g P concentration while K use efficiency (KUE) ranged from 742 to 1410 g shoot dry mass per g K concentration. Overall, the greatest variation in nutrient use efficiency was observed for Ca while the least variation was observed for N. Cultivar Jesa had the highest NUE values for most of the nutrients.

Genotypes that produced the highest shoot dry mass were not necessarily the ones that had the highest NER values and *vice versa*. The correlation analyses showed a weak and negative correlation between shoot dry mass and NER (Table 4.9). Nutrient use efficiency and shoot dry mass were positively related, and the correlation analysis showed a highly significant and positive correlation between the two (Table 4.9). However, care should be taken not to attach too much importance on this positive correlation, since the calculation of NUE as NER x dry mass implicitly should result in a positive correlation between NUE and dry mass.

4.3.8 NUTRIENT EFFICIENCY RATIO AND NUTRIENT USE EFFICIENCY IN KERNEL DM PRODUCTION

While kernel dry mass yields of the genotypes differed by as much as 57%, differences in their NER and NUE were even more pronounced (Table 4.7). With the exception of Ca, the nutrient efficiency ratios (g kernel DM per g nutrient) tended to be highest in genotypes that generally had the lowest kernel yields, while genotypes with the highest kernel yields generally had low NERs. While all the twelve breeding lines had higher CaER values than the check varieties, the values were highest in the lines that had the highest kernel yields (lines 106/96 and 338/5/2), and low in those lines that generally had the lowest kernel yields. Variations in nutrient use efficiency (NUE) for kernel production were of a greater magnitude than the NER (Table 4.7). The genotype that produced the highest kernel yield (line 106/96) was the most efficient in utilisation of all nutrients. Cultivars Jesa and Falcon were the least efficient in utilisation of Ca and P,

respectively. Overall, genotypes with the highest yields were the most efficient in nutrient use and *vice versa.*

High NERs in lines with the lowest kernel yields imply a negative relationship between NER and kernel yield. However, the suggested negative relationship was not demonstrated by the correlation analysis that showed positive but weak correlations between NER and kernel yield, with only the correlation between kernel yield and MgER negative (Table 4.9). Genotypes that produced the highest kernel yield generally had the highest NUE values, an indication of a positive relationship between nutrient efficiency and yields in groundnut. The correlation analysis confirmed this relationship, with highly significant and positive correlations being observed between pod yield, kernel yield and seed size with NUE. As already indicated, this positive correlation should be expected because of the factors included in the estimation of NUE.

4.3.9 RANKING OF GENOTYPES ACCORDING TO NER AND NUE

When the genotypes were ranked according to nutrient efficiency ratio with respect to shoot dry mass production, the check cultivar Jesa and line 328/5/12 ranked first in overall NUE, whereas the breeding line 106/96 which produced the highest shoot dry mass ranked 11th (Table 4.8). The ranking of genotypes for NUE was similar to that for NER for Jesa, Teal, lines 328/5/7 and 418/93, but differed from that for NER for the rest of the genotypes (Table 4.8). As regards kernel dry mass production, the rankings showed that line 106/96 with the highest kernel yield ranked eighth in NER and first in NUE (Table 4.8). Line 262/8/2 which produced the lowest kernel yield was ranked second in NER and tenth in NUE. The check cultivars ranked between 6 and 12, irrespective of the nutrient efficiency parameter used.

The study has demonstrated that there are considerable variations in NER and NUE in groundnut genotypes. With regard to kernel dry mass production, greater variation was recorded for nutrient use efficiency (NUE) than for nutrient efficiency ratio (NER), and the reverse trend was observed with respect to shoot dry mass production. Lesser variation in NER than in NUE was also observed in barley (Siddiqi & Glass, 1981) and in wheat (Woodend *et al.* (1989).

Table 4.7 Nutrient efficiency ratio (NER) and nutrient use efficiency (NUE) of groundnut genotypes

GENOTYPE	NER (mg shoot dry mass / mg nutrient in shoot DM)					NER (mg kernel dry mass / mg nutrient in kernel DM)				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
262/8/2	28	244	86	77	314	29	376	153	4274	679
297/7/16	29	292	105	102	376	24	278	123	4484	540
303B/7/5	28	244	103	102	361	27	369	161	5210	720
309/8/2	27	334	119	100	440	25	314	167	5179	675
316/5/3	33	278	95	96	290	25	265	136	4123	590
328/5/7	32	251	89	80	251	27	299	134	3915	611
328/5/12	27	399	128	126	475	27	337	154	4013	656
338/5/2	26	219	94	101	313	22	228	142	5360	632
19/82	29	238	96	109	333	24	289	127	4106	548
418/93	29	317	101	115	331	30	314	125	4783	570
95/96	27	231	77	81	254	20	288	139	4425	469
106/96	27	253	94	105	358	23	335	124	5350	571
Teal	30	274	112	102	395	26	318	157	3607	573
Jesa	28	306	129	138	410	25	305	136	2790	545
Falcon	29	280	86	113	296	27	228	136	3681	573
MEAN	**29**	**277**	**101**	**103**	**346**	**25**	**303**	**141**	**4353**	**597**
LSD$_{(0.05)}$	**1.06**	**26.46**	**9.40**	**9.59**	**37.59**	**1.26**	**26.36**	**7.47**	**547.70**	**23.92**
	NUE (g shoot dry mass / g nutrient in shoot DM)					NUE (g kernel dry mass / g nutrient in kernel DM)				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
262/8/2	251	2201	799	699	2871	59	779	312	8771	1392
297/7/16	255	2566	930	910	3336	72	799	371	12448	1615
303B/7/5	262	2262	946	944	3335	64	948	411	14384	1814
309/8/2	262	3281	1149	976	4289	60	749	408	13757	1633
316/5/3	256	2150	742	734	2279	56	607	309	9524	1346
328/5/7	287	2312	819	725	2266	60	612	297	8656	1370
328/5/12	250	3276	1023	1019	3650	75	925	454	11465	1889
338/5/2	273	2352	994	1072	3303	67	697	423	15945	1880
19/82	247	2040	827	945	2861	54	676	279	9851	1204
418/93	331	3715	1169	1345	3812	94	972	391	14657	1775
95/96	341	2865	953	1003	3157	62	976	483	12443	1472
106/96	346	3202	1172	1325	4510	87	1309	503	20679	2125
Teal	324	2920	1203	1094	4245	69	869	424	9801	1550
Jesa	312	3431	1410	1521	4538	61	745	342	6553	1360
Falcon	325	3046	935	1241	3269	65	535	340	7920	1414
MEAN	**288**	**2775**	**1005**	**1037**	**3448**	**67**	**813**	**383**	**11790**	**1589**
LSD $_{(0.05)}$	**20.67**	**300.48**	**97.72**	**115.73**	**356.51**	**7.31**	**122.7**	**51.88**	**2220**	**180.83**

Table 4.8 Ranking Genotypes according to NER and NUE

GENOTYPE	NER IN SDM PRODUCTION					Overall	NER IN KERNEL DM PRODUCTION					Overall
	N	P	K	Ca	Mg		N	P	K	Ca	Mg	
262/8/2	9	11	14	15	10	**13**	2	1	5	8	2	**2**
297/7/16	6	5	5	8	5	**5**	12	12	15	6	14	**15**
303B/7/5	8	12	6	7	6	**7**	6	2	2	3	1	**1**
309/8/2	12	2	3	11	2	**6**	8	6	1	4	3	**3**
316/5/3	1	7	9	12	13	**10**	9	13	10	9	7	**10**
328/5/7	2	10	12	14	15	**12**	5	9	11	12	6	**11**
328/5/12	13	1	2	2	1	**1**	4	3	4	11	4	**4**
338/5/2	15	15	10	10	11	**14**	14	14	6	1	5	**7**
19/82	7	13	8	5	8	**9**	11	10	12	10	12	**12**
418/93	4	3	7	3	9	**3**	1	7	13	5	11	**5**
95/96	11	14	15	13	14	**15**	15	11	7	7	15	**12**
106/96	14	9	11	6	7	**11**	13	4	14	2	10	**8**
Teal	3	8	4	9	4	**4**	7	5	3	14	9	**6**
Jesa	10	4	1	1	3	**1**	10	8	9	15	13	**12**
Falcon	5	6	13	4	12	**8**	3	15	8	13	8	**9**
	NUE in SDM production					**Overall**	**NUE IN KERNEL DM PRODUCTION**					**Overall**
	N	**P**	**K**	**Ca**	**Mg**		**N**	**P**	**K**	**Ca**	**Mg**	
262/8/2	13	13	14	15	12	**14**	13	8	12	12	11	**10**
297/7/16	12	9	11	12	7	**11**	4	7	9	6	7	**7**
303B/7/5	9	12	9	11	8	**10**	8	4	6	4	4	**4**
309/8/2	10	3	5	9	3	**5**	11	9	7	5	6	**9**
316/5/3	11	14	15	13	14	**14**	14	14	13	11	14	**14**
328/5/7	7	11	13	14	15	**12**	12	13	14	13	12	**13**
328/5/12	14	4	6	7	6	**7**	3	5	3	8	2	**3**
338/5/2	8	10	7	6	9	**9**	6	11	5	2	3	**5**
19/82	15	15	12	10	13	**13**	15	12	15	9	15	**14**
418/93	3	1	4	2	5	**3**	1	3	8	3	5	**2**
95/96	2	8	8	8	11	**7**	9	2	2	7	9	**6**
106/96	1	5	3	3	2	**2**	2	1	1	1	1	**1**
Teal	5	7	2	5	4	**4**	5	6	4	10	8	**7**
Jesa	6	2	1	1	1	**1**	10	10	10	15	13	**12**
Falcon	4	6	10	4	10	**6**	7	15	11	14	10	**11**

Variation in nutrient efficiency has been attributed to differences in absorption, translocation, shoot demand, dry matter production per unit of nutrient absorbed in addition to environmental interactions and genetic variability (Duncan & Baligar, 1990; Baligar & Fageria, 1997). Genotypic differences in nutrient efficiency are related to differences in efficiency in acquisition by the roots, or in utilization by the plant, or both. With regard to N, P, K and Mg, higher nutrient use efficiencies may be related to better use of stored nutrients, or by better retranslocation between organs (Clark, 1976; Marschner, 1995).

Calcium efficiency may differ depending on binding stage of Ca, transport rate to the apical meristem or differences in functional requirement within the tissue (Marschner, 1989). Differences in Ca efficiency have been reported in maize (Baligar *et al.,* 1997) and tomatoes (English & Maynard, 1981; Giordano *et al.,* 1982; Li and Gableman, 1990). Many of the differences in Ca efficiency have been linked to differences in root nutrient acquisition capacity, transport and utilization by the plant (Marschner, 1989). Similarly, in the present study, the observed differences in CaER and CaUE among the groundnut lines can possibly be explained in terms of differences in their abilities to absorb Ca and to utilise it after absorption. With tomato lines grown in nutrient solution, Giordano *et al.,* (1982) found that a Ca-efficient line removed 68% more Ca from the solution than an inefficient one. Furthermore, two tomato lines with similar total Ca uptake had different CaER, indicating that the more efficient line produced more dry mass per unit of Ca tissue than the inefficient cultivar. In the present study, the check lines Jesa and Falcon had the highest kernel Ca concentrations, but had the lowest CaER values, indicating a superior Ca uptake that was not matched by efficient utilisation of the Ca. Also, lines 106/96 and Falcon had identical Ca uptake in the kernels, but Falcon showed a much higher CaER than 106/96, and this can only be explained by a better Ca utilisation by Falcon.

Table 4.9 Correlation coefficients between yields and nutrient efficiency in groundnut

	SEED SIZE	POD YIELD	KERNEL YIELD	SHOOT DRY MASS
Seed size	1.000	0.399***	0.477***	0.229*
Pod yield	0.399***	1.000	0.961***	0.136ns
Kernel yield	0.477***	0.961***	1.000	0.201ns
Shoot dry mass (SDM)	0.229*	0.136ns	0.201ns	1.000
CaER in SDM	-0.070ns	-0.027ns	-0.017ns	-0.028ns
MgER " "	-0.094ns	-0.008ns	-0.024ns	-0.162ns
NER " "	-0.044ns	0.310**	0.312***	-0.077ns
PER " "	-0.142ns	0.135	0.129ns	-0.096ns
KER " "	-0.101ns	0.064ns	0.017ns	-0.161ns
CaER in Kernel yield	0.191ns	0.092ns	0.101ns	0.070ns
MgER in " "	-0.252ns	0.021ns	-0.076ns	-0.290ns
NER " " "	0.008ns	-0.274**	0.252**	-0.153ns
PER " "	0.127ns	0.082ns*	0.049ns	-0.087ns
KER " "	-0.254ns	0.371***	0.289**	-0.188ns
CaUE in SDM	0.105ns	0.056ns	0.104ns	.587***
MgUE	0.069ns	0.063ns	0.092ns	.518***
NUE	0.179ns	-0.051ns	0.005ns	0.868***
PUE	0.019ns	0.215ns	0.251**	0.569***
KUE	0.068ns	0.141ns	0.141ns	0.546***
CaUE in KDM	0.403***	0.611***	0.663***	0.129ns
MgUE	0.371***	0.931***	0.919***	0.080ns
NUE	0.508***	0.855***	0.891***	0.133ns
PUE	0.448***	0.769***	0.793***	0.128ns
KUE	0.295**	0.932***	0.937***	0.116ns

***, **, *, - Correlation is significant at the 0.01, 0.05, 0.10 level (2-tailed). ns Correlation is not significant

4.3.10 CLASSIFICATION OF GENOTYPES INTO EFFICIENT AND INEFFICIENT GROUPS

Four categories of genotypes with respect to NUE were identified using a method similar to that used by Fageria & Baligar (1999) to characterize wheat genotypes.

a) *Efficient and responsive genotypes.* These are genotypes that produced above average shoot dry mass or kernel yields and had above average NUE.

b) *Efficient and non-responsive genotypes.* These are genotypes that produced more than average yield but NUE was below average.

c) *Non-efficient and responsive genotypes.* These are genotypes that produced below average yield but NUE was above average.

d) *Non-efficient and non-responsive genotypes.* Those genotypes that produced below average yield and NUE was also below average.

Classification of the groundnut genotypes with regards to shoot dry mass production is shown in Figure 4.1. The check cultivars Teal and Jesa, and lines 106/96 and 418/93 were consistently classified as efficient and responsive to all the five nutrients, whereas lines with the least shoot dry mass (316/5/3 and 19/82) were consistently in the non-efficient and non-responsive group for all nutrients but K. No genotypes were classified in groups (c) and (d) for K, implying that all the genotypes were efficient in K utilisation, though some were not responsive to K application. The majority of genotypes were classified either in group (a) or (d).

Pertaining to kernel DM production, classification of the genotypes is shown in Figure 4.2. Check cultivars Falcon and Jesa, and the lines that produced the lowest kernel yields (262/8/2, 316/5/3, 19/82 and 328/5/7) were in the non-efficient and non-responsive group for all the five nutrients. Cultivar Teal was efficient in utilization of all five nutrients, but was not responsive to applied N, K, and Mg. Lines that produced the highest kernel yields (106/96, 95/96 and 418/93) were consistently in the efficient and responsive group for all five nutrients. Similar to shoot dry mass production, the genotypes were mainly classified either in group (a) or (d).

In summary, when the genotypes were categorized according to the four efficiency parameters (kernel yield, shoot dry mass, NER and NUE), line 106/96 ranked second, whereas line 418/93

that produced the third highest kernel yield ranked first. These two lines were also classified as efficient and responsive genotypes, and are thus the most desirable since they can yield well at low nutrient supply. The commercial cultivar Teal ranked fourth, and was classified as efficient and responsive to Ca and P, and efficient and non-responsive to Mg, N and K. This means that the cultivar can be grown in P and Ca deficient soils and produce good yields. It can also be grown in soils low in N, K and Mg and still produce above average yields. Cultivars Jesa and Falcon ranked fifth and tenth respectively, and were classified as non-efficient and non-responsive to N, P, K, Ca, and Mg.

4.4 CONCLUSIONS

The evaluated genotypes differed in yield, NER and NUE when grown on an acid sandy soil. The differences were more pronounced in kernel than in shoot dry mass yield. Since nutrient uptake, concentration and growth are intricately interwoven, genotypic differences in nutrient acquisition and utilization will ultimately result in differences in productivity. Several lines had pod and kernel yields superior to those observed in the best of the commercial cultivars used in this study, and this translated into superior NUE for most of the lines. Of particular note were breeding lines 106/96 and 418/93 that produced shoot and kernel DM yields and had higher NUE and NER values than the mean of the 15 genotypes. Release of these two lines for commercial production is most likely to improve groundnut productivity on acid sandy soils of Zimbabwe.

The differences in nutrient use efficiency between the efficient and inefficient genotypes were large enough to postulate that success in increasing groundnut yields on acid soils could be achieved by screening genotypes for tolerance to soil acidity in low fertility soils. Adaptation of plants to acid soils requires highly efficient uptake and/or utilization of nutrients, particularly Ca, Mg and P (Marschner, 1995), therefore identification of genotypes with greater tolerance to low soil levels of these nutrients, coupled with the ability to produce reasonable yields when grown on such soils, could go a long way in improving groundnut productivity on acid soils. The genotypes that were able to extract more nutrients from the soils generally produced high yields and were classified as efficient and responsive. This implies that they can be expected to perform well in acid soils where Ca, Mg and P are limiting, although this will inadvertently hasten the

depletion of the already scarce nutrients. The ideal genotype would be one that produces high yields with as little nutrients as possible, i.e. one with high nutrient utilization efficiency.

The most appropriate parameter for assessing the suitability of genotypes for acid soils is nutrient use efficiency, with the other parameters assisting in accurate characterization of the genotypes. With respect to groundnut productivity, Ca use efficiency would be the most reliable parameter for separating efficient from inefficient genotypes. It should, however, be mentioned that although use of nutrient efficient genotypes to increase crop production appears to be an attractive and feasible approach, on its own it might not be an adequate prescription for sustainable crop productivity on acid soils. It needs to be augmented with judicious use of lime and fertilizers.

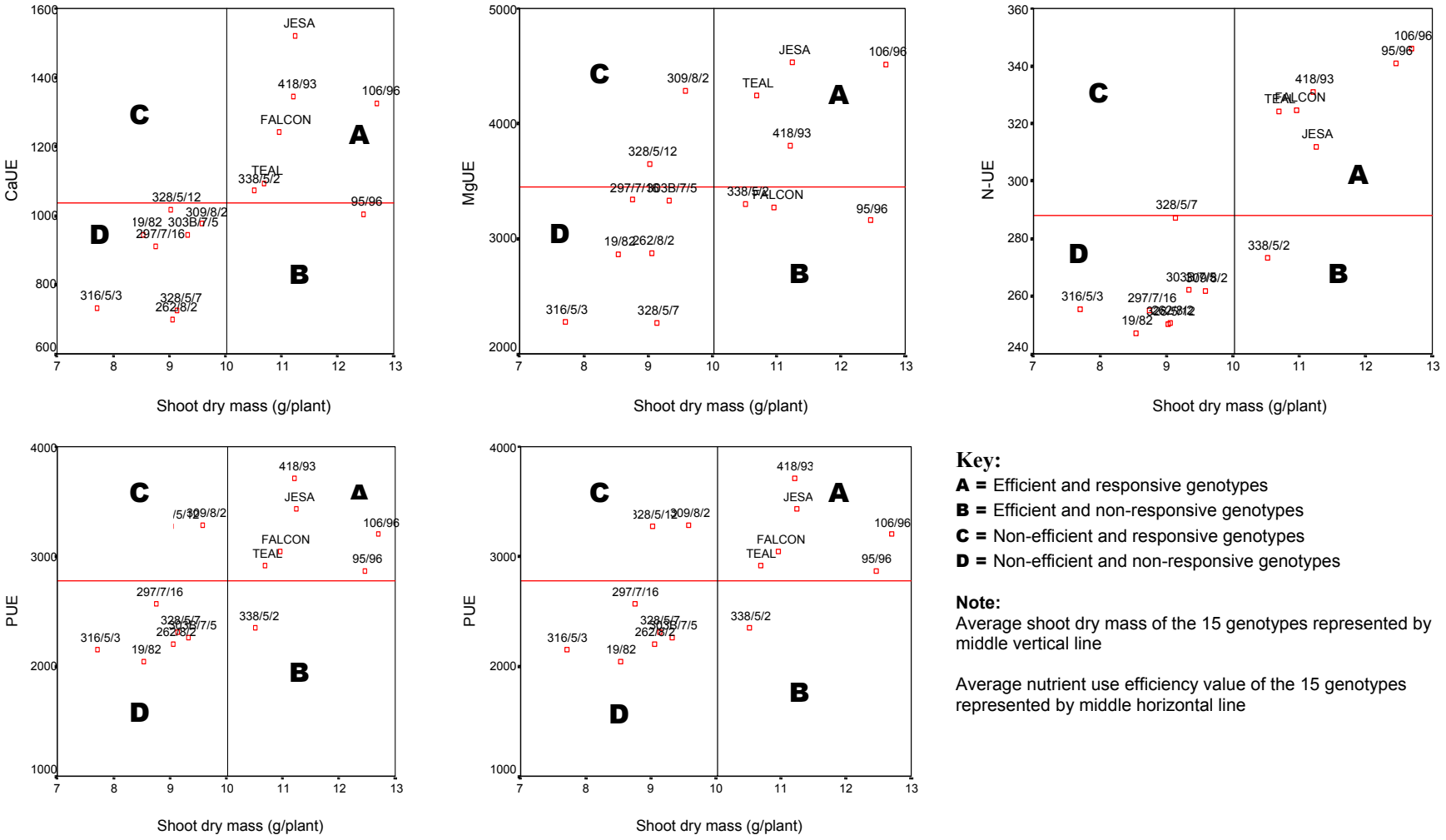
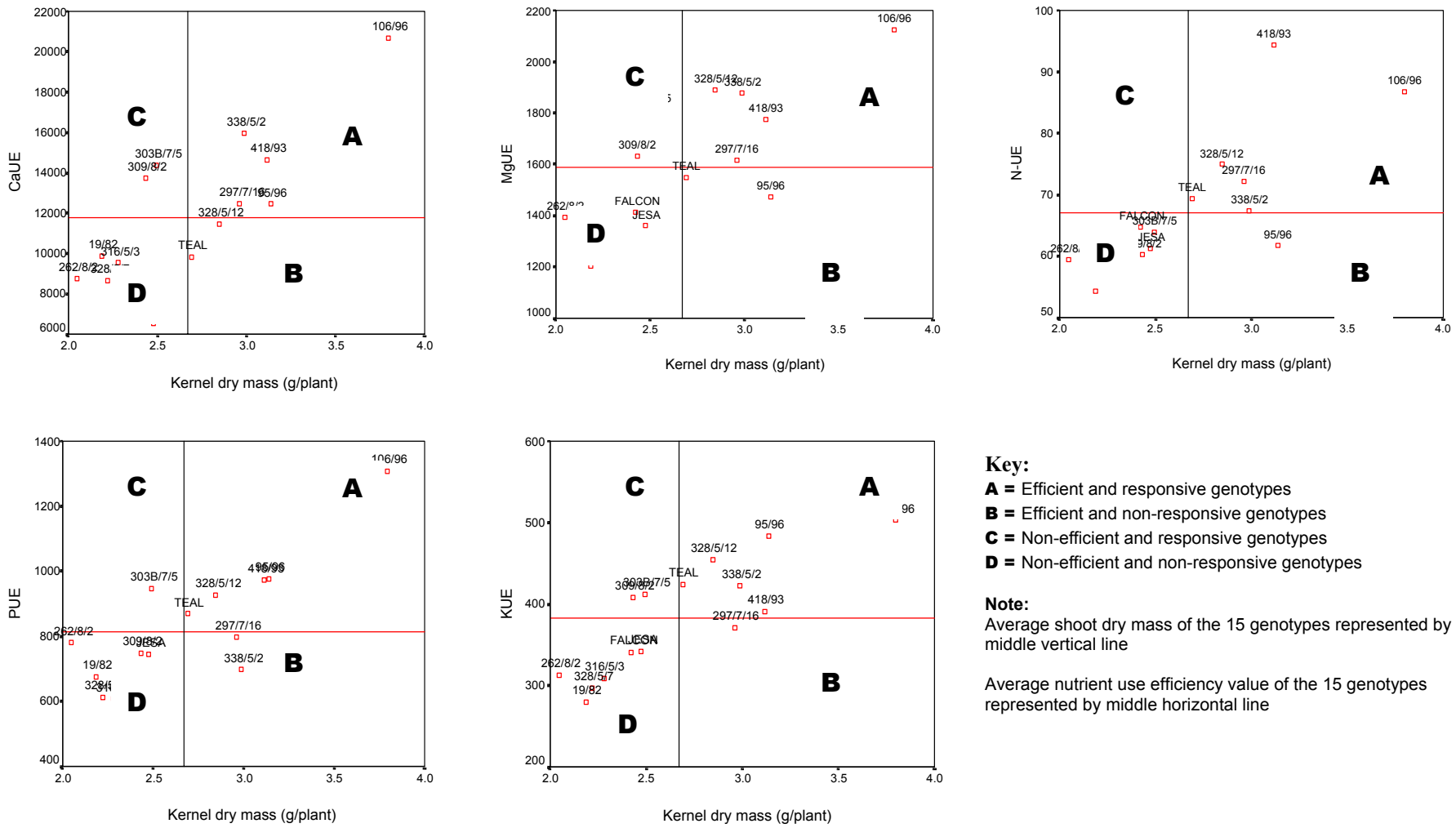


Figure 4.1 Classification of groundnut genotypes for nutrient use efficiency (g SDM / g nutrient concentration in SDM)



Key:

A = Efficient and responsive genotypes

B = Efficient and non-responsive genotypes

C = Non-efficient and responsive genotypes

D = Non-efficient and non-responsive genotypes

Note:

Average shoot dry mass of the 15 genotypes represented by middle vertical line

Average nutrient use efficiency value of the 15 genotypes represented by middle horizontal line

Figure 4.2 Classification of groundnut genotypes for nutrient use efficiency (g kernel dry mass / g nutrient concentration in kernel dry mass)

CHAPTER 5

EFFECT OF SOLUTION pH AND ITS INTERACTION WITH CALCIUM ON GERMINATION, EARLY VEGETATIVE AND REPRODUCTIVE GROWTH OF GROUNDNUT

5.1 INTRODUCTION

A low soil Ca level is one of the conditions often associated with acid-soils, particularly in the tropics (Sanchez, 1976; Von Uexkull & Mutert, 1995). This is in juxtaposition to the importance of Ca as a detoxifying agent of H^+, (Haynes, 1984; Foy, 1992) Al (Alva *et al.,* 1991; Mclay & Ritchie, 1993; Carvalho & van Raij, 1997) and Mn (Robson & Loneragan, 1970) toxicity to plants, also associated with many of the acid soils (Sanchez & Uehara, 1980; Clark, 1984; Foy, 1988, 1992; Noble *et al.,* 1988; Fageria *et al.,* 1990; Vaughan & Ord, 1991; Baziramakenga *et al.,* 1995). Arnon & Johnson (1942) concluded that the poor growth of lettuce, tomato and Bermuda grass grown in low solution pH was the result of a low Ca supply. Robson & Loneragan (1970) showed in a flowing solution culture study that Ca alleviates Mn toxicity on *Medicago* spp, while several studies have shown that high Ca concentrations in solution may alleviate Al toxicity in several legumes (Alva *et al.,* 1986; Cameron *et al.,* 1986; Munns, 1986; Noble *et al.,* 1986; Shamsuddin *et al.,* 1992).

A high concentration of H^+ ions in the soil solution is most consequential for legumes growing without N fertilizer as it affects rhizobial survival and multiplication in soils, and root infection and nodulation of the host plant (Andrew, 1978). Excess H^+ ions, because of the effects on nutrient uptake and retention by plant roots, can increase plant requirements for Ca and perhaps other nutrients in the growth medium (Foy, 1992). For groundnut, Ca deficiency results in blackened plumules, high incidences of pod rot and unfilled pods (pops), poor yields, inferior quality, poor seed germination, and disease susceptibility (Gascho & Davis, 1994). In acid soils, the direct effects of H^+ toxicity or absolute Ca deficiency on plant growth are difficult to determine because at soil pH<4.0, Al, Mn and other mineral elements may be present in toxic concentrations, and the availability of other elements essential for plant growth may be suboptimal (Foy, 1992). Because of

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these confounding effects, investigators use nutrient solutions or sand cultures to study the effects of low pH or Ca.

Investigations on the effect of Ca in alleviating acid-soil infertility for legumes have focused mainly on growth, nodulation, nitrogen fixation, nutrient uptake and mineral composition (Alva *et al,* 1990; Alva *et al,* 1991, van Rossum, *et al,* 1994; Tang & Thomson, 1996). Very little attention has been given to the effects of H^+ toxicity *per se* and Ca deficiency *per se* in the soil solution on germination and early seedling growth of legumes, particularly for groundnut. Because of their small size, seedlings are expected to be more vulnerable to acid-soil conditions. Studies that have investigated the effect of soil acidity at germination on yields of sweet clover and alfalfa (Haller, 1983), have shown that both crops grew well and produced large yields even on strongly acid soils (pH<4.0) provided that germination occurred in a neutral medium.

Groundnut is usually grown on light-textured soils that have a tendency to become acidic, but no attention has so far been given to effects of low soil pH in the pod-zone on groundnut pod development. Hence, it is not known to what extent low soil pH in the pod-zone affects groundnut productivity or to what extent the Ca applied in the pod-zone may alleviate soil acidity for the pods. This may be a topic that requires detailed research, and solution nutrient cultures can be more appropriate for further elucidation on the effects of solution pH and Ca on pod development.

5.2 MATERIALS AND METHODS

5.2.1 GERMINATION, SEEDLING SURVIVAL AND EARLY GROWTH

The objectives of the study were to examine the effect of pH and external Ca concentration on germination, seedling survival and early growth of groundnut in sand culture. Four growth chamber experiments were conducted between June and September 2000 at the Experimental farm of the University of Pretoria. Germination and early growth of the short season S*panish* groundnut cv. *Falcon* were tested for response to solution pH that was varied independently or in factorial combination with solution Ca concentration.

Experiment 1: Effect of pH on germination

In this experiment, the effects of four pH levels (3.0, 4.0, 5.0 and 6.0) on germination of groundnut were investigated. Healthy groundnut kernels that had been produced under conditions of adequate Ca nutrition were germinated between paper towels on acid-washed sand in seedling trays, and kept at 27^{o}C and 100% relative humidity under a 16-hr photoperiod. The sterilised sand was moistened with a dilute nutrient solution comprising (Φ*M*) 250 K, 250 N, 300 Ca, 400S, 100 Mg, 10 Fe (as EDTA), 10 Cl, 3B, 0.25 Zn, 0.10 Mn, 0.07Cu and 0.02 Mo. This solution had a pH of 6.5, and was titrated with either 0.1*M* H_2SO_4 or 0.1*M* HCl to obtain the target treatment pH values.

There were four replicates consisting of 100 seeds per treatment combination, resulting in a total of 400 seeds per pH treatment. The treatments were arranged in a randomized complete block design. Seeds showing radicle emergence (5 mm) were recorded as germinated (Mayer & Poljakoff-Mayber, 1975), and the germinated seeds were counted every day during the five-day experimental period. The experiment was repeated four times, twice acidifying the nutrient solution with H_2SO_4 and twice with HCl.

Experiment 2: Effect of pH on seedling growth

The pH treatments were similar to those in Experiment 1. For each treatment combination, twenty five pre-germinated kernels were planted 2.5 cm deep in acid-washed sand contained in 35 x 30 x 15 cm deep seedling trays. The sterilised sand was kept moist by periodic irrigation with the same nutrient solution as described in Experiment 1. The experiment was conducted with four replications.

After emergence, the seedlings were allowed to grow for 21 days during which seedling mortality was assessed at 7-day intervals. At 21 days after emergence, the surviving healthy plants were harvested, and roots were separated from their tops. Root length and root surface area were estimated using a GLS root scanner (HP Scanjet 3C). The roots were classified into three diameter categories: (a) roots with diameter <1.0 mm, (b) roots with diameter 1.0 B 2.0 mm, and (c) roots with diameter >2.0 mm. The root surface area was measured in mm^2. The plant tops and roots were oven-dried at 80^{o} C for 48 hrs to determine dry mass. The experiment was repeated

four times, twice acidifying the nutrient solution with H_2SO_4 and twice with HCl.

Experiment 3: Effect of pH and Ca on germination

Effects of three solution pH levels (pH 3.5, 4.5 and 5.5) and five levels of solution Ca concentration (0, 50, 100, 150 and 200 Φ*M* Ca) in factorial combination on germination were investigated. The basal nutrient solution was as in Experiment 1, but without the Ca. The desired Ca concentrations were obtained by adding the appropriate amounts of $CaSO_4$.$2H_2O$ to the nutrient solution. Since Ca was added to the nutrient solutions as the $CaSO_4$ salt, the concentration of S in the nutrient solution also varied from 100 Φ*M* in solutions that contained no Ca to 300 Φ*M* in those that contained 200 Φ*M* Ca. There were four replicates consisting of 100 seeds per treatment combination, resulting in a total of 400 seeds per treatment. The germination conditions were similar to those in Experiment 1, and the experiment was repeated four times.

Experiment 4: Effect of pH and Ca on seedling growth

The factorial pH and Ca combination treatments and replicates in this experiment were identical to those used in Experiment 3. Twenty five pre-germinated seeds per treatment combination were used. The experimental techniques were as in Experiment 2. At 21 days after emergence root length, root surface area and dry mass of the roots and shoots were determined. The experiment was also repeated four times.

Data Analysis

Since there were no differences in effects between solutions titrated with H_2SO_4, and those titrated with HCl, the results were combined for analysis. Analysis of variance (ANOVA) was performed using the General Linear Model procedure provided by the Statistical Analysis System (SAS, 1996). If ANOVA determined that the effects of the treatments were significant ($P \leq 0.05$), the treatment means were separated by Duncan's Multiple Range test.

5.2.2 REPRODUCTIVE GROWTH

Two growth chamber experiments were conducted between December 2001 and May 2002 at the Hatfield Experimental Farm of the University of Pretoria. Pod initiation and development of the

short season S*panish* groundnut cultivars *Falcon* and *Jesa* were tested for response to solution pH that was varied independently or in factorial combination with solution Ca concentration.

Experiment 5: Effect of pH on pod development

The effects of five solution pH values (pH 3.0, 4.0, 5.0, 6.0 and 7.0) on pod initiation and development were investigated. Seeds of cultivar *Jesa* were planted 2.5 cm deep in a moist coir/sand mix contained in rectangular PVC crates of 58 x 48 x17 cm. The seeds were planted in two rows spaced 35cm apart, with an in-row spacing of 10cm. Ten days after emergence the plants were thinned to six per crate (three per row). Throughout the experiment the plants were drip-irrigated with a complete nutrient solution, and vigorous plant growth with no apparent water or nutrient stress was observed. The nutrient solution contained (μM) 300 N, 2 P, 250 K, 300 Ca, 400 S, 100 Mg, 10 Fe (as EDTA), 10 Cl, 3B, 0.25 Zn, 0.10 Mn, 0.07Cu and 0.02 Mo. Following the methodology of Zharare *et al.,* (1998) flowers and gynophores produced close to the base of the plants were removed to encourage flowering higher up the plant for experimental convenience.

At gynophore initiation ten glass test tubes were buried in the sand around each plant. Gynophores of approximately the same age that were $\forall$5 cm long were individually positioned in 15ml of a simplified nutrient solution. The glass tubes were loosely covered with aluminium foil to allow adequate aeration but exclude light. The simplified nutrient solution containing only Ca, S, Fe and Zn was used to produce normal and healthy pods by Zharare (1997). The composition of the nutrient solution was (ΦM) 500 Ca, 540 S, 4 Fe (Fe-EDTA) and 0.5 Zn. This solution was titrated with 0.1M H_2SO_4 or KOH to obtain the target treatment pH values. The nutrient solution was refreshed daily for the five weeks during which the pods were cultured. A vacuum pump was used to suck out the solutions from the glass tubes. Refilling each tube with 15 ml of nutrient solution was done with the aid of a calibrated dispenser. An automatic irrigation system controlled by a Richdel irrigation controller was used to supply nutrient solution to the root zone.

The test tubes were inspected daily to establish the time to initial pod expansion (basal and apical seed compartments). The number of cultured gynophores that produced normal pods was recorded after five weeks (35 days), so were pod fresh and dry mass and kernel dry mass. Kernels from these

pods, as well as from pods that were allowed to develop in the sand medium were analysed for Ca content. For experimental convenience, each crate represented one pH level, and each of the six plants per crate was considered to be a replicate. The placement of ten tubes per plant resulted in a total of 60 gynophores per pH treatment.

Experiment 6: Effect of pH and Ca on pod development

Cultivar *Falcon* was used in the experiment, and the planting arrangements and crop management were similar to Experiment 5. The effects of three solution pH levels (pH 3.5, 5.0 and 6.5) and three levels of solution Ca concentration (500, 1000 and 2000 Φ*M* Ca), in factorial combination, on pod development were investigated. The treatments were arranged in a split plot design, with pH level as the main plots and Ca level as the sub-plots. There were three plants per treatment combination, and each plant was considered to be a replicate. Thirty gynophores per treatment combination were cultured.

The technique of culturing gynophores resembled that described in Experiment 5, and the nutrient solution was also similar to that used in Experiment 5, but without the Ca. The desired Ca concentrations were obtained by adding the appropriate amounts of $CaSO_4$.$2H_2O$ to the nutrient solution. Records taken in the experiment were similar to those described in Experiment 5.

Scanning electron microscopy

In both experiments, submerged portions of gynophores/pods were sampled, and the surface tissue checked for development of hairs. Mature seeds were sectioned longitudinally; one cotyledon of the seed was removed, leaving the plumule, hypocotyl and radicle intact and attached to the other cotyledon. Examinations of the excised seeds were carried out to determine embryo development at different Ca concentrations and at different pH levels using scanning electron microscopy.

Representative samples of gynophores/pods from each treatment were harvested at intervals during the experiment for microscopic analysis. The samples were immediately fixed in 2.5% gluteraldehyde in 0.075*M* phosphate buffer (pH 7.4) for 48 hours. The specimens were then

rinsed three times in the same buffer for 15 minutes per rinse. Dehydration of the samples in ethanol was in an ascending series: 50%, 70% and 90% for 10 minutes each. The samples were finally dehydrated three times for 15 minutes per dehydration in fresh 100% ethanol before being dried in a Biorad critical point drier (Biorad, Polaron Division, Watford, England). After drying, the specimens were mounted on aluminium stubs and coated with gold in a Polaron E5200 autocoating unit (Polaron Equipment Ltd, Watford, England). Specimens of the gynophores/pods were examined using a JSM-840 scanning electron microscope (JEOL, Tokyo, Japan) equipped with a Tracor image analysis system. Specimens of the seeds were examined with a light microscope (Nikon SMZ 800 stereo microscope) equipped with a Nikon DXM 1200 digital camera. The work was conducted in the Laboratory for Microscopy and Micro-analysis, University of Pretoria.

Data Analysis

Analysis of variance (ANOVA) was performed using the General Linear Model procedure provided by the Statistical Analysis System (SAS, 1996). If ANOVA determined that the effects of the treatments were significant ($P \leq 0.05$), the treatment means were separated by Duncan's Multiple Range test.

5.2 RESULTS AND DISCUSSION

5.2.1 GERMINATION, SEEDLING SURVIVAL AND EARLY GROWTH

Experiment1: Effect of pH on seed germination

The germination of groundnut seed was less sensitive to the effects of solution pH on day two compared to days three and five (Table 5.1). The proportion of germinated seeds increased with time in all solution pH treatments during the 5-day experimental period, though at a lower rate in the pH 3.0 treatment. By the end of the germination period, the number of germinated seeds was similar at pH 4.0, 5.0 and 6.0, but lower at pH 3.0. The final germination count on day five ranged from 86% at pH 3.0 to 93% at pH 6.0.

From an agronomic point of view, the faster the seedling emerges the greater the likelihood of escaping pre-emergence diseases, and the less damage will be exacted by seed and seedling pathogens (Melouk & Backman, 1995). Thus, the slower germination observed at pH 3.0 may

make the imbibed seeds in the soil more vulnerable to fungal and bacterial pathogens in the soil, leading to reduced seedling emergence.

Table 5.1 Effect of pH on germination of groundnut during a 5-day experimental period, and on seedling survival during a 21-day experimental period

Treatment	Experiment 1 Germination (%)			Experiment 2 Seedling survival (%)		
	Day 2	Day 3	Day 5	Day 7	Day 14	Day 21
PH 3.0	30	74	86	72	61	51
PH 4.0	31	81	91	84	83	78
PH 5.0	32	85	92	87	87	85
PH 6.0	32	84	93	97	94	92
Mean	**31**	**81**	**91**	**85**	**81**	**77**
LSD $_{(0.05)}$	**6.0**	**6.3**	**3.0**	**16**	**18**	**18**

**Each value is the average of 16 replicates.

Experiment 2: Effect of pH on seedling growth

All the pre-germinated seeds emerged from the sand, but the number of surviving seedlings at all pH levels gradually declined, starting 7 days after emergence (Table 5.1). Only 51% of the seedlings survived to 21 days after emergence in the pH 3.0 treatment, compared to 92% in the pH 6.0 treatment. In general, seedling survival improved as the pH increased.

The total root length at 21 days after emergence was 1.65 m per plant for plants grown at pH 3.0, and increased by 526% to 8.67 m for plants grown at pH 6.0 (Figure 5.1). At pH 4.0, the total root length was similar to that obtained at pH 5.0. Roots thicker than 2mm in diameter in the pH 3.0 and pH 4.0 treatments exhibited visual symptoms similar to those reported by Lund (1970) for H^+ injury on plant roots. These symptoms included stunted root growth, brownish colour and little lateral root development. Some of the roots were decayed. Root browning has been attributed to enhanced suberization, which may limit water (and nutrient) uptake (Barceló & Poschenrieder, 1990).

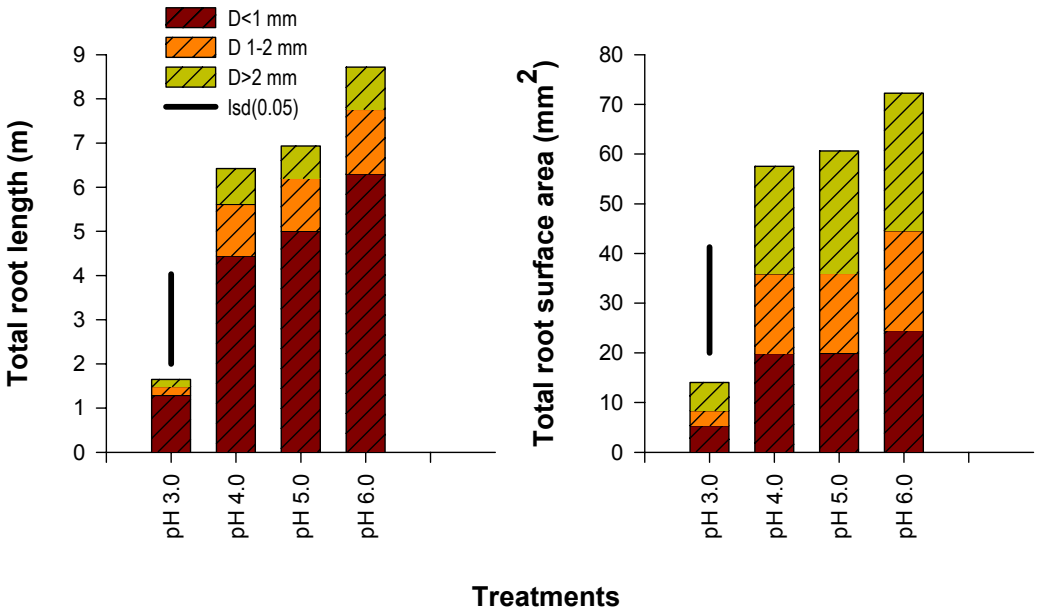


Figure 5.1 Effect of solution pH on total root length and total root surface area of groundnut at 21 days after mergence

Hydrogen-induced root injury may change root membrane permeability (membranes become leaky), interfere in absorption and transport of nutrients, increase loss of organic substrates (sugars, amino acids) and adsorbed cations, and reduce capacities for absorption of nutrients (Foy, 1992). Thus, plants grown in acid soils are bound to be restricted from utilising available water and nutrients when root proliferation and root function is limited by low pH (Goldman, 1989; Sanzonowicz *et al.,* 1998).

Root surface area for individual root diameter categories followed the same response trends as root length (Figure 5.1). At each root diameter category, root surface area increased by more than 300% for plants growing at pH 6.0 compared to those growing at pH 3.0. Total root surface area also increased with increasing solution pH. A large increase in total root surface area was observed in the pH 6.0 treatment (72 cm^2) compared to the pH 3.0 treatment (14 cm^2).

The detrimental effects of a solution pH of 3.0 on the shoots were evident within ten days of plant growth, when the shoot growth was visibly impaired and the leaves had a greyish-green colour. At three weeks after emergence, shoot dry mass increased in response to solution pH increases

(Table 5.2). The shoot dry mass was not significantly different at pH 5.0 and 4.0, although plants in the latter treatment displayed some symptoms of H^+ injury.

Table 5.2 Effect of pH on shoot and root dry mass (g plant^{-1}) of groundnut seedlings at 21 days after emergence

Treatment	Shoot dry mass (g plant^{-1})	Root dry mass (g plant^{-1})
pH 3.0	0.270	0.046
pH 4.0	0.372	0.052
pH 5.0	0.392	0.076
pH 6.0	0.460	0.096
Mean	**0.374**	**0.068**
LSD (0.05)	0.047	0.009

**Each value is the average of 16 replicates.

The effect of solution pH on root dry mass was analogous to that on shoot dry mass, only slightly more adverse (Table 5.2). Root dry mass increased in response to solution pH increases, ranging from 0.046 g plant^{-1} at pH 3.0 to 0.096 g plant^{-1} at pH 6.0. The adverse effects of pH on root dry mass were comparable at the lower pH levels (pH 3.0 and 4.0.). More severe depressions in root growth compared to shoot growth of some grain legume species grown at low pH have been observed (Jayasundara *et al.,* 1998), and attributed to decreased proton extrusion from the roots (van Beusichem, 1982; Schubert *et al.,* 1990; Yan *et al.,* 1992), which may lead to limited nutrient uptake. Van Beusichem (1982) observed a 40% reduction in root dry mass of field pea grown at pH 5.5 without a reduction in shoot dry mass. In the present study, a 53% reduction in root dry mass was observed when the pH decreased from pH 6.0 to pH 3.0, compared to 41% reduction in shoot dry mass at the same pH levels.

The adverse effects of low solution pH were greater on root surface area compared to root dry mass. More fine roots developed at high pH levels compared to the low pH levels (pH 3.0 and 4.0), where short and stubby roots were prominent. This phenomenon can be attributed to inadequate Ca uptake, which negatively impacts on cell division and elongation, resulting in a shorter and denser root system (Clarkson, 1984; Wild *et al.,* 1989; Yan *et al.,* 1992). It is

probable that low pH may trigger the redirection of more assimilates to the roots than to the shoot system in order to offset the adverse effects of unfavorable pH on root growth. This would result in the accumulation of assimilates in the roots, giving rise to the formation of short and stubby roots, hence the smaller differences in root dry mass at the different pH levels compared to the root surface area.

Experiment 3:Effect of pH and Ca on seed germination

At day two, only 50% of the kernels germinated at Ca concentrations <0.5m*M* (Figure 5.5). As the Ca concentration increased, the negative effect of pH diminished and germination improved. At day five, germination percentages of more than 92% were obtained with Ca concentrations of 1.0m*M* or higher, irrespective of the pH (Figure 5.2). At Ca concentrations of less than 1.0m*M,* germination percentages were lower, especially at pH 3.5.

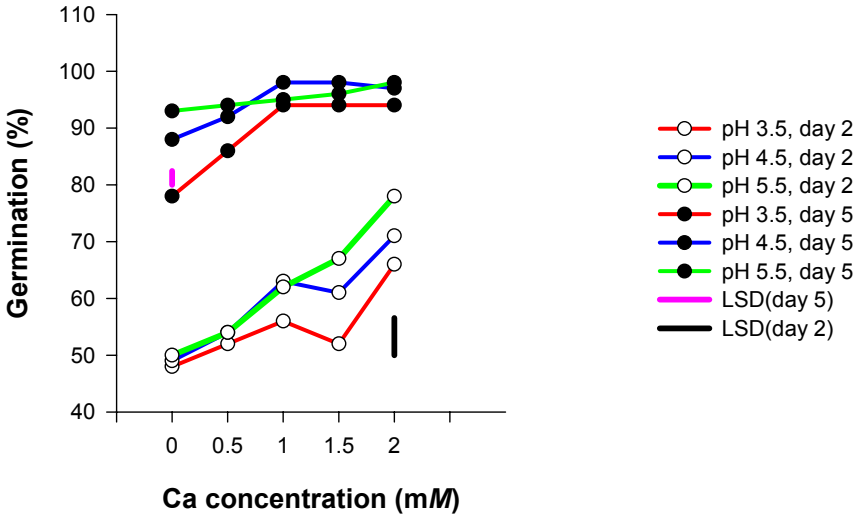


Figure 5.2 Effect of solution pH and Ca concentration on germination of groundnut

Experiment 4: Effect of pH and Ca on seedling growth

At 21 days after emergence, the solution pH and Ca concentration had significant interaction effects on seedling survival (Figure 5.3). At Ca concentrations less than 1.0 mM, there were large effects of pH on seedling survival, with survival percentages decreasing as the pH levels decreased. At pH 5.5 more than 95% of the seedlings survived, regardless of the Ca concentrations of the nutrient solution. At pH 3.5 seedling survival was similar to that obtained at

a pH of 5.5, provided adequate Ca was supplied. As the concentration of Ca decreased, seedling survival decreased to 80% with 0.5 m*M* Ca, and to 68% with no Ca in the solution. Seedling survival at pH 4.5 was intermediate to the responses observed at pH 5.5 and pH 3.5.

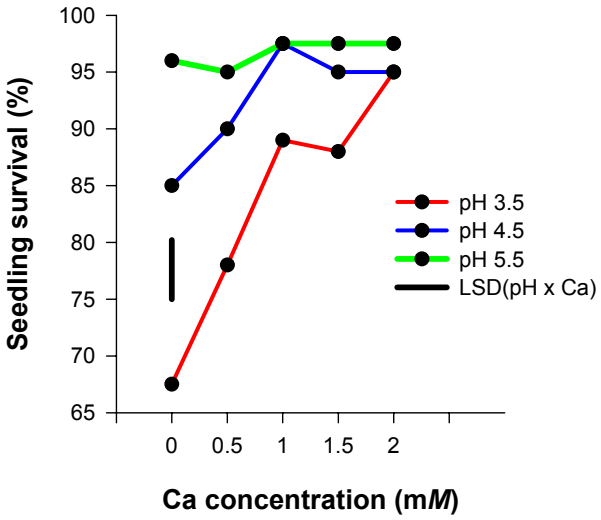


Figure 5.3 Effect of solution pH and Ca concentration on seedling survival of groundnut

The interaction effects of pH and Ca concentrations in the solutions were significant for root length for all root diameter categories (Figure 5.4). In the absence of Ca the length of roots increased when pH was increased from 3.5 to 5.5, and the increases were highest with roots of diameter <1.0 mm. Increasing the solution Ca concentration from 0.5 m*M* to 2.0 m*M* at pH 3.5 resulted in increases in root length of up to 104% for roots of diameter <1.0 mm. By comparison, the increases in root length (diameter < 1.0mm) over the same range of Ca increments were up to 133% at pH 4.5 and 92% at pH 5.5. At all pH values, root length generally increased with increases in solution Ca concentrations. The total root length per plant was highest (7.82 m) for plants grown at pH 5.5 with 2.0 m*M* Ca. Root formation in solutions without Ca was generally impeded.

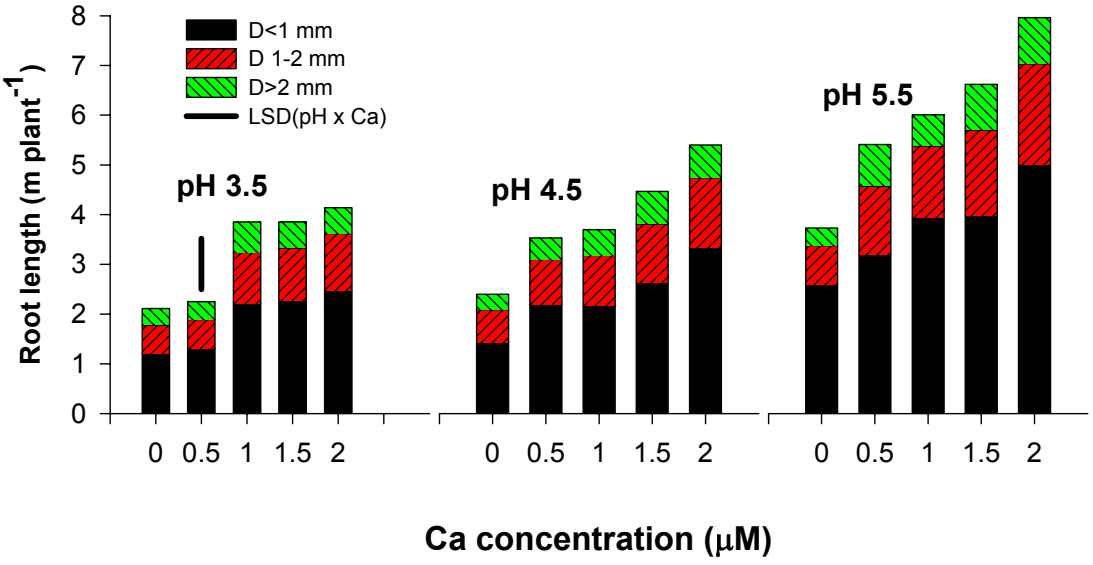


Figure 5.4 Effect of solution pH and Ca concentration on root length of groundnut at 21 days after emergence

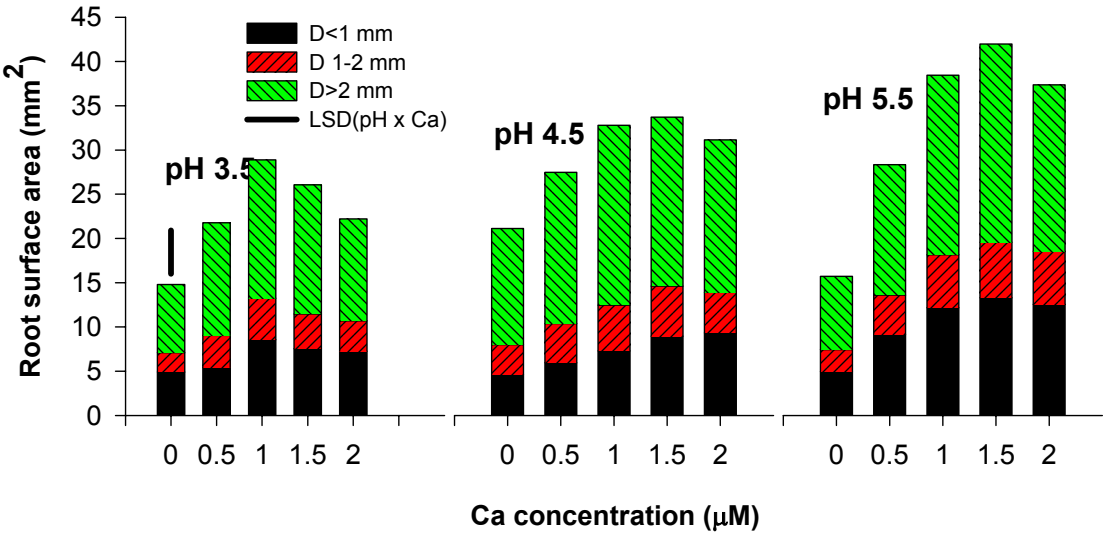


Figure 5.5 Effect of solution pH and Ca concentration on root surface area of groundnut at 21 days after emergence

Root surface area followed the same response trends as root length (Figure 5.5). In the absence of Ca, solution pH did not have an effect on root area for roots with diameter <2mm, whereas root surface area for roots with diameter > 2mm increased with increases in pH. With application

of Ca, root surface area for all root categories increased with increases in solution Ca concentrations. The increases were highest with 1.0 m*M* Ca at pH 3.5, and with 1.5 m*M* Ca at pH 4.5 and pH 5.5. The total root surface area at pH 5.5 was 95% higher than at pH 3.5. When averaged across solution pH treatments, increasing the Ca concentration from 0 to 2.0 m*M* Ca increased total root surface area by 76%. However, significant pH x Ca interactions occurred as can be seen in Figure 5.5. With application of Ca, total root surface area increased with increases in solution Ca concentrations up to a concentration of 1.0 m*M* Ca at pH 3.5 and up to 1.5 m*M* Ca at pH 4.5 and 5.5.

In this experiment, it was observed that there was a greater reduction in the development of the finer roots than of the thicker roots and taproot at the lower pH levels and lower Ca concentrations. Sanzonowicz *et al.* (1998) documented that H^+ toxicity inhibited the length of lateral roots of soybeans more than that of taproots. In their study, a 50% reduction in lateral root length occurred at pH 5.1, whereas a similar reduction in taproot length occurred at pH 4.7.

The effects of pH and Ca concentrations on shoot dry mass were significant, with shoot dry mass increasing as pH and Ca increased (Figure 5.6). The interaction effects between pH and Ca concentrations were also significant, showing a greater impact of pH on shoot dry mass at intermediate Ca concentrations. Plants grown with solution Ca concentration of 2.0mM produced similar dry mass at the three pH levels. The shoot dry mass at pH 3.5 was reduced from 0.48 g plant^{-1} at 2.0m*M* Ca to 0.29 g plant^{-1} with no Ca in the solution. Yan *et al.,* (1992) documented similar results in their studies on maize and broad beans, which showed that higher levels of solution Ca counteracted the negative effects of low solution pH on growth of the two crops.

Better root growth was observed when the solution pH was favourable (Figure 5.6). The root dry mass was highest at pH 5.5, and ranged from 0.04 g plant^{-1} with no Ca to 0.09 g plant^{-1} at 2.0m*M* Ca. At a pH of 3.5, root dry mass ranged from 0.04 g plant^{-1} at 0 Ca to 0.05 g plant^{-1} at 2.0m*M* Ca. Root dry mass responses at a pH of 4.5 were intermediate to those observed at pH 5.5 and pH 3.5. The interaction effects of solution pH and Ca concentration on root dry mass were significant, showing smaller increases in root dry mass at Ca concentrations <1.0 1.0 m*M*, but significant increases at Ca concentrations > 1.0 m*M*.

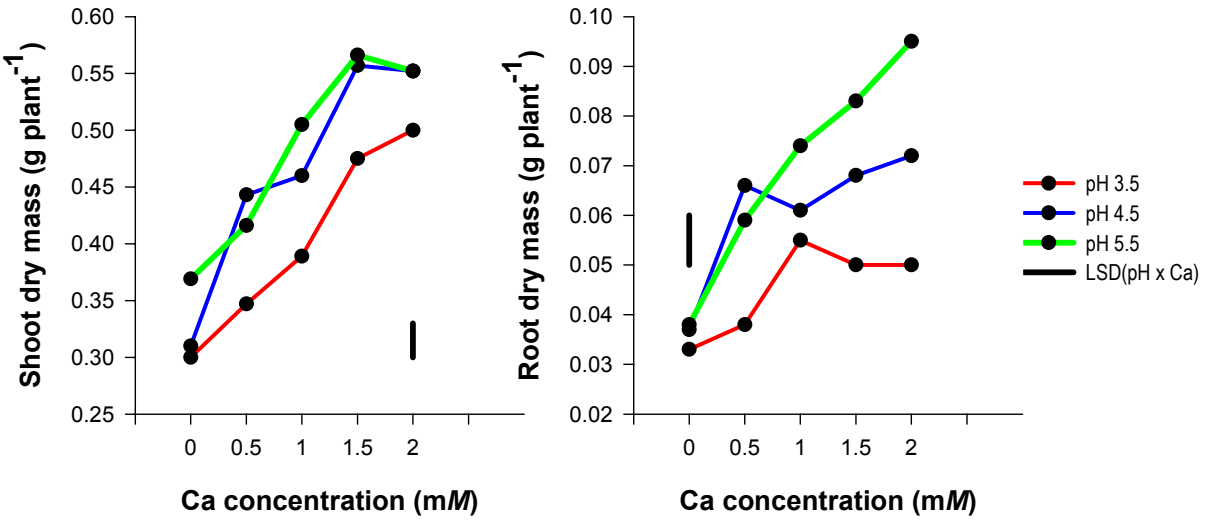


Figure 5.6 Effect of solution pH and Ca concentration on shoot and root dry mass of groundnut at 21 days after emergence

The results showed that the adverse effects of pH on root growth were more at low solution Ca concentration. This would be expected because competition with H^+ on absorption at low pH may induce Ca deficiency, resulting in inhibited root growth since Ca is needed for mitosis and cell elongation (Rost-Siebert, 1985). Koyama *et al.* (2001) observed that the roots of *Arabidopsis thaliana* growing at pH 5.0 required less Ca to maintain elongation compared to those growing at pH 4.5 or 4.8, and concluded that the amelioration of low-pH damage by application of Ca demonstrated the involvement of a Ca-requiring process.

5.3.2 REPRODUCTIVE GROWTH

Experiment 5: Effect of pH on pod development

For both the apical and basal seed compartments, the time to initial pod expansion was significantly affected by solution pH. At solution pH 5.0, 6.0 and 7.0, the expansion of the basal compartment started at approximately six days after submergence of the gynophores (Table 5.3). In the pH 4.0 treatment visible pod development was observed 11 days after submergence of the gynophores. There was a marked delay in pod development in the pH 3.0 treatment, with initial expansion of the basal compartment being visible 16 days after submergence of the gynophores.

Table 5.3 Pod formations and time to visible pod expansion of groundnut *cv* Jesa cultured in nutrient solution at different pH levels

Treatment	Days to initial pod expansion (basal seed compartment)	Days to expansion of apical seed compartment	% Cultured gynophores that produced normal pods
pH 3.0	16.3±1.3	ND	11.7±7.65
pH 4.0	11.0±1.0	11.9±0.89	55.0±3.31
pH 5.0	6.9±0.85	8.1±0.52	91.6±2.4
pH 6.0	5.5±0.2	6.5±0.5	95.0±1.0
pH 7.0	6.1±0.5	7.9±0.37	93.3±0.9
Mean	**9.2**	**8.6**	**69.3**
LSD $_{(0.05)}$	1.71	1.60	10.63

* *Data are means of six replicates ± standard deviation ND - not detected

Expansion of the apical seed compartment was even more sensitive to solution pH (Table 5.3). Rapid expansion (6.5 days after expansion of the basal seed compartment) was observed at pH 6.0, followed by pH 7.0. It took 12 days for expansion of the apical seed compartment to commence at pH 4.0. In the pH 3.0 treatment no expansion of the apical pod compartment was observed at termination of the experiment, 35 days after submergence of the gynophores.

The percentage of gynophores that developed into pods ranged from 95% at pH 6.0 to 12% at pH 3.0 (Table 5.3). While pod expansion was initiated by all the 60 gynophores submerged in solution with pH 3.0, only seven (12%) showed visible pod expansion and developed into one-compartment pods. At pH 4.0 the number of gynophores that developed into pods increased to 55%. These were mainly two-compartment pods as in the rest of the pH treatments. Symptoms attributed to H^+ injury were observed on pods formed at pH 4.0. The pods showed patches of brown discoloration typical of H^+ injury. Similar symptoms were observed by Zharare (1997) on pods grown in nutrient solutions containing no Ca. Pod-set in gynophores cultured at solution pH 6.0 and 7.0 was >90%, with the highest number of pods being formed at pH 6.0. Better pod growth was observed when the solution pH was favourable (Figure 5.7).

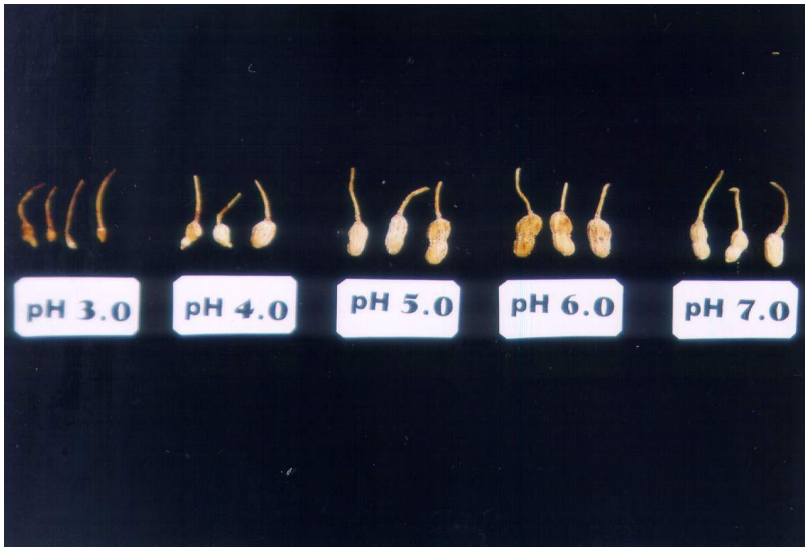


Figure 5.7 Effect of pH on pod development

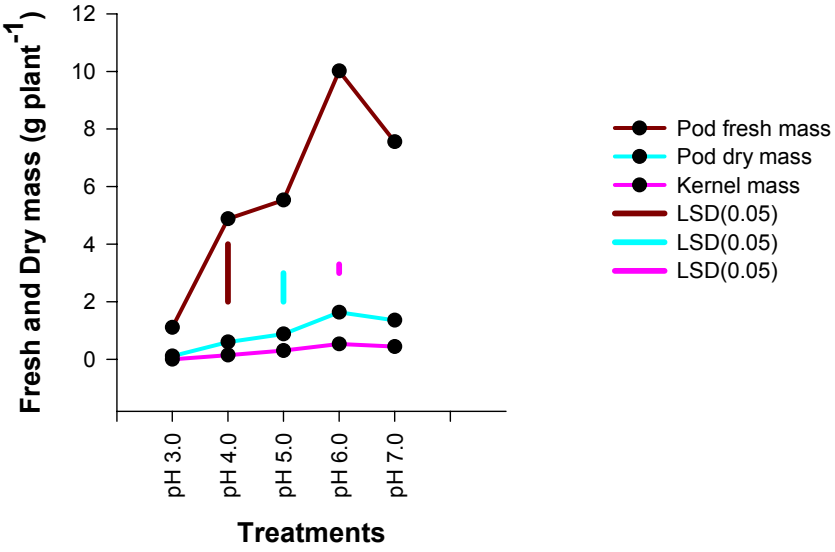


Figure 5.8 Pod fresh and dry mass, and kernel weight of groundnut *cv* Jesa cultured in nutrient solution at different pH levels

Pod fresh and dry mass increased in response to solution pH increases up to pH 6.0, but the increases were larger for the fresh than for the dry mass (Figure 5.8). Whereas the pod fresh mass at pH 7.0 was significantly lower than that at pH 6.0, the dry mass observed at both pH

levels was not statistically different. Although the kernels were not physiologically mature at the time of harvest, kernel dry mass showed significant effects of solution pH (Figure 5.8). Kernel dry mass increased with increasing solution pH up to pH 6.0, and ranged from 0.15 g kernel^{-1} at pH 4.0 to 0.54 g kernel^{-1} at pH 6.0. There was a 17% reduction in kernel dry mass at pH 7.0 relative to pH 6.0.

The poor pod development at low pH can be explained in terms of the inhibitory effects of low pH on proton release which is perceived as the driving process for the uptake of nutrient cations (Leonard, 1984; Briskin, 1986). Since the groundnut gynophores and developing pods absorb nutrients directly from the soil (Skelton & Shear, 1971; Beringer & Taha, 1976; Chahal *et al.,* 1979), proton release should also be the driving process for the uptake of nutrient cations. It is therefore possible that the high H^+ activity in the low solution pH resulted in a net H^+ influx into the pods, which in turn led to limited nutrient uptake and pod growth. There are striking similarities in the symptoms of low pH injury obtained in this study, and those of Ca deficiency obtained by Zharare (1997), suggesting that Ca deficiency may have played a role in the impairment of pod growth at low pH. Bledsoe *et al.,* (1949) documented that Ca requirements for pod growth are greatest at the start of gynophore swelling, and any deficiency in Ca at this stage results in failure of gynophores to expand into pods. Nonetheless, the restricted pod growth at low solution pH in this study could have been the direct effects of proton toxicity as a result of high proton influx into the pods

White patches showed on the surfaces of gynophores cultured at all pH levels, starting from approximately 48 hours after submergence until the pods were harvested (Figure 5.9). Normal developing gynophores have minute white hairs that give a downy appearance (Seshadri, 1962), and are shed as the pods mature. Zharare (1997) observed the appearance of these patches approximately 14 hours after the gynophores had been submerged in nutrient solution, and these were tufts of hair covered with mucilage. Developing gynophores may bear unicellular structures resembling root hairs that can reach very high density and lengths of up to 0.75 mm (Zharare *et al.*, 1993; Gascho & Davis, 1994). In this study an examination of these white patches showed some fungal hyphae, especially at pH 3.0 and to a lesser extent pH 4.0 (Figure 5.10). The presence of fungal infection at low pH is not surprising, since fungi in general seem to dominate acid soils more than bacteria because they have hyphae and thicker cell walls that may make them more adaptable at lower soil pH (Bezdicek *et al.,* 2002).

Figure 5.9 Developing pod showing white patches

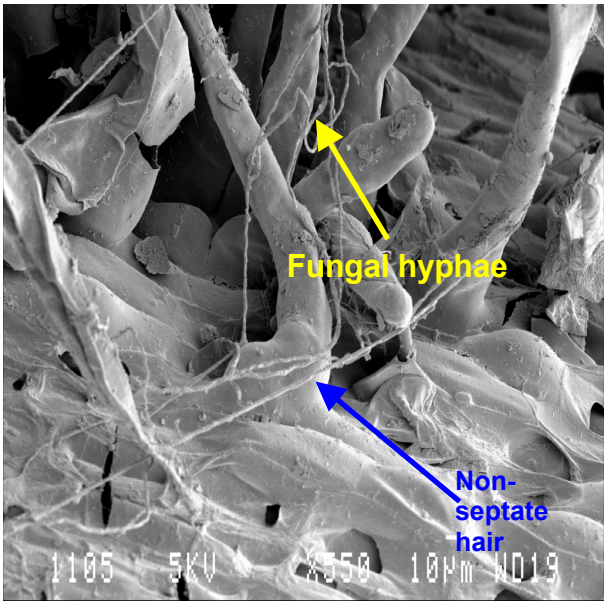


Figure 5.10 Scanning electron micrograph of gynophore surface showing non-septate hairs and fungal hyphae at pH 3.0

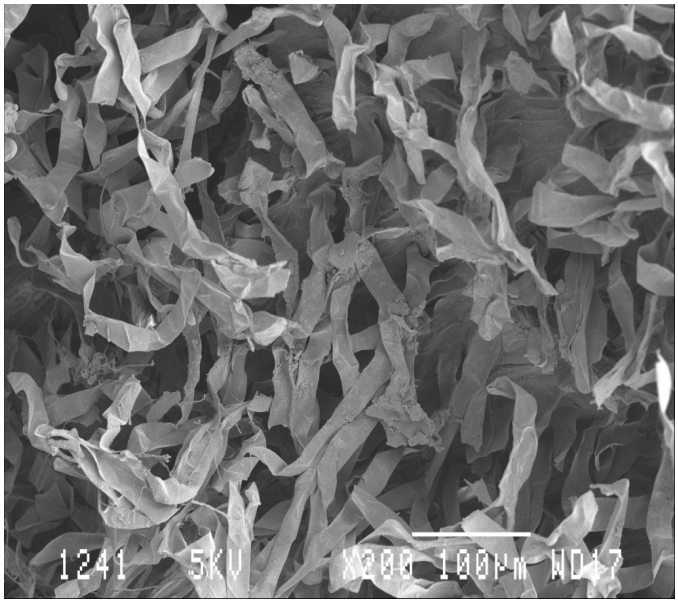


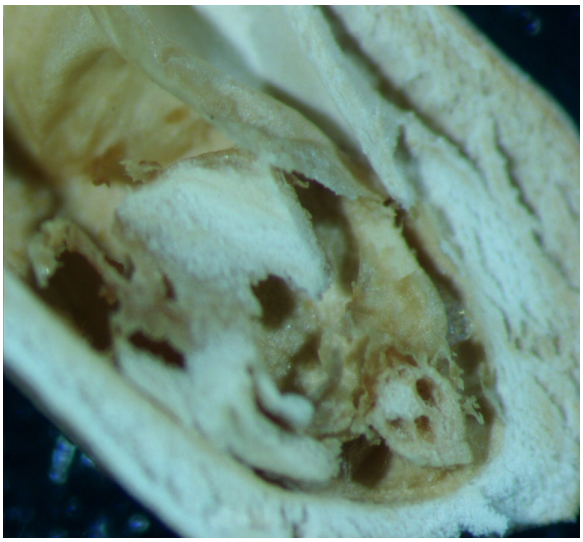
Figure 5.11 Scanning electron micrograph showing dense hair formation on gynophore surface cultured at pH 5.0.

Solution pH did not influence pod hair development since well-developed septate and non-septate hairs were observed even at pH 3.0. As described by Zharare (1997), the non-septate hairs arose as outgrowths of the primary epidermis, and had swollen bases (Figure 5.10). After shedding of the primary epidermis, branched, septate hairs were revealed. Literature on the effect of pH on groundnut gynophore and pod hairs is scarce. In other plant species, root hair development has been shown to be associated with acidification of the apoplast, for example in *Arabidopsis thaliana* (Bibikova *et al.,* 2001). The authors observed acidification at the root hair initiation site, and this acidification was maintained to the point where the process of root hair initiation ceased and tip growth began. They concluded that localized changes in apoplastic and cytoplasmic pH are associated with root hair development. It is probable that gynophore hair development is also associated with this phenomenon, hence the occurrence of peg hairs at pH levels as low as pH 3.0.

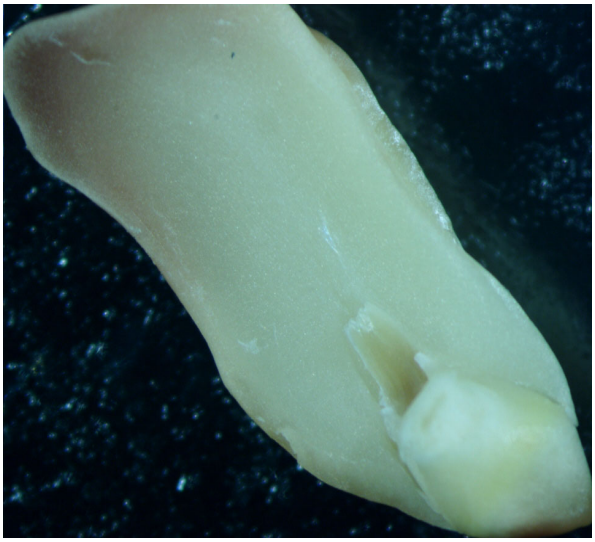
Although hair formation on gynophore surfaces was observed at all pH levels, the degree of hairiness appeared to decline with time at a faster rate with increased acidity. The results imply that while peg hair initiation can take place at low pH, its persistence (longevity) may be curtailed at low pH. Dense hair formation was observed at pH 5.0 and higher (Figure 5.11). Since the pod is capable of direct nutrient absorption from the soil, the density of hairs on the surfaces of developing pods might be expected to influence the uptake of Ca and other nutrients by the developing pods. If dense hair formation implies better nutrient uptake because of increased area of the absorption surface, the results would imply that better nutrient uptake could be expected at higher solution pH levels. Wissuwa & Ae (2001) observed that root hair density, as well as the ability of groundnut genotypes to form root hairs correlated with the presence and density of hairs on gynophores, suggesting a substantial increase in the surface area of roots and pods, which leads to increased nutrient uptake efficiency.

Kernel development

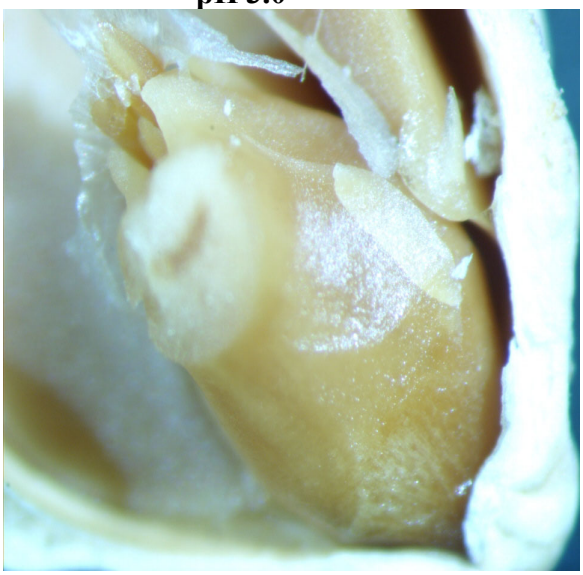
Microscopic examinations of the excised seeds showed that normal embryos were formed at pH 5.0 and above, and plumule development appeared to improve as the pH levels increased, with no differences in the overall appearance of the embryonic plumules being observed between pH 5.0 and 7.0 (Figure 5.12).



pH 3.0

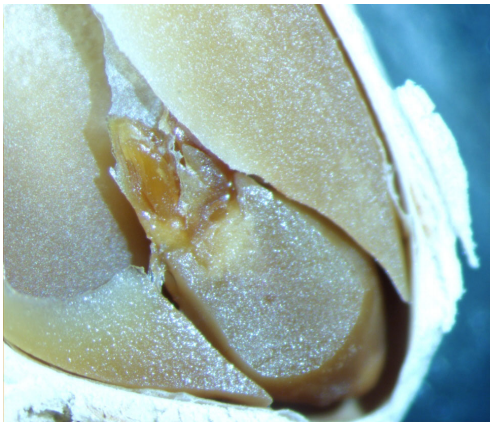


pH 4.0



pH 5.0

pH 6.0



pH 7.0

Figure 5.12 Photomicrographs of cotyledons and embryos produced at different pH

Seeds with slightly discolored cotyledons and a hollow area in the cotyledon were observed at pH 4.0. This abnormality is referred to as hollow heart, and is associated with Ca and B deficiencies (Harris & Brolmann, 1966). At pH 3.0 the whole embryonic axis (plumule, hypocotyl and radicle) was necrotic and largely undifferentiated. These symptoms were similar to those described by Zharare (1997) for groundnut TMV-2 pods grown in nutrient solution lacking Ca. Whatever the mechanism involved, it appears that the injuries caused by low pH (high H^+ activity) and low Ca to the developing groundnut embryo could be inter-linked. Zharare (1997) hypothesized that injuries to developing pods and kernels at low Ca in the pod environment could be caused by H^+ toxicity because of an enhanced H^+ influx into the pods from the pod environment in response to K^+ efflux. Zharare (1997) further hypothesized that one of the major functions of Ca in the pod environment is to prevent H^+ toxicity to developing pods by substituting for H^+ influx associated with the K^+ efflux. Furthermore, there could be mutual uptake inhibition between Ca and H^+ (Haynes, 1984; Foy, 1992). Thus, the symptoms of injury from high H^+ and Ca deficiency could be similar, as is the case with respect to root-tip growth (Lund, 1970). Hence, the necrosis of the embryonic axes at low pH could be the result of direct toxicity of H^+ activity or could be a result of Ca deficiency. Competitive effects of nutrients (soluble NH_4, K, Mg and Na salts) in the pod zone can also cause Ca deficiency or pod rot to develop (Csinos, 1986). Furthermore, the involvement of fungal pathogens in necrosis of the embryonic axis may not be precluded, since some fungal hyphae were observed on surfaces of gynophores growing at pH 3.0 and pH 4.0.

The effects of pH on seed quality were distinct, as evidenced by the embryo characteristics at the various pH levels (Figure 5.12). Though same age gynophores were cultured, the plumules after 40 days of pod growth were at different stages of development, with more advanced development being observed at solution pH 5.0 and higher. Thus, spatial pH variations within a groundnut field may increase the tendency of the pods to be at various stages of physiological maturity at harvest, in addition to variations caused by the tendency of groundnut to be indeterminate in growth habit. More mature seeds at the time of harvest can be expected at higher pH levels.

Experiment 6: Interaction effects of pH and Ca on pod development

Pod formation was observed in all treatment combinations of pH and Ca levels tested (Table 5.4). Approximately 58% of the gynophores cultured in treatment combinations with pH 3.5 produced normal pods, compared to 94% in combinations with pH 5.0 or 6.5. At pH 3.5 and 5.0, increases in solution Ca concentration significantly improved pod production, whereas at pH 6.5 the improvements were not significant, indicating that Ca has an ability to counteract the injurious effects of low pH to groundnut pod growth. In this respect, the alleviation of Ca on injurious effects of low pH on pod growth is similar to the alleviation it has on injurious effects of low pH on root growth (Sanzonowicz *et al.,* 1998). The lack of significant effect of Ca concentrations on pod production at pH 6.5 is also probably an indication of better Ca availability at this pH level, which would result in lower Ca concentrations being adequate for normal pod growth. Once the amount of Ca needed to satisfy the needs of the actively growing meristematic tissues of the pods has been absorbed, the excess absorbed Ca is precipitated within the tissues as insoluble Ca oxalate (Tisdale & Nelson, 1975).

Solution pH had a significant effect on the time taken from submergence of the gynophore to initial expansion of the basal seed compartment (Table 5.4). Generally, the initial expansion of the basal seed compartment was significantly delayed at pH 3.5 compared with pH 5.0 and 6.5 irrespective of the Ca concentration in the solution. On average, the initial expansion of the basal seed compartment at pH 3.5 was observed approximately 11 days after submergence, whereas pod expansion became visible at 6 and 7 days after submergence at pH 5.0 and 6.5 respectively. Generally, increasing the solution Ca concentration from 500 to 2000 :M had little effect on time taken to initial pod expansion. Zharare *et al*. (1998) made similar observations with a number of groundnut lines grown in solution Ca concentrations ranging from 0 to 2500 :M.

The effects of pH and Ca concentrations on time taken to initial expansion of the apical seed compartment were significant, with faster pod expansion being observed at the higher pH and Ca levels (Table 5.4). The effect was more marked for pH than for Ca. When averaged across Ca levels, expansion of the apical seed compartment commenced 9 days after the onset of the basal seed compartment expansion at pH 3.5, and 5 days at pH 5.0 and 6.5. Significant interaction effects between pH and Ca concentrations on time taken to expansion of the apical seed

compartment were observed, showing a greater influence of Ca at low pH. Again this observation confirmed that Ca alleviates the injurious effects of low pH on pod development.

Table 5.4 Pod formations and time to visible pod expansion of groundnut *cv* Jesa cultured in nutrient solution at different pH and Ca concentration levels

PH	Ca level (µM)			
	500	**1000**	**2000**	**Mean**
	Days to initial pod expansion of basal seed compartment			
3.5	11.5	12.08	11.07	11.55
5.0	6.58	6.35	6.92	6.62
6.5	6.33	6.25	5.67	6.08
Mean	**8.14**	**8.23**	**7.89**	**8.08**
$LSD_{(0.05)}$ pH = 0.79	**Ca = Non Significant**		**pH x Ca = Non Significant**	
	Days to initial pod expansion of apical seed compartment			
3.5	10,0	9.92	8.50	11.55
5.0	5.34	5.25	4.87	5.15
6.5	5.00	5.00	4.70	4.90
Mean	**6.78**	**6.72**	**6.02**	**7.2**
$LSD_{(0.05)}$ pH = 0.23	**Ca = 0.23**		**pH x Ca = 0.47**	
	% Cultured gynophores that produced pods			
3.5	52.2	58.7	64.0	58.3
5.0	91.3	93.3	96.7	93.9
6.5	95.0	93.5	93.3	93.9
Mean	**79.5**	**81.8**	**84.7**	**82.0**
$LSD_{(0.05)}$ pH = 1.84	**Ca = 1.84**		**pH x Ca = 2.25**	

**Data are means of three replicates

Kernel Ca concentration

An analysis for Ca concentration of the kernels obtained at the different pH and Ca concentrations showed substantial increases in Ca concentration as the pH was increased from pH 4.0 to 7.0 (Table 5.5). This can possibly be attributed to the reduction in the H^+ concentration at higher pH levels, which would result in less ability of H^+ to inhibit Ca uptake. Increasing the Ca levels in the solution from 500 to 2000 µM substantially increased kernel Ca concentrations. In groundnut, the kernel Ca concentration range 0.04 to 0.08 % is considered sufficient for proper

kernel development (Gascho & Davis, 1994). Thus in the present study, the Ca levels in the kernels (Table 5.5) were adequate in all treatments except the pH 4.0 treatment, and the pH 3.5 at 500 μM Ca treatment. In comparison, kernels produced in sand had a much higher Ca concentration than those produced in solution at a similar pH. This can be ascribed to differences in pod surface area and pod volume, which are important factors influencing Ca absorption by the seed (Boote *et al.,* 1982). Although the pods grown in nutrient solution were just as morphologically normal as those grown in sand, the latter pods were larger, probably because they had a natural mechanical stimulus (contact with soil) for better growth, compared to aeration as the stimulus in nutrient solution. Smal *et al.* (1989) observed increased Ca uptake in pods with higher pod surface area.

Table 5.5 Effect of solution pH and Ca concentration on Ca content of groundnut kernels

Solution pH	**Solution Ca**			
	500	**1000**	**2000**	**Mean**
	Kernel Ca concentration (%)			
4.0	0.03			
5.0	0.05			
6.0	0.07			
7.0	0.08			
3.5	0.03	0.06	0.07	**0.05**
5.0	0.04	0.09	0.12	**0.08**
6.5	0.06	0.10	0.09	**0.08**
6.2 (sand)	0.18			

The pod fresh and dry mass was significantly influenced by solution pH, but little affected by solution Ca concentration (Figure 5.13). The average pod fresh mass at pH 3.5 was 1.52 g pod^{-1}, and was increased to 2.98 and to 4.05 g pod^{-1} at pH 5.0 and pH 6.5 respectively. The pod fresh mass at pH 3.5 was reduced from 2.04 g pod^{-1} at 2000 :*M* Ca to 0.77 g pod^{-1} at 500 :*M* Ca. At pH 6.5 the effect of Ca concentration was much less, indicating that higher levels of solution Ca counteracted the negative effects of low solution pH on pod formation. Similar reductions in pod

dry mass were observed at the same pH level. Differences in pod fresh and dry mass at the different Ca concentrations were of a lesser magnitude at pH 5.0 and 6.5 compared to those observed at pH 3.5. In experiments on effects of solution Ca on concentration in the podding environment on pod dry mass Zharare (1997; 1998) observed significant depressions in dry mass at 0 and at 2500 ΦM Ca, with maximum yield observed at solution Ca ≤ 100 ΦM.

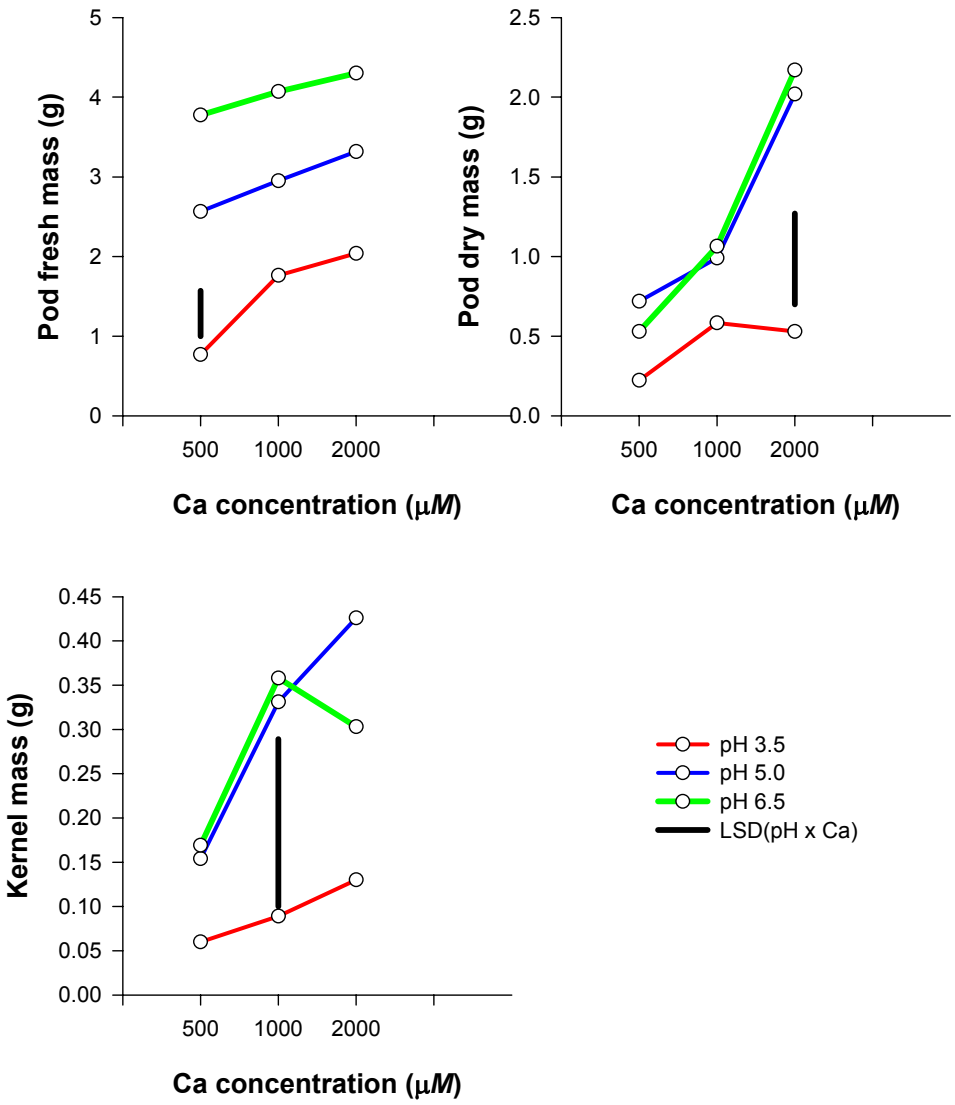


Figure 5.13 Pod and kernel mass of groundnut *cv* Falcon cultured in nutrient solution at different pH and Ca levels

While the impact of increasing the solution Ca concentrations on pod mass was greater at pH 3.5 than at pH 5.0 or 6.5, there was a tendency for pod mass to increase with increase in solution Ca concentrations at all pH levels. Smal *et al.,* (1989) similarly observed increases in pod dry mass of a runner type as the Ca level in the pod zone was increased from 25 to 1875 μ*M*. In the present study, the largest increases in pod mass due to increases in Ca concentrations were observed at pH 3.5 where increasing the Ca concentrations from 500 to 1000 μ*M* increased fresh mass by 130%, and dry mass by 167%. The interaction effects of solution pH and Ca concentration on pod mass showed significant effects at pH 3.5, but a tendency for pod mass to increase with increase in solution Ca concentrations at pH 5.0 and 6.5.

Average kernel weight at pH 3.5 was 0.10 g kernel^{-1}, and was increased to 0.30 g kernel^{-1} at pH 5.0, and to 0.28 g kernel^{-1} at pH 6.5 (Figure 5.13). The kernel weight was highest at pH 5.0, and ranged from 0.15 g kernel^{-1} with 500 μ*M* Ca to 0.43 g kernel^{-1} at 2000 μ*M* Ca. At pH 3.5 kernel weight ranged from 0.08 g kernel^{-1} at 500 μ*M* Ca to 0.13 g plant^{-1} at 2000 μ*M* Ca. Kernel weight responses at pH 6.5 were less than those observed at pH 5.0. The observed pH x Ca interaction showed that the effects of Ca concentration on kernel weight were largest at the intermediate pH level, and diminished at pH 3.5 or 6.5.

Reasons for poor productivity of legumes on acid soils include failure to nodulate as pH decreases (Andrew, 1976; Munns, 1978; Franco & Munns, 1982), reduced nodule function (Franco & Munns, 1982), or limited plant growth (Franco & Munns, 1982). Since none of these factors were observed in my experiment (due to adequate nutrient supply at optimum pH in the root zone), the low yields observed at the low pH levels can be ascribed to the detrimental effects of low pH *per se* on nutrient uptake and growth. According to Kidd & Proctor (2001), plants growing in very acid soils appear to be faced firstly with toxic H^+ ion concentrations before they encounter other unfavourable factors (toxic concentrations of Al and Mn or deficiencies of N, P and Ca), thus supporting the premise that the direct toxicity of the H^+ ion concentration is the proximal cause of the poor growth of non-tolerant plants on acid soils. The low yields at pH 3.5 compared to pH 5.0 or 6.3 imply that the high H^+ activities were toxic irrespective of Ca concentration, in other words, the ameliorating effect of Ca at low pH was limited. Shamsuddin *et al.,* (1992) found little evidence of an ameliorative Ca effect on groundnut nodulation and growth in the presence of toxic concentrations of Al.

As in Experiment 5, the tufts of hair covered with mucilage showed on the surfaces of gynophores cultured at all pH levels and all Ca concentrations, and they continued to show until the pods were harvested five weeks later. Septate and non-septate hairs were observed on gynophore and pod surfaces at all pH and Ca concentrations, but sparse cover of hairs was observed at low pH and Ca concentrations while pods formed at higher pH and Ca levels generally had dense cover of hairs. The ability to form hairs on gynophore surfaces even at low pH and Ca levels could be viewed as plant adaptation to low pH and Ca, and coupled with corresponding root hair formation, could substantially increase the tolerance of groundnut to low pH and Ca.

Microscopic examinations of the excised seeds showed that normal embryos were formed even at pH 3.5 at the lowest Ca concentration (Figure 5.14). However, plumule development was much improved with 1000 μM Ca at pH 5.0 or 6.5 compared to pH 3.5. The cotyledons were not affected by pH or Ca concentration. Microscopic and histological studies by Harris & Brolman (1966) on comparison of calcium and boron deficiencies of groundnut showed that boron deficiency affected the inside of cotyledons and sometimes caused the tips of the plumules to be small and pointed, whereas Ca deficiency affected mainly the vascular system at the base of the plumules.

Little information is available on the effect of Ca on pod growth and maturity of groundnut. However, accelerated growth can be expected at higher Ca concentrations, since Ca^{2+} ions play an important role in cell growth (Bush, 1995). The importance of Ca in plant nutrition stems from its role in membrane stability and the maintenance of cell integrity (Epstein, 1972). With Ca deficiency the membranes become leaky and solutes are lost from the cytoplasm. This means that at low pH levels where Ca^{2+} is displaced by H^{+} (Kinraide *et al.,* 1994), retarded pod growth could be expected. There is a decline in Ca influx in fruits during development because of an increase in solute influx through the phloem, a decline in the rate of cell division and the formation of new binding sites for Ca, and a change in volume/surface area (Kirkby & Pilbeam, 1984). All these factors would be expected to influence pod growth.

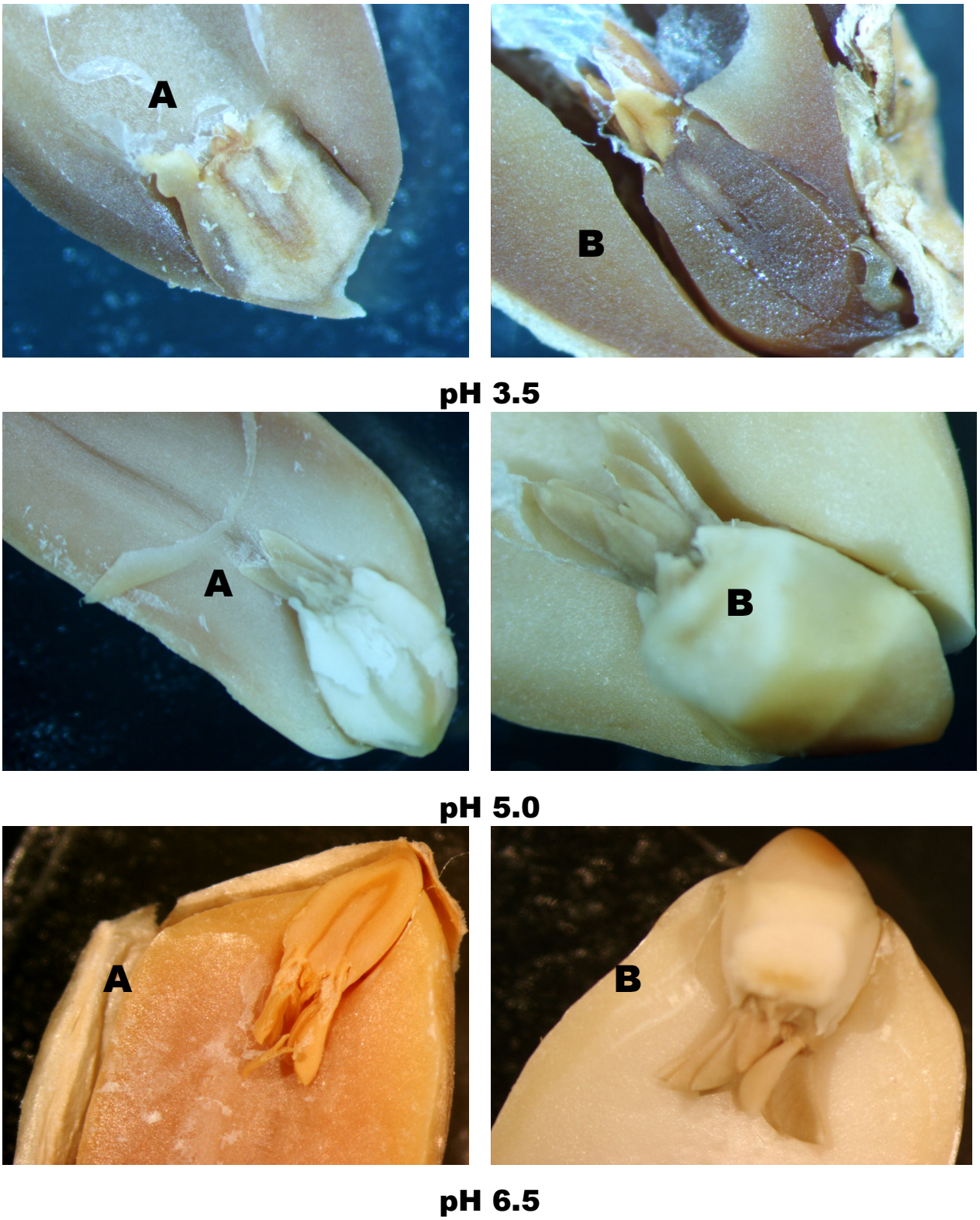


Figure 5. 14 Photomicrographs of cotyledons and embryos produced at different pH levels with 500 µM Ca (A) and 1000 µM Ca (B)

5.4 CONCLUSIONS

5.4.1 GERMINATION, SEEDLING SURVIVAL AND EARLY GROWTH

The results of this study indicate that low pH *per se* does not have a major impact on the germination of groundnut seed, but significantly influences the seedling survival and early growth. The germination of groundnut seed was tolerant of low solution pH; given that even at pH 3.0 a germination percentage of 86% was attained, and that increasing the pH in the range 4.0 to 6.0 had no appreciable effect on germination.

The adverse effects of low pH on germination and seedling survival were more pronounced in the absence of Ca, and became progressively less as the solution Ca concentration increased. Seedling survival was more sensitive to the effects of pH than seed germination, and both parameters were improved as the Ca concentration and pH values were increased. Groundnut seedlings survived best in the pH range 5.0 - 6.0. Seedling growth (root and shoot dry mass, root length and root surface area) also improved with increasing Ca concentrations in the solution. The combination of low Ca and low pH severely retarded lateral root formation. These results imply that early growth of groundnut can be improved in strongly acid soils if adequate Ca is made available to the germinating seed.

5.4.2 REPRODUCTIVE GROWTH

This work has shown that low pH *per se* has a significant effect on pod formation, yield and quality of groundnut. Pod initiation and expansion were highly sensitive to low solution pH, given that the latter caused significant delays in pod initiation, and resulted in no meaningful pod expansion, with only 12% and 55% of the cultured gynophores developing into pods at pH 3.0 and pH 4.0. Groundnut pod and kernel yields were best in the pH range 5.0 - 6.0, so was kernel quality. At lower pH values the quality of the seed was markedly deteriorated.

Low pH was more deleterious to pod initiation and expansion in the absence of Ca, and the damage was ameliorated by increasing the solution Ca concentration, thus indicating the involvement of a Ca-requiring process in overcoming proton toxicity as observed by Koyama *et*

al., (2001). At high solution pH levels (pH 5.0 and 6.5) Ca concentration had smaller effects on pod initiation, development and dry mass production compared to pH 3.0.

The observed dense pod hair formation and persistence at higher pH levels implies that uptake of Ca and other nutrients by the developing pods might be increased at higher solution pH levels. The persistence of the pod hairs during the crucial pod initiation stage would ensure adequate Ca supply, which would result in normal pod development.

These results support the hypothesis that in addition to Ca deficiency, high H^+ ion concentration *per se* can be a limiting factor for groundnut productivity in acid soils. It also implies that productivity of groundnut can be improved in strongly acid soils if adequate Ca is made available to the developing pods.

CHAPTER 6

GROUNDNUT SEEDLING SURVIVAL IN ACID SOILS AS AFFECTED BY SEED PELLETING OR PRIMING WITH CALCIUM

6.1 INTRODUCTION

Growth of groundnut in soils with pH values below 5.3 is poor due to nutrient deficiencies or toxicities associated with low pH stress. In highly weathered soils, soil solutions tend to be low in nutrient cations, including Ca (Bell & Gillman, 1978; Isbell, 1978). Consequently, Ca deficiency is a common problem even for plants with low Ca requirements (Juo & Uzu, 1977). The susceptibility of legumes to soil borne fungi is higher in soils with low Ca content, resulting in poor establishment (Bateman & Lumsden, 1965). For groundnut production in acid soils, Ca is the essential element most commonly deficient (Gascho & Davis, 1994). While the most important consequences of Ca deficiency for groundnut productivity occur in the reproductive stages of development, some indications of Ca insufficiency may be evident in the vegetative stages of growth (Gascho & Davis, 1994). Low Ca concentrations in the soil as well as in the seed result in greatly reduced germination and seedling survival (Harris & Brolman, 1966; Adams & Hartzog, 1991). Poor germination and seedling survival were observed in sandy soils with Ca levels below 21 mg kg^{-1} in the upper 15 cm of the soil profile (Gascho & Davis, 1994). In Experiment 3 (Chapter 5), adequate Ca during germination considerably improved the survival rate of groundnut seedlings at low soil pH.

While liming may ameliorate most of the infertility factors associated with soil acidity (Foy, 1992), increasing the pH by liming is sometimes expensive or impractical, especially in low-input agriculture, thus warranting the need to look for alternative strategies to improve productivity on acid soils. Pelleting seeds with lime is a strategy often used to combat unfavourable soil conditions such as low pH (Loneragan *et al.,* 1955; Kumar Rao & Patil, 1977; Pijnenborg & Lie, 1990; McGuire & Hannaway, 1996). The practice of pelleting legume seeds with lime and the appropriate *rhizobia* is to provide a microenvironment around the seed more favourable for rhizobial survival, thereby improving legume production on acid soils. This practice is

commonly used on soybeans, clover and alfalfa in order to ensure successful nitrogen fixation (Lowther, 1974; Cordero & Blair, 1978; Rice & Olsen, 1983; Pijnenborg & Lie, 1990; Spilde, 1997).

Seed pelleting is essentially a "seed coating" technique used primarily to improve the plantability of crops. The pelleting material is composed of an amalgam of fillers such as calcium carbonate, talc, clays, vermiculite etc., and cementing agents or binders such as various starches, sugars, gelatin, methyl cellulose, waxes, gum arabic, polyvinyl alcohol or even water (Cordero & Blair, 1978; Desai *et al*, 1997). The advantage of pelleting is that beneficial compounds can be incorporated into the pellet, while the major disadvantage is the tendency for the pellet to dry out under low moisture conditions, halting germination. Baker & Hatton (1987) documented that coating rice seed with calcium peroxide increased germination and plant establishment. In their various forms, seed coatings have become an important part of modern agriculture, and some have been shown to improve emergence and seedling growth in agronomic crops (Mikkelsen, 1981; McGuire & Hannaway, 1996; Spilde, 1997).

Seed priming or osmoconditioning, is a water-based process that is carried out on seeds to increase uniformity of germination and emergence, and enhance plant establishment. It entails the partial germination of seeds by soaking them in water (or in a solution of salts) for a specified period of time, and then re-drying them just before the radical emerges (Copeland & McDonald, 1995; Desai *et al*, 1997). Priming stimulates many of the metabolic processes involved with the early phases of germination. Given that part of the germination process has already been initiated, seedlings from primed seeds emerge faster, grow more vigorously, and perform better in adverse conditions (Baker & Hatton, 1987; Desai *et al*, 1997). The duration of the emergence period is decreased, leading to a more uniform plant stand (Mikkelsen, 1981; Baker & Hatton, 1987).

While pelleting or enriching seed with nutrients have been successfully practiced on some agronomic crops (Mikkelsen, 1981; McGuire & Hannaway, 1996; Spilde, 1997), information on effects of the techniques on groundnut is scant. Chapter 5 showed seedling survival is severely reduced at low soil pH. Haller (1983) observed that it was imperative for sweet clover and alfalfa to germinate in a neutral medium if reasonable yields were to be achieved on strongly acid

soils (pH<4.0). This study was thus designed to determine the value of coating seed with Ca (pelleting) or fortifying it with Ca (priming) in improving germination and seedling growth of groundnut in acidified sand culture or in an acid soil in the field. The study hypothesized that pelleting or fortifying (priming) groundnut seed with Ca can provide sufficient Ca to ameliorate the adverse effects of acidification in the sensitive seedling stage, and that the benefit of Ca pelleting or priming on seedling survival would be due to counteraction of acidity in the vicinity of the germinating seed, in addition to the improved supply of calcium to the seed. This hypothesis was based on previous observations that both germination and seedling survival were improved as the Ca concentrations and pH values were increased (see Chapter 5).

6.2 MATERIALS AND METHODS

The effect of Ca pelleting or Ca priming on the seedling survival of groundnut was studied in two experiments conducted in growth chambers at the University of Pretoria. The validity of the data obtained in the growth chamber studies was investigated by conducting a third experiment in the field at the University of Pretoria Experimental Farm.

6.2.1 SEED PREPARATION

Seed priming

Ca solutions were prepared by dissolving the appropriate quantity of each Ca source in 500 ml of water. To ensure that the Ca-material was thoroughly dissolved, the solution was placed on a shaker for 10 minutes or until completely dissolved. Seeds were imbibed for 2½ hours in the Ca solutions, after which they were spread out on paper towels to dry in the shade for 48 hrs.

Seed pelleting

The pelleting technique entailed dilution of 100ml of a 3% non-ionic wetting and sticking agent (*Sandovit*) in 300 ml of water, and thoroughly mixing the solution using a magnetic stirrer. Seeds were wetted with the sticky solution before being rolled in lime or gypsum, encasing the seed in a thick coating. The seeds were spread out on paper towels to dry. To minimize flaking of the pellet the seed was planted one hour after treatment.

6.2.2 TREATMENTS AND EXPERIMENTAL MANAGEMENT

EXPERIMENT 1

The experiment evaluated the effect of priming and pelleting seed with various Ca sources on seedling survival of groundnut grown in growth chambers at 27^{o}C and 100% relative humidity under a 16-hr photoperiod. The treatments used in the experiment are shown in Table 6.1, and they were arranged in a randomised complete block design with four replications.

Table 6.1 Description of the treatments used in Experiments 1 and 2.

Experiment 1	Experiment 2
1. Seed primed with 500 µM $CaSO_4$	1. Seed primed with 250 µM $CaSO_4$
2. Seed primed with 500 µM $CaCl_2$	2. Seed primed with 625 µM $CaSO_4$
3. Seed primed with 500 µM $Ca(NO_3)_2$	3. Seed primed with 1000 µM $CaSO_4$
4. Seed primed with 500 µM Calcimax**	4. Seed pelleted with 50 mg kg^{-1} $CaSO_4$
5. Seed pelleted with 50 mg kg^{-1} $Ca(SO_4)$	5. Seed pelleted with 50 mg kg^{-1} $CaCO_3$
6. Seed pelleted with 50 mg kg^{-1} $CaCO_3$	6. Control
7. Control	

**Calcimax is an organic chelate containing 8% Ca.

Seeds of cultivar *Kwarts* were planted in acid-washed sand contained in 35 x 30 x 15 cm deep seedling trays. The sterilized sand was moistened with a dilute nutrient solution whose composition was (µ*M*): 250 K, 250 N, 400S, 100 Mg, 10 Fe (as EDTA), 10 Cl, 3B, 0.25 Zn, 0.10 Mn, 0.07Cu and 0.02 Mo. This solution had a pH of 6.5, and was titrated with 0.1*M* H_2SO_4 to obtain two treatment pH values, namely pH 4.0 and pH 5.5.

The seedlings were allowed to grow for 21 days during which seedling mortality was assessed at 7-day intervals. At 21 days after emergence the surviving healthy plants were harvested, and roots were separated from the tops. The plant tops and roots were oven-dried at 80^{o} C for 48 hrs to determine dry mass.

EXPERIMENT 2

The experiment evaluated the effect of priming seed with $CaSO_4$ at various Ca concentrations or pelleting with $CaCO_3$ on seedling survival of groundnut grown at pH 4.0 and pH 5.5 in growth chambers set at 30^{o}C and 100% relative humidity under a 16-hr photoperiod. The treatments used in Experiment 2 are given in Table 6.1, and the experimental design and procedure were similar to those in Experiment 1. Seeds of cultivar *Falcon* were used in Experiment 2.

In addition to the seedling survival test, early growth rate of the seedlings was determined by planting batches of 100 seeds per treatment at 5 cm depth in sterilised sand in seedling trays. Hypocotyl and taproot elongation were determined on healthy normal seedlings after four days. The hypocotyl and taproot elongation tests were not replicated.

The seedlings were allowed to grow for 21 days during which seedling mortality was assessed at 7-day intervals. At 21 days after emergence, the surviving healthy plants were harvested, and roots were separated from their tops. The plant tops and roots were oven-dried at 80^{o} C for 48 hrs to determine dry mass. Root length and root surface area were estimated using a GLS root scanner (HP Scanjet 3C). The roots were classified into three diameter categories: (a) roots with diameter <1.0 mm, (b) roots with diameter 1.0 – 2.0 mm, and (c) roots with diameter >2.0 mm. The root surface area was measured in mm^2.

EXPERIMENT 3

The experiment evaluated the effect of seed pelleting and priming on seedling survival and early growth of groundnut in the field. The treated seeds (Table 6.2) were planted in an acid sand clay loam at the Hatfield Experimental Farm of the University of Pretoria. The pH (KCl) of this soil was 4.8. The soil is classified as mesotrophic, luvic dark red brown soil of the Hutton form (Soil Classification Group, 1991) and by the USDA Soil Taxonomy System (Soil Survey Staff, 1990), as loamy, mixed, thermic Rhodic Kaundidalf (Nel *et al.,* 1996). Cultivar *Kwarts* was planted in plots that comprised of two rows, each 1m long, on 7 February 2002, while *Falcon* was planted in similar plots on 21 February 2002. The plots were arranged in a randomised complete block design replicated eight times.

The surviving plants of cultivar *Falcon* were harvested 28 days after emergence while those of cultivar *Kwarts* were harvested 42 days after emergence. The measurements taken for both cultivars at harvest included plant height (distance from the ground level to tip of the longest stem), number of leaves on main stem and on whole plant, leaf area and shoot dry mass. The plant tops and roots were oven-dried at 80^{o} C for 48 hrs to determine dry mass.

Data for all three experiments were analysed using the GLM procedure of the SAS program package (SAS Institute, 1996). Samples of the treated seeds were analysed for Ca concentrations at the Central Analytical Laboratories (Pty) Ltd, Pelindaba, RSA.

Table 6.2 Description of the treatments used in Experiment 3

Treatments	Treatment code
1. Seed primed with 1000 µM $CaSO_4$	G-1000 µM
2. Seed primed with 2500 µM $CaSO_4$	G-2500 µM
3. Seed primed with 1000 µM Calcimax**	C/max-1000 µM
4. Seed primed with 1000 µM $CaNO_3$	$CaNO_3$ µM
5. Seed pelleted with 100 mg kg^{-1} $CaSO_4$	Gypsum
6. Seed pelleted with 100 mg kg^{-1} $CaCO_3$	Lime
7. Control	Control

**Calcimax is an organic chelate containing 8% Ca.

6.3 RESULTS AND DISCUSSION

EXPERIMENT 1

At 7 days after emergence seedling survival at pH 4.0 was not affected by low solution pH, but survival gradually declined during the 21-day experimental period (Figure 6.1). The decline in seedling survival was at a slower rate for seeds pelleted or primed with Ca. When the seed was not treated with Ca, seedling survival was 92% at 7 days after emergence, and declined to 71% at 21 days after emergence. With the exception of the $CaCl_2$ treatment, all the other seed treatments had survival rates greater than 90% at 21days after emergence. The adverse effects of low pH on seedling survival were minimised when seed was either pelleted or primed with Ca.

At pH 5.5, the seedling survival trend was similar to that observed at pH 4.0 (Figure 6.1). The lowest survival rates were observed in the control treatment (86%) and in the $CaCl_2$ treatment (89%). Seedling survival in the other treatments ranged between 94% and 100%, and pelleted seed tended to have higher survival rates compared to primed seed. It is interesting to note that even at this relatively favourable pH (pH 5.5) seedling survival was significantly improved by seed treatment with Ca.

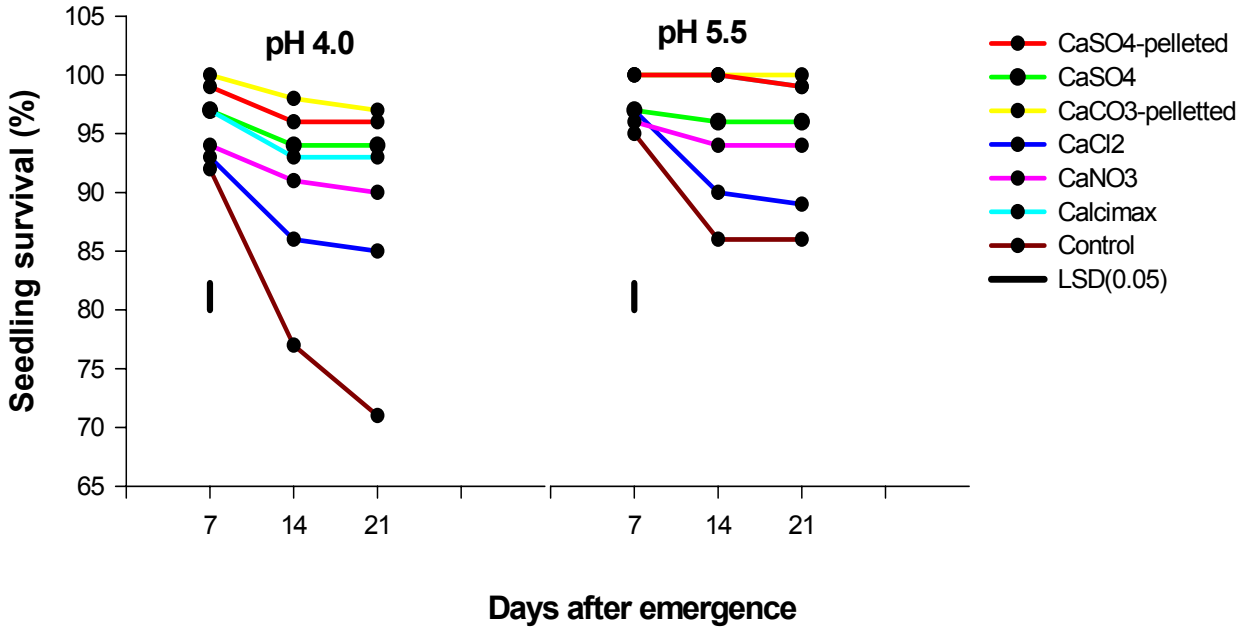


Figure 6.1 Effect of seed pelleting or priming on seedling survival at 7, 14 and 21 days after emergence -Experiment 1

Pelleting or priming the seed with Ca improved seedling growth (Figure 6.2). There was a significant interaction between Ca seed treatment and solution pH on shoot growth at 21 days after emergence (Table 6.3). For the control, calcimax and $CaCl_2$ treatments there were no improvements in shoot dry mass as the pH was increased from 4.0 to 5.5, but significant increases in dry mass were observed for the rest of the treatments. At pH 4.0, the shoot dry mass ranged from 0.24 g plant^{-1} in the control treatment to 0.42 g plant^{-1} in the gypsum pelleted treatment. At pH 5.5 the shoot dry mass in the control treatment was significantly lower (0.29 g plant^{-1}) than in all the other treatments except the $CaCl_2$ treatment. Thus, both pH and seed treatment had significant effects on shoot growth.

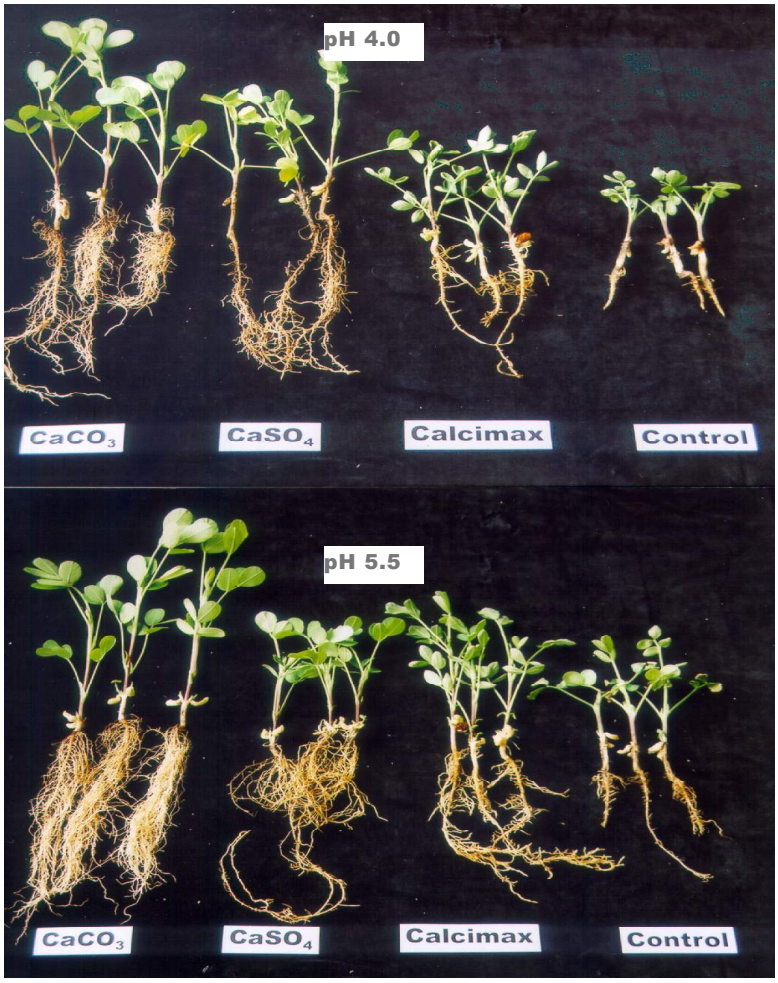


Figure 6.2 Effect of pelleting or priming seed with Ca on growth of seedlings at pH 4.0 or 5.5.

In general, pelleting the seed attained the highest increases in shoot dry mass at both pH levels, with similar values being observed whether the seed was pelleted with lime or gypsum. Pelleting or priming the seeds appeared to improve shoot growth more at pH 5.5 than at pH 4.0. This differential effect could be attributed to improved nutrient availability associated with favorable pH. Improved availability of Ca would result in improved root growth, since Ca is involved in cell division and cell elongation (Hertel, 1983). The detrimental effects of low pH on root capacity to absorb nutrients can explain the inhibited growth at pH 4.0, since excess H^+ ions interfere with ion transport and uptake, and the membranes of plant roots exposed to low pH for a long time become leaky, resulting in the loss of already absorbed nutrients (Foy, 1992).

Table 6.3 Effect of Ca-treatment on shoot and root dry mass and shoot:root ratio of groundnut at 21 days after emergence

Treatment	Shoot dry mass ($g\ plant^{-1}$)		Root dry mass ($g\ plant^{-1}$)		Shoot:root ratio	
	pH 4.0	**pH 5.5**	**pH 4.0**	**pH 5.5**	**pH 4.0**	**pH 5.5**
1. $CaSO_4$	0.308	0.456	0.081	0.103	4.1	4.4
2. $CaCl_2$	0.285	0.322	0.083	0.082	3.4	3.9
3. $Ca(NO_3)_2$	0.306	0.463	0.080	0.082	3.9	5.6
4. Calcimax	0.312	0.352	0.079	0.073	4.0	4.8
5. $Ca(SO_4)$ pellet	0.416	0.558	0.085	0.096	4.9	5.8
6. $CaCO_3$ pellet	0.409	0.631	0.080	0.106	5.1	5.9
7. Control	0.238	0.285	0.076	0.082	3.0	3.5
Mean	**0.325**	**0.438**	**0.081**	**0.089**	**4.1**	**4.8**
LSD $_{(0.05)}$ pH	*0.023*		*0.021*		*0.194*	
Ca-source	*0.043*		*0.013*		*0.428*	
pH x Ca-source	*0.061*		*0.036*		*0.512*	

The low survival rates and insignificant effects on shoot dry mass of seeds treated with $CaCl_2$ cannot be explained since chlorine toxicity has not been found in groundnut (Gascho & Davis, 1994). Studies with other legumes have pointed to the possibility of yield depressions due to chloride toxicity (Islam *et al.,* 1987). When they tested the response of plants to Ca concentrations with chloride or sulphate as counter-ion they observed that a number of dicotyledons (soybean, french bean, lupin, sunflower, safflower) exhibited large growth responses to a much higher range of solution Ca concentration when $CaSO_4$ was the source of Ca, compared to $CaCl_2$. They observed mild chlorosis of the lower leaves and yield depressions in soybean and french bean at 3000 µM $CaCl_2$, which they attributed to a possible calcium-induced Mg deficiency, since the same symptoms were not observed in the $CaSO_4$ treatment that had a higher solution Mg concentration.

Irrespective of the seed treatment, the effect of solution pH on root dry mass was not significant, with root dry mass averaging 0.08 g plant^{-1} at pH 4.0, and 0.09 g plant^{-1} at pH 5.5 (Table 6.3). The less adverse effects of pH on root dry mass compared to shoot dry mass of legumes has been observed by other investigators (van Beusichem, 1982; Yan *et al.,* 1992). Tang & Thomson (1996) reported that root dry mass of a number of grain legume species responded to solution pH in a similar manner to shoot mass, but the effect of low pH on root weight was less than on shoot weight. This effect could be due to low pH triggering the plants to direct more assimilates to the roots than to the shoot system. Although pH did not affect root dry mass, pelleting or priming the seed resulted in non-significant increases in root dry mass of up to 12% at pH 4.0, and by up to 29% at pH 5.0, compared to the control treatment.

The ratio of shoot to root growth was significantly influenced by pH and by Ca treatment, with higher ratios being observed at pH 5.0 compared to pH 4.0 (Table 6.3). The shoot-root ratio at pH 4.0 was 3.0 in the control treatment, and 5.1 in the lime pelleting treatment. At pH 5.5, the shoot-root ratio increased from 3.5 in the control treatment to 5.9 in the lime pelleting treatment. Breeze *et al.* (1987) similarly observed that for white clover the shoot-root ratio was lower at pH 4.0 than at pH 5.0, 6.0 or 7.0. The lower ratios at low pH could be attributed to the partitioning of photosynthate between shoots and roots under nutrient-limiting conditions when roots become relatively stronger sinks for carbohydrate (Clarkson, 1984).

EXPERIMENT 2

In experiment 2, 100 germinating seeds per treatment were removed and measured for hypocotyl and taproot root elongation after four days, the results of which are presented in Table 6.4. The average length of the hypocotyls in the control treatment was 18mm at pH 4.0 and 19mm at pH 5.5. Seed pelleting resulted in improved hypocotyl development, with lengths of 25mm at pH 4.0 and 28.5mm at pH 5.5. In the primed treatments the hypocotyls were even longer at 31mm at pH 4.0 and 38 mm at pH 5.5. The taproots in the primed treatments had elongated up to 52mm at pH 4.0 and 66 mm at pH5.5, compared to 32 and 37mm at pH 4.0 and pH 5.5 respectively, in the control plots. The results showed a tendency for the hypocotyls and taproots of primed seeds to elongate at a faster rate than those of the pelleted seeds. This outcome would be expected, since many of the metabolic processes involved with the early phases of germination had already been

initiated during priming. With a faster rate of hypocotyl elongation, the primed seeds emerged on the fourth day after planting, and by day six all the seedlings had emerged, whereas emergence in the other treatments was complete by day 10. From an agronomic standpoint, this means that the fortified seed will be less vulnerable to soil fungal and bacterial pathogens since it emerges faster, and can also lead to a more uniform plant stand. A uniform stand of healthy, vigorous plants is essential if the yields and quality needed for profitable groundnut production are to be achieved.

Table 6.4 Hypocotyl and taproot elongation at 4 days as affected by seed treatment

Treatment	Hypocotyl length (mm)		Taproot length (mm)	
	pH 4.0	pH 5.5	pH 4.0	pH 5.5
1. 250 µM $CaSO_4$ - F	26	31	46	57
2. 625 µM $CaSO_4$- F	30	37	52	63
3. 1000 µM $CaSO_4$- F	31	38	50	66
4. $CaSO_4$- P	25	29	47	59
5. $CaCO_3$- P	25	28	49	59
6. Control	18	19	32	37

The number of seedlings surviving at pH 4.0 tended to decline from 7 to 21 days after emergence (Figure 6.3). In the control treatment only 77% of the original number of seedlings survived up to 21 days after emergence, compared to 97% when the seed was pelleted with lime. Seedling survival in the primed treatments improved from 87% to 93% as the Ca concentration increased from 250 to 1000 µM. The decline in the number of seedlings surviving at pH 5.5 in the primed and pelleted treatments was of a lesser magnitude than at pH 4.0. In the control treatment survival of the seedlings declined from 92 to 85% (Figure 6.3). Significant effects of pH on seedling survival were observed when the seed was not treated with Ca, with improved survival being observed at pH 5.5 compared to pH 4.0.

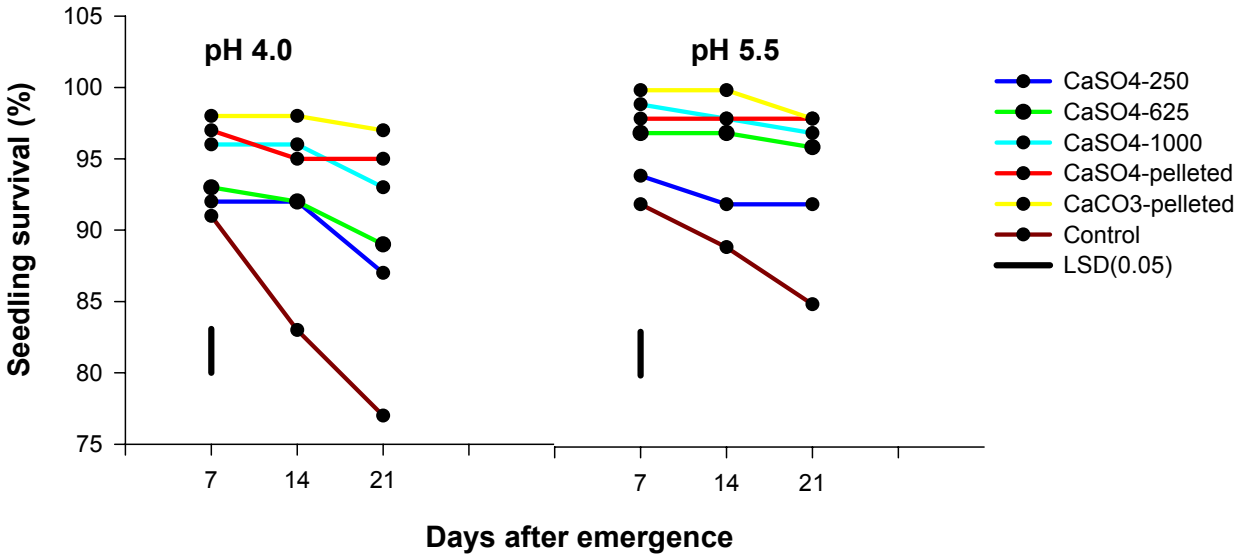


Figure 6.3 Effect of seed priming or pelleting on seedling survival (%) at 7, 14 and 21 days after emergence – Experiment 2

Overall, pelleting the seed with lime or gypsum resulted in the highest survival rates at both pH levels, and the harmful effects of pH were diminished when the seeds were either pelleted or primed with Ca. According to Asher (1987) legume seedlings rely on external Ca concentration at an early growth stage, because the seeds have low Ca content compared to the vegetative plant tissue (Welch, 1986), and Ca availability is low (Helms & Davis, 1973). Consequently, low Ca availability, coupled with low pH might inhibit plant emergence and establishment. Buerkert & Marschner (1992) postulated that the main effect of Ca supply on seedling survival of bean seedlings was to decrease exudation of amino acids and carbohydrates from seeds and seedlings. Exudates attract and activate zoospores, thereby resulting in increased fungal infection (Kuan & Erwin, 1980).

Seedling survival percentages showed that pelleting or priming seeds with small amounts of Ca sources appeared to provide sufficient Ca to enable groundnut seeds to establish well in acid soils. This observation was substantiated by an analysis of the primed seeds for Ca content, which showed increases in Ca content of 28% to 286% when seed was fortified with different concentrations and sources of Ca as shown in Table 6.5.

Table 6.5 Effect of pelleting or priming seed on the seed Ca content

Treatment	% Ca content
$CaSO_4$ at 250 µM	0.09
$CaSO_4$ at 625 µM	0.09
$CaSO_4$ at 1000 µM	0.11
$CaSO_4$ at 2500 µM	0.21
Calcimax at 1000 µM	0.17
$CaNO_3$ at 1000 µM	0.17
$CaCO_3$ pelleted at 50 mg kg^{-1}	0.27
Untreated seed (control)	0.07

Priming the seed with Ca positively influenced plant growth, and the higher the Ca concentration the better the growth (Figure 6.4).

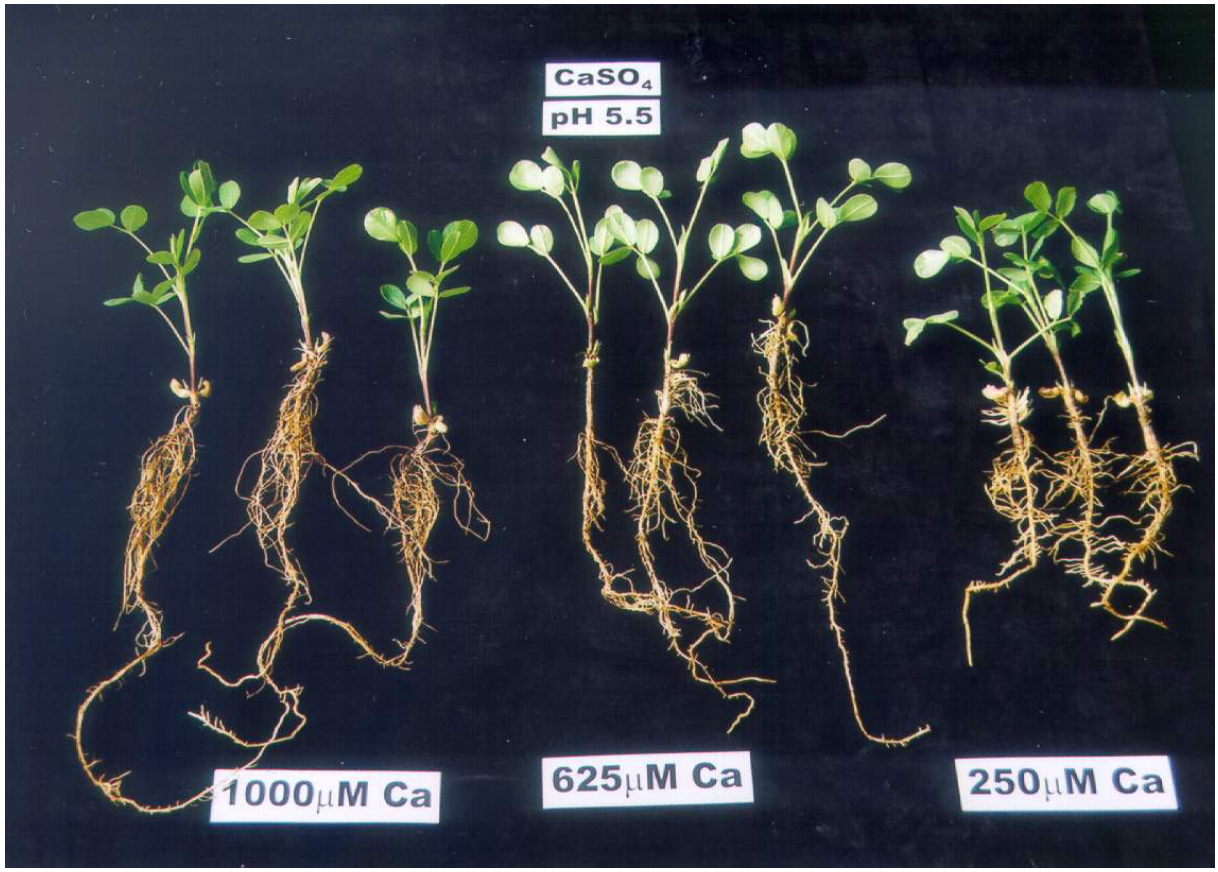


Figure 6.4 Seedling growth at 21 days after emergence as influenced by seed priming with gypsum at different Ca concentrations.

Shoot dry mass 21 days after emergence was significantly affected by seed priming and pelleting, but not by pH (Figure 6.5). The increases in shoot dry mass due to pelleting were 381% at pH 4.0 and 293% at pH 5.5. Seed priming increased the shoot dry mass by up to 275% at pH 4.0 and 241% at pH 5.5. In the seed priming treatments, a significant interaction was observed between pH and Ca concentration. The interaction showed significant increases in shoot dry mass as the Ca concentrations increased at the higher pH level. Plants pelleted with either lime or gypsum produced similar dry mass at both pH levels.

The root dry mass responded to seed priming or pelleting and to pH in a similar manner to shoot dry mass (Figure 6.5). At pH 4.0, root dry mass was highest (0.11 g plant^{-1}) when the seed was pelleted with lime, and up to 0.08 g plant^{-1} when the seed was primed with 1000 µM Ca. In the priming treatments root dry mass increased as the Ca concentrations increased. The root dry mass was higher at pH 5.5 compared to pH 4.0, especially in the pelleted treatments and in primed treatments when Ca concentrations were 625 µM or greater. Plants in the pelleted treatments produced significantly higher root dry mass compared to those primed with 1000 µM Ca.

There was no response pattern in the ratio of shoot to root growth, though there was a slight trend towards increased ratios at pH 4.0 compared to pH 5.0. These results are at variance with observations in Experiment 1, and this could be attributed to the differences in conditions in the growth chambers where the experiments were conducted. Luxuriant vegetative growth of groundnut has been observed in controlled environment experiments under warm temperatures (Marshall *et al,* 1992) or low irradiance (Ketring, 1979). Talwar *et al.* (1999) attributed enhanced plant growth under high temperature (35/30 ^{o}C) to the development of alternative sinks. In this experiment, the temperature in the growth chambers was set at 30^{0} C and 100% relative humidity under a 16-hr photoperiod, thus providing optimal conditions for luxuriant vegetative growth, especially the pelleted treatments (Figure 6.6). This resulted in very high vegetative biomass which contributed to the low shoot to root ratios.

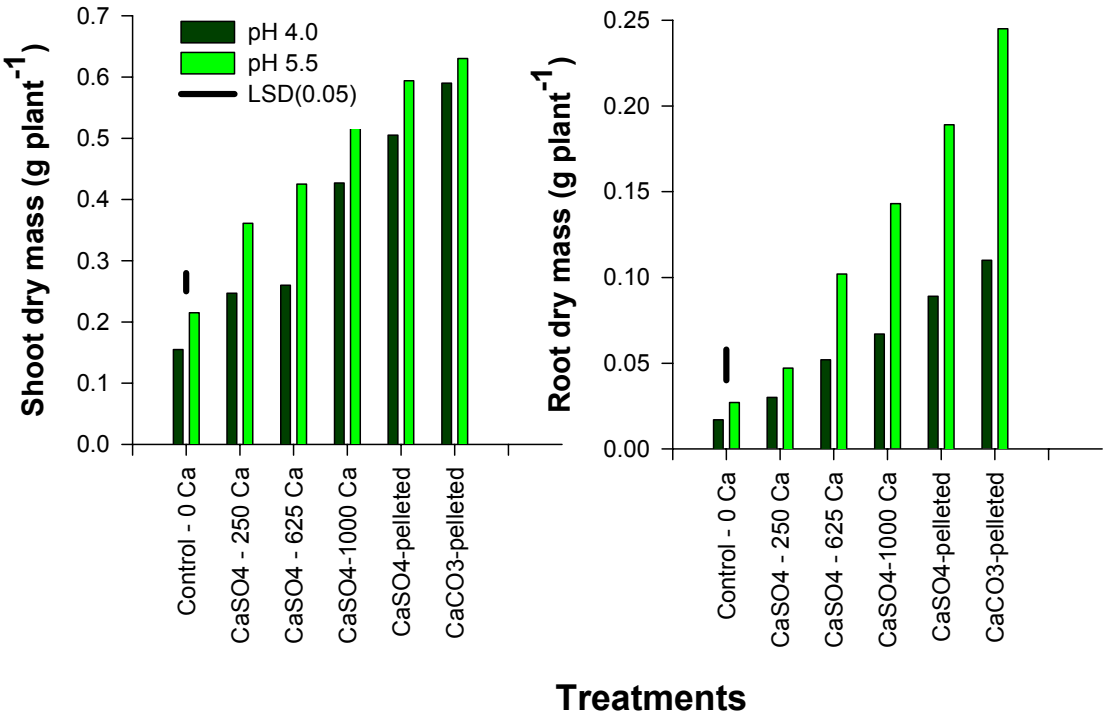


Figure 6.5 Effect of seed pelleting with $CaCO_3$ and seed priming with $CaSO_4$ on shoot and root dry mass at 21 days after emergence.

The total root length for plants grown at pH 4.0 was 230 mm per plant in the control treatment, and increased 29 times to 6530 mm for plants grown in the lime-pelleted treatment (Figure 6.7). At pH 5.5, the total root length of plants grown in the lime-pelleted treatment was 12530 mm. By comparison, plants pelleted with gypsum obtained a total root length of 6670 mm at the same pH level. At both pH levels, primed seeds did not have as good growth as pelleted seeds. Within the seed priming treatments, increasing the Ca concentrations from 250 to 1000 µM resulted in increases in root length of >300% at both pH levels. The interactive effects of pH and seed treatment on total root length were significant, with better root growth being observed at the higher pH level with the pelleted treatments. Pelleting the seed with gypsum resulted in better root growth than fortifying the seed with gypsum, even with 1000 µM.

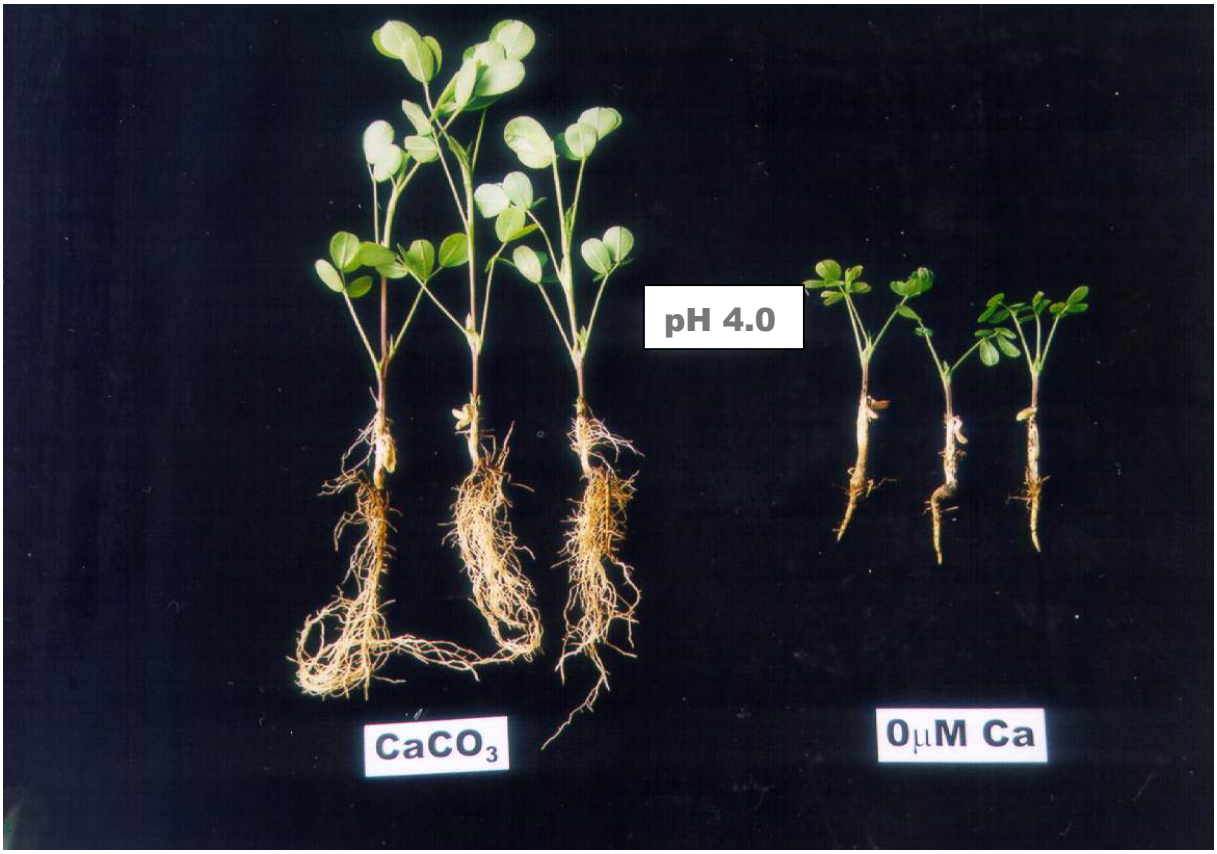


Figure 6.6 The effect of lime pelleting on seedling growth at pH 4.0 at 21 days after emergence.

Total root surface area per plant followed the same response trends as total root length (Figure 6.7). At pH 4.0, root surface area increased from 22mm^2 for plants of the control treatment to 220mm^2 for plants of the lime-pelleted treatment. Total root surface area also increased with increasing Ca concentrations in the primed treatments. At pH 5.5, the total root surface area was 396mm^2 in the lime-pelleted treatment compared to 35mm^2 in the control treatment. Overall, the root surface area increased as the pH was increased from pH 4.0 to 5.5. The increases in total root surface area were greater in the pelleted treatments compared to the primed treatments.

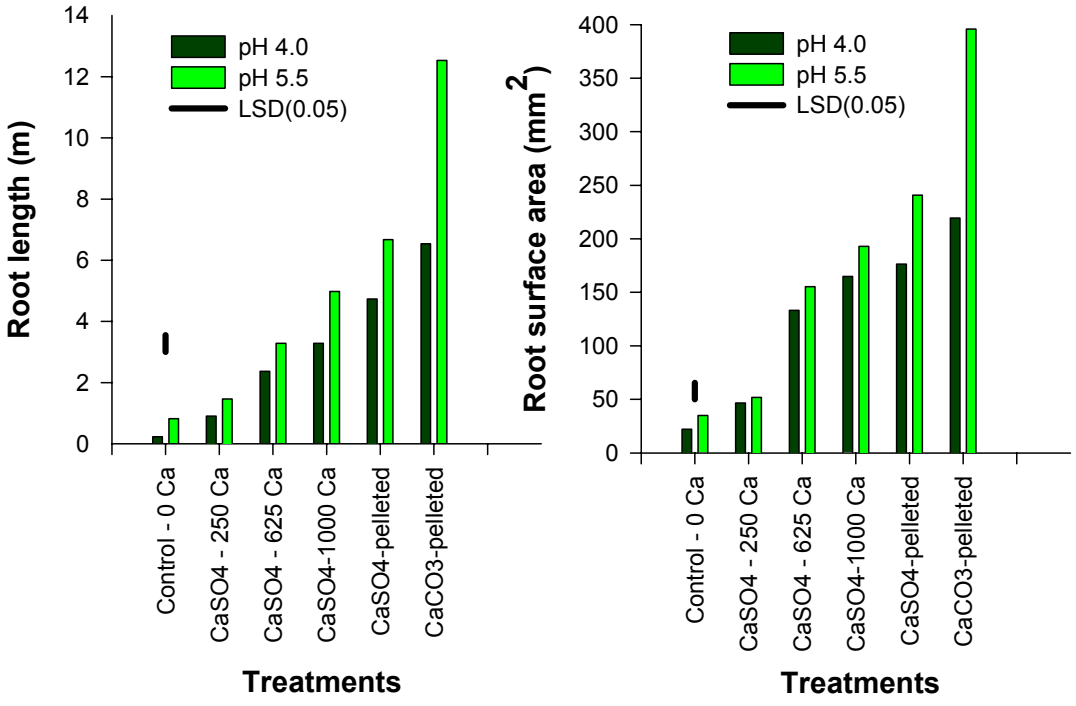


Figure 6.7 Effect of seed pelleting with $CaCO_3$ and seed priming with $CaSO_4$ on total root length and root surface area at 21 days after emergence.

Comparison of the priming versus pelleting effects on root development showed that the latter treatment was superior. The superiority of pelleting could be the result of a "liming effect" caused by the dissolution of lime or gypsum encasing the seed. This means that roots of the germinating seedlings pass through a band of "treated soil", which should facilitate better root growth. Determination of the pH of the soil solute after the plants were harvested at 21 days after emergence showed the pH values to be significantly higher in the pelleted treatments compared to the fortified treatments (Table 6.6). One can therefore deduce that pelleting, especially with lime improved the conditions for root growth in the microenvironment around the seed. In all the treatments the determined soil solute pH values were lower than the solution pH treatments, and this could partly be explained by the phenomenon of proton release in exchange for cations by roots, which results in acidification of the soil solution (Moore, 1974; Schubert *et al*, 1990). In addition, it is known that plants using NH_4^+ as a source of N decrease the pH of the rhizosphere (Nye, 1981; Galvalez & Clark, 1991), and the nutrient solution used in the experiment contained

a mixture of NO_3^- and $NH4^+$. Other possible causes of pH decreases in the rhizosphere include root exudation of amino acids and organic acids (Richards, 1987), or root respiration that results in dissociation of H_2CO_3 to supply H^+ ions (Mengel & Kirkby, 1987).

Table 6.6 Mean pH of soil solute at 21 days after emergence

Treatment	**pH 4.0**	**pH 5.5**
1. Seed fortified with 250 µM $CaSO_4$	3.6	5.1
2. Seed fortified with 625 µM $CaSO_4$	3.7	5.2
3. Seed fortified with 1000 µM $CaSO_4$	3.7	5.1
4. Seed pelleted with 50 mg kg^{-1} $CaSO_4$	3.9	5.4
5. Seed pelleted with 50 mg kg^{-1} $CaCO_3$	3.9	5.4
6. Control	3.6	4.8
Mean	**26.4**	**36.5**
LSD $_{(0.05)}$ pH	**0.051**	**0.061**
Ca-source	**0.074**	**0.097**
pH x Ca-source	**0.102**	**0.135**

EXPERIMENT 3

Seedling survival under field conditions was similar to that observed under controlled environments. The number of seedlings surviving in the control treatment gradually declined starting from 7 days after emergence (Table 6.7). For cultivar Falcon 82% of the original number of seedlings from the untreated seeds survived 21 days after emergence, whereas for cultivar Kwarts, the number of seedlings surviving in the control treatment declined from 90% at 7 days after emergence to 77% at 21 days after emergence. Overall, the decline in survival rates was of a lesser magnitude compared to the growth chamber experiments. Treating the seed with Ca significantly improved seedling survival of both cultivars, and pelleting resulted in the highest numbers of surviving seedlings. Increasing the Ca concentration from 1000 to 2500 µM in the gypsum priming treatment did not result in better seedling survival. Priming the seeds with 1000 µM Ca as either $Ca(NO_3)_2$ or calcimax achieved similar seedling survival as priming with 2500 µM gypsum. Overall, pelleting or priming the seed resulted in better seedling survival, and lime had the highest survival rates in both cultivars.

Table 6.7 Effect of seed treatment on groundnut seedling survival in the field

Treatment	Seedling survival (%) at 7, 14 and 21 days after emergence (DAE)					
	cultivar ***Falcon***			cultivar ***Kwarts***		
	7 DAE	**14 DAE**	**21 DAE**	**7 DAE**	**14 DAE**	**21 DAE**
Priming						
G-1000 µM	92	92	90	91	91	88
G-2500 µM	96	93	92	93	92	85
C/max-1000 µM	96	93	92	91	88	84
$CaNO_3$ –1000 µM	93	93	92	90	88	84
Pelleting						
Gypsum	97	93	91	96	92	90
Lime	99	97	97	99	95	92
Control	90	88	82	83	81	77
Mean	**95**	**93**	**91**	**92**	**90**	**86**
LSD $_{(0.05)}$	**6.56**	**5.55**	**6.70**	**5.13**	**6.15**	**7.62**

For cultivar Falcon all the vegetative growth parameters increased significantly when the seed was pelleted or primed (Table 6.8). Plants in the control treatments produced the least number of leaves per plant (10), had the least total leaf area per plant (91.4 cm^2) and the least shoot dry mass (0.84 g $plant^{-1}$). Priming or pelleting increased the number of leaves by up to 120%, leaf area by up to 179%, and shoot dry mass by up to 282%. Similar increases in the growth parameters were observed for cultivar Kwarts (Table 6.9).

For both cultivars, plants in the lime treatment bore more leaves per plant, had the highest leaf area and shoot dry mass compared to plants in the rest of the treatments. Priming the seed with gypsum at 2500 µM Ca did not have an advantage over priming with 1000 µM Ca for all the growth parameters. Overall, pelleting seed with lime or gypsum at planting gave better results than priming the seed. For both cultivars performance of seeds primed with gypsum was more enhanced than that of seeds primed with either calcimax or $Ca(NO_3)_2$.

Table 6.8 Effect of seed treatment on vegetative parameters of *Falcon* at 28 days after emergence

Treatment	Plant height (cm)	No. of leaves per plant	Total leaf area per plant cm^2)	Shoot dry mass (g $plant^{-1}$)
Priming				
G-1000 µM	12.6	18	175.6	2.44
G-2500 µM	11.5	18	181.4	2.21
C/max-1000 µM	11	13	123.6	1.95
$CaNO_3$ -1000 µM	10.9	12	132.7	2.17
Pelleting				
Gypsum	12.6	16	186.0	2.04
Lime	13.4	22	255.5	3.21
Control	9.8	10	91.4	0.84
Mean	**11.7**	**16**	**163.8**	**2.12**
LSD $_{(0.05)}$	**1.295**	**2.804**	**28.890**	**0.490**

Table 6.9 Effect of Ca-treatment on vegetative parameters of *Kwarts* assessed at 42 days after planting

Treatment	Plant height (cm)	No. of leaves per plant	Total leaf area per plant (cm^2)	Shoot dry mass (g $plant^{-1}$)
Priming				
G-1000 µM	15	23	323.0	3.11
G-2500 µM	13.6	22	233.0	2.68
C/max-1000 µM	12.8	22	234.9	2.13
$CaNO_3$ -1000 µM	12.5	22	255.8	2.79
Pelleting				
Gypsum	13.6	23	397.0	4.41
Lime	17.9	32	634.6	6.00
Control	11.3	16	156.1	1.69
Mean	**13.8**	**23**	**319.2**	**3.26**
LSD $_{(0.05)}$	**2.169**	**4.031**	**58.758**	**1.120**

Similar results on improved plant growth in acid soils due to lime pelleting have been observed (Loneragan & Dowling, 1958; Deinum & Eleveld, 1986; Pijnenborg & Lie, 1990). Loneragan & Dowling (1958) observed better growth of *Trifolium subterraneum* L. after coating the seeds with lime to counteract acidity. Deinum & Eleveld (1986) reported that lucerne seeds pelleted

with 30 kg ha^{-1} $CaCO_3$ nodulated significantly better and produced almost similar dry mass to seeds grown in soils limed with 1000 kg ha^{-1} $CaCO_3$. Pijnenborg & Lie (1991) observed better seedling establishment and nodulation of lucerne (*Medicago sativa* L.) due to lime-pelleting, and this resulted in improved nitrogen yield.

6.4 CONCLUSIONS

The results demonstrate that priming or pelleting groundnut seed with Ca improved seedling survival and the vegetative growth of the plant at low pH. The most effective source of Ca for pelleting groundnut seeds was $CaCO_3$, while $CaSO_4$ was the most efficient source of Ca for seed priming. Coating or priming seeds with small amounts of these Ca sources appeared to provide sufficient Ca to enable groundnut seeds to establish well in acid soils. Thus, efforts to optimise conditions for better seedling establishment in acid soils by providing "starter" Ca to the seed should be further investigated for consideration in situations where adequate lime cannot be applied. Experiments to establish whether the enhanced growth observed during the early vegetative stages will be reflected in improved yields should be initiated on the acid sandy soils in the smallholder sector of Zimbabwe.

CHAPTER 7
GENERAL DISCUSSION

7.1 EFFECT OF AMENDMENTS ON SOIL CHEMICAL PROPERTIES

Because the fruits of groundnut develop underground, they are just as vulnerable to direct effects of soil acidity as the roots are, thereby necessitating an assessment of the effects of acidity both in the pod zone (0 – 10 cm soil depth) and root zone (20 – 30 cm soil depth) environments of groundnut. Results reported in Chapter 2 showed that with the exception of the control, gypsum (G) and superphosphate (SSP) treatments, lime treatments increased the soil pH in both soil depth layers at the two sites. The pH was raised more in the pod zone than the root zone. The largest pH increases were recorded in the 4000 kg ha^{-1} calcitic (CL) or dolomitic lime (DL) treatments. Combining gypsum and/or SSP with 2000 kg ha^{-1} CL did not affect soil pH differently than applying the lime alone.

In pot experiments reported in Chapter 3, gypsum increased the soil pH by up to 0.48 units, whereas CL and DL increased the soil pH by up to 1.28 and 1.48 units respectively. The small effect of gypsum on soil pH is most probably due to the "self liming" effect which hypothesizes that alkalinity is produced by ligand exchange that takes place between the added SO_4^{2-} and OH^- groups (Sumner, 1993). SO_4^{2-} adsorption neutralizes the positive charge present in acid soils, and generates a negative charge until the surface reaches a new zero point charge. This process determines the effect of gypsum on soil pH (Mora *et al.,* 1999). In this study, the small changes in soil pH due to gypsum application may imply the presence of a low positive charge in the acid soil, resulting in limited exchange between the SO_4^{2-} and OH^- ions.

The observed dissipation of the effects of ameliorants on soil pH by the third season, particularly in the pod zone supports the hypothesis that the groundnut plant is more exposed to soil acidity in the pod zone than in the root zone. Over the three seasons, the root zone pH values in the 4000 kg ha^{-1} lime treatment declined by 0.1 to 0.2 units at HRC, and 0.2 to 0.7 units at MES. In comparison, the decline in the pH values in the pod zone was by 0.9 to 1.0 units at HRC, and 0.6 to 0.8 units at MES. Scott *et al.* (1999) have reported a relationship between the rate of pH decline in the 0-10 cm soil depth with the pH increase achieved after lime application: the higher

the initial pH increase after lime application, the faster the rate of the decline and *vice versa*. Similarly, in this study, the decline in soil pH was more pronounced at MES where initial increases in pH of >2.0 units had been observed. This may imply that it will be more advantageous to apply lower rates of lime regularly.

The overall effects of the different Ca sources on soil N, P, K, Ca and Mg levels have been demonstrated in field experiments reported in Chapter 2 and in pot experiments reported in Chapter 3. The ameliorants did not cause any appreciable changes in soil N, P and K levels. However, the improved mineral N levels observed in the pod zone in the second season, particularly in the limed plots, may be a reflection of the influence of lime on groundnut productivity during the previous season, resulting in more crop residues on some plots. The absence of any treatment effects on soil P content could partly be attributed to the adequacy of plant available P in the soils at both sites. The soil K levels in this study are considered too low for production of groundnut, which requires not less than 80 mg K kg^{-1} soil for optimal yields (Swanevelder, 1998). Therefore, potassium fertilization may be necessary to improve plant available K in the soils used in this study. The observed K changes in the root and pod zones due to the excreting of root-absorbed K through the pods have implications on the K-fertilization programmes in cropping systems that include groundnut. Shallow-rooted crops can be sequenced with groundnut so that the shallow-rooted crops can utilize the recycled K.

Significant increases in soil exchangeable Ca and Mg levels were observed with application of CL or DL, and the higher the application rate, the greater the increase. Gypsum application increased exchangeable Ca levels, but not Mg, whereas in the SSP treatment the Ca and Mg levels were generally not different from the control treatment. Most of the residual effect of the applied ameliorants on exchangeable Ca was found in the root zone, which agrees with the soil pH levels in that zone. This suggests that in this sandy soil most of the Ca applied will be leached out of the pod zone into the root zone within about three years after application.

The most consistent effect on soil acidity amelioration by gypsum was one of increased exchangeable Ca, whereas CL and DL increased soil pH and exchangeable Ca and Mg levels. The effects of applied ameliorants on soil N, P and K content were not always consistent, making

the interpretations of improved plant growth difficult. Overall, the soil pH levels in the control, gypsum and SSP-treated plots were below the optimum levels (pH 5.5 to 6.2) for groundnut growth (Gibbons, 1980). The K and Mg levels were also limiting. The suggested optimum soil Ca levels for Spanish-type groundnuts are around 125 mg kg^{-1} (Cox *et al.,* 1982). In view of that, the Ca levels in the pod zone were adequate in all but the control plots at both sites, and the gypsum and SSP-treated plots at MES.

7.2 EFFECT OF AMENDMENTS ON PLANT MINERAL COMPOSITION

The response trends of the leaf nutrient concentrations generally reflected the soil nutrient status. The direct and residual effects of ameliorants improved soil Ca and Mg levels, so did they improve the leaf Ca and Mg levels. Magnesium concentrations were within the established sufficiency ranges in all treatments, whereas adequate leaf Ca concentrations were mostly observed in plants growing in limed plots. The direct as well as residual effects of the applied ameliorants on leaf N, P and K concentrations were not significant, just like they were not significant for soil N, P and K levels. However, the concentrations of N and P in the shoots appeared to be adequate for unrestricted growth of groundnut, whereas K concentrations were deficient. The tendency for the leaf nutrient content to reflect the soil nutrient status demonstrates the value of leaf nutrient analysis for purposes of diagnosing nutrient deficiencies.

Despite the significant effects of applied ameliorants on the exchangeable Ca content of the soil, the kernel Ca content was not influenced to the same extent. The kernel Ca concentrations were within sufficiency levels in all but the control, gypsum and SSP treatments. Application of the ameliorants significantly influenced the kernel Mg concentrations, but had small and variable effects on N, P and K concentrations. The shell nutrient concentrations showed clearer and consistent responses to application of ameliorants, particularly Ca. It therefore appears that analysis of the shells rather than the kernels will give a more reliable indication of the soil Ca status.

7.3 EFFECT OF AMENDMENTS ON GROWTH, PRODUCTIVITY AND QUALITY OF GROUNDNUT

The direct and residual benefits of application of ameliorants were manifested in improved plant stands, better growth, nodulation, productivity and quality of groundnut. From the pot experiments it was observed that increasing the Ca application rates of CL, DL and gypsum up to 403 kg ha^{-1} elicited the best effects on growth and productivity of groundnut. The better growth in the lime treatments appeared to be the result of the synergistic effects of favorable soil pH and Ca levels. Despite the reduced nodulation in the gypsum treated plots, growth was not retarded, and neither did the plants show any clear N-deficiency symptoms. Overall, the influence of the ameliorants on vegetative growth of groundnut was of the order CL>DL>G.

At equal Ca application rates, groundnut kernel yield from the gypsum treatment was comparable to that obtained with lime, particularly dolomitic lime. The similar yields appeared to result from the influence of gypsum on yield components. Results from the pot experiments showed that plants in the gypsum treatment had the highest proportions of mature pods per plant, sound mature kernels and shelling percentage, and the least percentage of pops. All these parameters influence kernel yield. These results confirm the superiority of Ca from gypsum in improving groundnut quality because of the higher solubility of gypsum. The higher yields in the CL treatment compared to gypsum are attributed to the added advantage of lime not only increasing the Ca and Mg status, but also creating favorable conditions by reducing toxicities of H, Al and Mn, if present.

Over the three seasons of the field experiments the yield responses to applied ameliorants were consistent, with the highest yields being obtained from the CL or DL treatments. It appears that the changes in soil Ca content were largely responsible for the observed increases in yield. The reasons for higher increases in yield in the second and third seasons compared to the first are not obvious. However, it is probable that in addition to the influence of seasonal variations in rainfall amount and distribution, there were additional benefits from application of the ameliorants such as improved Mo availability, more crop residues, improved microbial breakdown of organic matter and other spin-offs that would only manifest themselves after some time.

Despite the various significant correlations between kernel yield, yield components and soil parameters, path coefficient analysis proved an effective tool for isolating the specific causes of poor groundnut growth on acid sandy soils. Pod number was the most important determinant of kernel yield, while plant stand and percentage of pops were the least important plant parameters influencing kernel yield. This implies that management strategies that increase number of pods per ha should be adopted. The soil parameters observed to be highly correlated with kernel yield were pH and Ca at both sites, in addition to Mg at MES. The greatest influence of soil pH on plant parameters was on plant stand, whereas Ca and Mg influenced the other plant parameters more than plant stand, leading to the conclusion that poor groundnut yields on the acid soils at both sites are largely caused by deficiencies of Ca and Mg, and by low pH *per se*.

7.4 GENOTYPIC VARIATION IN NUTRIENT USE EFFICIENCY

The study on variation in efficiency of nutrient uptake and utilization by groundnut genotypes showed that there are genetic differences in groundnut yield potential and nutrient utilization efficiency. The genotypes that were able to extract more nutrients from the soils generally produced high yields. Since the adaptation of plants to acid soils requires highly efficient uptake and/or utilization of nutrients, particularly Ca, Mg and P (Marschner, 1995), identification of genotypes with greater tolerance to low soil levels of these nutrients has potential to improve groundnut productivity on acid soils. It is suggested that the most appropriate parameter to identify groundnut genotypes with high yield potential in acid soils is Ca use efficiency in kernel production. It should, however, be realized that genotypes more efficient in the uptake/utilization of nutrients like Ca, Mg, P, Mo, provide only an interim solution to the acid soil problem. Ultimately, liming to ameliorate acid soil infertility will be essential to sustain productivity.

7.5 EFFECT OF pH AND CA ON VEGETATIVE AND REPRODUCTIVE PRODUCTIVITY

In this study, low pH *per se* did not have a major impact on the final germination of groundnut seed, given that germination percentages as high as 86% were attained at pH 3.0. However, the slower germination observed at low pH suggests that the imbibed seeds in the soil could have been more vulnerable to soil fungal and bacterial pathogens, leading to reduced seedling

establishment. This assertion is supported by the highly significant path coefficients relating soil pH to plant density reported in Chapter 2.

Low soil pH was shown to significantly influence the seedling survival and early growth of groundnut, with the adverse effects more pronounced in the absence of Ca. Seedlings survived best in the pH range 5.0 - 6.0. Seedling growth (root and shoot dry mass, root length and root surface area) was also best in the pH range 5.0 - 6.0. Rooting environments low in exchangeable Ca present a hostile environment for root proliferation, and any increase in soluble Ca is likely to promote rooting (Hanson, 1984). Thus, the poor root growth observed at low solution pH and Ca concentrations would be expected because high H^+ concentration in the root zone interferes with nutrient uptake (Foy, 1992). Competition between H^+ with Ca on absorption sites may induce Ca deficiency, which results in inhibited root growth as a consequence of reduced mitosis and cell elongation (Rost-Siebert, 1985),

There were substantial increases in kernel Ca content as the pH was increased from pH 4.0 to 7.0, and adequate kernel Ca concentrations were observed at pH levels ≥ 5.0. The increases in kernel Ca concentration as the pH was increased from pH 4.0 to 7.0 perhaps reflect increased abundance and longevity of pod hairs as the pH increased. While peg and pod hair initiation took place at low pH, the longevity of the hairs was short. At pH 5.0 and above, hair density was higher, and the hairs lived longer, which could most likely improve Ca uptake by the reproductive structures during the crucial pod initiation, pod expansion and seed embryo formation stages, hence production of healthy pods. However, the increases in kernel Ca content with increasing pH could also result from a reduced amount of the H^+ ion in competition with Ca for uptake by the developing pods.

Low pH levels of 3.5 in the pod zone had detrimental effects on pod initiation and development. The effects included delayed pod expansion, which could be alleviated to some extent by increasing the solution Ca concentration from 500 to 2000 μM (Chapter 5). The significant delay in pod expansion caused by low pH could reduce the number of mature pods per plant at harvest. With pod number being the most influential determinant of kernel yield (Chapter 2), the

importance of adopting management practices to improve the proportion of mature pods per plant cannot be overemphasised.

Microscopic examinations of the excised seeds showed that normal embryos were formed at pH 5.0 and above. This result is of importance to the smallholder farmers who recycle groundnut seed for several years, as it partly explains the poor crop stands generally observed in their fields. Planting poor quality seed in soils with low soil pH values could also exacerbate the poor crop stands (see Chapter 2). The occurrence of necrotic embryonic axes at low pH could be the result of Ca deficiency or caused by nutrient complexities in the pod zone associated with the low pH. The importance of maintaining favourable pH levels in the pod zone by applying lime is clear.

7.6 IMPROVEMENT OF SEEDLING SURVIVAL THROUGH SEED PELLETING OR PRIMING WITH CA

The advantages of treating seed (either pelleting or priming with Ca) to improve seedling survival and early growth were demonstrated. Pelleting or priming the seeds significantly reduced seedling mortality. Of all the Ca sources used to prime the seed $CaSO_4$ was the most effective. Significant improvements in numbers of surviving seedlings were obtained with concentrations as low as 250 μM Ca.

The advantage of pelleting over priming the seed was manifested in improved overall plant growth (dry mass production, leaf development and leaf area). However, priming had the advantage of earlier germination and complete emergence in a short period. The top layer of sandy soils dries easily, thereby reducing plant stands of seeds that take long to germinate. On these soils, seed priming would be beneficial in improving plant stands. Overall, lime pelleting was superior to gypsum pelleting, although the differences were not statistically significant.

7.7 CONCLUSIONS

- This study has shown that there is potential for improving productivity of groundnut on acid sandy soils of the smallholder-farming sector of Zimbabwe by applying Ca-containing materials to ameliorate soil acidity. Application of the Ca materials resulted

in increases in soil pH, which in turn significantly increased concentrations of Ca and Mg in the soil, leaves, kernels and shells of groundnut, but had small or variable effects on N, P and K concentrations. Annual applications of 200 kg ha^{-1} gypsum and 250 kg ha^{-1} SSP were not as effective as the traditional liming materials in ameliorating acid soils in which nutrient deficiencies and low pH *per se* are limiting groundnut growth and productivity. The observed rapid dissipation of the lime effect on soil pH implies that most of the Ca applied would be leached from the pod zone in a period of three years, thereby necessitating reliming. Application of lime at 2000 kg ha^{-1} was as effective as combining the same rate with either gypsum or SSP, implying that the combinations would impose an unnecessary cost burden.

- While calcitic and dolomitic lime were superior to gypsum in improving the vegetative and reproductive growth of groundnut, gypsum was superior in improving pod and kernel quality of groundnut, thus supporting the argument for dusting short-season groundnuts with gypsum in order to improve kernel quality.

- Path coefficient analysis identified the reasons for poor growth on the acid soils at HRC and MES as deficiencies of Ca and Mg, and low pH *per se,* and showed that pod number was the most influential determinant of kernel yield, implying that management strategies that increase number of pods per ha should be adopted.

- Variation existed among groundnut genotypes in yield, nutrient efficiency ratio (NER) and nutrient use efficiency (NUE) when grown on acid sandy soils. However, use of nutrient efficient genotypes to increase crop production should be augmented with judicious use of lime and fertilizers so that sustainable groundnut productivity on acid soils can be achieved.

- Use of the split-medium technique, in conjunction with pod culturing in nutrient solutions enabled a better assessment of the separate effects of pH and Ca in the pod zone. Results on the effects of pH and Ca on early growth and productivity of groundnut support the hypothesis that the direct toxicity of the H^+ ion concentration *per se* causes poor seedling

establishment, growth, yield and quality of groundnut. The negative effects are aggravated by the absence or low Ca supply. These results imply that growth and productivity of groundnut can be improved in strongly acid soils if adequate Ca is made available to the germinating seed, and to the developing pods.

- Pelleting seeds with $CaCO_3$, or priming with $CaSO_4$ appeared to provide sufficient Ca to enable groundnut seedlings to establish better in acid soils.

7.8 RECOMMENDATIONS

- With the magnitude of the yield responses and economic returns to lime demonstrated in this study, it is clear that the practical solution to poor groundnut productivity on acid sandy soils is to apply either calcitic or dolomitic lime. It is suggested that smallholder farmers cropping on acidic soils be encouraged to invest in lime, arguably still one of the more affordable inputs, in order to improve and maintain groundnut productivity. For those farmers who cannot afford to purchase the lime, amelioration of acid soil infertility using modest annual applications of gypsum or super phosphate is the most attractive ameliorative strategy for economic reasons.

- It is suggested that the breeding lines 106/96 and 418/93 that had high nutrient use efficiency (NUE) and nutrient efficiency ratios (NER) when grown on acid soils could be used in breeding programs screening for tolerance to soil acidity. This work needs to be carried out in conjunction with research on agronomic strategies to improve nutrient use efficiency in groundnut cropping systems so that sustainable groundnut productivity on acid soils can be achieved.

- The persistence and density of the pod hairs during the crucial pod initiation stage is envisaged to ensure adequate Ca supply, which would result in normal pod development. Studies on the genetics of peg hair formation and persistence at low pH would go a long way in assisting the plant breeders to improve the tolerance of groundnut to Ca deficiency.

- Efforts to optimise conditions for better seedling establishment in acid soils by providing starter Ca to the seed should be further investigated for consideration in situations where adequate lime cannot be applied. Furthermore, studies are needed to establish whether the effects of seed priming and pelleting observed during the early vegetative stages will persist into the reproductive stage.

SUMMARY

Various authors have emphasized acid soil infertility as a major limitation to sustainable crop production on Zimbabwean light-textured soils, particularly in the smallholder sector where the bulk of the country's groundnut crop is grown. Consequently, productivity of groundnut on these soils has declined, with pod yields averaging only 0.5 t ha^{-1}. Calcium (Ca) materials are universally used for ameliorating soil acidity, but their effectiveness depends on the soil type, and differs between the materials. Hence, the overall goal of this study was to examine the effects of soil acidity amelioration by four Ca-containing materials on vegetative and reproductive growth of groundnut so as to improve productivity on acid soils. The research questions that the study sought to answer were:

a) Which acid-soil infertility factors are limiting groundnut productivity on the acid sandy soils in Zimbabwe?
b) What are the effects of the Ca-source on soil pH and availability of the essential nutrients [Ca, magnesium (Mg), nitrogen (N), phosphorus (P) and potassium (K)] in the root and pod environments?
c) Do groundnut genotypes differ in their tolerance to acid soil infertility?
d) What are the effects of low pH *per se,* or the interactive effects of pH and availability of Ca on (i) germination, (ii) seedling survival, (iii) vegetative growth and (iv) reproductive growth of groundnut?
e) Can seed priming or pelleting with Ca provide sufficient Ca to ameliorate the effects of acidification in the sensitive seedling stage?

A field experiment was conducted over three seasons on acid soils at the Horticulture Research Station (HRC) and Makoholi Experiment Station (MES) to determine the direct and residual effects of application of calcitic lime (CL), dolomitic lime (DL), gypsum (G) and single superphosphate (SSP) on soil pH, nutrient status, growth and productivity of Spanish groundnut *cv.* Falcon. In addition, a greenhouse experiment was conducted at Harare Research Station with potted acid soil to monitor the chemical changes of the soil following application of the four Ca-containing materials and the resultant effects on groundnut productivity. In both the field and greenhouse experiments, the lime application rates were from 0 to 4000 kg ha^{-1}, while gypsum

application rates were from 0 to 3450 kg ha^{-1}, and those of SSP were from 0 to 250 kg ha^{-1}. The overall effects of CL and DL applied at 2000 or 4000 kg ha^{-1} were to increase soil pH, Ca and Mg content in both the pod and root zones. Leaf, and shell Ca and Mg concentrations were also influenced by application of CL and DL, whereas smaller effects were observed in kernels. Gypsum and SSP applications at 200 and 250 kg ha^{-1} respectively, had no significant effects on pH, Ca and Mg levels. However, when applied in equivalent amounts of Ca as CL or DL, gypsum improved the soil Ca status. Effects of the four ameliorants on the N, P and K levels in the soils and in plant material were generally neither significant nor consistent, making the interpretation of improved plant growth difficult. However, the concentrations of N and P were generally adequate both in the soils and in the plants. Application of CL or DL was more beneficial in improving crop growth and productivity compared to G or SSP and their combinations. However, G was the superior Ca-source in improving pod and kernel quality. The residual benefits of application of lime lasted for the duration of the field experiments despite the decline in soil pH over the seasons, and were manifested in improved plant stands, better growth, nodulation, productivity and quality of groundnut. By the end of the third season, the increases in cumulative kernel yields due to application of 4000 kg ha^{-1} lime over the control treatment were 110% at HRC, and 319% at MES. The study established that the most important factors limiting groundnut yields on the acid soils at HRC and MES were predominantly deficiencies of Ca and Mg, and low pH *per se.*

One way of increasing groundnut productivity on acid soil is to grow cultivars that are tolerant of soil acidity. Intra-species differences in plant tolerance to soil acidity have been observed for many crops. Some of the differences arise partly from different abilities in uptake and utilization of nutrients (Ca, Mg, P) whose availability is low under acidic conditions. Thus, another field experiment was conducted on an acid soil at MES to evaluate 12 advanced breeding lines and three commercial cultivars of groundnut on their tolerance to soil acidity. The groundnut genotypes showed significant differences in yield and nutrient utilization efficiency. Breeding lines 106/96 and 418/93 were the most efficient in nutrient uptake and nutrient use in acid soils with low fertility. They performed better than all the genotypes including the three commercial cultivars Jesa, Falcon and Teal.

Poor germination and seedling survival are among the factors that reduce crop yields. Because of their small size, plants are expected to be most vulnerable to soil acidity at early seedling growth stages. In groundnut, the pod growth and maturation occurs in the soil, which also exposes the developing pod to soil acidity. Thus, soil acidity is expected to adversely affect groundnut both in the root and pod environments. The greenhouse and growth chamber experiments conducted at the Hatfield Experimental Farm provided an opportunity for detailed studies on the basic effects of pH *per se* (pH 3.0 - 7.0) and its interaction with Ca (0 - 2000 μ*M* Ca) on germination, seedling survival, vegetative and reproductive growth of groundnut. The experiment on early seedling growth utilised potted sand that was watered with a nutrient solution containing various pH and Ca treatments. The experiment on reproductive growth involved the culture of attached gynophores in nutrient solutions containing the appropriate pH and Ca treatments. The results of this study indicated that low pH *per se* has a major detrimental impact on seedling survival, growth, pod formation, yield and quality of groundnut, but not on germination. The adverse effects of low pH were more pronounced in the absence of Ca, and became progressively less as the solution Ca concentrations increased. Significant delays in pod initiation and expansion were caused by low pH, with very little pod formation taking place at pH < 4.0. Although seeds were formed even at pH 3.0, normal embryos were only formed at pH 5.0 and above. Increasing the solution Ca concentration from 500 to 2000 μM had more effect on pod formation, yield and quality at pH 3.5 than at pH ≥ 5.0.

Since soil acidity adversely affects seedling survival and early growth, it is imperative to minimize these adverse effects by liming in order to increase crop productivity per unit area. For most resource-poor farmers, the cost of liming is beyond their reach. With these concerns in mind, experiments in growth chambers and in the field were conducted to determine the feasibility of counteracting the adverse effects of soil acidity on groundnut germination and seedling survival. The techniques examined were pelleting groundnut seeds with a Ca material (CL or G) or priming the seed with a solution containing Ca ($CaSO_4$, $CaCl_2$, $Ca(NO_3)_2$ or Calcimax). Significant reductions in seedling mortality were obtained with gypsum priming at Ca concentrations as low as 250 μM. The results of these experiments showed that groundnut establishment on acid soils can be significantly improved by pelleting seeds with small amounts of $CaCO_3$, or priming with $CaSO_4$.

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APPENDICES

Appendix Table A2.1 **Soil pH in the 0-10 cm and 20-30 cm soil depth layers at physiological maturity period of groundnut at HRC and MES, 1999/2000- 2000/01 seasons**

Treatment	HRC						MES					
	1999/2000		2000/01		2001/02		1999/2000		2000/01		2001/02	
	Soil depth layer (cm)											
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	5.1	4.8	4.9	5.0	4.6	4.8	4.2	4.0	4.3	4.4	4.4	4.6
L-2000	5.6	4.8	5.2	5.3	5.1	5.3	5.4	4.1	5.1	4.6	4.5	5.0
CL-4000	5.8	5.0	5.6	5.8	5.4	5.7	6.1	4.4	5.0	5.5	4.5	5. 1
DL-4000	5.8	4.9	5.2	5.5	5.4	5.3	5.9	4.3	5.3	5.1	4.5	5.0
SSP-250	5.1	4.8	4.9	4.7	4.8	4.8	4.1	4.1	4.2	4.5	4.8	4.5
G + CL	4.8	4.9	5.3	5.4	5.0	5.1	5.7	4.1	5.2	4.7	4.3	4.6
G + SSP	4.9	4.9	5.1	5.0	4.8	4.9	4.3	4.2	4.7	4.6	4.7	4.4
SSP + CL	5.5	4.8	5.5	5.2	4.9	5.1	5.0	4.1	5.2	4.7	4.3	4.9
SSP + G + CL	5.6	4.5	5.5	5.3	5.6	5.7	5.5	4.1	5.3	5.6	4.3	4.8
Control	4.6	4.8	4.7	4.3	4.5	4.3	4.1	4.0	4.2	4.2	4.3	4.1
Mean	***5.3***	***4.8***	**5.2**	**5.2**	**5.0**	**5.1**	**5.0**	**4.1**	**4.9**	**4.8**	**4.5**	**4.7**
LSD $_{(0.05)}$	***0.36***	***0.28***	**0.11**	**0.11**	**0.22**	**0.29**	**0.45**	**0.18**	**0.29**	**0.27**	**0.17**	**0.23**

Appendix Table A2.2 **Soil Ca and Mg levels in the 0-10 cm and 20-30 cm soil depth layers at physiological maturity period of groundnut at HRC, 1999/2000 and 2000/01 cropping seasons**

Treatment	1999/2000				2000/01			
	Soil nutrient level (mg kg^{-1})							
	Ca		Mg		Ca		Mg	
	Soil depth layer (cm)							
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	158	188	20	24	171	165	35	28
L-2000	233	143	34	27	195	189	30	25
CL-4000	332	145	35	28	239	266	42	30
DL-4000	282	160	91	34	236	233	54	42
SSP-250	209	150	29	25	145	179	35	26
G + CL	168	158	29	25	191	192	34	31
G + SSP	159	153	27	28	183	184	31	23
SSP + CL	232	142	29	21	170	185	33	26
SSP + G + CL	275	141	33	20	211	210	42	32
Control	167	131	23	24	106	99	31	26
Mean	**221**	**151**	**35**	**26**	**184**	**190**	**37**	**29**
LSD $_{(0.05)}$	**95.88**	**53.50**	**20.00**	**8.65**	**121.2**	**54.5**	**11.83**	**10..29**

Appendix Table 2.3 Soil Ca and Mg levels in the 0-10 cm and 20-30 cm soil depth layers at physiological maturity period of groundnut at MES, 1999/2000 and 2000/01 cropping seasons

Treatment	1999/2000				2000/01			
	Soil nutrient level (mg kg^{-1})							
	Ca		Mg		Ca		Mg	
	Soil depth layer (cm)							
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	71	52	7	6	135	129	29	27
L-2000	100	100	30	8	158	128	33	33
CL-4000	277	116	35	10	196	157	36	40
DL-4000	139	103	55	15	220	174	28	34
SSP-250	88	49	5	5	140	128	29	25
G + CL	189	86	20	8	184	143	23	31
G + SSP	74	59	8	7	146	137	27	26
SSP + CL	141	72	15	6	168	138	27	30
SSP + G + CL	171	72	19	8	202	162	29	30
Control	64	49	8	6	105	104	22	25
Mean	**131**	**76**	**20**	**8**	**165**	**140**	**38**	**30**
LSD $_{(0.05)}$	**109**	**61.8**	**8.33**	**3.05**	**112.1**	**79.2**	**12.38**	**9.98**

Appendix Table A2.4 **Soil N, P and K levels in the 0-10 cm and 20-30 cm soil depth layers at physiological maturity period of groundnut at HRC and MES, 1999/2000 season**

	HRC						MES					
	Soil nutrient level (mg kg^{-1})											
	N		P		K		N		P		K	
	Soil depth layer (cm)											
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	9	14	24	22	20	16	5	4	64	54	15	14
L-2000	10	7	26	24	18	14	2	4	48	55	19	11
CL-4000	6	6	23	23	20	16	3	5	43	51	23	10
DL-4000	5	10	27	24	17	12	2	2	42	43	24	11
SSP-250	5	6	30	21	16	16	1	3	74	60	14	11
G + CL	5	7	28	19	13	13	3	1	42	59	25	10
G + SSP	7	9	31	29	15	19	2	5	55	40	15	12
SSP + CL	4	8	23	23	12	12	1	1	61	59	15	12
SSP + G + CL	7	4	27	25	13	13	3	4	51	71	18	13
Control	6	3	23	23	18	14	2	5	67	55	21	18
Mean	**6**	**7**	**26**	**23**	**16**	**15**	**2**	**3**	**55**	**55**	**19**	**12**
LSD $_{(0.05)}$	**1.563**	**2.873**	**2.897**	**2.999**	**2.596**	**3.030**	**1.178**	**2.054**	**6.040**	**7.224**	**3.461**	**1.936**

Appendix Table A2.5 **Soil N, P and K levels in the 0-10 cm and 20-30 cm soil depth layers at physiological maturity period of groundnut at HRC and MES, 2000/01 season**

Treatment	HRC						MES					
	Soil nutrient level (mg kg^{-1})											
	N		P		K		N		P		K	
	Soil depth layer (cm)											
	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30	0-10	20-30
G-200	12	11	27	18	20	21	13	11	25	30	14	14
L-2000	11	7	18	17	13	21	12	12	24	27	14	12
CL-4000	10	11	23	20	17	21	12	8	25	29	13	11
DL-4000	11	35	22	28	17	23	14	8	19	25	12	11
SSP-250	9	10	23	23	17	19	10	10	20	25	13	12
G + CL	16	13	16	16	17	19	17	10	16	24	15	13
G + SSP	11	17	36	24	15	17	15	9	15	30	13	13
SSP + CL	7	13	24	24	15	17	17	9	17	26	14	14
SSP + G + CL	13	13	31	19	13	15	12	9	22	23	12	11
Control	12	11	19	13	20	19	20	6	21	21	17	17
Mean	**11**	**14**	**24**	**20**	**16**	**19**	**11**	**9**	**34**	**26**	**14**	**13**
LSD $_{(0.05)}$	**5.19**	**4.83**	**3.98**	**3.71**	**3.77**	**4.14**	**3.23**	**2.81**	**2.030**	**5.16**	**2.32**	**2.04**

Appendix Table A2.6 **Total correlation coefficients between soil, kernel and shell nutrient contents at HRC and MES**

	HRC					MES				
	Soil Nutrients									
	Ca	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**
Kernel Ca	0.044^{ns}	0.067^{ns}	0.241^{ns}	0.011^{ns}	0.072^{ns}	0.231^{ns}	0.173^{ns}	0.161^{ns}	0.177^{ns}	0.126^{ns}
" **Mg**	0.551**	0.081^{ns}	0.021^{ns}	0.353*	0.169^{ns}	0.532**	0.029^{ns}	0.134^{ns}	0.235^{ns}	0.232^{ns}
" **N**	0.249^{ns}	0.148^{ns}	0.213^{ns}	0.268^{ns}	0.060^{ns}	0.132^{ns}	0.032^{ns}	0.066^{ns}	0.034^{ns}	0.145^{ns}
" **P**	0.009^{ns}	0.182^{ns}	0.094^{ns}	0.016^{ns}	0.100^{ns}	0.061^{ns}	0.119^{ns}	0.202^{ns}	0.079^{ns}	0.081^{ns}
" **K**	0.250^{ns}	0.026^{ns}	0.328*	0.315*	0.020^{ns}	0.204^{ns}	0.111^{ns}	0.272^{ns}	0.245^{ns}	0.009^{ns}
Shell Ca	0.459**	0.180^{ns}	0.263^{ns}	0.207^{ns}	0.095^{ns}	0.472**	0.163^{ns}	0.230^{ns}	0.090^{ns}	0.229^{ns}
" **Mg**	0.485**	0.358*	0.227^{ns}	0.104^{ns}	0.104^{ns}	0.267^{ns}	0.224^{ns}	0.341*	0.099^{ns}	0.343*
" **N**	0.173^{ns}	0.313*	0.042^{ns}	0.097^{ns}	0.035^{ns}	0.246^{ns}	0.264^{ns}	0.031^{ns}	0.062^{ns}	0.085^{ns}
" **P**	0.127^{ns}	0.011^{ns}	0.046^{ns}	0.115^{ns}	0.089^{ns}	0.046^{ns}	0.113^{ns}	0.024^{ns}	0.137^{ns}	0.037^{ns}
" **K**	0.364*	0.311*	0.385*	0.180^{ns}	0.116^{ns}	0.313*	0.250^{ns}	0.154^{ns}	0.094^{ns}	0.119^{ns}

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). ^{ns} Correlation is not significant

Appendix Table A 2.7 **Effect of soil ameliorants on the proportion of mature pods and empty pods (pops) at MES**

Treatment	1999/2000		2001/02	
	Mature pods %)	Pops (%)	Mature pods (%)	Pops (%)
G-200	76.6	11.2	74.8	12.5
L-2000	73.6	13.2	71.2	14.3
CL-4000	79.6	10.2	78.7	10.6
DL-4000	74.8	12.6	69.2	13.9
SSP-250	73.1	13.4	69.7	15.1
G + CL	71.8	14.1	72.4	13.7
G + SSP	72.9	13.6	71.1	14.5
SSP + CL	73.1	13.5	74.5	12.7
SSP + G + CL	79.1	10.5	77.8	11.3
Control	57.5	21.3	45.4	22.3
Mean	**73.2**	**13.6**	**70.4**	**14.1**
LSD $_{(0.05)}$	**4.04**	**1.26**	**3.87**	**0.78**

Appendix Table A3.1 **Effect of Ca source and rate on soil chemical parameters at peak flowering period of groundnut - Pot Experiment 2000/01 season**

Ca Source	Ca rate ($kg\ ha^{-1}$)	pH ($CaCl_2$)	Soil nutrient level ($mg\ kg^{-1}$)				
			Ca	Mg	N	P	K
1. Calcitic Lime	**115**	4.51	144	37.3	18.0	21.6	46.9
2. Calcitic Lime	**403**	5.97	404	63.7	19.3	24.7	38.4
3. Calcitic Lime	**690**	6.23	492	50.3	12.3	26.3	36.0
4. Dolomitic Lime	**115**	4.47	136	51.0	24.3	15.3	41.1
5. Dolomitic Lime	**403**	5.90	348	62.7	23.3	15.7	38.3
6. Dolomitic Lime	**690**	6.13	444	82.3	21.3	14.7	39.2
7. Gypsum	**115**	4.17	140	30.0	18.0	14.9	33.5
8. Gypsum	**403**	4.20	327	34.3	22.3	14.8	24.9
9. Gypsum	**690**	4.63	384	41.0	23.0	19.1	29.7
10. SSP	**53**	4.28	147	26.0	23.7	21.5	44.0
11. SSP + Calcitic lime	**743**	5.95	436	68.7	26.3	35.8	57.4
12. SSP + Gypsum	**743**	5.13	347	31.3	33.7	26.7	40.2
13. Control	**0**	4.10	104	20.7	20.3	14.6	29.2
$LSD_{(0.05)}$ Ca Source		**0.30**	**71.0**	**9.7**	**5.6**	**2.8**	**6.3**
Ca Rate		**0.37**	**87.0**	**11.9**	**6.9**	**3.4**	**7.7**
Source x Rate		**0.53**	**123.1**	**16.9**	**9.8**	**4.9**	**10.9**

Appendix Table A3.2 **Effect of Ca source and rate on shoot and root dry mass and nodule size - Pot Experiment 2000/01 season**

Ca Source		Ca rate (kg ha^{-1})	SDM (g plant^{-1})	RDM (g plant^{-1})	Nodule size (mg nodule^{-1})
1.	**Calcitic Lime**	**115**	10.0	4.65	6.14
2.	**Calcitic Lime**	**403**	10.3	5.46	5.09
3.	**Calcitic Lime**	**690**	12.3	5.72	5.66
4.	**Dolomitic Lime**	**115**	9.3	5.30	5.04
5.	**Dolomitic Lime**	**403**	12.3	5.41	4.35
6.	**Dolomitic Lime**	**690**	13.9	5.41	3.68
7.	**Gypsum**	**115**	11.4	4.88	11.18
8.	**Gypsum**	**403**	12.6	4.63	6.32
9.	**Gypsum**	**690**	14.2	4.40	6.82
10.	**SSP**	**53**	7.4	4.16	8.98
11.	**SSP + Calcitic lime**	**743**	12.1	4.48	3.97
12.	**SSP + Gypsum**	**743**	12.6	4.25	4.18
13.	**Control**	**0**	5.4	3.36	5.81
LSD $_{(0.05)}$ Ca Source			**2.78**	**0.59**	**0.66**
	Ca Rate		**2.62**	**0.56**	**0.63**

Source x Rate	**4.54**	**0.96**	**1.08**

Appendix Table A3.3 **Effect of Ca source and rate on leaf nutrient content at peak flowering period of groundnut - Pot Experiment 2000/01 season**

Ca Source	Ca rate ($kg\ ha^{-1}$)	Leaf nutrient concentration (%)				
		Ca	Mg	N	P	K
1. Calcitic Lime	**115**	0.94	0.53	2.28	0.28	2.45
2. Calcitic Lime	**403**	1.25	0.44	2.41	0.17	3.89
3. Calcitic Lime	**690**	1.46	0.44	2.78	0.42	4.23
4. Dolomitic Lime	**115**	0.82	0.79	2.22	0.18	2.35
5. Dolomitic Lime	**403**	1.30	0.75	2.35	0.27	3.32
6. Dolomitic Lime	**690**	1.45	0.72	2.64	0.22	3.79
7. Gypsum	**115**	1.61	0.61	1.83	0.22	2.62
8. Gypsum	**403**	1.63	0.48	1.97	0.32	4.52
9. Gypsum	**690**	2.09	0.45	2.01	0.20	3.07
10. SSP	**53**	1.16	0.47	1.84	0.31	4.19
11. SSP + Calcitic lime	**743**	1.82	0.52	2.65	0.48	4.20
12. SSP + Gypsum	**743**	1.42	0.54	2.31	0.34	2.75
13. Control	**0**	0.76	0.25	1.71	0.15	2.21
$LSD_{(0.05)}$ Ca Source		**0.262**	**0.09**	**0.20**	**0.05**	**0.46**

Ca Rate	**0.302**	**0.11**	**0.26**	**0.07**	**0.59**
Source x Rate	**0.524**	**0.19**	**0.45**	**0.12**	**1.02**

Appendix Table A3.4 **Effect of Ca source and rate on basal and apical kernel yields and kernel quality parameters - Pot Experiment 2000/01 season**

Ca Source		Ca rate (kg ha^{-1})	Basal kernel yield (g plant^{-1})	Apical kernel yield (g plant^{-1})	Sound mature kernels (%)	Shrivelled kernels (%)	Discolored kernels (%)	Rotted kernels (%)
1.	**Calcitic Lime**	**115**	1.84	1.47	87	12.1	1.00	0.00
2.	**Calcitic Lime**	**403**	2.83	2.54	90	6.9	0.76	0.00
3.	**Calcitic Lime**	**690**	3.04	2.50	92	4.1	0.00	0.00
4.	**Dolomitic Lime**	**115**	2.72	1.97	85	15.2	0.00	0.21
5.	**Dolomitic Lime**	**403**	2.41	2.24	87	11.4	0.22	1.01
6.	**Dolomitic Lime**	**690**	2.96	2.61	91	8.9	0.00	0.00
7.	**Gypsum**	**115**	2.30	1.75	94	5.9	0.00	0.00
8.	**Gypsum**	**403**	2.75	2.10	87	10.0	0.97	1.74
9.	**Gypsum**	**690**	2.09	1.56	90	10.1	0.00	0.28
10.	**SSP**	**53**	0.89	0.66	74	26.1	1.93	2.41
11.	**SSP + Calcitic lime**	**743**	2.75	2.28	95	4.3	0.23	0.34
12.	**SSP + Gypsum**	**743**	2.86	2.39	93	6.8	0.00	0.00
13.	**Control**	**0**	0.47	0.34	44	54.9	6.12	2.31
LSD $_{(0.05)}$ Ca Source		**0.264**	**0.264**	**0.201**	**3.514**	**3.59**	**0.295**	**0.407**
	Ca Rate	**0.28**	**0.28**	**0.213**	**3.727**	**3.808**	**0.313**	**0.431**

Source x Rate	**0.458**	**0.458**	**0.348**	**6.086**	**6.218**	**0.511**	**0.704**

THE IMPACT OF SOIL ACIDITY AMELIORATION ON GROUNDNUT PRODUCTION ON SANDY SOILS OF ZIMBABWE

by

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THE IMPACT OF SOIL ACIDITY AMELIORATION ON GROUNDNUT PRODUCTIVITY ON SANDY SOILS OF ZIMBABWE

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ABSTRACT

The bulk of Zimbabwe's groundnut (*Arachis hypogaea* L.) crop is grown on sandy soils in the smallholder sector where sustainable production is hindered by acid soil infertility. The study goal was thus to examine the effects of soil acidity amelioration by four Ca-containing materials on nutrient composition, vegetative and reproductive growth, and quality of groundnut to formulate ameliorative strategies to improve productivity on acid soils. The effectiveness of calcitic lime (CL), dolomitic lime (DL), gypsum (G) and single superphosphate (SSP) in ameliorating soil acidity was determined in field experiments conducted for three seasons at two Research Stations in Zimbabwe, and in greenhouse experiments conducted for two seasons at Harare Research Station. In both experiments the lime application rates were from 0 to 4000 kg ha^{-1}, while G application rates were from 0 to 3450 kg ha^{-1}, and those of SSP were from 0 to 250 kg ha^{-1}. Calcitic or dolomitic lime applied at 2000 or 4000 kg ha^{-1} increased soil pH and Ca and Mg contents in the pod and root zones, and in the plant material. Gypsum and SSP applications at 200 and 250 kg ha^{-1} respectively, had no significant effects on pH, Ca and Mg levels, but when applied in equivalent amounts of Ca as lime, gypsum improved soil Ca status. Effects of the four ameliorants on the N, P and K levels in the soils and in plant material were generally neither significant nor consistent. The direct and residual benefits of application of CL or DL were manifested in improved plant stands, better growth, nodulation, productivity and quality of

groundnut. Gypsum applied at equal Ca rates as CL or DL was the superior Ca-source in improving pod and kernel quality. By the end of the third season, the increases in cumulative kernel yields due to application of 4000 kg ha^{-1} lime over non-application were up to 319%. The major growth-limiting factors on the studied acid soils were identified as deficiencies of Ca and Mg, and low pH *per se.*

In a field experiment conducted to evaluate the tolerance of 15 groundnut genotypes to soil acidity, significant differences in yield and nutrient utilization efficiency of the genotypes were observed, implying that productivity on acid soils can be increased by growing genotypes efficient in uptake and utilization of nutrients.

Results from greenhouse and growth chamber studies conducted to examine the effects of pH (3.0 - 7.0) and its interactions with Ca (0 - 2000 μ*M* Ca) on early seedling growth and reproductive growth of groundnut indicated that low pH *per se* has a major detrimental impact on seedling survival, growth, pod formation, yield and quality of groundnut, but not on germination. The adverse effects of low pH were more pronounced in the absence of Ca, and became progressively less as the solution Ca concentrations increased. Further experiments showed that it is feasible to mitigate the adverse effects of soil acidity on groundnut germination and seedling survival by pelleting seeds with small amounts of $CaCO_3$, or priming with $CaSO_4$.

Key words: *Arachis hypogaea*, calcium, germination, nutrient efficiency ratio (NER), nutrient use efficiency (NUE), pH, seed pelleting, reproductive growth, seed priming, soil acidity amelioration, vegetative growth.

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