Fertilization of Peanut (*Arachis hypogaea* L.) with Calcium: Influence of Source, Rate, and Leaching on Yield and Seed Quality

by

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Abstract

Soil surface horizons in the Southeastern U.S. Coastal Plains region are physically favorable to peanut (*Arachis hypogaea* L.) production but are often depleted of calcium. Peanuts lacking calcium may form undeveloped pods called "pops" or have poor germination and vigor. Peanuts develop just below the soil surface in the "pegging zone," and this is where the developing pods acquire calcium. Calcium requirements of peanuts are affected by seed size and genetics. Thus, calcium recommendations need to be continually re-evaluated as production shifts to new varieties. Furthermore, maintaining adequate calcium during high rainfall years is also a challenge due to the poor cation retention in the sandy Coastal Plain soils. The objectives are to (1) evaluate the effect of gypsum rate and calcium source (i.e., gypsum, lime, and liquid calcium fertilizer) on yield and seed quality of current varieties of small- and large-seeded runner peanuts and (2) evaluate the effectiveness of using electrical conductivity (EC) probes to observe gypsum leaching from the pegging zone and to quantify the amount of rainfall required to leach gypsum from the pegging zone of peanuts. All field sites were located at Headland, AL, and Tifton, GA, and research was conducted from 2008 to 2010. Gypsum treatments of 0, 560, and 1120 kg ha^{-1} were applied to small-seeded Georgia Green (GG) and large-seeded Georgia-06G (06G). Lime and liquid calcium fertilizer treatments were applied to 06G in Headland. Yield, total sound mature kernels (TSMK), seed calcium, and germination were analyzed at harvest. Gypsum generally improved

TSMK, germination, and seed calcium in GG and 06G. Liquid calcium and lime treatments did not improve yield and TSMK of 06G above control, but lime did improve germination. Yield response to gypsum treatments varied with initial soil calcium levels for both GG and 06G. Improvement in yield of 06G and GG peanuts above the control plot was observed twice for both varieties when soil calcium was above the critical level (150 mg kg^{-1}) established for traditional runners. This suggests that current recommendations for gypsum application to runner peanuts may slightly underestimate the needs of current runner-type peanuts. Gypsum generally increased germination across a variety of soil calcium levels. This supports the recommendation by the Alabama Crop Improvement Association for seed producers to apply gypsum regardless of pegging zone soil calcium levels. The liquid calcium fertilizer evaluated was not an effective calcium supplement to increase yield, which is in agreement with results of from studies evaluating similar products. Producers may not expect an increase in yield or with lime application on 06G when soil calcium levels are above 252 mg kg^{-1} or in a drought year.

For the gypsum leaching experiments, rainfall was continuously simulated at 5 cm hr^{-1} on columns of commercial sand, Dothan loamy sand, and Tifton loamy sand with surface-applied gypsum. Gypsum leaching was monitored by electrical conductivity probes installed 9 cm deep. Leaching of gypsum applied at 560, 1120, and 1680 kg ha^{-1} was also performed on a Dothan loamy sand. Leaching of gypsum in the field was evaluated in Tifton and Headland in the pegging zone of established peanuts. Probes were horizontally placed 9 cm below the soil surface with gypsum surface applied at 0, 560, 1120, and 1680 kg ha^{-1}. Results of the column study indicate that increasing gypsum application rates did not increase the residence time of the gypsum, but did increase the maximum EC measured. The amount of rainfall required before the peak EC occurred was lower in the sand compared with the loamy sand. Electrical conductivity was near baseline after 12 cm of rainfall in the soil column. This was also observed in field experiments at both sites. Unlike the column experiment, the 1680 kg ha^{-1} gypsum rate provided an EC response to gypsum for a longer period than the lower rates. Using EC probes is an effective way to determine if gypsum still resides in the pegging zone, but may not be as useful in quantifying the amount of calcium leached as direct analysis of calcium.

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I. Literature Review

Introduction

Soils favorable to peanut production are well drained, sandy, friable, and high in calcium (York and Cowell, 1951). Runner peanuts (*Arachis hypogaea* L.) are grown on Coastal Plain soils in Alabama, Georgia, and Florida. These soils meet the physical requirements for peanut production, but they are naturally low in calcium (Adams and Hartzog, 1979) due to the tendency of calcium to leach. Addition of calcium to low calcium soils improves yield (Adams et al., 1993), increases the percentage of sound mature kernels (SMK) (Adams et al., 1993), and improves germination and vigor (Sorenson and Butts, 2008). One might expect calcium to translocate from the roots to the developing pods; however, this does not happen readily (Skelton and Shear, 1971). Developing pods must acquire calcium from the surrounding soil, which is called the pegging zone (Sumner et al., 1988).

Calcium is typically applied to the pegging zone as lime or gypsum. Application of lime and gypsum depends on initial soil calcium (Hartzog and Adams, 1973), goal of the grower (i.e., yield or seed production; Harris, 1998), and size of peanuts to be grown (Slack and Morill, 1971). Determination of the amount of calcium to apply is also potentially affected by peanut genotype. In the Southeast U.S., past calcium recommendations for soils were based on runner-type peanuts from different genetic lines than current ones, and new runner-type peanuts may differ in their calcium requirement (Tillman et al., 2010).

Reevaluation of the effect of calcium on yield and seed quality on small- and large-seeded runner-type peanuts currently grown in the Southeast U.S. will ensure proper calcium recommendations for peanut producers. Understanding how different calcium sources, i.e., gypsum, lime, and calcium in solution, provide calcium to current peanut varieties will provide producers with additional knowledge of the tools available to ameliorate calcium deficiency. In addition, the ability to predict loss of calcium through leaching in the pegging zone will allow producers to evaluate whether adequate calcium is available to developing peanuts throughout the growing season.

Peanut development

Peanut seed development is unique from other plants. Once flowers are pollinated, a peg is formed which moves downward. The peg develops into a pod and eventually a full-grown peanut just under the soil surface in the pegging or fruiting zone. Pegging zone depths have been recorded to range between 5 and 10 cm (Sumner et al., 1988; Jones et al., 1976; Kiesling and Walker, 1978). Soil type affects pegging zone depth because clay tends to restrict depth. Pegging depths have been measured to 10 cm in loamy sand, while depths were only 5 cm in sandy clay loam (Kiesling and Walker, 1978). Peanuts prefer a sandy, friable, and high calcium soil (York and Cowell, 1951). Sandy, friable surfaces promote peg entry into the soil and facilitate digging peanuts at harvest with minimal loss of peanuts from the vines. While sand provides ideal physical properties for peanut cultivation, its chemical properties are not ideal. Sandy surface horizons of the Southeastern Coastal Plains have low cation exchange capacities, which indicate the ability of the soil to retain cationic nutrients, such as calcium. Cation exchange capacities of the Southeastern Coastal Plain soils for peanut production range from 0.65 to 2.64 $cmol_c\ kg^{-1}$ (Adams et al, 1993; Levi et al., 2010).

Adequate calcium in the pegging zone is essential for proper peanut development because this is where developing pods obtain calcium. Pods must acquire calcium from the surrounding soil due to lack of xylem flow into the peg and immobility of calcium in the phloem (Kiesling and Walker, 1982; Brady, 1947). Lack of xylem flow into the peg is attributed to the lack of transpiration once it is underground (Bledsoe et al., 1949; Weirsum, 1951; Skelton and Shear, 1971). Calcium enters the seed by diffusing directly from soil into the hull, where it is channeled to the funiculus. This is the only point where the developing seed is physiologically attached to the surrounding hull. From the funiculus, the calcium is delivered to the seed (Sumner et al., 1988).

Calcium supplements

Pegging zone calcium is typically increased by adding lime ($CaCO_3$) or gypsum ($CaSO_4{\cdot}2H_2O$). Liquid calcium fertilizers are also on the market and claim to provide sufficient calcium for quality peanut production. Each of these amendments has advantages and disadvantages.

Lime increases soil pH, alleviates aluminum toxicities, and increases pegging zone calcium (Hartzog and Adams, 1973). Lime has been shown to improve yield and SMK (Adams and Hartzog, 1979). It has been demonstrated that lime increases soil calcium (Reed and Brady, 1947), which has been shown to benefit germination (Adams et al., 1993). Lime is usually applied before planting and is disked into the top 15 cm where it can supply calcium to the pegging zone for up to 20 months (Reed and Brady, 1945). The long residence time of lime is due to its low solubility. Lime has a solubility of 0.01 g L^{-1}, while gypsum has a solubility of 2.6 g L^{-1}. The disadvantage of longer residence time and lower solubility is a lower calcium concentration in soil solution, which reduces the calcium gradient to the developing pod. It is suggested that increased dissolution creates a higher calcium gradient that enhances the rate of diffusion into the developing seed (Sumner *et al*., 1988). Loganathan and Krishomoorthy (1977) found shoot calcium in peanut plants was higher in plants treated with gypsum rather than lime presumably due to greater soluble calcium in the root zone. If this is similarly true for the pod, gypsum should provide more available calcium than lime and result in higher seed calcium concentrations when applied on an equivalent calcium basis.

Gypsum applications have been shown to improve yield, grade, and germination (Hallock and Allison, 1980a). While gypsum does not increase pH as lime does, literature suggests that gypsum may be more beneficial to developing pods than lime. Gypsum was observed to produce fewer pods per plants than lime, but the quantity of fully developed pods was greater (Reed and Brady, 1948). While gypsum has many benefits, there are some disadvantages. Applications of gypsum may reduce the availability of potassium and magnesium in the pegging zone (Alva and Gascho, 1991). This may lead to potassium and magnesium deficiencies in the seed, which reduces their quality, or to the vegetative plant, which reduces plant health and growth. Gypsum is also subject to leaching from the pegging zone. High rainfall events and years with above normal precipitation may remove gypsum from the pegging zone and create deficiencies in peanuts developing late in the season.

While lime and gypsum are traditionally applied in solid form, they have also been marketed as slurries and solutions along with other soluble calcium salts. These liquid forms have not performed as well as dry applications and are not recommended as applications (Hartzog and Adams, 1973; Daughtry and Cox, 1974). Adams and Hartzog (1979) compared 50% lime slurry with a bagged fine dolomitic limestone and a bulk agricultural-grade dolomitic limestone. They cite a trade journal listing in the advantages of the lime slurry as no dust being produced and quickly increasing the soil pH. The recommended rate of lime resulted in higher peanut yield than the lime slurry. Differences between treatments are likely due to the lower lime per weight of application of the lime slurry compared to the dry forms.

Gypsum in solution has also been found to be less effective than dry applications. Hartzog and Adams (1973) examined "Magi-Cal®", which was described as a liquid $CaSO_4{\cdot}2H_2O$ product for South Alabama growers. They concluded that on low calcium soils, this type of spray-on calcium did not increase peanut yield or grade on soils where gypsum did improve yield and grade. Walker (1975) also looked at Magi-Cal® along with a chelated calcium solution. Gypsum improved yield and percentage of SMK greater than either of the liquid fertilizers. Differences between dry and liquid fertilizers are likely due to the total amount of calcium applied. Application of gypsum resulted in 86 kg calcium ha^{-1}, while Magi-Cal® and chelated calcium were 10.5 and 6.6 kg calcium ha^{-1}, respectively. Thus, gypsum supplied almost eight times as more calcium than Magi-Cal® and 13 times more calcium than the organically-chelated calcium (Walker, 1975). Another reason for the poor performance of the liquid fertilizer was that it was applied on a sandy surface. Sandy surfaces are more permeable than clays and may allow the liquid fertilizer to leach more quickly than solid amendments through the pegging zone.

Leaching of gypsum and lime

When lime is applied properly, adequate amounts of calcium will stay in the pegging zone during a growing season (Hartzog and Adams, 1973). Reed and Brady (1945) found that after application of 2,759 and 1,379 kg ha^{-1} of lime, soil calcium was elevated for 20 months in a Norfolk loamy sand and Bradley sandy loam and returned to the initial level in a Craven fine sandy loam. However, leaching of gypsum from the pegging zone may occur before the end of the growing season. A significant amount of gypsum has been observed to leach out of the pegging zone with 15 cm of simulated rain, which is equivalent to one month of rainfall in Georgia based on a 50 year average (Alva and Gascho, 1991). Because the majority of applied gypsum may leach within a month of application, it is traditionally applied 40 days after planting or at early bloom. This ensures that gypsum is present during pegging and when pods are developing. Applying at early bloom does not ensure that the gypsum will supply calcium during the entire growing season. Peanuts will continue to flower 70 to 90 days after initial blooming and create pods that require calcium (Alva et al., 1989; Schenk, 1961). If applied calcium leaches from the pegging zone prior to harvest, the pods that develop later in the season may be limited by calcium.

Rate of leaching is dependent on the amount of gypsum applied (Walker, 1975), soil texture (Alva and Gascho, 1991), and rainfall pattern (Kiesling and Walker, 1978). The simplest factor determining how long gypsum will provide calcium is the amount supplied. Jones et al. (1976) found increases in soil calcium (0 to 15.24 cm depth) at harvest when 560 kg ha^{-1} of powdered gypsum was applied, while the 280 kg ha^{-1} did not increase soil calcium.

Particle size will also affect the rate of leaching. Smaller particles have a higher surface area than larger particles. Increased surface area increases the amount of contact gypsum or lime has with the water, which enhances dissolution. Coarse gypsum has been shown to supply calcium in the pegging zone longer than fine gypsum (Keisling and Walker, 1978).

Weather can also affect the residence time of gypsum in the pegging zone. Increasing rainfall was found to decrease Mehlich-1 (0.5 N HCl – 0.25 N H_2SO_4) soil calcium at the 0 to 5.1 cm depth (Jones et al., 1976). Applications of powdered gypsum were observed to increase soil calcium initially and then rapidly decrease soil calcium after "excessive" rainfall (Alva et al., 1989). Cumulative precipitation alone may not be a good indicator of when or how much gypsum has leached. Frequency and magnitude affect the rate of leaching. In the Southeast U.S., high magnitude rainfalls over several days from hurricanes and tropical events may occur during the growing season. These low frequency, high magnitude rainfalls cause more leaching than high frequency, low magnitude rainfalls (Kiesling and Walker, 1978). Alva et al. (1990) found that one application of 15.2 cm of rain caused 21 and 31% loss of calcium on a Tifton loamy sand (87% sand) and Lakeland sand (93% sand), respectively. When the 15.2 cm of rain was divided into 12 equal applications the calcium losses were 14 and 30% for the Tifton and Lakeland soil, respectively. Magnitude and frequency also affect potassium and magnesium in the pegging zone, as low frequency high magnitude rains also leach more potassium and magnesium (Alva et al., 1990).

Once gypsum dissolves, the rate of leaching is controlled by soil texture. Alva and Gascho (1991) examined gypsum leaching in a soil column with six different soils: Carnagie sand (90% sand), Dothan sand (86% sand), Fuquay sand (93% sand), Tifton sand (89% sand), Faceville sandy clay loam (66% sand), and Greenville sandy clay loam (68% sand). Calcium was found to leach out of the sandier soils faster. Application of 15 cm of water leached 50 to 56% of the applied calcium from the top 8 cm of the sandy soils, compared to 28 to 36% in the sandy clay loams (Alva and Gascho, 1991).

Soil calcium levels

Soil calcium is an important factor when evaluating need for calcium fertilization. Typically, additions of lime and gypsum do not show improvements in yield or seed quality when the soil has adequate calcium. Critical soil calcium concentrations that have been considered yield limiting are: 168 (Hartzog and Adams, 1973), 125 (Adams et al., 1993), and 250 mg kg^{-1} (Georgia soil test standards; Alva et al., 1989). Soil calcium prior to planting also determines if calcium applications will increase peanut grade. An increase in percent SMK of runner-type peanuts was observed when gypsum was applied to a soil with an initial calcium concentration of 127 kg ha^{-1}, but not when soil calcium was 665 kg ha^{-1} (Alva et al., 1989).

Germination is also limited by inadequate soil calcium. Maximum germination rates for four different runner-type peanuts were found when soil calcium ranged from 235 to 252 mg kg^{-1} (Adams et al., 1993). Growers producing peanuts for seed are advised by the Alabama Crop Improvement Association (Dr. Bostick, personal communication, 2010) and University of Georgia (Harris, 1998) to apply gypsum at bloom even if soil calcium levels are high.

Differences in the reported critical values for soil calcium may be due to variability in calcium extraction methods used. Hartzog and Adams (1973) used an extract of 1 N ammonium acetate at pH 7 and reported a lower critical soil calcium value for yield than Adams et al. (1993) using a Mehlich-1 extract. Extractants are expected to represent calcium that is available for uptake by the developing pod and not calcium in unavailable forms. To examine the relationship between extractable calcium and calcium utilized by the seed, Sumner et al. (1988) compared two soil extracting solutions, 0.01 M sodium nitrate and Mehlich-1 extractant, to seed calcium. Sodium nitrate provided a higher correlation of soil calcium to seed calcium than -1I with correlation coefficients of 0.51 and 0.30, respectively (Sumner et al., 1988).

Soil calcium levels are not the only factor to consider when determining if a soil is limited by calcium. The calcium to potassium ratio is also important. If it is less than three to one, then the plant may be limited in its ability to absorb calcium (Alva et al., 1989). This is due to competition between calcium and potassium during the diffusion process into the hull. High concentrations of potassium will limit calcium diffusion. Sullivan et al. (1974) found potassium applications reduced yield, percent SMK, and extra-large kernels, and slightly increased the incidence of dark plumule. The effects of potassium application were not observed when calcium was also applied. The activity ratio of calcium [i.e., mol calcium/(mol potassium+ mol calcium+ mol magnesium)] has also been considered as an indicator for the proper balance of cations needed for peanut production. An activity ratio of 0.25 produces maximum yield cavity^{-1} (Wolt and Adams, 1979). Conversely, over-application of calcium may limit general potassium and magnesium uptake by the plant and subsequently reduce yields.

Relationship between soil and seed calcium

It is important that the seeds have sufficient calcium to ensure adequate germination and vigor of seedlings. Calcium is integral to cell membrane structure and selective permeability (Marschner, 2008). This may be why it is so important to the development of the plumule and hypocotyls (Meyer et al., 1960; Wyn Jones and Lunt, 1967). Burkhart and Collins (1941) attribute seedling abortion to low calcium content and inability to recycle calcium. Insufficient seed calcium causes developing roots to degrade before plumule emergence.

Two types of germination failures attributable to calcium deficiency are physiological root breakdown and watery hypocotyl (Sullivan et al., 1974). The hypocotyl is found where the seed and the emerging root join together. In physiological root breakdown, the hypocotyl and root will develop normally for about three days before a leak appears at the connection between the hypocotyl and root. Watery hypocotyl is first observed when a leak appears half-way down the hypocotyl, three to four days after germination.

Higher soil calcium shows a positive relationship to seed calcium. Correlation coefficients between soil calcium and seed calcium of four different runner-type peanuts were 0.49, 0.51, 0.52, and 0.54 (Adams et al., 1993). A correlation coefficient of 0.40 was observed by Adams and Hartzog (1991), but authors state that this correlation may be weakened by the various moisture regimes of the peanuts used in the study. Soil moisture can contribute to or hinder the rate of calcium diffusion from the soil solution to the developing pods.

Higher seed calcium corresponds to improved germination. Correlation coefficients between seed calcium and germination have been calculated to be 0.40 to 0.45 (Hallock and Allison, 1980a), 0.80 (Adams and Hartzog, 1991), 0.77, 0.66, 0.94, and 0.84 (Adams et al., 1993). Variations in these coefficients may be related to genotypic variability or to the effect of soil moisture regimes on calcium uptake similar to that described for the soil calcium to seed calcium relationship. Seed calcium concentrations producing maximum germination have been reported for four small runner-type peanuts ranging from 368 to 414 mg kg^{-1} (Adams et al., 1993). On soils where calcium is yield limiting, the critical value for germination was found to be lower, 282 mg kg^{-1} (Adams and Hartzog, 1991).

Effect of variety on seed calcium

Soil calcium and seed calcium critical values may differ by seed size, ability of a particular cultivar to accumulate seed calcium, seed germination, and peanut tolerance to low calcium soils (Tillman et al., 2010). A difference in seed size is clearly noted among the four major peanut cultivar groups: Virginia, Valencia, runner, and Spanish, listed in order of decreasing size. Virginia seed weights range from 0.85 to 1.2 g $seed^{-1}$, compared to the smaller runner-type ranging from 0.55 to 0.75 g $seed^{-1}$ (Tillman et al., 2010). The critical seed calcium value for seed germination of Virginia peanuts is 420 mg kg^{-1} (Cox et al., 1976) and is similar to the runner-type (368 to 414 mg kg^{-1}) when soil calcium is not limiting to yield (Adams et al., 1993). These two types require about the same seed calcium concentration, but the difference in size equates to greater total calcium in the Virginia than the runner-type peanut. This relationship between total seed calcium and size has been shown by Smal et al. (1989) and Kiesling et al. (1982).

In addition to a larger seed size, some larger-seeded types also have a thicker pericarp, the fleshy membrane surrounding the fruit. This pericarp may absorb most of the calcium and deplete the kernel of needed calcium (Walker, 1975). Burkhart and Collins (1941) found that the pericarp had about five times more calcium than the kernel.

Differences among runner-type peanuts to the same calcium treatment have also been observed (Adams et al., 1993). Runner varieties of the 1970's and 80's had a common ancestor of Florunner, Jenkins Jumbo, or Florispan. With the prevalence of tomato spotted wilt topovirus (TSWV), breeders wanted to introduce resistance to TSWV into the runner-type peanuts. This was accomplished with PI 203396. The calcium demands of PI 203396 are not established and differ from previous runner varieties. PI 203396 is the grandparent of Georgia Green (Branch, 1996) and great grandparent of Georgia-06G (Branch, 2007; Tillman et al., 2010). Georgia Green is a small-seeded type with an average weight of 55.7 g 100 seed^{-1} (Tillman et al., 2010), which is moderately resistant to TSWV (Wells et al., 2002). To increase seed size and maintain TSWV resistance, Georgia Green was crossed with C-99R to produce Georgia 06 (Wells et al., 2002). Georgia-06G produces more jumbo-sized runners than the Georgia Green, 41% compared to 18%, respectively (Branch, 2007). Runner-type peanuts with the introduced genetics of PI 203396 might have more variation in calcium absorption than a line without its parentage in the Southeast U.S. (Tillman et al., 2010). Knowledge of this variation between PI 203396 and non-PI 203396 lines is important because as PI 203396 lines are becoming the most common runner-types planted.

In 1999, 90 to 95% of peanuts planted in Georgia were Georgia Green, and it was accepted as the benchmark for TSWV resistance and field growth for other runners

(Wells et al., 2002). By 2009, Georgia 06G accounted for 36% of the runners planted in Alabama, Georgia, and Florida, while Georgia Green accounted for 10% (Hollis, 2010). In 2010, Georgia 06G made up 67% of peanut acreage planted in Georgia, and Georgia Green seed availability is limited (Hollis, 2011). The reduction in percentage of PI 203396 lines from 1999 to 2011 may be attributed to the variety of desirable traits offered in new breeds. Non-PI 203396 Florida-07 (Gorbet and Tillman, 2009) and Tifguard (Holbrook et al., 2008) accounted for 18 and 15% of the market planted in 2009, respectively (Hollis, 2010). Florida-07 was created to have high oleic acid content. Tifguard was produced for resistance to peanut root-knot nematode. These new traits expand grower's options to produce peanuts that fulfill an economic niche or that have resistance for pests or diseases specific to their growing conditions. While PI 203396 lines may not be the dominant seed planted in the future, significant acreage will be planted for growers looking for TSWV resistance.

Summary

Runner-type peanuts are grown in the Southeastern Coastal Plain soils. Peanuts are unique from other plants in that once their flower is pollinated it forms a peg and submerges into the soil. The zone that the peg enters is called the pegging zone and can be up to 10 cm deep depending on the surface clay content (Kiesling and Walker, 1978). Sandy surface horizons are favorable to the physical aspect of peanut production but not the nutritional (York and Cowell, 1951). Sandy surfaces of the Coastal Plains have low cation exchange capacity and poorly retain cationic nutrients such as calcium.

Calcium is important to the peanut for proper development. Calcium additions to low calcium soils can improve yield, SMK (Adams et al., 1993), and germination

(Sorenson and Butts, 2008). Replenishing pegging zone calcium is important because peanut plants do not translocate calcium from the roots to developing peanuts (Skelton and Shear, 1971). Calcium may be applied as lime, gypsum, or liquid fertilizer. Each product has its advantages and disadvantages. Lime stays in the pegging zone longer but creates a lower calcium gradient. Gypsum creates a higher calcium gradient but can be leached after significant amount of rain. Liquid fertilizers supply very little calcium when compared to lime or gypsum, but they are readily available to the developing pod.

Initial soil calcium levels are important to consider when assessing the need for calcium fertilizer. Maximum yield and SMK require lower soil calcium than that for maximum germination. The amount of soil calcium required may differ among cultivars as there may be differences in seed size, ability to accumulate seed calcium, seed germination requirements, and tolerance to low calcium soils (Tillman et al., 2010). Differences among runner-types to similar treatments have been observed (Adams et al., 1993). Peanuts descended from PI 203396 may have more variation in calcium absorption than traditional runners (Tillman, 2010).

II. Effect of calcium source and rate on yield and seed quality of runner peanuts

Abstract

Sandy surface horizons of Coastal Plain soils of the Southeast U.S. are naturally depleted of bases, particularly calcium. Peanuts (*Arachis hypogaea L.*) require adequate calcium in the top 10 cm of soil, or pegging zone, for proper development because calcium is adsorbed directly from the soil and is not translocated from the roots to the developing pods. Producers traditionally apply gypsum ($CaSO_4 \cdot 2H_2O$) or lime ($CaCO_3$) to replenish pegging-zone calcium. Calcium demands may vary with seed size and genetics. The objective of this study is to examine the yield and seed quality effects of gypsum rate on small- and large-seeded runners and source of calcium in the form of gypsum, lime, and liquid calcium fertilizer on large-seeded runners. The uptake of calcium throughout growth stages will also be examined. Small-seeded Georgia Green (GG) and large-seeded Georgia-06G (06G) were planted at Headland, AL and Tifton, GA from 2008 to 2010. Gypsum was applied at rates of 0, 560, and 1120 kg ha^{-1} 40 days after planting. Applications of 1120 kg ha^{-1} of lime and 11.2 L ha^{-1} of a 4% calcium solution derived from gypsum were applied only to 06G at Headland. Yield; seed calcium, potassium, and magnesium; and germination were analyzed at harvest. In most years and locations, gypsum improved grade (i.e., percentage of total sound mature kernels (TSMK)), germination, and seed calcium. Gypsum increased yield on soils considered high in soil calcium by the recommendations made by Hartzog and Adams (1973) and Adams et al. (1993) at three of six sites for 06G and two of six sites for GG.

Lime did not improve yield or TSMK in any year or location. Germination increased with lime at one of two sites. Liquid calcium did not improve yield, TSMK, or germination compared to the control plots. Results from this study suggest that current recommendations for gypsum application to runner peanuts may slightly underestimate the needs of current runner-type peanuts. Liquid calcium was not an effective calcium supplement to runner peanuts.

Introduction

Soils in the Southeast U.S. are physically favorable to peanut production. Sandy surface horizons allow for ease of digging peanuts at harvest. These sandy horizons are depleted of basic cations, such as calcium, that are important to seed quality. Calcium supplements have been shown to improve yield, total sound mature kernels (TSMK; Hallock and Allison, 1980), and germination (Sorenson and Butts, 2008). It is important that adequate levels of calcium are present in the top 10 cm of soil, or pegging zone, (Sumner et al., 1988) because this is where developing pods must acquire calcium. Translocation of calcium from the roots to developing pods via xylem or phloem is limited due to lack of evapotranspiration under the soil surface (Skelton and Shear, 1971) and low phloem mobility (Marschner, 1995).

Peanut producers can replenish pegging zone calcium with gypsum ($CaSO_4 \cdot 2H_2O$) or lime ($CaCO_3$) in a dry or wet form. Gypsum and lime have been shown to improve yield and SMK (Hartzog and Adams, 1973; Hallock and Allison, 1980). Gypsum has also been shown to improve germination (Hallock and Allison, 1980).

While gypsum does not increase pH as lime does, gypsum may be more readily available than lime. Application of gypsum to peanuts produces fewer pods per plants than lime, but the quantity of fully developed kernels was greater (Reed and Brady, 1948). Peanut plants treated with gypsum have also been observed to have higher peanut shoot calcium concentrations compared to lime-treated plants (Loganathan and Krishomoorthy, 1977). Sumner et al. (1988) suggest that gypsum creates a higher calcium gradient between the soil and developing peanut because it is more soluble than lime and releases more calcium to the soil solution. The higher calcium gradient enhances calcium diffusion into the seed.

Applying gypsum in a more soluble form has been marketed as a method to apply calcium in an effective and economical manner. In the past, products with gypsum in solution, such as Magi-Cal® (No company information given), and solutions of organically-chelated calcium, did not increase peanut yield or grade on soils were gypsum did improve yield and grade (Hartzog and Adams, 1973; Walker, 1975). Even with subpar performances, fertilizer companies still market calcium solutions to peanut producers. Currently, there are several liquid calcium fertilizers marketed to peanut producer, including Agro-Culture Liquid Calcium Fertilizer (4% calcium solution derived from gypsum; Agro-Culture, St Johns, MI), N-Cal Liquid Calcium Nutrient (12-13% (w/w) calcium chloride solution; Tetra Chemicals, The Woodlands, TX), and TigerCal (30% calcium carbonate with humate; Plant Agra Products, Two-Way Trading Co. Inc. Dothan, AL). The effectiveness of these products on peanut production is not established in scientific literature.

Knowing when calcium fertilization is needed to increase yield and grade or germination is important for producers. Additional calcium has increased yield when soil calcium was < 168 mg kg^{-1} (Hartzog and Adams, 1973; Adams et al., 1993; Adams and

Hartzog, 1991). Furthermore, additional calcium has increased peanut grade when soil calcium was < 130 mg kg^{-1} (Alva et al., 1989; Adams and Hartzog, 1991). Based on these studies, Auburn University Soil Testing Laboratory recommends application of gypsum or lime when soil calcium is < 150 mg kg^{-1} for general peanut production (Hartzog and Adams, 1976). This is lower than recommendations by University of Georgia Soil Testing Laboratory, which suggests additional calcium should be applied when soil calcium is < 250 mg kg^{-1} (Alva et al., 1989). Recommendations by Georgia also include that if the ratio of calcium to potassium (Ca:K) is < 3:1 then calcium is needed even if soil calcium is > 250 mg kg^{-1} (Alva et al., 1989). Traditional runners such as Florunner and Sunrunner did not show an increase with gypsum in soils with calcium levels of 158 mg kg^{-1} or higher, and GK-7 did not show a response when soil calcium was 218 mg kg^{-1} or greater (Adams et al., 1993).

The soil calcium level that results in a germination response with gypsum applications is poorly understood. Adams et al. (1993) observed germination increases with gypsum applications sporadically across a soil calcium range from 48 to 242 mg kg^{-1} in three runner varieties. However, they did determine optimum germination rates on for four different runner-type peanuts when soil calcium ranged from 235 to 252 mg kg^{-1} (Adams et al., 1993). The critical soil calcium value for germination determined by Adams et al. (1993) was 250 mg kg-1, which is higher than the critical value for yield (i.e., 150 mg kg^{-1}). This demonstrates that more calcium is required for optimum germination than optimum yield. Due to the importance of calcium for seed germination, growers producing peanuts for seed are advised by the Alabama Crop Improvement

Association (Dr. Jim Bostick, personal communication, 2010) and University of Georgia (Harris, 1998) to apply gypsum at bloom even if soil calcium levels are high.

Seed size can also affect the calcium requirement. A relationship between increasing seed size and increasing total calcium has been observed by Smal et al. (1989) and Kiesling et al. (1982). One explanation for this may be that the larger seed requires more calcium for proper development, as it has more biomass than smaller seeds. This may also be due to the thicker pericarp found in larger seeds. The fleshy membrane surrounding the seed, or pericarp, has a calcium concentration about five times greater than the seed (Burkhart and Collins, 1941) and has been suggested to withhold more calcium from larger seeds than smaller seeds (Walker, 1975)

Different varieties of runner-type peanuts respond differently to gypsum treatments (Adams et al., 1993). Introduction of exotic lines may induce variability in the calcium needs of newer peanut breeds. Runner peanuts produced in the 1970's and 80's were mostly the progeny of Florunner, Jenkins Jumbo, or Florispan. With the increase incidence of Tomato Wilt Spot Virus (TSWV), breeders introduced resistant lines, such as PI 203396 from Brazil. Progeny from PI 203396, such as Georgia Green or Georgia-06G, may have different calcium demands from traditional runner-type peanuts grown in the Southeast U.S. (Tillman et al., 2010).

The objectives of this study are to 1) determine the effect of gypsum rate on yield, grade, and germination of current small- and large-seeded runner peanuts, 2) examine the effect of gypsum, lime, and liquid calcium fertilizer on a large-seeded runner peanut, and 3) evaluate calcium content of peanut seeds at various developmental stages.

Materials and Methods

The experiment was conducted at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and at the Coastal Plains Research Station (CPRS) in Tifton, GA. The experiment was conducted from 2008 to 2010 rotating to different sites on the station each year. Sites were selected with relatively low calcium in the pegging zone (top 10 cm of surface soil) and with similar soil (i.e., Dothan loamy sand at Headland and Tifton loamy sand at Tifton). Runner varieties used were the large-seeded Georgia-06G (Branch, 2007) and small seeded Georgia Green (Branch, 1996) because of their size difference and current popularity with producers. Treatments were arranged in a randomized complete block design (n = 4). Treatments included 0, 560, 1120 kg ha^{-1} gypsum, respectively, equal to 0, 146, 291 kg calcium ha^{-1} to Georgia Green (GG) and Georgia 06G (06G) at both sites. Treatments of 2240 kg ha^{-1} lime and 11.2 L ha^{-1} liquid calcium fertilizer were applied to 06G at Headland. At Tifton, a 1680 kg ha^{-1} gypsum treatment was included in 2010 on GG and 06G. Plots were at least 10 m in length with 4, 6 or 8 rows to accommodate the equipment available at the research stations. Row spacing at Headland and Tifton was 91 and 61 cm, respectively. Plant and soil samples were taken from the rows adjacent to the border rows when plots were 6 or 8 rows wide. Samples were taken from the border rows when plots were 4 rows wide. The rows between the sample rows were harvested for yield, grade, and germination assessments. All sites were non-irrigated, except for the site at Headland in 2008. All herbicides and pesticides were applied as prescribed by the respective experiment station. Timing of peanut harvests was determined by the hull scrape method (Williams and Drexler, 1984).

Flue gas desulfurized gypsum (26% Ca) was obtained from Georgia Power's Yates Power Plant in Newnan, GA, or from Agri-B in Albany, GA marketed as Agri-Cal and was either banded or broadcast applied at rates of 560, 1120, and 1680 kg ha^{-1} 40 days after planting (DAP) at Headland and Tifton as described above. Agricultural lime (Georgia Hi-Cal, Blakely, GA, estimated 35% Ca) was broadcast at 2240 kg ha^{-1} prior to planting. A liquid calcium fertilizer (Agro-Culture Liquid Calcium Fertilizer, Agro-Culture Fertilizers, St. Johns, MI) was applied as directed, 11.2 L ha^{-1} at 40 DAP. At the given application rates, gypsum provided 146, 291, 437 kg calcium ha^{-1}, lime provided 784 kg calcium ha^{-1}, and liquid calcium fertilizer provided 0.49 kg calcium ha^{-1}. Rates for the different calcium sources were based on recommended practices for each source.

Soil samples were taken from each plot prior to treatment application and bi-weekly during the blooming and peanut development season (Table 1). Soil samples were taken from the top 7 cm, within 15 cm of the base of the plant, using a hand-held soil probe from the two sample rows. Approximately 20 cores were taken per plot, combined in a bucket, and mixed well to provide a composite sample. Soils were dried at $60^{o}C$ for 48 h and sieved to < 2 mm.

Calcium, potassium, phosphorus, and magnesium were extracted from soil with the Mehlich-1 extract (Mehlich, 1953). Briefly, 5 g of dried and sieved soil was shaken with 20 ml mixture of hydrochloric (0.5 N) and sulfuric acid (0.25 N) for 5 minutes (Adams et al., 1993; Mehlich, 1953). The samples were then filtered with #40 Whatman filter paper (Whatman Laboratory Division, Springfield Mill, UK) or equivalent. The extract was analyzed with an inductively-coupled plasma spectrometer (ICP; Spectro Ciros CCD, side on plasma, SPECTRO Analytical Instruments Inc., Kleve, Germany).

Peanut samples were taken bi-weekly from the two sample rows (atleast 3 whole plants per row) during the pod development period. Seeds were pulled from the plant and dried for 48 h at 60^{o}C in a forced-air drier. Seeds and hulls were ground separately in a coffee grinder (Smartgrind® Stainless Steel, Black & Decker® Corporation, Towson, MD). In 2008, seeds were dry ashed in a muffle furnace at 450°C, then 10 mL of 1 N nitric acid was added and evaporated using a hot plate. The residue was dissolved with 10 mL of 1 N hydrochloric acid and filled to 100 mL volume with deionized water and filtered using Whatman #40 or equivalent (Adams et al., 1993; Hue and Evans, 1986). In 2009 and 2010, ground seed (1 g) was microwave digested for at least 30 min in concentrated nitric acid (Mars Xpress®, CEM Corporation, Matthews, NC) using the EPA 3051 procedure and filtered using Whatman #40 or equivalent. The sample volume was adjusted to 100 mL with deionized water. Digested samples were analyzed for calcium, magnesium, and potassium using ICP. Total seed and hull calcium was calculated by multiplying the calcium concentrations by the mass of hull or seed tissue.

Peanut yield was determined by averaging the weight of the pods from the two center rows of each plot after drying to 10% moisture. Grade was calculated as the percent TSMK in a 200 g sample, which includes SMK and sound splits.

Warm germination tests were performed by the Georgia Department of Agriculture – Seed Laboratory at Tifton, GA according to procedures defined by the Association of Official Seed Analysis (AOSA). Germination percentage was determined by treating seed with the fungicide Vitavax ® PC (Bayer CropScience LP, Research Traingle Park, NC) and placing on germination paper (25.4 x 38.1 cm). Seeds were then placed in a germinator at 25^{o}C. After 10 days in the germinator, the percent germination was recorded.

Peanuts from different development stages were collected at Tifton on September 9 and 23 in 2010 and at Headland on September 2, 2010 from the 560 kg ha^{-1} plots. Peanuts that were collected at Headland were limited as a drought prevented an ample supply of sample. The 560 kg ha^{-1} rate was chosen because it would ensure calcium was available for absorption, as opposed to the 0 kg ha^{-1} rate. Peanuts were pressure washed to reveal the hull color and sorted by development stages (white, yellow 1, yellow 2, orange, brown, and black) based on the color table produced by Williams and Drexler (1984). Seeds were dried for 48 h at 60^{o}C, hulled, weighed, and finely ground in a coffee grinder. Seeds were analyzed as previously described.

Peanut yield, grade, germination, seed and hull elements were compared within the same year, site, and variety and subjected to PROC Glimmix using the LSmeans option with α at 0.10 in Statistical Analysis Systems 9.2 (Cary, NC). Background soil data from the control plots was compared among the two sites and three years using PROC Glimmix with the LSmeans option and α at 0.05.

Results and Discussion

Yield and grade

The effect of gypsum treatments on 06G and GG yield was examined over the course of 3 years at two locations (Table 2). Addition of 560 kg ha^{-1} gypsum increased 06G yield at Tifton in 2009 compared to the control (P=0.003). The higher 1120 kg ha^{-1} treatment rate increased 06G yield above the control at Tifton in 2010 (P=0.06). At Tifton, 1120 kg ha^{-1} of gypsum improved yield of GG above the control in 2009 and 2010 (P=0.049 and 0.08, respectively). Non-significant yield increases were also observed for both varieties in Headland in 2008 and 2010 and in Tifton in 2008. In

Headland in 2009, 06G yield decreased compared to the control with the application of 1120 kg ha^{-1} (P=0.06) but not the 560 kg ha^{-1} (P=0.37). A similar trend was observed at the same site and year with GG but differences were not significant between the 0 and 560 and 1120 kg ha^{-1} applications (P=0.96 and 0.19, respectively).

All sites had initial soil calcium levels > 150 mg kg^{-1}, which is the critical value established for traditional runner peanuts in Alabama (Hartzog and Adams 1976). All soils were within ± 50 mg kg^{-1} of the critical value for gypsum application according to Georgia recommendations, which are to apply gypsum when soil calcium is < 250 mg kg-1 or Ca:K ratio < 3:1 (Alva et al., 1989). Sites at both locations were above the 3:1 Ca:K ratio. Thus, a yield increase due to applied gypsum would not be expected, except possibly at the three sites slightly below the 250 mg kg^{-1} critical value. Increases in yield due to gypsum may indicate that the critical soil calcium level or calcium to potassium ratio may be higher for the varieties evaluated. Low yields and lack of response to gypsum in Headland in 2010 are likely due to the extreme drought conditions. Lack of response to gypsum in 2008 at both sites may be due to heavy rains from tropical storm Faye, which may have leached a majority of gypsum from the pegging zone, rendering it unavailable to developing pods.

In Headland in 2009, 06G yield decreased with 1120 kg ha^{-1} gypsum application (P = 0.06), and a similar trend was observed with the GG variety. This yield reduction at a relatively high soil calcium level may indicate that too much calcium was applied to peanuts. The initial Ca:K ratio was 9:1 and was greater than all other sites except for Headland in 2010. Excess calcium in the pegging zone competes with other basic cationic nutrients, such as magnesium and potassium, and can cause slight deficiencies that can depress yield.

Peanut grade

Addition of gypsum improved peanut grade on all sites where yield improved and on some sites where yield increase was not significant (Table 3). This result shows the importance of calcium to peanut quality than overall yield. Comparison of the two varieties revealed an increase in TSMK of 06G due to gypsum application at all sites, while TSMK of GG increased at only three of five sites. This suggests that 06G may have a slightly higher calcium requirement than GG.

For both cultivars, a significant increase in grade due to applied gypsum was observed at the highest initial soil calcium level of 296 mg kg^{-1}. Gypsum applied to this soil at 560, 1120, and 1680 kg gypsum ha^{-1} improved TSMK in 06G and GG compared to the control (P=0.01, 0.0005, and 0.0003, respectively for 06G and P=0.02, 0.04, and 0.02, respectively for GG). This suggests that the critical soil calcium level of 150 mg kg^{-1} recommended by Alabama may be too low and the Georgia recommendations may be more adequate for the current runners.

The application rate of gypsum required to improve peanut grade was not consistent among variety, location, or initial soil calcium level. Application of 560 kg gypsum ha^{-1} improved 06G at both sites in 2008 and 2010, and GG at Tifton in 2009 and 2010. Gypsum applied at 1120 kg ha^{-1} was needed to improve TSMK of 06G at Tifton in 2009 and GG at Tifton in 2008. Many factors likely influence how application rate affects grade; however, timing and quantity of rainfall is likely to be highly influential on gypsum dissolution and leaching. From 2008 to 2010, rainfall was highly variable within and among years at both locations. In 2008, Headland and Tifton received 38 and 31 cm of rainfall during the growing season, respectively. More rain fell in 2009 as Headland and Tifton received a seasonal cumulative 48 and 41 cm of rainfall, respectively. The driest year was 2010 as 16 and 18 cm of cumulative rainfall was recorded at Headland and Tifton, respectively.

Germination

Results from the germination test show that germination increased with increasing gypsum application rate at almost all sites (Table 4). Increases were not significantly above the control with 560 or 1120 kg ha^{-1} in GG in Tifton in 2008 (P=0.25 and 0.26, respectively) and in 06G in Headland in 2009 (P=0.89 and 0.39, respectively). Application of 560 kg ha^{-1} improved germination of 06G at Tifton in 2008 and 2009 and GG germination in 2009 at both sites. The 1120 kg ha^{-1} rate increased germination of 06G at Headland in 2008 and Tifton in 2010 and GG at Headland in 2008. Lack of a significant increase in germination of GG at Tifton in 2008 is unknown, but it may be due to the 19 cm rainfall in a three day period following gypsum application. This rain event may have leached a considerable amount of calcium beyond the pegging zone, limiting calcium to developing pods. This is further supported by lack of effect of gypsum on yield and grade.

Increases in germination due to added gypsum are not expected when initial soil calcium is based on the critical soil calcium level of > 242 mg kg^{-1} established by Adams et al. (1993) on three traditional runner peanuts. Germination increased with added gypsum at all initial soil calcium levels evaluated (up to 296 mg kg^{-1}). This may further indicate that the critical soil calcium level for 06G and GG for maximum germination is higher than the critical level for yield.

Seed and hull calcium

Seed calcium concentration of both varieties increased with either 560 or 1120 kg ha^{-1} gypsum treatments except for 06G and GG at Tifton in 2010, which increased with 1680 kg ha^{-1} (Table 5). The high calcium requirement in Tifton in 2010, may be explained by the dry year not allowing gypsum to dissolve and diffuse into the pods.

To compare uptake of calcium by the larger 06G and smaller GG peanut varieties, total seed calcium within each gypsum treatment was analyzed (Table 6). Total seed calcium did not differ between 06G and GG within a treatment at any study site. At Tifton in 2010, 06G and GG did not differ in total seed calcium at the 0, 560, 1120, and 1680 kg ha^{-1} rate with P values of 0.29, 0.29, 0.49, and 0.36, respectively. At Headland the 06G and GG varieties did not differ in total seed calcium with 0, 560, and 1120 kg ha^{-1} of gypsum applied in 2009 (P=0.50, 0.43, and 0.94, respectively) and in 2010 (P=0.32, 0.73, and 0.36, respectively). Even though total seed calcium did not differ, concentration did differ in most treatments at both sites. Thus, the difference in concentration was due to differences in seed size, which was suggested by Walker (1975). Lack of differences in total seed calcium indicates that the larger surface area of the seed does not improve calcium absorption and suggests that 06G might require more calcium than GG.

Hull calcium was determined in 2009 and 2010 for each treatment (Table 7). Hull calcium of 06G increased with the 560 and 1120 kg ha^{-1} rates compared with the control at Tifton in 2009 (P= 0.08 and 0.10, respectively). An increase in 06G hull calcium above the control was also seen at Headland in with 1120 kg ha^{-1} in 2009 (P=0.04) and with the 560 and 1120 kg ha^{-1}rates in 2010 (P=0.04 and 0.0002, respectively). Hull calcium of 06G was similar to the control in 2009 at Headland with 560 kg ha^{-1} gypsum applied (P=0.46) and with the 560, 1120, and 1680 kg ha^{-1} rates in 2010 at Tifton (P=0.85, 0.71, and 0.62, respectively). Lack of increase of 06G in Tifton in 2010 is consistent with lack of increase in seed calcium for the same site. Increasing hull calcium with added gypsum is consistent with respective seed calcium increases in 06G but not with GG. For the most part, hull calcium did not increase with added gypsum with GG. This may indicate a difference in diffusion between hull and seed between the varieties.

Seed potassium and magnesium

The effect of gypsum application on seed potassium was examined to test if calcium applied in high rates would out compete potassium and magnesium for uptake (Table 8). Seed potassium of 06G was reduced with 1120 kg ha^{-1} gypsum at Headland in 2008 and Tifton in 2010 (P=0.04 and 0.03, respectively). These reductions were observed on the two sites with the highest initial soil calcium levels, 252 and 296 mg kg^{-1} at Headland and Tifton, respectively. Reduction in GG seed potassium due to 560 kg ha^{-1} gypsum treatment was seen at Headland in 2008 (P=0.03). The higher application rate of 1120 kg ha^{-1} reduced GG seed potassium concentrations at Tifton in 2008 and 2010 (P=0.049 and 0.002, respectively). Reduction in seed potassium due to gypsum application was not consistent with initial soil calcium ratings for the GG variety. The reduction in potassium with increasing calcium suggests that over application of gypsum may lead to potassium deficiency.

Gypsum application had minimal affect on seed magnesium. No differences in 06G seed magnesium was observed among gypsum rates. The 1680 kg ha^{-1} gypsum rate lowered GG seed magnesium concentration compared to seeds from the 1120 kg ha^{-1} gypsum treatment (P=0.099) but not compared to the control plot (P=0.28) This suggests that magnesium deficiency from over applying gypsum is unlikely.

The reduction in seed potassium may be due to the reduction of potassium on exchange sites in the soil. Alva and Gascho (1991) observed that gypsum applications induced leaching of both potassium and magnesium from the pegging zone. The reduced availability of potassium may explain the reduction in potassium seed concentration but does not explain the lack of reduction in the magnesium concentration. Calcium applications have been observed to repress the uptake of magnesium (Marshner, 2008), which makes the lack of a reduction in magnesium concentration harder to explain. A possible explanation is that the applied calcium displaced the monovalent potassium more readily than the divalent magnesium from soil exchange sites, as divalent ions are preferred for adsorption to soil exchange sites over monovalent ions (Foth, and Ellis, 1997). Once displaced, potassium was subject to greater leaching making it more unavailable to the developing pods compared to magnesium.

Calcium Sources

The effects of gypsum, lime, and liquid calcium on 06G yield, TSMK, germination, seed calcium, and seed potassium were examined at Headland from 2008 to 2010 (Table 9). Yield did not differ among any of the treatments in 2008 and 2010. In 2009, yield of 06G was greater in the control and liquid calcium fertilizer treatments than in the 1120 kg gypsum ha^{-1} treatment. This may be due to over-application of calcium on soils with initially high calcium (292 mg kg^{-1}) and high calcium to potassium ratio of 9:1. At the recommended application rate, the liquid calcium fertilizer provided only 0.49 kg ha^{-1} of calcium compared to 784, 146, and 291 kg ha^{-1} from the lime and two gypsum rates, respectively. The lack of effect of gypsum, lime, and liquid calcium on yield agrees with Hartzog and Adams (1976) as initial soil calcium levels were > 150 mg kg^{-1}.

This data is in contrast to the yield results of the previous objective because the increases in yield with gypsum were observed only at Tifton, while this study was performed only at Headland. Main differences between the sites are the calcium to potassium ratios, which were 5.3, 9.3, and 7.5 at Headland in 2008, 2009, and 2010, respectively, while in Tifton the ratios were 3.6, 3.3, and 5.6, respectively by year. This may further emphasize the importance of taking the calcium to potassium ratio into account when making future recommendations.

Grade did not improve above the control with any treatment, except for liquid calcium in 2010 (P=0.06). In 2008, the lime treatment improved grade compared to the liquid calcium fertilizer treatment; however, the reverse occurred in 2010. This may have occurred because of calcium out competing other cations needed for proper seed development, as limed seed had a higher seed calcium concentration than liquid calcium (P=0.06). In 2010, lime was likely to be much less likely to dissolve than gypsum due to limited rainfall, while in 2008, high rainfall was more likely to dissolve lime.

Warm germination test showed that germination was affected by calcium treatments in 2008 but not in 2009. Application of 1120 kg gypum ha^{-1} and lime improved germination in 2008 compared to the control. In the same year, the liquid calcium treatment produced a lower germination rate than gypsum and lime, but not the control. Reduced germination is likely due to the difference in total calcium applied compared to gypsum and lime. The liquid calcium fertilizer used was a 4% calcium solution applied at 11.2 L ha^{-1}, which provides 0.49 kg ha^{-1} of calcium. Gypsum is 26% (w/w) calcium and 560 kg ha^{-1} will provide 151 kg ha^{-1} of calcium or more than 300 times more calcium than liquid calcium. This is consistent with research by Walker (1975), which concluded that calcium applied in solution delivers less total calcium to peanuts than dry calcium applications.

Lack of difference in germination in 2009 may be caused by either the initial high soil calcium or the damage sustained to two lime treatment plots and two gypsum treatment plots. The 1120 kg ha^{-1} gypsum and the lime treatment did show higher mean germination than the control and liquid calcium treatments, but the lower sample number, caused from damage to two of the 0, 560, and 1120 kg ha^{-1} gypsum plots, two limed plots and one liquid calcium plot, may not have allowed for proper statistical delineation. Similar germination rates of the 1120 kg ha^{-1} gypsum and lime treatments in 2008 suggests that lime provides adequate calcium for seed production as long as there is adequate rainfall; however, more data is needed to make a conclusion.

Seed calcium was the most responsive parameter to calcium treatments. For all three years, the highest seed calcium concentrations were found in the 560 and 1120 kg gypsum ha^{-1} and lime treatments. Increases in seed calcium did not generally translate into increases in yield, grade, and germination. This may be due to adequate calcium for optimum yield and grade, but the added calcium still diffused into the seed.

Liquid calcium did not elevate seed calcium levels above the control from 2008 to 2010. This is consistent with the yield, grade, and germination results as liquid calcium performed the same as the control. Results agree with Hartzog and Adams (1973) and Walker (1975) that calcium supplied as a liquid is not suggested as a proper supplement for runner peanuts.

Calcium Uptake During Pod Development

Calcium concentration did not differ as greatly throughout the developmental stages of GG or 06G as the weight per seed (Figure 1). This difference shows the importance examining seed size along with calcium concentration. It is important to look at total calcium in the seed rather than calcium concentration alone, because uptake of calcium may not be evident through concentration alone. If the peanut stopped absorbing calcium after the first couple stages of development, the concentration would be diluted in later stages as the seed continued to grow. Total calcium generally increased in both varieties throughout the developmental period (Figure 1). Linear regression lines of the rate of calcium uptake show that both varieties absorb calcium at similar rates with slopes of 0.0023 and 0.003 for 06G and GG, respectively (Figure 2). While Reed and Brady (1948) suggest that the first 15 to 35 days after pegging is a critical period, calcium was observed to be absorbed throughout most of the developmental stages. It is likely that as peanut size increases more calcium is absorbed, thus increasing the total calcium. This may explain why generally smaller stages (White, yellow 1, yellow 2) have a lower total calcium than the larger stages. The white stage having the least amount of total calcium maybe exclusively due to its seed size as it is much smaller than the other stages. For peanuts that develop with 15 days per stage, 06G peanuts absorb calcium for up to 60 days and GG for 75 days after pegging.

Conclusions

Improvement in yield and grade of 06G and GG peanuts was observed for both varieties at Tifton in 2009 and 2010 when soil calcium was above the critical level (150 mg kg^{-1}) established by Hartzog and Adams (1973) and Adams et al. (1993). This may suggest that current recommendations for gypsum application to runner peanuts may slightly underestimate the needs of current runner-type peanuts. This would also indicate that recommendations for current varieties may need reevaluation. Application of gypsum on high calcium soils may repress yield as seen at Headland in 2009 on 06G. Peanut grade, represented as TSMK, increased on more occasions than yield in both varieties. This may indicate that these runner-type peanuts need more calcium for optimum yield and grade than previous varieties. A greater response of TSMK than yield to gypsum may suggest that seed quality requires more calcium than seed quantity. Gypsum increased germination in both varieties at 4 of 5 site-years. This supports the recommendation by ACIA to apply gypsum when growing peanuts for seed production regardless of pegging zone soil test calcium. Calcium applications occasionally decreased seed potassium but not magnesium. Potassium deficiencies may be responsible for yield decreases when calcium is over-applied, especially on soils with high Ca:K ratios such as 9:1.

Liquid calcium is not advised as a calcium supplement as it did not increase yield, or germination rates above the control. Liquid calcium did improve TSMK in 2010, but not in 2008. Producers may not expect an increase in yield with lime application on 06G when initial soil calcium levels are above 252 mg kg^{-1} or in a drought year.

Calcium was observed to be absorbed by 06G up to the brown stage (about 75 days after pegging) and by GG up to the black stage (about 90 days after pegging). If gypsum is leached soon after application, an additional application may be beneficial for pods developing later in the season. Results may lead to increases in yield, grade, and germination. Additional research is needed to test additional applications in high rainfall years.

Table 1. Soil calcium, potassium, magnesium, phosphorus, and pH at Headland, AL, and Tifton, GA, prior to experiments.

Site	Year	Ca†	K	Mg	P	Ca:K	pH‡
		------------------- mg kg^{-1} ----------------					
Headland	**2008**	252 AB§	47 C	41 BC	54 B	5 DC	5.2 A
	2009	292 A	31 D	37 BC	26 D	9 A	5.2 A
	2010	188 B	25 D	25 C	16 E	8 B	5.0 B
Tifton	**2008**	203 B	60 B	44 BC	83 A	4 D	4.8 BC
	2009	246 AB	74 A	48 B	46 C	4 D	4.6 C
	2010	296 A	51 C	84 A	54 B	6 C	5.0 B

† soil nutrients determined with shaking 5 g of soil in 20 mL of mehlich-1 for 5 minutes

‡ pH determined with 10 g of soil in 20 mL of DI water

§ letters represent differences at $\alpha = 0.05$ with proc glimmix using lsmeans option

Table 2. Yield of Georgia 06G and Georgia Green peanuts grown with different rates of gypsum. Data are listed in order of increasing initial soil calcium.

			Georgia 06G				Georgia Green			
			Gypsum rate (kg ha^{-1})							
Site	**Year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	Yield (kg ha^{-1})							
Headland	2010	188	181	316	400		273	241	417	
Tifton	2008	203	5803	6155	6650		5623	6013	5578	
Tifton	2009	246	5854 B †	6936 A	7230 A		6013 B	6455 AB	6641 A	
Headland	2008	252	5521	5681	5410		4562	4743	4363	
Headland	2009	292	4363 A	4028 AB	3586 B		4010	3992	3379	
Tifton	2010	296	2357 B	2586 AB	3365 A	3391 A	2283 B	2684 AB	3147 A	2994 AB

† Letters are significant at $\alpha = 0.10$. Comparisons are within rows and varieties.

Table 3. Peanut grade expressed as percentage of total sound mature kernels (% TSMK) in 200 g seed of Georgia 06G and Georgia Green peanuts grown with different rates of gypsum. Data are listed in order of increasing initial soil calcium.

			Georgia 06G				Georgia Green			
			Gypsum added (kg ha^{-1})							
Site	**Year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	% TSMK							
Headland	2010	188	64 B †	68 A	67 AB		66	68	68	
Tifton	2008	203	69 B	74 A	75 A		70 B	73 AB	74 A	
Tifton	2009	246	73 B	74 AB	76 A		70 B	73 A	73 A	
Headland	2008	252	74 B	77 A	77 A		75	76	75	
Tifton	2010	296	64 C	69 B	71 AB	72 A	67 B	71 A	70 A	71 A

† Letters are significant at α = 0.10. Comparisons are within rows and varieties.

Table 4. Germination of Georgia 06G and Georgia Green peanuts grown with various rates of gypsum. Germination is based on warm germination test. Data are listed in order of increasing initial soil calcium.

			Georgia 06G				Georgia Green			
			Gypsum added (kg ha^{-1})							
Site	**year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	**Germination (%)**							
Tifton	2008	203	72 B †	84 A	87 A		83	90	89	
Tifton	2009	246	80 B	86 A	89 A		84 B	91 A	91 A	
Headland	2008	252	83 B	88 AB	95 A		87 B	93 AB	95 A	
Headland ‡	2009	292	89	90	93		87 B	92 A	95 A	
Tifton	2010	296	73 B	81 A	86 A	86 A	74 B	86 A	84 A	88 A

† Letters are significant at $\alpha = 0.10$. Comparisons are within rows and varieties.

‡ Three replicates were used at this site.

Table 5. Seed calcium concentrations of Georgia 06G and Georgia Green peanuts grown with various rates of gypsum at Headland, AL, and Tifton, GA. Data are listed in order of increasing initial soil calcium.

			Georgia 06G				Georgia Green			
			Gypsum added (kg ha^{-1})							
Site	**Year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	**Seed calcium (mg kg^{-1})**							
Headland	2010	188	139 B †	273 A	332 A		240 B	386 A	338 AB	
Tifton	2008	203	172 B	269 A	300 A		228 B	336 AB	383 A	
Tifton	2009	246	243 B	340 A	316 AB		286 B	345 AB	415 A	
Headland	2008	252	225 C	356 B	527 A		278 B	368 AB	483 A	
Headland	2009	292	439 B	583 A	616 A		531 B	638 AB	771 A	
Tifton	2010	296	322 AB	263 B	426 A	431 A	305 B	435 AB	499 AB	402 A

† Letters are significant at $\alpha = 0.10$. Comparisons are within rows and varieties.

Table 6. Total seed calcium in Georgia 06G (06G) and Georgia Green (GG) peanuts grown in Headland, AL, and Tifton, GA, from 2009 to 2010 with 0, 560, 1120, and 1680 kg ha^{-1} applied gypsum.

			---------------------- kg ha^{-1} ---------------------			
Site	**Year**	**Variety**	**0**	**560**	**1120**	**1680**
			----------- Total calcium (mg seed^{-1})--------			
Headland	**2009**	**06G**	0.32†	0.42	0.41	
		GG	0.30	0.36	0.40	
Headland	**2010**	**06G**	0.06	0.16	0.19	
		GG	0.10	0.16	0.16	
Tifton	**2010**	**06G**	0.18	0.15	0.29	0.28
		GG	0.13	0.23	0.27	0.23

† Comparisons within rows and varieties do not differ at $\alpha = 0.1$.

Table 7. Peanut hull calcium concentration in Georgia 06G and Georgia Green peanuts grown in Headland, AL, AL, and Tifton, GA, from 2009 and 2010.

			Georgia 06G				Georgia Green			
			Gypsum added (kg ha^{-1})							
Site	**Year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	**mg kg^{-1}**							
Headland	2010	188	987 C	1306 B	1663 A		1320	1472	1474	
Tifton	2009	246	684 B	858 A	842 AB		845	816	841	
Headland	2009	292	963 C †	1079 BC	1304 AB		1081 B †	1351 AB	1557 A	
Tifton	2010	296	1376	1314	1335	1254	1745	1659	1921	1342

† Letters are significant at $\alpha = 0.10$. Comparisons are within rows and varieties

Table 8. Seed potassium concentrations of Georgia 06G and Georgia Green peanuts grown with various rates of gypsum at Headland, AL, and Tifton, GA, from 2008 to 2010. Data are listed in order of increasing initial soil calcium.

			Georgia 06G				Georgia Green			
			Gypsum added (kg ha^{-1})							
Site	**Year**	**Soil Ca**	**0**	**560**	**1120**	**1680**	**0**	**560**	**1120**	**1680**
		mg kg^{-1}	Seed potassium (mg kg^{-1})							
Headland	2010	188	5013	6223	5990		5678	7109	5704	
Tifton	2008	203	6106	5812	5722		6071 A	5731 AB	5637 B	
Tifton	2009	246	5421	5667	5498		5191	5861	5585	
Headland	2008	252	5565 A †	5315 AB	5121 B		5490 A	4968 B	5248 AB	
Headland	2009	292	5330 AB	5596 A	5222 B		5533	5419	5582	
Tifton	2010	296	5628 A	4802 AB	4704 B	4786 B	5906 A	4680 B	4289 B	4420 B

† Letters are significant at $\alpha = 0.10$. Comparisons are within rows and varieties.

Table 9. Georgia 06G yield, total sound mature kernels (TSMK), germination, and seed calcium in response to gypsum, lime and liquid calcium fertilizer applications in Headland, AL, from 2008 to 2010.

	Gypsum			Lime	Liquid calcium
	kg ha^{-1}				L ha^{-1}
	0	**560**	**1120**	**2240**	**11.2**
			Yield		
Year			kg ha^{-1}		
2008	5521	5681	5410	5552	5593
2009 ‡	4363 A †	4028 AB	3586 B	4074 AB	4288 A
2010	181	316	400	386	244
			Total sound mature kernels		
Year			% (w/w)		
2008	75 B	77 A	77 A	77 A	74 B
2010	65 BC	68 AB	68 ABC	64 C	69 A
			Germination		
Year			%		
2008	82 B	87 AB	95 A	94 A	83 B
2009 ‡	89	90	93	95	87
			Seed calcium		
Year			mg kg^{-1}		
2008	225 C	356 B	527 A	384 B	254 C
2009	439 B	583 A	616 A	648 A	455 B
2010	139 B	273 A	332 A	274 A	154 B
			Seed potassium		
Year			mg kg^{-1}		
2008	5565 AB	5315 BC	5121DC	4908 D	5811 A
2009	5330 AB	5596 A	5222 BC	5030 C	5537 A
2010	5013	6223	5990	5848	6072

† Letters indicate differences at α =0.10 level.
‡ Two repetitions for lime and 0, 560, and 1120 kg gypum ha^{-1} are reported

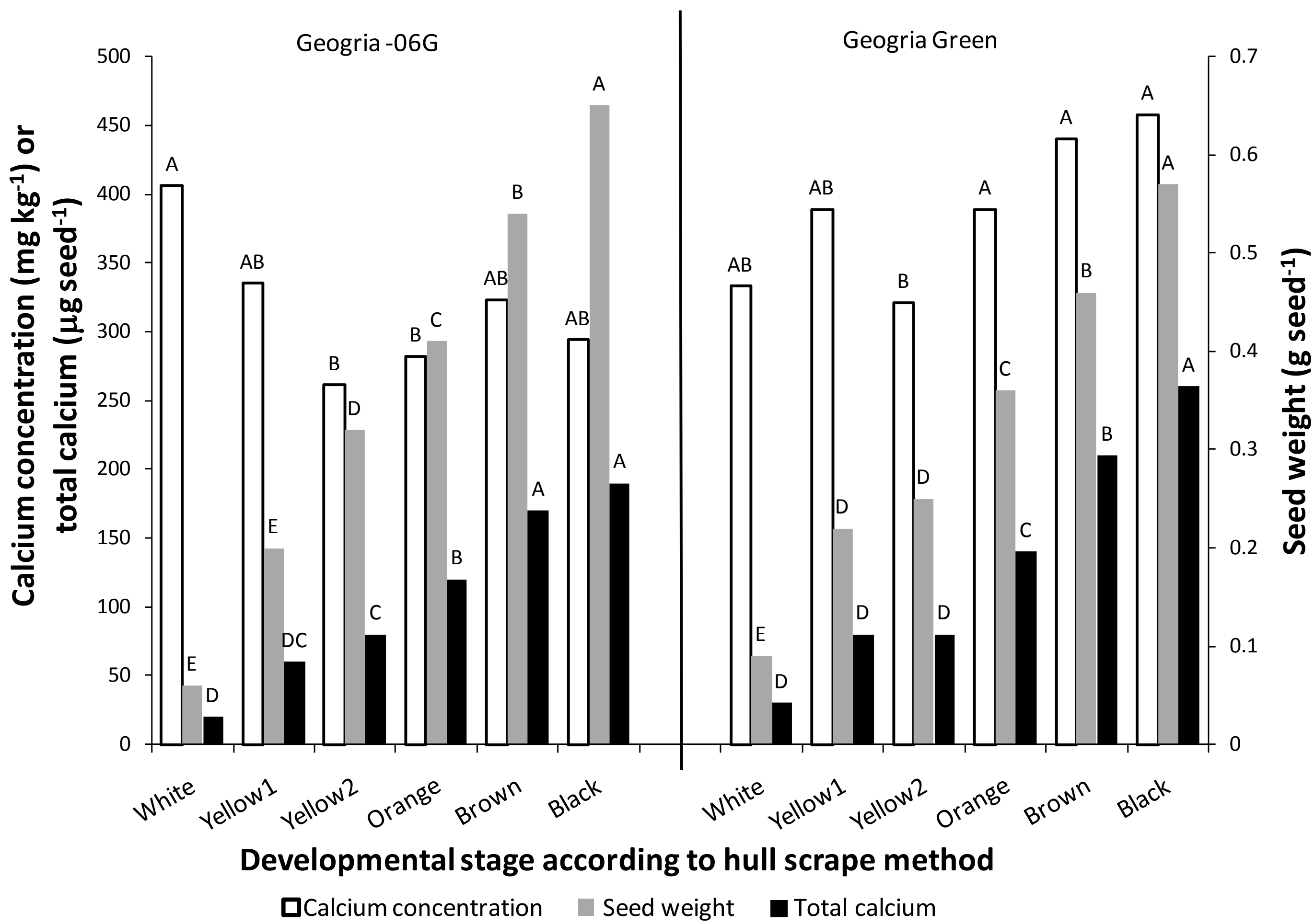

Figure 1. Seed calcium concentration (mg kg^{-1}), seed weight (g $seed^{-1}$), and total seed calcium (µg $seed^{-1}$) in Georgia-06G as divided into development stages using the hull scrape method by Williams and Drexler, 1984. Differences are at $\alpha = 0.05$ level.

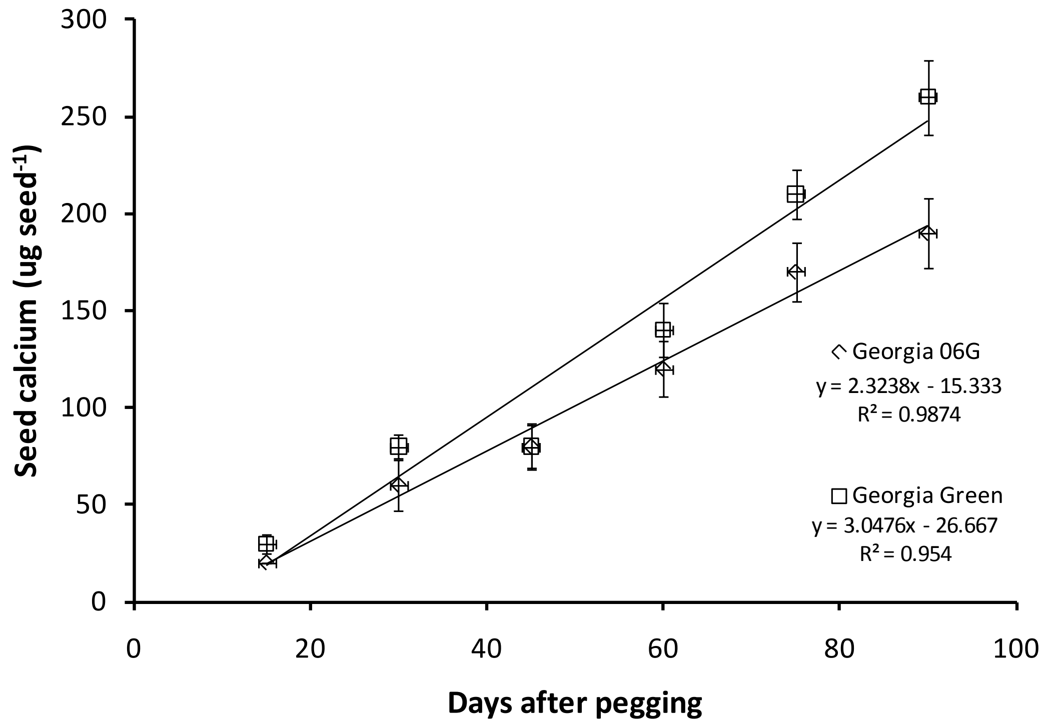

Figure 2. Total seed calcium in Georgia-06G and Georgia Green peanut seeds after approximate days after pegging based on the hull scrape method by Williams and Drexler, 1984.

III. Effect of rainfall on leaching of surface-applied gypsum in sandy surface soils

Abstract

Peanut (*Arachis hypogaea* L.) requires calcium in the upper 7 cm of soil (pegging zone) for proper pod development. In areas prone to heavy rains from tropical storms and hurricanes, gypsum may leach before all peanuts may develop. Ability to predict loss of calcium during a growing season may be beneficial, especially if heavy rains occur shortly after gypsum application, when there is time to reapply calcium. The objective was to evaluate the usefulness of electrical conductivity (EC) probes to observe the movement of gypsum through the pegging zone and determine the quantity of rainfall required to leach applied calcium from the pegging zone. Column experiments were performed by simulating rainfall (5 cm h^{-1}) on commercial sand and Dothan and Tifton loamy sand (86 and 87 % sand, respectively) with gypsum applied at 1120 kg ha^{-1} (560 and 1680 kg ha^{-1}on Dothan soil additionally). Leached gypsum was detected with EC probes at 10 cm depth. Results of soil column experiments indicate calcium is leached ten times faster from 5 to 9 cm of rainfall than from 9 to 38 cm. Increasing gypsum application rates did not increase residence time, but did increase the maximum EC. A field study was performed in Headland, AL, and Tifton, GA, on Dothan and Tifton loamy sand, respectively. The EC probes were installed 9 cm below the soil surface and gypsum was broadcast at 0, 560, 1120, and 1680 kg ha^{-1}. In the field, the 1680 kg ha^{-1} gypsum treatment showed elevated EC above the control for a longer period than the lower rates. No EC response from gypsum treatments above the control was seen after

12.0 and 12.2 cm of rainfall at Headland and Tifton, respectively. Using EC probes is an effective way to observe if gypsum has leached through the pegging zone in the field, but it may not be as effective as collecting soil samples or leachate when quantifying the percent of calcium leached.

Introduction

Application of gypsum to runner peanuts (*Arachis hypogaea* L.) is a common practice in the Southeast U.S. Gypsum supplies calcium to the pegging zone, 0 to 10 cm soil depth, where peanut development occurs (Kiesling and Walker, 1978). Calcium improves yield, increases sound mature kernels (SMK) (Adams et al., 1993), and can increase germination by reducing dark plumule (Harris and Brolmann, 1966; Cox and Reid, 1964). Gypsum is typically applied 40 days after planting, or early bloom, to minimize calcium leaching losses during pod formation (Daughtry and Cox, 1974). Blooming can continue for 70 to 90 days after flowering is initiated creating pods in the soil that require calcium (in Alva et al., 1989; Schenk, 1961). A Virginia peanut has been measured to absorb 8% of total pod calcium in the first 20 days after pegging, 69% between days 20 and 30, and 23% from days 30 to 80 (Mizuno, 1959; in Kvien et al., 1988). If gypsum is lost from the pegging zone before the end of the growing season, peanuts that develop later may lack calcium. Thus, adequate calcium in the pegging zone from 40 to 50 days after pegging (i.e., pod development phase) is essential for adequate yield and peanut quality.

In the Southeast U.S., peanuts are commonly grown on sandy loam, loamy sand, and sandy surface soils, which facilitate digging during harvest. These soils meet the physical requirements for peanut production, but they are naturally low in calcium (Adams and Hartzog, 1979). Furthermore, added calcium is poorly retained due to the high rainfall in the region, which averages about 15 cm per month during the growing season (Alva and Gascho, 1991).

Several column, greenhouse, and field studies have evaluated the persistence of gypsum in the pegging zone in sandy soils (Table 10). In a column study, Daughtry and Cox (1976) recovered 60 to 87% of the applied calcium in the leachate when it was added to sand and sandy loam soils placed in a 6.5 cm column and leached with 17.2 cm of water in 1.32 cm incremental additions. In a greenhouse study, soil calcium decreased by 50% in the top 5 cm of soil after 27.7 cm of rain was added to a pot with 560 kg ha^{-1} powder gypsum applied to the surface (Jones et al., 1976). A field study by Alva et al. (1990) found that one rainfall event of 15.2 cm on surface-applied gypsum resulted in 21 and 31% loss of calcium from the top 8 cm of soil in soils with 87 and 93% sand, respectively. When the 15.2 cm of rain was divided into 12 applications, loss of calcium was 14 to 30%. This shows that total rainfall is not a good indicator of how much gypsum has leached from the pegging zone. Frequency and intensity of the rainfall affects the amount of gypsum leaching. High frequency, low magnitude rainfalls result in less leaching than low frequency, high magnitude rainfalls (Alva et al., 1990).

The objective of this study was to evaluate the usefulness of EC probes in detecting gypsum leaching from the pegging zone and to quantify the amount of rainfall required to leach gypsum once applied.

Methods and Materials

Column Experiment

The top 7 to 10 cm of a Dothan soil (Fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and Tifton soil (Fine-loamy, kaolinitic, thermic Plinthic Kandiudult) were collected from peanut production fields at the Wiregrass Experiment and Research Center (WREC) in Headland, AL, and the Coastal Plains Research Center (CPRS) in Tifton, GA. Dothan soil was 86, 10, and 4% sand, silt, and clay, respectively, while the Tifton was 87, 8 and 5% sand, silt, and clay, respectively. All soils were sieved to < 2 mm and dried at 60^{o}C for 48 hrs. Sand was acquired from M & M Trucking Company (Auburn, AL) and dried as previously mentioned. Sand was not sieved but was measured to have 1%, (w/w) particles slightly larger than 2 mm in diameter. Flue gas desulfurized (FGD) gypsum from Georgia Power's Yates Power Plant in Newnan, GA was used as the source of gypsum in both the column and field experiments. Gypsum was sieved < 2 mm and was dried for 48 hrs at 60^{o}C. A 0.2 g sample of gypsum was digested in 0.1 L of 0.3 M hydrochloric acid, analyzed by inductively-coupled plasma (ICP) spectroscopy (Spectro Ciros CCD, side on plasma, SPECTRO Analytical Instruments Inc., Kleve, Germany), and found to be 26% calcium.

Two columns with 10.2 cm diameter and 20 cm height were constructed from polyvinyl chloride (PVC). A 3.5 cm (width) by 1 cm (height) rectangular slit was made 2.5 cm above the bottom of each column. An electrical conductivity (EC) probe (5TE EC/T/MC, Decagon Devices, Pullman, WA) was installed in the slit and sealed with silicone. Probes were connected to an Em50 ECH$_2$O Digital/Analog Data Logger

(Decagon Devices, Pullman, WA). Data logger recorded EC, temperature, and moisture content every minute during the experiment for both columns simultaneously.

To hold the soil in the column and allow for free drainage, a polyester mesh and plastic canvas were attached and sealed with silicone to the bottom of the column. A funnel was attached and sealed with silicon below the plastic mesh to collect the leachate. A Masterflex L/S peristaltic pump (Cole-Parmer, Vernon Hills, IL) with two distributers was used to deliver simulated rainfall at 6.8 ml min^{-1}, which is equivalent to 5.1 cm hr^{-1}. This set up allowed for two column leaching runs to be performed simultaneously. Rainfall rate was selected based on a heavy rate that would provide saturated flow, but not cause water to pond on the soil surface. To simulate rainfall and distribute it over the entire surface of each column, five small-diameter tubes (1 mm inside diameter) were inserted into a larger tube attached to the pump. These tubes were sealed in place with silicone and held apart 2.5 cm apart from each other with glue in the four corners and center of a 4.4 x 4.4 cm plastic canvas with grid size of 2.5 mm square. The five small tubes rotated within the 10.2 cm diameter column at 4.4 revolutions per minute, above the soil. Column walls acted as a guide to ensure the tubes always delivered water on the soil surface.

All soil columns were packed to a height of 12.5 cm with soil or sand, usually requiring between 1500 and 1600 g of soil. Packing to this consistent height allowed for the 5TE probes to rest 2.5 cm above the bottom of the column, and 10 cm below the soil surface. Columns were equilibrated with the simulated rain solution (0.01 M $CaCl_2$) until a baseline EC was established usually after 20 cm of rain were applied. Powdered gypsum was applied at an 1120 kg ha^{-1} rate (0.91 g per column) to the soil surface of sand, Dothan loamy sand, and Tifton loamy sand in the column and the simulated rainfall was applied until EC returned to baseline. Column leaching runs were replicated in duplicate for the 1120 kg ha^{-1} rate on the Dothan soil and triplicate for the sand and Tifton loamy sand. To study the effects of different gypsum application rates, three repetitions of 560 and 1680 kg ha^{-1} rates and two repetitions of 1120 kg ha^{-1}, were surface applied by adding 0.45, 1.36, and 0.91 g, respectively, to the Dothan soil packed into the column as previously described. Runs from the same treatment were averaged.

Electrical conductivity data were used to estimate the percent calcium lost as rainfall was applied. This was accomplished by determining the area under the curve of graph provided from the EC data with increasing rainfall for each soil. Because the average breakthrough curves of the three soils returned to the EC baseline at different rainfall amounts, the area from 0 cm of rainfall to 32.1, 34.7, and 40.7 cm were operatively defined to contain 100% of the area for the Tifton, sand, and Dothan soils, respectively. The area was calculated by summing the EC recorded at each minute from 0 cm of rainfall to the baseline return. The percent area for each minute was calculated by dividing the individual EC response of that minute by the whole area. To quantify how much calcium had leached at the baseline, leachate was collected and analyzed using an ICP. To obtain the amount of calcium leached that was contributed to the applied gypsum the calcium concentration from the leachated was multiplied by the volume of leachate collected and then subtracted the amount of calcium supplied by the 0.01 M calcium chloride solution. The percent calcium lost as rainfall was applied, which was calculated using EC data, was then corrected for total calcium leached.

Statistics for the individual column runs were analyzed using PROC Glimmix with the LSmeans option in SAS 9.2 (Statistical Analysis Systems, Cary, NC). Data analyzed included the peak EC, amount of rainfall at maximum EC, and the residence time, or time required for the breakthrough curve to return to baseline.

Field Experiment

The field experiment was performed at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and the Coastal Plain Experiment Station (CPES) in Tifton, GA. Decagon® 5TE ECH_2O probes were horizontally installed at 9 cm depth just under the peanut canopy at early bloom. Gypsum was evenly applied with a sieve to a 0.1 m^2 area at rates of 0, 560, 1120, and 1680 kg ha^{-1}. Treatments were established in the field in a randomized complete block design with all treatment data collected by one data logger per block. A square frame was used to ensure uniform gypsum application over the area above the installed probe. Four replications were performed at both sites; however, one replication at Headland was discarded due to probe malfunction. Soil EC, temperature, and moisture content were recorded every 30 minutes. Precipitation was recorded hourly at Headland by Alabama Mesonet Weather Data (AWIS Weather Services, Inc., Auburn, AL), and daily at Tifton by Georgia Weather Network. The EC readings from the no gypsum control treatments were subtracted from the gypsum treatments to account for native salts present in the soil and rainfall.

Data was analyzed in two ways. The first was to take the raw data from the probes, subtract it from the control in the same block, and then average the response of the three treatments above the control. This method assumes that any response above 0 dS m^{-1} of the treatment average indicated that gypsum is still preset in the pegging zone.

The second method is to take the individual results from each probe within a treatment and compare the means of the treatments statistically. This method assumes that any response of the gypsum applied plots that are statistically higher than the control indicates that gypsum is still present in the pegging zone. Statistics for the treatments comparisons were analyzed using PROC Glimmix with the LSmeans option in SAS 9.2 (Statistical Analysis Systems, Cary, NC).

Results and Discussion

Column Experiments

Electrical conductivity data from the column studies portray a breakthrough curve that has four important parts of interest (Figure 3). These points are: the amount of rain required before the EC spikes, the amplitude of the EC, the point at which the EC goes from a steep negative slope after the maximum EC to a less steep slope, and the point at which the EC returns to baseline, or the residence time. The EC peak is attributed to mass flow of gypsum through the soil under saturated conditions. The residual tail is thought to be a result of cation retention by the soil and slower dissolution of gypsum at the surface from larger particles. Hydrodynamic dispersion may also cause the residual tail as the high amount of gypsum applied may cause an increase in the rate of diffusion.

The amount of rainfall required to reach maximum EC differed between the loamy sand and sand soils (P=0.002). Dothan and Tifton soils reached peak EC with 6.9 and 5.7 cm of rainfall, respectively, while the sandy soil only required 3.5 cm of rain. This is expected as mass flow in sand is likely to be faster than soil with higher clay content due to the commonly observed decrease in hydraulic conductivity with increases in clay (Radcliffe and Rasmussen, 2000).

There was no difference in the maximum EC recorded between sand and loamy sand soils with the 1120 kg ha^{-1} rate ($P = 0.63$). The Tifton soil had a maximum EC of 0.51 dS m^{-1} followed by the Dothan at 0.39 dS m^{-1} and sand at 0.36 dS m^{-1} (Figure 3). A similar maximum EC among the three soils was expected as the same amount of gypsum was applied to the soils and there is a minimal retention of calcium to these sandier soils.

Electrical conductivity returned to baseline in the three soils with varying amounts of rainfall. Baseline EC values were observed approximately after 15.8, 28.6, and 33.7 cm of simulated rainfall in the sand, Dothan, and Tifton soils, respectively; however, differences are not significant ($P = 0.33$). Previous studies observed variability in leaching due to soil texture and cation exchange capacity properties (Daughtry and Cox, 1976). This may aid in the explanation of why sand had the shortest residence time, even though it was not significant. Reasons for variability in residence time may be caused by differences in particle size, aggregation, cation exchange capacity, or the detection limit of the 5TE EC probe. The end tail of the breakthrough curves is long and slightly elevated above 0 dS m^{-1} for a prolonged time (Figure 3). Decagon Devices ® states that the EC resolution of the 5TE probes is 0.01 dS m^{-1} but that there is a $\pm$ 10 % error in the reading from 0 to 7 dS m^{-1}. Since a 10 % error may not account for the probe reading slightly above baseline for an extended period, the slight EC elevation may be due to recalcitrant gypsum particles slowly dissolving or to hydrodynamic dispersion.

Increasing application rates of gypsum to the Dothan soil did not increase residence time (Figure 4). A return of the EC to baseline was observed in the 560, 1120, and 1680 kg ha^{-1} rates after 16, 25, and 33 cm of rainfall (P=0.42), respectively. Reasons for this difference in mean retention volumes that are not statically different may be caused by gypsum particles resistant to dissolution. The amount of rainfall required before the EC peaked did not differ with increasing gypsum application rates. The 560 kg gypsum ha^{-1} rate peaked with 6.9 cm of rainfall and did not differ from the 1120 and 1680 kg ha^{-1} rates which required 6.6 and 7.0 cm of rainfall before peaking, respectively (P=0.69 and 0.52, respectively). The 1120 and 1680 kg ha^{-1} rates did not differ (P=0.87). The similarity in the amount of rainfall inducing a maximum EC is probably because the rates were applied to the same textured soil, packed in similar manners. This similarity indirectly lends evidence that application rate may not affect residence time of gypsum.

The fast dissolution rate of gypsum may have an impact on the residence time of the increasing gypsum rates as enough rainfall may have been supplied to dissolve the gypsum in relatively similar time. If more gypsum had been applied to a point where the amount of rainfall was not enough to dissolve the applied gypsum in a short time the residence time may be extended. Residence time may also be affected by the size of the gypsum particles. In this study the application of gypsum in a powdered form would promote rapid dissolution. If more coarse particles were applied, the residence time might increase, and the dissolution rate may be slower.

While the amount of rainfall required before the gypsum breakthrough curve peaked, the amplitude of the EC peak did increase with increasing gypsum rates. The 1680 kg ha^{-1} gypsum treatment resulted in a maximum EC of 0.50 dS m^{-1} that was similar to the 1120 kg ha^{-1} gypsum treatment , 0.33 dS m^{-1} (P=0.30), but greater than 560 kg ha^{-1} treatment, 0.17 dS m^{-1} (P =0.03). This indicates that a greater concentration of gypsum was leached at one time. Interestingly the 1120 kg ha^{-1} rate did not produce a higher maximum EC from the 560 kg ha^{-1} rate (P=0.30); however, the area of the peak was larger for the higher application rate. Regardless, data suggests that higher application rates may be able to provide more available calcium, but that the calcium can be leached from the pegging zone with similar rainfall amounts as the lower application rates. Sumner et al. (1988) suggest that calcium diffuses from soil solution to the developing pod. Thus, an increase in calcium would increase the passive calcium gradient from the soil solution to the peanut and provide more calcium to the developing peanut.

Previous leaching studies did not use EC as an indicator for leaching but used calcium leachate collected instead (Table 10). Comparison of gypsum leaching with previously performed column studies was made possible by collecting the leachate and comparing the amount of calcium leached from the column with the EC response over time in the soil column. The leachate collected from the 1120 kg ha^{-1} gypsum applied to the sand and Dothan soils revealed that 47 and 37% of the applied calcium leached from the column once the EC baseline was reached. Rainfall needed to leach similar percents of gypsum in other studies is consistent with the results of this study. Alva and Gascho (1991) required 15 cm of rain to leach 50 and 30% of calcium applied as gypsum to 8 cm deep in a sand and sandy clay loam, respectively. The sand in this study required about 10 cm of rain to leach 30% calcium, which may a little faster rate of leaching than in the Alva and Gascho (1991) study as they looked at a shallower depth and with 5 cm more rain saw a 20% greater loss of calcium.

Daughtry and Cox (1976) found a calcium leaching rate more similar to this study than Alva and Gascho (1991). Daughtry and Cox (1976) observed that 17 cm of rain was required to leach 62, 41, and 30% of calcium applied as gypsum to 6.5 cm deep in a loamy sand, sandy loam, and fine sandy loam, respectively. The 30% calcium leached in the sandy loam was similar to that leached in the current study of 16 and 22 in the Tifton and Dothan, respectively. The loamy sand in Daughtry and Cox (1976) leaching twice as much calcium as this study and 12 % more than the sand in Alav and Gascho (1991). This may be due to the gypsum they used and their application method.

The source of gypsum used in the Alva and Gascho (1991) and Alva et al. (1989) study was a powdered form of Gold Bond™ gypsum that is 20.6% calcium. Daughtry and Cox (1976) used laboratory grade gypsum 79% calcium sulfate equal to 23% calcium. The source of gypsum may affect results as the solubility of the agricultural grade products may be less than the laboratory grade gypsum. A difference may also exist between the solubility of Gold Bond gypsum and the FGD gypsum used in this study.

Difference in results between the current study and previous studies may be due to the higher rainfall rate used in this study that simulated continuous saturated flow, while other studies used lower rates, intermittent rainfall, and unsaturated flow (Daughtry and Cox, 1976; Alva and Gascho, 1991). In addition, this study differs from the other study in that rain is distributed over a soil surface. Alva and Gascho (1991) applied simulated rainfall at a low rate (2.34 cm hr^{-1}) and to center of a 7 cm diameter PVC pipe relying on filter paper to evenly distribute the rainfall. Daughtry and Cox (1976) applied rain to the soil surface (3.1 cm in diameter) in 10 mL increments daily. This would quickly dissolve any gypsum on the surface and allow soil to partially dry between additions.

The approach used in this study was to simulate rainfall in a continuous manner and also over the entire surface instead of relying on filter paper to distribute the rain. While the rain drops in this study hit a vast majority of the surface, a small portion did not receive direct rainfall. Some of the gypsum in the small excluded areas is dissolved by the saturated soil, while a portion remains undissolved. Furthermore, the method of recording the amount of gypsum leaching also differs from direct measurements of leachate fractions to real-time detection using EC. The use of EC probes allows for a continuous relationship between rainfall applied and leaching; however, may not be the best method for quantifying calcium leached.

Field Experiment

A field study was initiated at Headland and Tifton in 2010 to compare the soil column results to actual rainfall events. It was unfortunate that during the growing season rainfall was very limited at both locations; a total of 14.7 and 17.6 cm of rain was recorded at the Tifton and Headland sites, respectively, during the growing season. Electrical conductivity attributable to applied gypsum was detected at most rain events > 0.3 cm in all gypsum application rates until harvest, October 9, 2010 at Tifton and November 11, 2010 at Headland (Table 11 and 12). Tables 11 and 12 are presented for illustrative purposes in Figure 5 and 6. Harvest at Headland was about a month later than usual as a drought severely damaged the crop. Maximum EC during each rainfall event is dependent on the amount of water in the soil, which causes variation in the concentration of salts in solution. However, an EC measurement greater than the control plot with any rainfall event indicates that gypsum is still present. From averaging the EC response of gypsum applied plots from that of the control plots a gypsum response was observed up until harvest at both sites. This is not surprising given the drought conditions during the season. Column studies estimate that an EC response of applied gypsum at 1120 kg ha^{-1} would have a slight response in EC for up to 29 cm in Dothan and 34 cm in Tifton soils. When using an alternative method of comparison by comparing the gypsum applied plots EC to the control plots EC, the gypsum plots did not have a higher EC than the control at harvest. The amount of rainfall at both sites in which a difference between the gypsum and control EC was not seen is about 12 cm. Not seeing a difference among the gypsum and control plots after 12 cm of rainfall might be expected as the soil column results showed that after about 12 cm of rainfall the slope of the EC response goes from steeply declining to gradually declining.

Soil column experiments suggest that application of greater rates of gypsum would increase maximum EC values. In the field, increasing gypsum rates increased the maximum EC values of the 1680 kg ha^{-1} rate above the 560 kg ha^{-1} rate twice at Headland and three times at Tifton (Table 13 and 14). The 1680 kg ha^{-1} gypsum treatment was significantly higher than the 560 kg ha^{-1} rate at Headland with rainfall events on September 21 and 25, 2010 (P = 0.01 and 0.003, respectively). The 1680 kg ha^{-1} rate had a higher EC than the 560 kg ha^{-1} at Tifton on August 24, 2010 (P= 0.02). The 1680 kg ha^{-1} rate was higher than the 560 and 1120 kg ha^{-1} rate on August 28, 2010 (P=0.01 and 0.03, respectively) and on September 25, 2010 (P=0.04 and 0.04, respectively). This agrees with the soil column study that applying 1680 kg ha^{-1} of gypsum will increase the calcium gradient above that of the 560 kg ha^{-1} rate. This higher gradient may facilitate faster diffusion of calcium into developing pods.

While the maximum EC response with increasing gypsum agrees with the soil column experiments, the residence time of increasing gypsum rates does not agree. Field data show that the higher rates of gypsum application gave an EC response above the control for longer periods. All gypsum treatments contributed to a spike in the EC above that of the control three times at Headland and once at Tifton. All gypsum treatments at Headland produced higher EC values than the control on August 19, 22, and 27, 2010 (P=0.003, 0.001, and 0.003, respectively) and at Tifton on July 12, 2010 (P=0.001). The 1120 and 1680 kg ha^{-1} treatments at Headland were higher than the control on September 21 (P=0.014 and 0.002, respectively) and 25, 2010 (P=0.002, and 0.0002, respectively). The 1680 kg ha^{-1} treatment was the only treatment higher than the control at Headland on September 26 (P=0.02) and at Tifton on August 24, 28 and September 25, 2010 (P=0.01, 0.001, and 0.03, respectively). The experiment was continued beyond harvest at Headland, but no differences in EC among the gypsum rate and control treatments were measured. This may be due to probe failures limiting the sample number and preventing complete statistical analysis.

When considering the EC responses with the amount of rain, the higher gypsum rates gave an elevated EC above the control after greater levels of rainfall. The 560 kg ha^{-1} rate returned to a similar level as the control after 4.45 and 6.43 cm of rain at Headland and Tifton, respectively. The 1120 kg ha^{-1} treatment returned to levels similar to the control after 6.68 and 6.43 cm of rain at Headland and Tifton, respectively. The EC response of the 1680 kg ha^{-1} rate was higher than the control with 12.0 cm of rainfall at Headland and Tifton (P= 0.02 and 0.03, respectively). After 12 cm of rainfall, the gypsum-applied plots were not greater than the control. A lack of probes operating may be the reason for lack of significance beyond 12 cm of rainfall; however, the rainfall just prior to Harvest at Tifton did not show a statistical difference between the gypsum applied plots and control. This lack of EC response in the field may be compared to the soil column where after about 12 cm of rainfall the EC returns relatively close to baseline. The soil column and field data at Tifton may indicate that after 12 cm of rainfall the applied gypsum is no longer effective at supplying calcium to developing pods.

The residence time of gypsum in the different gypsum treatments differs from the soil column results but agrees with Walker (1975). The discrepancy between the field and column results may be due to the application method as the column study continuously supplies rainfall while rain in the field is sporadic.

Antecedent moisture may affect the amount of rainfall that actually contributes to leaching in the field. Antecedent moisture is the volumetric soil moisture content before a rainfall event. The lower the volumetric moisture content the more rainfall that is required to wet the soil before mass flow begins. The effect of antecedent moisture can be seen as the absence of a spike in EC when rainfall was > 3 cm (Tables 11 and 12). The volumetric moisture contents at Headland and Tifton at which mass flow was assumed to begin were 0.24 and 0.34 $m^3 m^{-3}$, respectively.

The effect of antecedent moisture on calcium leaching from the pegging zone may explain the results seen by Alva et al. (1990). In their study, they compared a single application of 15.2 cm of rain to twelve equal proportions adding up to 15.2 cm of rain. The single application caused a loss of 21 and 31% of calcium on a loamy sand and sand, respectively, while the 12 applications caused a 14 and 30% calcium in the loamy sand

and sandy soil, respectively. The difference in the amount leached when applied in one application versus twelve maybe due to soil drying after each application. Subsequent applications must first saturate the soil before leaching begins. Taking antecedent moisture into account when calculating how much rain is required to leach gypsum may be necessary.

Antecedent moisture and the amount of rainfall that is considered to contribute to leaching were calculated at Headland and Tifton. Over the eight month period in Headland, 45.8 cm of rain was recorded, using field saturation and antecedent moisture, it is estimated that 41.8 cm of rain contributed to leaching, which is 9% less than total rainfall (Table 11). Rainfall in Tifton was recorded over three months in which 14.7 cm of rainfall was recorded. Using 0.34 $cm^3\ cm^{-3}$ as field saturation, it is estimated that 12.1 cm contributed to gypsum leaching, 18% less than the total rainfall (Table 12).

Attempts were made to model the rate of calcium leaching from the column studies. The mean percent calcium lost in sand, Dothan, and Tifton experiments were averaged and graphed (Figure 7). Calcium loss in the sand equals 16.811 × ln(rainfall, cm) – 10.598, $R^2 = 0.97$. Calcium loss in the Tifton soil equals 16.752 × ln(rainfall, cm) – 17.992, $R^2 = 0.92$. And, calcium loss in the Dothan soil equals 16.456 × ln(rainfall, cm) – 21.175, R^2=0.94.

While field studies showed that the 1680 kg ha^{-1} rate resided in the pegging zone longer than the lower gypsum rates, this difference was not seen in the soil column. Regardless of this discrepancy Figure 8 illustrates the lag time, the initial higher rate of calcium loss with rain, followed by a slow rate of calcium loss. The three rates were averaged together and two lines fit from 5 to 9 cm and from 9 to 38 cm. The first lines equation of percent calcium leached equals 5.5361 × (rainfall, cm) – 28.84, $R^2 = 0.99$, and the second half is percent calcium leached equals 0.5067 × (rainfall, cm) + 19.32, R^2=0.93. Calcium is lost at a rate 10 times greater from 5 to 9 cm of rainfall than from 9 to 38 cm. This high rate of loss from 5 to 9 cm may be due to mass flow, while the slow rate of loss after 9 cm may be due to cation retention of the soils and hydrodynamic dispersion.

The predicted numbers for gypsum loss in the three soils and the three rates are somewhat close to those reported by Alva et al. (1990) Table 10. They observed losses between 14 and 30% calcium with 1120 kg ha^{-1} gypsum applied to Tifton loamy sand and Lakeland sand, respectively, with 15 cm of rainfall. Comparing leaching of 1120 kg ha^{-1} gypsum with 15 cm of rainfall on the Tifton loamy sand and commercial sand in this study would have predicted losses of 23, 27, and 35% in Dothan, Tifton and sand, respectively, using the natural log equations. When using the linear equation from the three difference rates of gypsum application 26.9% calcium is predicted to be lost after 15 cm of rainfall. These numbers are close to those observed by Alva et al. (1990).

Comparing gypsum losses by collecting soil samples or leachate in other studies may be more appropriate than just measuring the EC as gypsum moves through the soil. Gathering EC data does provide a real time method of determining if calcium from gypsum is still present in the soil without requiring an ICP or atomic adsorption machine. A producer could utilize EC probes in peanut fields and see if gypsum is present in the pegging zone with each rainfall.

Conclusions

Results from the column study show that there was no difference among the residence times of gypsum in the pegging zone of a loamy sand, and sandy soil. While the residence time of gypsum in sand and loamy sand did not differ, the EC peak was observed was with less amounts of rainfall on the sandy soil than the loamy sand. The differences observed in the amount of rain required before the EC peaked in the sand and loamy sand soils may be a more appropriate measure of the potential residence time of gypsum in a soil. Increasing application rates of gypsum did not increase the residence time in the soil column but did increase the maximum EC recorded as the 1680 kg ha^{-1} rate EC was higher than the 560 kg ha^{-1} rate. This may show that a higher rate of gypsum application increases the calcium gradient, and subsequently the rate of calcium diffusion into the developing pod. Generally, EC response from gypsum was seen to gradually approach baseline after 12 cm of rainfall in the soil column. After 12 cm of rain in Tifton and Headland, the gypsum treatments did not have a higher EC than the control. This may suggest that after 12 cm of rainfall most gypsum is leached. This 12 cm of rainfall mark may be important to producers as a hurricane soon after gypsum application has the potential to leach most of the applied gypsum. Measuring rainfall alone is not appropriate for estimating gypsum loss as soils with higher field saturation requirements may require more rainfall before leaching begins. Electrical conductivity probes may not be appropriate for measuring exact losses of calcium from gypsum but can give an indication of gypsum presence in the pegging zone.

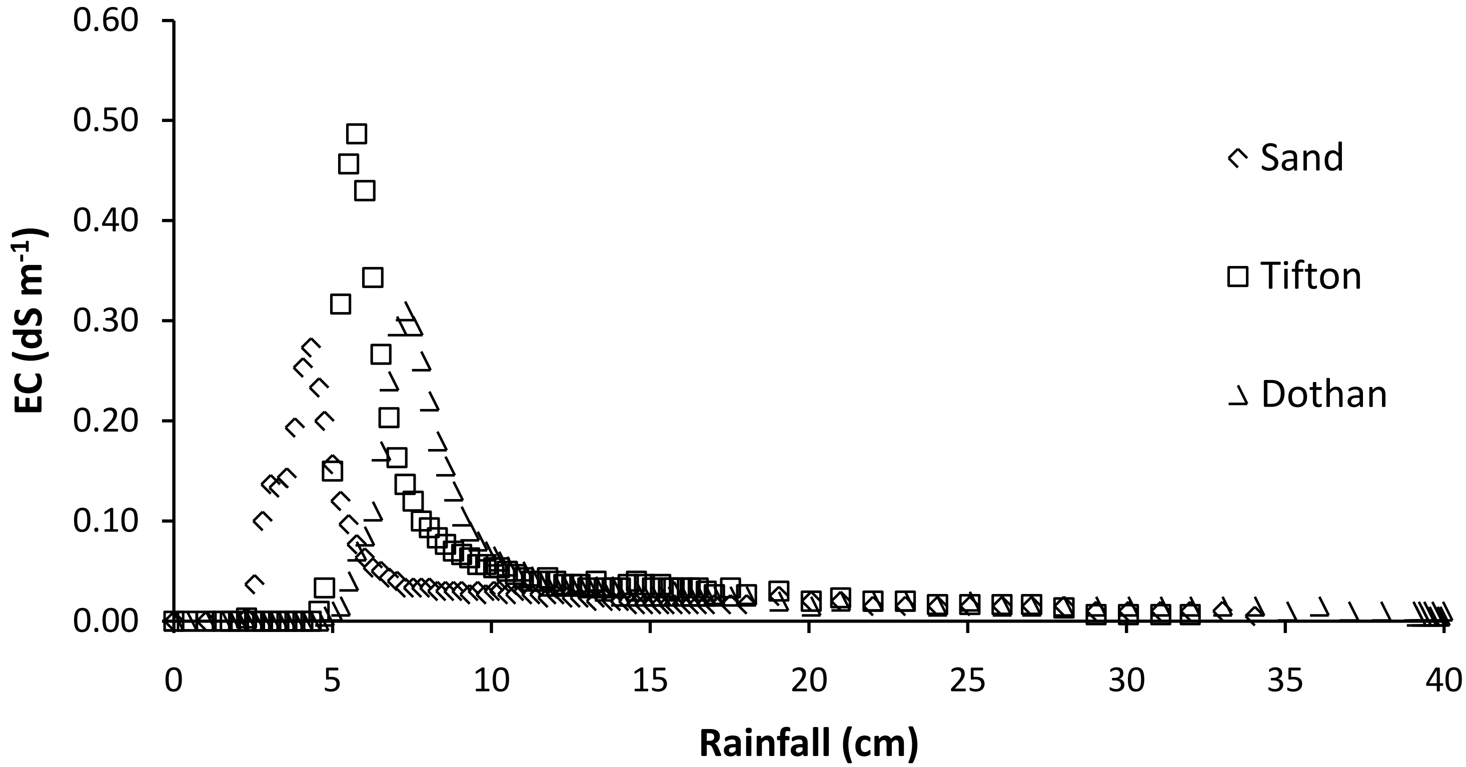

Figure 3. Electrical conductivity at 10 cm depth produced with 1120 kg ha^{-1} gypsum applied to the surface of a soil column (10 cm diameter, 12.5 cm deep) with simulated rainfall (5 cm hr^{-1}) on commercial sand, Tifton loamy sand, and Dothan loamy sand. Rainfall produced saturated flow, but water did not pond on soil surface.

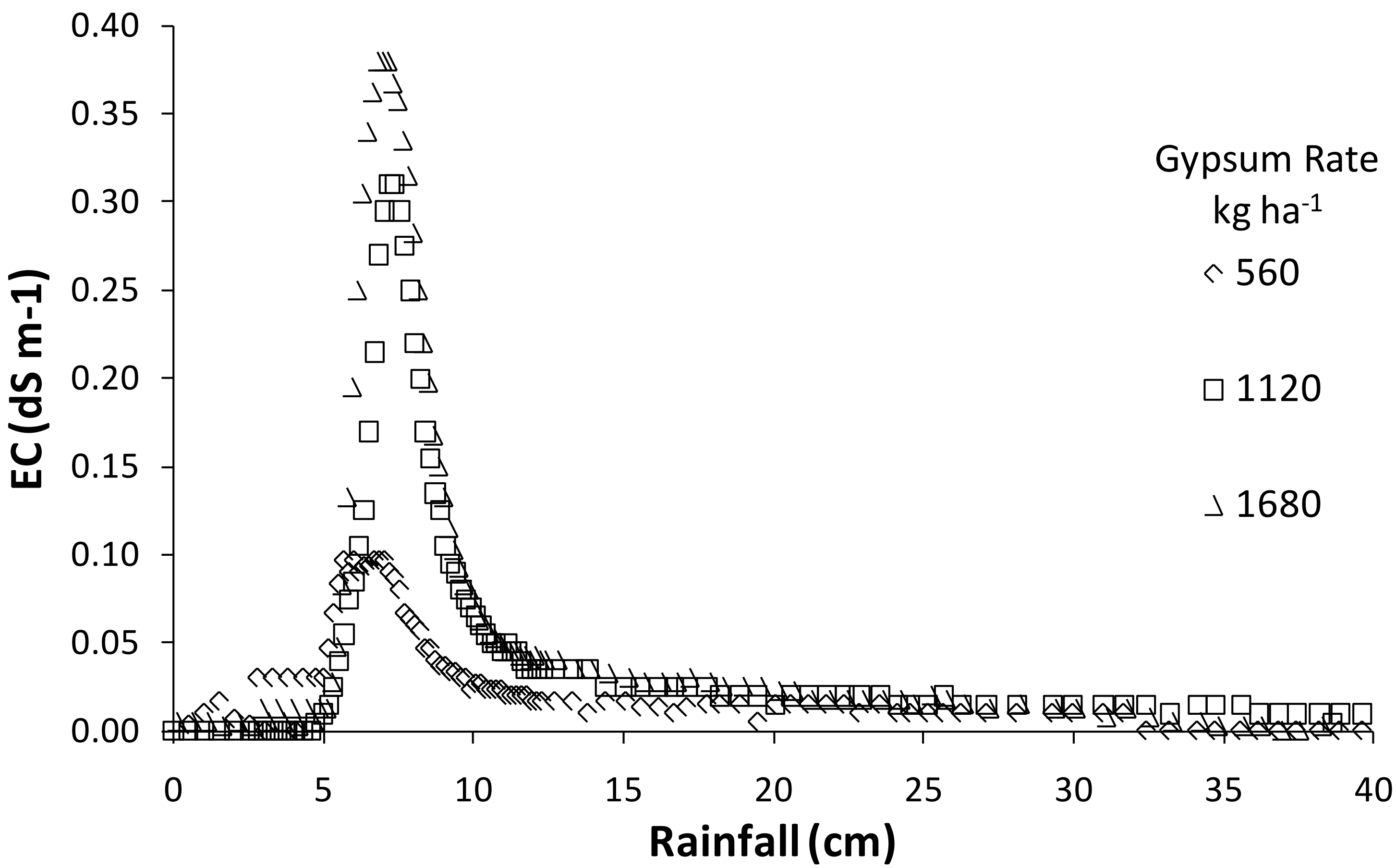

Figure 4. Electrical conductivity at 10 cm depth in soil with 560, 1120, and 1680 kg ha^{-1} gypsum treatments applied to the surface of a soil column (10 cm diameter, 12.5 cm deep) with simulated rainfall (0.01 M $CaCl_2$ at 5 cm hr^{-1}) on a Dothan loamy sand. Rainfall produced saturated flow, but water did not pond on soil surface.

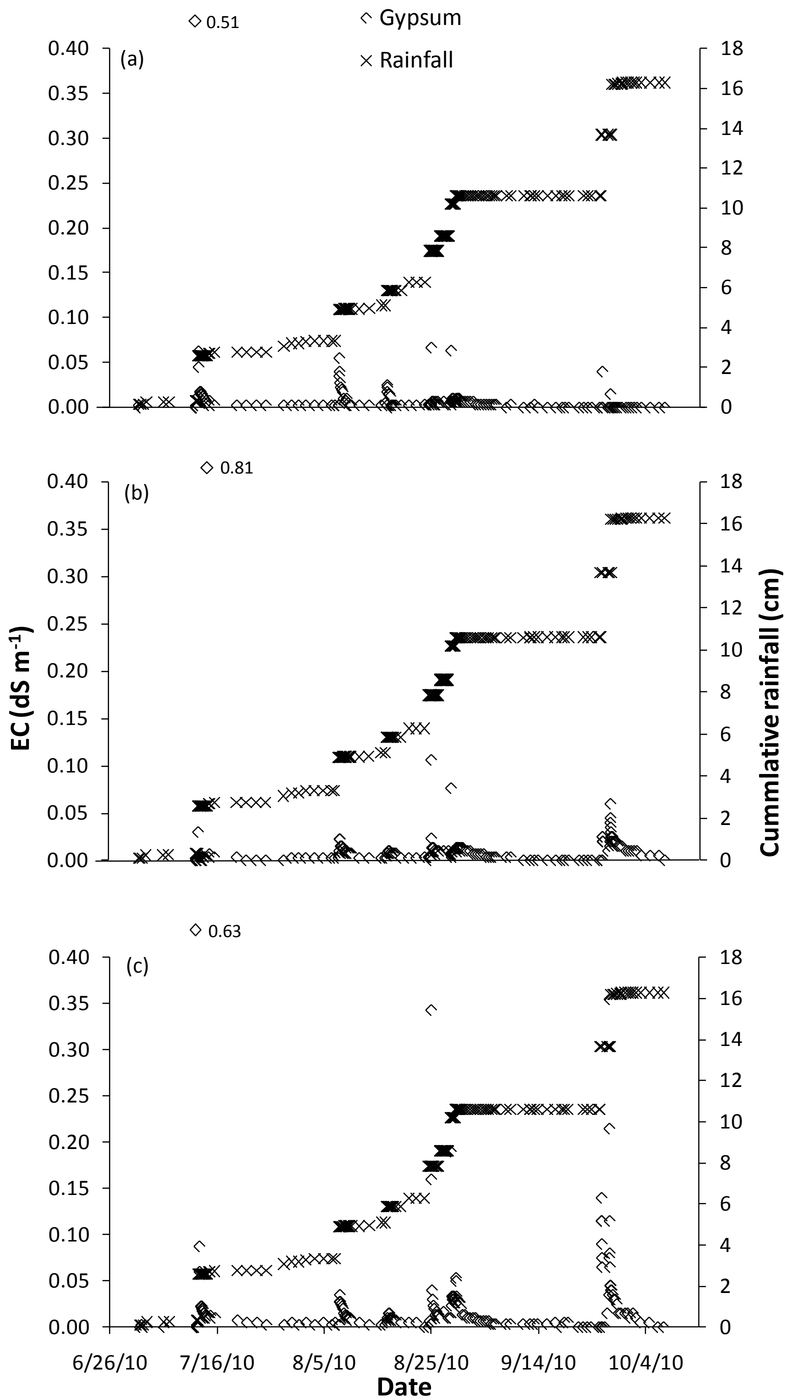

Figure 5. Electrical conductivity measured at 9 cm depth from (a) 560, (b) 1120, and (c) 1680 kg ha^{-1} gypsum treatments above the control at Tifton, GA, in 2010. Cumulative rainfall is graphed with time.

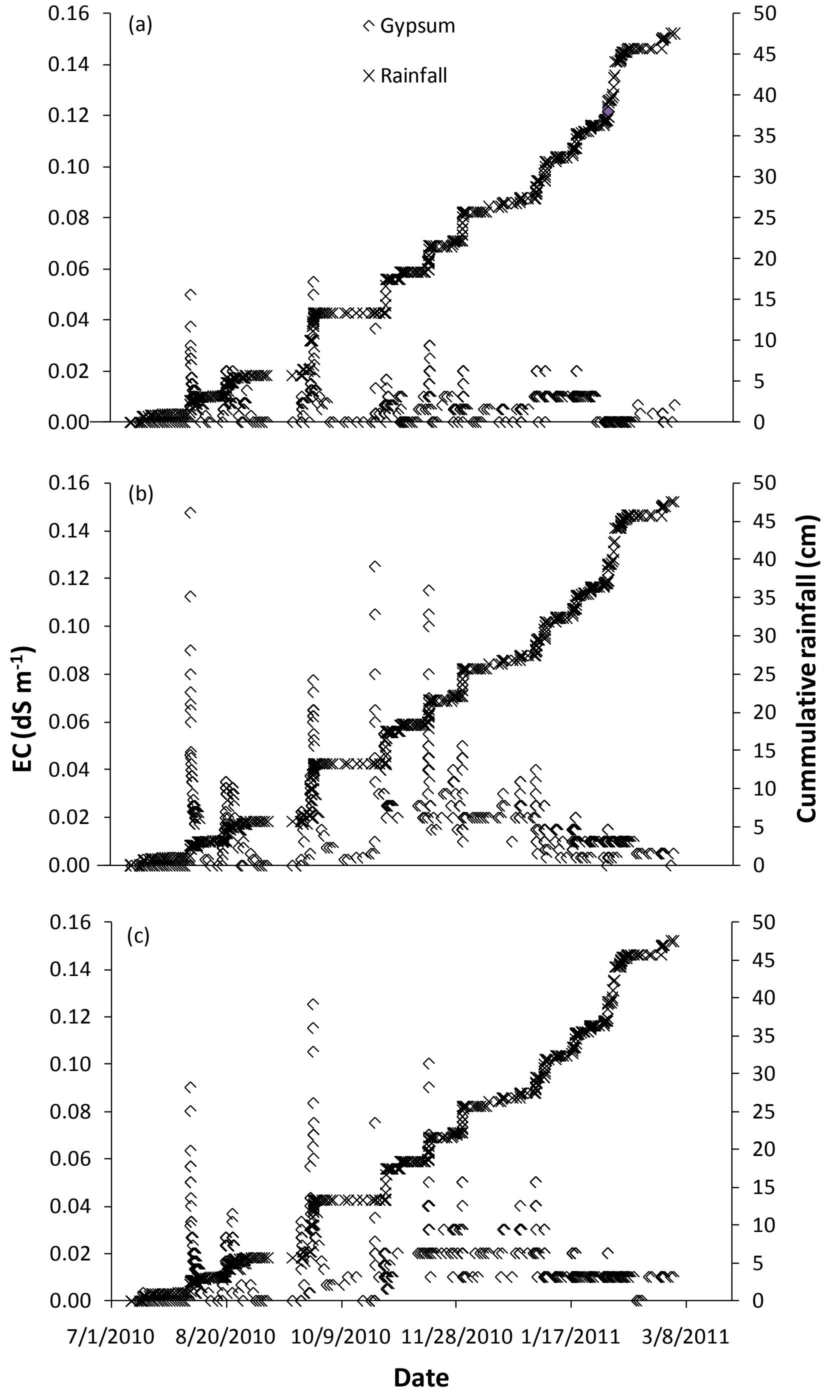

Figure 6. Electrical conductivity measured at 9 cm depth from (a) 560, (b) 1120, and (c) 1680 kg ha^{-1} gypsum treatments above the control at Headland, AL, in 2010 and 2011. Cumulative rainfall is graphed with time.

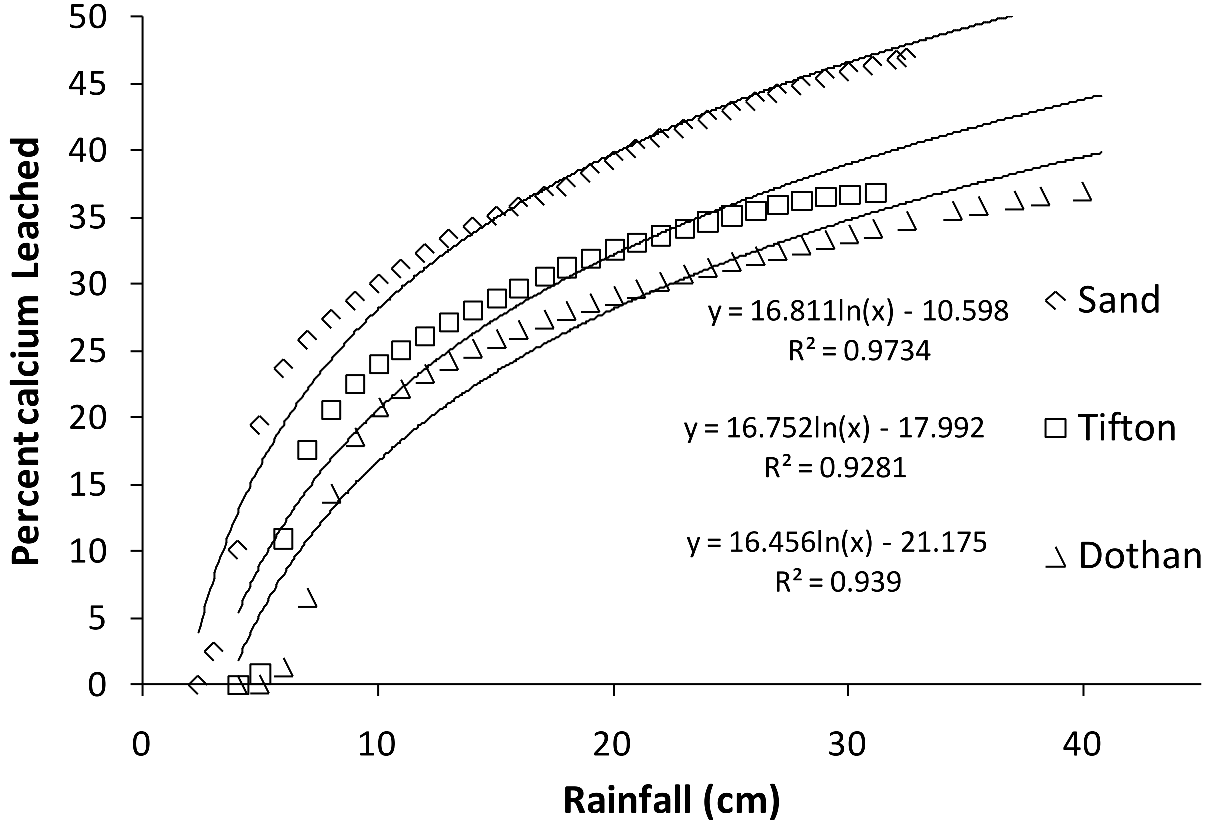

Figure 7. Percent of the 1120 kg ha^{-1} gypsum treatment applied to the surface of a soil column (10 cm diameter, 12.5 cm deep) leached at 10 cm depth with simulated rainfall (0.01 M $CaCl_2$ at 5 cm hr^{-1}) on commercial sand, Tifton loamy sand, and Dothan loamy sand in a column experiment.

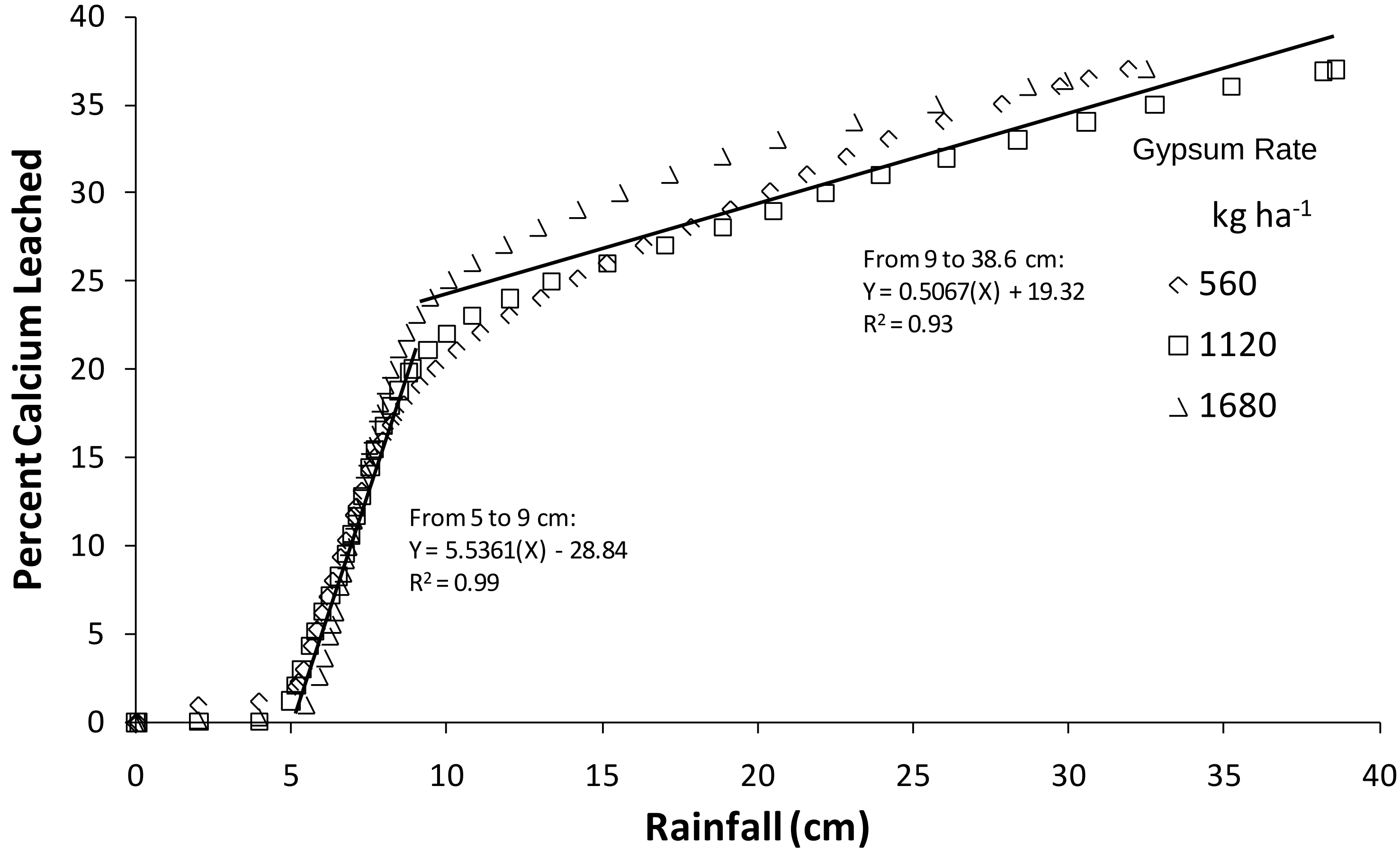

Figure 8. Percent of the 560, 1120, 1680 kg ha^{-1} gypsum treatments leached at 10 cm depth with increasing rainfall (0.01 M $CaCl_2$ at 5 cm hr^{-1}) on a Dothan loamy sand in a column experiment (10 cm diameter, 12.5 cm deep).

Table 10. Column, greenhouse, and field studies investigating gypsum leaching in sandy surface soils used for peanut production in the Southeast U.S.

Study	Gypsum	Texture ‡	Depth	leached	Rain	Rate	Application	Location
	kg ha^{-1}		cm	% Ca	cm	cm hr^{-1}		
Alva and Gascho, 1991	1120	s - Tifton, Dothan, Carnegie, and Fuquay	8	50	15	2.34	Continuous	Column
Alva and Gascho, 1991	1120	scl - Green ville and Faceville	8	30	15	2.34	Continuous	Column
Daughtry and Cox, 1976	848	fsl - Rains	6.5	30	17	0.06 †	Daily	Column
Daughtry and Cox, 1976	848	ls - Lakeland	6.5	62	17	0.06	Daily	Column
Daughtry and Cox, 1976	848	sl - Norfolk	6.5	41	17	0.06	Daily	Column
Alva et al., 1990	1120	ls - Tifton	8	21	15	14.8	Once	Field
Alva et al., 1990	1120	s - Lakeland	8	31	15	14.8	Once	Field
Alva et al., 1990	1120	ls- Tifton	8	14	15	14.8	Twelve times	Field
Alva et al., 1990	1120	s - Lakeland	8	30	15	14.8	Twelve times	Field
Current study	560	ls - Dothan	10	50	9	5.08	Continuous	Column
Current study	1120	ls - Dothan	10	50	8	5.08	Continuous	Column
Current study	1680	ls - Dothan	10	50	8	5.08	Continuous	Column
Current study	1120	ls - Tifton	10	50	7	5.08	Continuous	Column
Current study	1120	s - pure sand	10	50	6	5.08	Continuous	Column

† Rainfall Rate for Daughtry and Cox (1976) is calculated from 10 ml additions of water to a 7.5 cm^2 soil surface daily

‡ Dothan and Tifton - Fine-loamy, kaolinitic, thermic Plinthic Kandiudult

Greenville - Fine, kaolinitic, thermic Rhodic Kandiudult

Faceville - Fine, kaolinitic, thermic Typic Kandiudult

Lakeland - Thermic, coated Typic Quartzipsamment

Norfolk - Fine-loamy, kaolinitic, thermic Typic Kandiudult

Rains - Fine-loamy, siliceous, semiactive, thermic Typic Paleaquult

Carnegie - Fine, kaolinitic, thermic Plinthic Kandiudult

Fuquay - Loamy, kaolinitic, thermic Arenic Plinthic Kandiudult

Table 11. Average electrical conductivity measured at 9 cm depth from 560, 1120, and 1680 kg ha^{-1} gypsum treatments minus the control at Headland, AL, in 2010.

Date	Antecedent moisture	Rain	Contributed to leaching †	Treatment			Total rainfall	Attributed to leaching
				----------- kg ha^{-1} ---------				
				560	1120	1680		
	cm^3 cm^{-3}	-------- cm -------		------- dS m^{-1} ------			----------- cm -----------	
7/14/10	0.03	0.61	0.40	0.00	0.00	0.00		
8/4/10	0.02	1.55	1.33	0.05	0.15	0.09	1.55	1.33
8/7/10	0.09	0.45	0.30	0.01	0.02	0.01	2.00	1.63
8/20/10	0.09	1.62	1.47	0.02	0.03	0.03	3.62	3.10
8/23/10	0.08	0.53	0.37	0.02	0.03	0.03	4.15	3.47
8/27/10	0.05	0.30	0.11	0.01	0.02	0.02	4.45	3.58
9/21/10	0.03	0.73	0.52	0.01	0.02	0.03	5.18	4.10
9/25/10	0.05	3.50	3.31	0.01	0.04	0.06	8.68	7.42
9/27/10	0.12	3.30	3.19	0.05	0.06	0.12	11.99	10.61
10/28/10	0.09	4.14	3.99	0.02	0.04	0.01	16.13	14.60
11/3/10	0.09	0.86	0.71	0.01			16.99	15.31
11/16/10	0.08	3.12	2.96	0.03	0.12	0.10	20.11	18.27
11/26/10	0.09	0.61	0.46	0.00	0.04	0.03	20.72	18.73
11/30/10	0.11	3.53	3.40	0.02	0.04	0.03	24.25	22.13
12/12/10	0.09	0.69	0.54	0.00	0.02	0.02	24.94	22.67
12/17/10	0.10	0.40	0.26	0.00	0.03	0.03	25.34	22.92
12/25/10	0.08	0.64	0.48	0.00	0.03	0.03	25.97	23.40
1/1/11	0.09	2.08	1.93	0.02	0.02	0.04	28.06	25.33
1/5/11	0.12	2.18	2.07	0.02	0.02	0.03	30.24	27.40
1/10/11	0.11	0.56	0.43	0.01	0.01	0.01	30.80	27.82
1/17/11	0.10	1.12	0.98	0.01	0.01	0.02	31.92	28.80
1/18/11	0.14	1.75	1.66	0.02	0.01	0.02	33.67	30.46
1/21/11	0.15	0.23	0.13	0.01	0.01	0.01	33.90	30.59
1/25/11	0.12	0.81	0.69	0.01	0.01	0.01	34.71	31.28
1/31/11	0.12	0.61	0.49	0.00	0.01	0.01	35.32	31.77
2/1/11	0.15	2.46	2.37	0.00	0.01	0.02	37.79	34.15
2/3/11	0.15	0.61	0.52	0.00	0.01	0.01	38.39	34.66
2/4/11	0.20	2.34	2.30	0.00	0.01	0.02	40.73	36.96
2/4/11	0.18	1.70	1.64	0.00	0.01	0.01	42.43	38.60
2/7/11	0.14	1.14	1.04	0.00	0.01	0.01	43.58	39.65
2/9/11	0.12	0.46	0.34	0.00	0.01	0.01	44.03	39.98
2/25/11	0.08	1.24	1.08	0.00	0.00	0.01	45.28	41.07
2/28/11	0.09	0.56	0.41	0.00	0.00	0.01	45.84	41.48

† Field saturation considered 0.24 cm^3 cm^{-3}

Table 12. Average electrical conductivity at 9 cm depth measured from 560, 1120, 1680 kg ha^{-1} gypsum treatments minus the control at Tifton, GA, in 2010.

Date	Antecedent moisture	Rain	Contributed to leaching †	Treatment			Total rainfall	Attributed to leaching
				-------- kg ha^{-1} ------				
				560	1120	1680		
	cm^3 cm^{-3}	-------- cm ------		------ dS m^{-1} ------			--------- cm --------	
7/1/10	0.04	0.13		0.00	0.00	0.00	0.13	0.00
7/12/10	0.06	2.26	1.98	0.51	0.81	0.63	2.39	1.98
7/14/10	0.12	0.13		0.01	0.01	0.01	2.51	1.98
8/7/10	0.05	1.57	1.28	0.05	0.02	0.04	4.09	3.27
8/16/10	0.06	0.76	0.48	0.02	0.01	0.01	4.85	3.75
8/24/10	0.04	1.57	1.27	0.07	0.11	0.34	6.43	5.02
8/26/10	0.10	0.71	0.47	0.01	0.01	0.02	7.14	5.49
8/28/10	0.09	1.60	1.35	0.06	0.08	0.19	8.74	6.84
8/29/10	0.15	0.41	0.22	0.01	0.01	0.05	9.14	7.06
9/25/10	0.04	3.05	2.75	0.04	0.02	0.11	12.19	9.81
9/27/10	0.11	2.54	2.31	0.01	0.06	0.35	14.73	12.12

† Field saturation considered 0.34 cm^3 cm^{-3}

Table 13. Comparison of electrical conductivity at 9 cm depth measured from responses of 0, 560, 1120, 1680 kg ha^{-1} gypsum treatments at Headland, AL, in 2010 and 2011.

Date	Moisture Content	0	560	1120	1680	Cumulative rain
		---------------- Gypsum (kg ha^{-1}) --------------				
	m^3 m^3	-------------- EC response (dS m^{-1}) -----------				---- cm ----
7/15/2010	0.06	0	0	0	0	0.61
8/4/2010	0.20	0.02 B†§	0.07 AB	0.17 A	0.11 AB	2.16
8/6/2010	0.11	0.01 B	0.02 AB	0.03 A	0.03 AB	2.61
8/19/2010	0.12	0.01 B	0.03 A	0.04 A	0.03 A	4.23
8/22/2010	0.14	0.00 B	0.03 A	0.03 A	0.04 A	4.76
8/27/2010	0.11	0.00 B	0.01 A	0.02 A	0.02 A	5.06
9/21/2010	0.11	0.00 C	0.01 BC	0.03 AB	0.04 A	5.79
9/25/2010	0.15	0.00 B	0.02 B	0.04 A	0.06 A	9.29
9/26/2010	0.19	0.01 B	0.07 AB	0.07 AB	0.14 A	12.60
10/23/2010	0.04	0.01	0.04	0.14	0.09	‡
10/28/2010	0.20	0.00	0.03	0.04	0.02	16.74
11/3/2010	0.15	0.01	0.02			17.60
11/16/2010	0.18	0.01	0.05	0.14	0.12	20.72
11/26/2010	0.13	0.01	0.01	0.05	0.04	21.33
11/30/2010	0.18	0.01	0.03	0.06	0.08	24.86
12/18/2010	0.12	0.00	0.01	0.03	0.03	25.95
12/25/2010	0.13	0.00	0.01	0.03	0.04	26.58
1/1/2011	0.18	0.02	0.05	0.04	0.07	28.67
1/5/2011	0.18	0.01	0.03	0.02	0.03	30.85
1/10/2011	0.13	0.00	0.01	0.01	0.01	31.41
1/17/2011	0.17	0.00	0.01	0.01	0.02	32.53
1/18/2011	0.20	0.01	0.02	0.01	0.02	34.28
1/21/2011	0.14	0.00	0.01	0.01	0.01	34.51
1/25/2011	0.15	0.00	0.01	0.01	0.01	35.32
1/31/2011	0.16	0.00	0.00	0.01	0.01	35.93
2/4/2011	0.19	0.00	0.00	0.01	0.01	41.34
2/4/2011	0.20	0.00	0.01	0.01	0.01	43.04
2/7/2011	0.17	0.00	0.00	0.01	0.01	44.19
2/10/2011	0.16	0.00	0.00	0.01	0.01	44.64
2/25/2011	0.14	0.00	0.00	0.00	0.01	45.89

† Letters represent differences at $\alpha = 0.05$ level

‡ No rainfall recorded on this day but an increase in moisture and EC was noticed

§ Type III test of fixed effects for 8/4/10, 8/6/10, and 9/26/10 are 0.11, 0.07, and 0.09, respectively.

Table 14. Comparison of electrical conductivity at 9 cm depth measured from responses of 0, 560, 1120, 1680 kg ha^{-1} gypsum treatments at Tifton, GA, in 2010.

		------------- Gypsum (kg ha^{-1}) ------				
Date	**Moisture Content**	**0**	**560**	**1120**	**1680**	**Cumulative rain**
	m^3 m^3	---------- **EC response (dS m^{-1})** -----				**cm**
7/1/2010	0.13	0.01 AB‡	0.01 AB	0.00 B	0.01 A	0.13
7/12/2010	0.35	0.12 B†	0.64 A	0.90 A	0.76 A	2.39
7/14/2010	0.13	0.00	0.01	0.01	0.02	2.51
8/7/2010	0.18	0.01	0.06	0.03	0.05	4.09
8/16/2010	0.11	0.00	0.02	0.01	0.01	4.85
8/24/2010	0.30	0.01	0.07	0.13	0.33	6.43
8/26/2010	0.13	0.00	0.01	0.01	0.02	7.14
8/28/2010	0.29	0.01 B	0.06 B	0.09 B	0.20 A	8.74
8/29/2010	0.20	0.00	0.02	0.02	0.06	9.14
9/25/2010	0.29	0.03 B	0.06 B	0.06 B	0.22 A	12.19
9/27/2010	0.27	0.01	0.03	0.05	0.21	14.73

† Letters represent differences at $\alpha = 0.05$ level.
‡ Type III test of fixed effects for 7/1/2010 and 9/25/10 are Pr > F = 0.20 and 0.07, respectively.

IV. Conclusions

Improvement in yield of 06G and GG peanuts above the critical soil calcium level several sites for both varieties. This may suggest that the recommendations based on for traditional runner yield of 150 mg kg^{-1} (Hartzog and Adams, 1973) was observed at traditional runners may slightly underestimated calcium requirements of current runner-type peanuts. Grade was improved on more occasions than yield for 06G and GG, suggesting that even when soil calcium may be high enough for optimum yield, the quality of the pods may still improve with gypsum applications. Gypsum increased germination in both varieties at most sites on soil calcium levels as high as 296 mg kg^{-1}. This reaffirms the ACIA recommendation of applying gypsum to peanuts grown for seed, regardless of soil calcium concentrations. Lime and liquid calcium are not advised on soils with calcium levels above 250 mg kg^{-1} as yield did not improve. Grade was improved by lime in 2008 and liquid calcium in 2010. Lime did improve TSMK and germination in 2008, which was a high rainfall year, but more research is needed before a recommendation for applying lime to peanuts grown for seed can be made.

Leaching of gypsum in the soil column experiment showed that an increased application rate of gypsum did increase the EC measured but did not prolong the residence time of gypsum in the pegging zone. The residence time of various applications in the field do not agree with the soil column as the 1680 kg ha^{-1} rate provided a response above the control for a longer period than the lower rates. After 12 cm of rain at both sites, none of the gypsum-applied treatments provided a higher EC response than the control. This may suggest that after 12 cm of rainfall, the applied gypsum is no longer beneficial to developing peanuts. The lack of response after 12 cm at Headland however may be due a reduction in probe numbers or to the gypsum actually leaching from the pegging zone. This may suggest that after 12 cm of rainfall most gypsum is leached; however, more field studies are required. The use of EC probes is effective for detecting if gypsum is still in the pegging zone, but is not as effective as taking soil samples for quantifying the amount of gypsum leached after a given amount of rainfall.

Results from column experiments were compared with field results from 2008 to 2010. In 2008, tropical storm Faye provided a three day rainfall amount of 16 and 19 cm at Headland and Tifton, respectively, about 50 days after gypsum application. If this amount of rainfall was enough to leach a majority of pegging zone calcium, then no yield, grade, or germination response would be expected on the gypsum applied plots. These expected results were observed with yield but not grade or germination. Lack of yield response may be explained by the higher initial soil calcium at these sites (203 and 252 mg kg^{-1}, respectively), but an increase was observed when soil calcium was 246 and 296 mg kg^{-1} in both varieties in other years. Grade and germination increased with gypsum applications for 06G at both sites and at Headland for GG. High rainfall may have increased calcium gradient up until gypsum was leached from the soil, thus the differences in the more sensitive measures of grade and germination.

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