Boron and Calcium Effects on Runner Peanut Production

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 4, 2019

Keywords: peanut, boron, calcium

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Abstract

Calcium (Ca) and boron (B) deficiencies in peanut (*Arachis hypogaea* L.) reduce seed quality, yield, and crop value. Southeastern U.S. Coastal Plain soils are inherently low in Ca and B, requiring supplementation to reach soil and plant tissue levels sufficient for peanut growth and development. In addition, coarse textured surface horizons with low cation exchange capacity (CEC) and rapid permeability coupled with high rainfall promote nutrient leaching. Therefore, nutrient management in peanut production systems presents challenges. To understand these challenges, two studies investigating Ca and B application rate, source, and timing effects on runner peanut production were conducted.

Current B recommendations for runner peanut varieties were developed using smaller-seeded cultivars and have not been updated for currently produced larger-seeded cultivars. To evaluate foliar-applied B effects on larger-seeded runner peanut (cv. Georgia-06G) yield and seed quality, B application rate (0.02, 0.28, 0.56, 1.12, and 2.24 kg B ha^{-1}), source (boric acid and sodium borate), and timing (single and split applications at early bloom) were tested at the Wiregrass Research and Extension Center (WREC; Headland, AL) in 2015, 2016, and 2017. No yield or grade responses to B treatments were observed, and minor B deficiency was observed in 2017 only. Seed B concentration was not affected by B rate, timing, or source. Applied B described at least 83% of leaf B concentration variability. A high rate of applied B (2.24 kg B ha^{-1} as sodium borate) was the most effective treatment for increasing leaf tissue B. Source did

not affect leaf B when similar rates were compared. Application timing did not affect leaf B when similar sources were compared. Though foliar B applications did not improve grade or yield, applied B increased leaf tissue B concentrations without harming productivity.

Adequate soil Ca levels and water in the pegging zone are essential as developing pods obtain Ca directly from soil solution through diffusion. Calcium is highly susceptible to leaching in these soils, and products that potentially increase retention warrant investigation. To evaluate Ca source effects on yield and seed quality, a study was conducted at WREC in 2015, 2016, and 2017 comparing lime ($CaCO_3$), gypsum ($CaSO_4$), and products containing humic acid or micronutrients. Calcium sources were applied at state or product recommended rates. Yield and grade were not improved by Ca treatments, which is likely due to adequate initial soil test Ca levels (>150 mg kg^{-1}). Lime and gypsum applications resulted in significantly higher ($P < 0.05$) seed and soil Ca levels compared to the untreated control. Alternative Ca sources did not increase seed Ca above the control, but one product containing 21% humate increased late season soil Ca above the control. Though alternative Ca sources did not consistently result in different seed or soil Ca levels compared to the control, they often resulted in levels comparable to gypsum applications, suggesting these products could have value for peanut production.

Acknowledgements

I would like to thank Dr. Julie Howe and Dr. Audrey Gamble for their guidance and support. I would also like to thank my committee members, Dr. Thorsten Knappenberger and Dr. Kip Balkcom, as well as the Crop, Soil and Environmental Sciences Department faculty and staff for their advice, support, and time. I would like to thank the staff at the Wiregrass Research and Extension Center and undergraduate and graduate students that helped with this project for field and laboratory assistance. Finally, I would like to thank my parents for their unconditional love and encouragement throughout all endeavors.

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List of Abbreviations

ACES	Alabama Cooperative Extension System
B	Boron
Ca	Calcium
CEC	Cation exchange capacity
d	Day(s)
DAP	Day(s) after planting
DAT	Day(s) after treatment
SMK	Sound mature kernel(s)
SS	Sound split(s)
TSMK	Total sound mature kernels
WREC	Wiregrass Research and Extension Center

I. Literature Review

Introduction

The southeastern U.S. peanut (*Arachis hypogaea* L.) growing region (Georgia, Alabama, Mississippi, and Florida) produces 73% of U.S. peanuts, earning over $1 billion annually in 2016 and 2017 (USDA-NASS, 2018). Southern Coastal Plain soils are well suited for peanut production due to coarse textured, friable surface horizons that allow peg entry into and pod removal from soil at harvest. Upland Coastal Plain surface horizons also tend to be well-drained, a necessity for peanut growth as pods develop in the upper 10 cm of soil (termed the pegging zone). These soil properties combined with a long growing season with sufficient rainfall render this region ideal for peanut production. Despite these advantages, southeastern U.S. peanut producers face significant challenges with nutrient management. Essential nutrients readily leach with high rainfall in these highly weathered, sandy, low activity soils with low organic matter. While N, P, and K fertility is rarely a concern in peanut production, boron (B) and calcium (Ca) quantities in these soils are inherently low, and supplementation is often necessary to reach sufficient soil levels for peanut production. Insufficient soil B and Ca supplies can reduce yield, seed quality, and crop value. Thus, strategies to prevent and correct B and Ca deficiencies are necessary to optimize production and guard against economic loss.

Boron

Boron is essential for plant growth, cell wall structure, and membrane function (Warington, 1923; Brown et al., 2002). Insufficient B affects cell wall properties (e.g., porosity and strength) and disrupts reproductive growth (Brown et al., 2002; Camacho-Cristóbal et al., 2008). Boron requirements are higher during reproductive relative to vegetative growth due to the role B plays in flowering and seed production, and an adequate B supply throughout the reproductive growth period is critical (Mozafar, 1993). In peanut, B deficiency results in seed damage in the form of shrunken, hollow, and darkened inner surfaces of cotyledons; this defect is termed "hollow heart" and occurrence decreases yield, seed quality and crop value (Harris and Gilman, 1957; Harris and Brolmann, 1966a). Similarly, excess B in peanut can reduce growth and productivity. Therefore, maintaining adequate B levels in plant tissue and soil is necessary for proper peanut development and requires consideration of several factors including plant uptake; soil B availability; and B application method, source, timing, and rate.

<u>Uptake and Mobility</u>

In the optimum soil pH range for plant growth, boric acid ($B(OH)_3$) is taken up by plants in its undissociated, neutral form (Marschner, 1995). Plants acquire B from the soil solution through both active and passive processes (Dannel et al., 2000; Stangoulis et al., 2001). Once in the plant, B is primarily transported via the xylem, with limited redistribution through phloem tissues (Raven, 1980; Brown and Shelp, 1997). However, because pods develop belowground and transpiration is minimal (Moctezuma, 1999), B translocation to the seed is thought to occur via phloem rather than xylem tissues (Campbell, 1975). Konsaeng et al. (2010) observed that B was retranslocated from older to younger peanut leaves and concluded that this likely occurred via the phloem, though the mechanism is unclear. They also observed increases in seed B with foliar-applied B and concluded that foliar applications effectively supply B to peanut seed.

Availability

Boron deficiency occurs in the southeastern United States due to a combination of environmental and soil factors that reduce B availability and uptake. Highly weathered southeastern Coastal Plain soils have low inherent B, and plant-available forms rapidly leach from coarse textured surface and eluvial horizons with high rainfall (Shorrocks, 1997). Plant uptake can be affected by soil texture (Wear and Patterson, 1962), moisture (Chrudimsky and Morrill, 1973), and pH (Berger and Truog, 1945). Wear and Patterson (1962) found that plant availability was greater in sandy soils, as clayier soils with higher CEC had greater B retention but reduced availability. Though availability is higher in sandy soils with low CEC, the potential for leaching is also higher. Leaching is a concern with greater soil water content, while B availability is an issue with lower soil water content (Goldberg, 1997). Soil solution pH also affects availability, and Wear and Patterson (1962) observed that B availability decreased with increasing pH from 5 to 7.

Nutrient interactions in the soil solution can also affect B uptake. Interactions between B and Ca have been reported to impact yield and seed quality (Harris and Brolmann, 1966b; Hill and Morrill, 1975). Hill and Morrill (1975) found peanuts grown in the greenhouse that received high rates of Ca without B had greater yields but reduced seed quality; however, no differences were observed in the field. Cox and Reid (1964) did not observe an interaction between Ca and B with respect to seed damage but found that deficiency symptoms were related to seed concentrations. Interactions between B and other nutrients have been reported. Hill and Morrill (1975) also saw an increase in yield when potassium (K) was applied with B, except at the highest rate of each (100 mg K kg^{-1} and 0.5 mg B kg^{-1}) where yield decreased. Kabir et al. (2013) did not observe an interaction between B, Ca, and phosphorus (P) with regard to yield.

<u>Boron Management</u>

Method

Boron amendments are often soil-applied; however, foliar applications are similarly effective on crops such as rutabaga (Gupta and Cutcliffe, 1978) and corn (Peterson and MacGregor, 1966). While within-plant mobility is a major consideration in B delivery method, climate and soil properties are also important factors. Singh et al. (2017) found that peanuts grown in humid, wet climates responded more favorably to foliar-applied B compared to soil applications, while the reverse was observed of peanuts grown in hot, dry regions. In addition, leaching losses due to low soil B retention and availability can be avoided with foliar application.

Application rate and timing also influence delivery method. Because B toxicity is more likely to occur with foliar compared to soil application, rates are typically reduced when B is foliar-applied (Mortvedt and Woodruff, 1993). Hartzog and Adams (1973) suggested that foliar-applied rates higher than 1.12 kg B ha^{-1} could be toxic. Therefore, to safely deliver higher B amounts to the plant, repeat applications at lower rates have been suggested (Mortvedt and Woodruff, 1993).

Timing

Boron requirements are high during reproductive growth, due to the significant role B plays in flowering and seed development (Mozafar, 1993). In particular, sufficient B is critical during the early stages of peanut reproductive growth (30-35 days after planting, DAP). Hill and Morrill (1974) found that applications between 12 and 61 DAP were effective in preventing and/or correcting hollow heart in spanish peanuts, but applications at 74 and 92 DAP were not. Although it is often recommended (Kissel and Sonon, 2008), little research has investigated split applications of either foliar- or soil-applied B on peanut. It is logical that this approach could minimize risk of B losses and/or toxicity while ensuring adequate B supplies during reproductive growth.

Source

Boron is commonly soil- or foliar-applied as boric acid or sodium borate. Boric acid products and Solubor (a sodium borate product) are water-soluble and often foliar-applied (Mortvedt and Woodruff, 1993). Singh et al. (2017) reported similar peanut yield responses, but different leaf and B seed levels, with foliar applications of either boric acid or Solubor applied at 1.0 kg B ha^{-1}.

Rate

Effects of B deficiency on peanut yield and seed quality are commonly observed when grown under greenhouse conditions; however, similar results are not typically observed under field conditions (Harris and Gilman, 1957; Hill and Morrill, 1975). Response differences between field and greenhouse studies have been attributed to greater control in the greenhouse, presence of boron in fertilizers and/or irrigation water, low soil volume in the greenhouse, and plant access to subsurface horizons in the field (Harris and Gilman, 1957; Cox and Reid, 1964; Hill and Morrill, 1974, 1975; Brar et al., 1980).

Harris and Gilman (1957) observed yield and grade increases as well as hollow heart reduction in runner type peanut (‘Dixie Runner’ and ‘Early Runner’) with application of 0.3 kg B ha^{-1} as boric acid on plants grown in the greenhouse. Application of 0.56 kg B ha^{-1} effectively reduced hollow heart in virginia type peanut (cv. NC 4X) in a North Carolina field study (Cox and Reid, 1964). Harris and Brolmann (1966b) noted an increase in yield and grade of virginia type peanut (cv. Florigiant) with application of 0.4 kg B ha^{-1} in both greenhouse and field studies in Florida. In Oklahoma, foliar B applications of 0.56 and 1.12 kg B ha^{-1} effectively reduced hollow heart incidence in spanish type peanuts, though no differences in yield or grade were observed, even where hollow heart was detected (Hill and Morrill, 1974). This study included 17 test sites, 10 of which showed B deficiency symptoms. Applications of 0.56 kg B ha^{-1} reduced hollow heart incidence in both virginia type and runner type peanut grown on Alabama farms and evaluated over 13 peanut growing seasons from 1973 to 1986 (Hartzog and Adams, 1988).

Overapplication can also occur resulting in yield losses. Hill and Morrill (1975) saw a decrease in pod yield when plants were grown in soil with B levels of 0.30 mg kg^{-1}, two times greater than the critical soil B level of 0.15 mg kg^{-1} (hot water extractable B) reported in the study.

Current Recommendations

In Alabama, an application of 0.33 to 0.56 kg B ha^{-1} is recommended, independent of soil test B (Mitchell and Huluka, 2012). In Georgia, soil B levels above 0.15 mg kg^{-1} (hot water extraction; Berger and Truog, 1939) are considered adequate and B supplementation is not recommended when soil test B is above 0.50 mg kg^{-1} (Kissel and Sonon, 2008).

Initial soil B levels can be used to assess risk of B deficiency, as initial soil B content has been related with seed quality (Bell et al., 1990). Alabama field trials extending over a 13-year period reported an average critical value for initial soil B of 0.05 mg B kg^{-1} (Hartzog and Adams, 1988). While hot water extraction (Berger and Truog, 1939) is the most widely accepted method to estimate plant available soil B, a relationship between hot water soluble B with Mehlich-1 and Mehlich-3 extractable B in southeastern U.S. soils suggests that either extractant could be used in its place (Shuman et al., 1992).

Detection of deficiency during the growing season can be a challenge for producers. Visual assessment is not always feasible as pods develop belowground, and aboveground plant appearance does not necessarily reflect plant B status due to lower B levels needed for vegetative growth that may not support proper reproductive growth (Mozafar, 1993). Leaf tissue B can be used to assess B supply during growth (Hill and Morrill, 1974; Brar et al., 1980), and in the southeastern United States, leaf B content between 20 and 60 mg B kg^{-1} at early bloom is considered sufficient (Southern Cooperative Series, 2013).

Cultivar Variability

Boron needs vary among peanut types and cultivars (Harris and Gilman, 1957). Currently produced larger-seeded peanut cultivars could potentially have greater nutrient requirements than previously produced smaller-seeded cultivars, for which currently used recommendations were developed (Cope et al., 1981; Tillman et al., 2010). Keerati-Kasikorn et al. (1991) observed differences in response to applied B between two spanish type cultivars related to seed size and proposed that B requirements could increase with seed size. Singh et al. (2007) reported that B requirements were higher in large-seeded cultivars compared to small-seeded cultivars when evaluated within the applied B range of 0.5 to 2 kg B ha^{-1}. They observed greater yield increases with large-seeded cultivars (23.3%) compared to small-seeded cultivars (11.7%) under similar conditions (i.e., application rate, timing, and source).

Calcium

Calcium is an essential nutrient for proper peanut development and plays an important role in cell wall structure (Marschner, 1995). Insufficient Ca uptake during development can result in unfilled pods (Colwell and Brady, 1945; Smith, 1954), darkened seed plumules (Cox and Reid, 1964), and reduced germination (Harris and Brolmann, 1966c). Unfilled pods, or pops, can cause significant yield loss and grade reduction, and Ca additions can reduce occurrence of aborted seed, thereby improving peanut yield and grade (York and Colwell, 1951). Seed plumules are important for germination, and damage caused by insufficient Ca can significantly reduce germination rates (Harris and Brolmann, 1966c; Adams et al., 1993). Calcium requirements are higher for peanut produced for seed, and Ca additions have been shown to increase seed Ca levels and improve germination in the absence of yield or grade effects (Cox et al., 1982; Tillman et al., 2010). Adams et al. (1993) observed an effect of seed Ca on germination rate, with seed Ca required for optimum germination between 368 and 414 mg kg^{-1} for small-seeded runner type peanut. Howe et al. (2012) observed 95% germination when seed Ca concentrations were greater than 600 mg kg^{-1} in large-seeded runner peanut.

Uptake

During vegetative growth, Ca is taken up by roots and transported via the xylem to transpiring tissues. Once pegs enter the soil during reproductive growth and transpiration ceases, Ca is no longer supplied to the developing pod from the aboveground plant portion (Skelton and Shear, 1971). Instead, pods absorb Ca directly from the soil solution through passive diffusion (Sumner et al., 1988). Calcium uptake occurs throughout reproductive growth, with highest uptake rates occurring in the first 20 to 30 days following peg entry into soil (Brady, 1947; Mizuno, 1959). During the 20 to 30-day window plants are nearing peak pod fill, and sufficient soil Ca and water content are critical for maximum productivity (Stansell et al., 1976).

Availability

The Ca fraction in soil solution, rather than on exchange sites, constitutes Ca available for reproductive growth, due to uptake by developing pods through passive diffusion (Adams et al., 1993); therefore, availability is dependent on soil Ca levels in addition to soil water content (Cox et al., 1982). Southeastern U.S. Coastal Plain soils are inherently low in Ca, often requiring supplemental Ca to reach sufficient soil Ca levels for reproductive growth. Calcium amendments are susceptible to leaching in these highly weathered, coarse textured soil surface horizons with high rainfall, due to low soil solution pH and low CEC (Sullivan et al., 1974). Calcium amendments are also ineffective if soil water content is not sufficient for maintaining soil solution Ca levels needed for proper peanut development. Because water holding capacity is low in these soils, balancing leaching losses with adequate soil water can be a challenge.

Calcium Source

Proper seed development requires high quantities of available Ca throughout the growing season. Lime and gypsum are the most commonly used Ca amendments for peanut production, due to their ability to supply adequate Ca to peanut throughout reproductive growth (Hartzog and Adams, 1988). Calcium sources that could improve application effectiveness, such as humate-containing fertilizers or liquid suspensions, could be of value to producers.

Lime (calcium carbonate, $CaCO_3$) is a commonly used Ca amendment for peanut production on acidic southeastern Coastal Plain soils. Lime is applied to increase Ca content and raise solution pH. Solubility of lime in water is low but increases when mixed with an acid soil. Therefore, effectiveness of lime as a Ca source is dependent on application timing and method, and maximum efficacy is achieved when lime is incorporated into the pegging zone prior to planting (Hartzog and Adams, 1988).

Gypsum (calcium sulfate, $CaSO_4$) is a highly soluble Ca amendment that does not affect pH. For this reason, gypsum is used in place of lime when pH levels are sufficient. Due to its solubility, gypsum is highly susceptible to leaching from the pegging zone, and timing of gypsum applications is critical to ensure adequate soil Ca for pod development throughout the growing season (Daughtry and Cox, 1974).

Alternative Ca sources that could have value in peanut production systems are those that reduce leaching losses and improve Ca use efficiency. Liquid lime suspensions have finer particle size than ground limestone, and react quicker with soil, providing immediately available Ca to developing pods (Mitchell and Kessler, 2006). However, Adams and Hartzog (1979) observed higher yields with agricultural lime compared to liquid lime. Humic substances have been added to fertilizer on the premise of increasing soil nutrient retention and availability, water holding capacity, and biological activity (Mayhew, 2004). However, there has been little agronomic research conducted to investigate effects of humate-containing fertilizers, and reports on effectiveness of these products are mixed (Lyons and Genc, 2016).

Current Recommendations

Calcium source recommendations are based on initial soil conditions (i.e., pH and soil Ca content), and application timing is dependent on product solubility. Yield and grade increases have been observed with gypsum applied at early bloom compared to preplant applications and with lime applied prior to planting (Colwell and Brady, 1945). Application rate recommendations are dependent on soil Ca content as well as soil water management strategies, due to the high soil water requirement for Ca uptake.

In Alabama, Ca is recommended if soil test Ca is less than 150 mg kg^{-1} (300 lb $acre^{-1}$). If pH is less than 5.8, lime is recommended to raise pH and supply Ca. If pH is adequate, gypsum applications of 280 to 560 kg ha^{-1} (250 to 500 lb $acre^{-1}$) are recommended (Mitchell and Huluka, 2012). In Georgia, if soil test Ca is less than 250 mg

kg^{-1} (500 lb $acre^{-1}$), 1120 kg ha^{-1} (1000 lb $acre^{-1}$) of gypsum or lime is recommended. Further, gypsum applied at 1120 kg ha^{-1} (1000 lb $acre^{-1}$) is recommended for peanut grown for seed, regardless of soil test Ca (Kissel and Sonon, 2008).

Summary

Calcium and B are essential nutrients for peanut development, and deficiencies of either nutrient can lead to severe productivity losses. Physical and chemical properties of southeastern U.S. Coastal Plain soils make nutrient management a challenge in this growing region, as both Ca and B are prone to leaching with high rainfall.

Currently produced varieties of runner peanut varieties are larger in seed size than the varieties for which B recommendations were originally developed (Cope, 1981), and seed B requirements have been observed to differ among runner type varieties (Harris and Gilman, 1957). Recommendations for rate, source, and timing of B application have not been re-evaluated for currently produced larger-seeded runner-type peanut cultivars. Recommendations for B fertilization need to be re-examined with regards to the potential nutrient requirement increase for larger-seeded runner peanut cultivars. Alternative Ca sources have the potential to ameliorate management challenges of peanut production on Coastal Plain soils (e.g., nutrient leaching, water holding capacity, nutrient availability). These products could benefit growers in this region; however, little research has been conducted with regard to effects of these products on peanut.

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II. Boron Rate, Source, and Timing Effects on Runner Peanut Productivity

Abstract

Boron deficiency in peanut (*Arachis hypogaea* L.) production is a concern on southeastern U.S. Coastal Plain soils, as insufficient B during reproductive growth can result in decreased crop yield, seed quality, and crop value. The objective of this study was to update B fertilization recommendations for currently produced, larger-seeded runner peanut cultivars. The effects of foliar-applied B source (boric acid and sodium borate), rate (0.02, 0.28, 0.56, 1.12, and 2.24 kg B ha^{-1}), and timing (single and split applications) on large-seeded runner peanut (cv. Georgia-06G) were evaluated in Headland, AL, on a Lucy loamy sand map unit (loamy, kaolinitic, thermic Arenic Kandiudult) in 2015, 2016, and 2017. Products included Borosol 10 (10% B as H_3BO_3, Loveland Products, Inc., Greeley, CO), Solubor (20.5% B as $Na_2B_8O_{13}\cdot 4H_2O$, U.S. Borax, Inc., Boron, CA), and B Xtra (5% B as H_3BO_3, Custom Ag Formulators, Inc., Fresno, CA). Foliar-applied B treatments included single applications of Solubor (1.12 and 2.24 kg B ha^{-1}), B Xtra (0.02 kg B ha^{-1}), and Borosol 10 (0.28, 0.56, and 1.12 kg B ha^{-1}); split applications of Borosol 10 (0.56 and 1.12 kg B ha^{-1}); and an untreated control. Yield and grade responses to treatment were not observed, and minor incidence of B-deficient seed was observed only in one year of the study. Lack of B-deficient seed suggests that soil B levels were sufficient for peanut growth and development. Seed and leaf B concentrations at 65 days after planting (DAP) were not affected by B source or

application timing when applied at similar rates. While applied B did not affect seed B, applied B described 83% of leaf B variability. Solubor applied at 2.24 kg B ha^{-1} was the most effective treatment for increasing leaf tissue B, and this high rate did not result in B toxicity. Results suggest that current B recommendations are adequate for meeting plant B requirements.

Introduction

Boron is an essential nutrient for proper peanut (*Arachis hypogaea* L.) growth, playing an important role in cell wall and membrane structure and function (Camacho-Cristóbal et al., 2008). Inadequate B during pod development can cause malformed, discolored seeds; this defect is referred to as "hollow heart" (Harris and Gilman, 1957). Hollow heart can reduce yield, seed quality, and crop value. Therefore, strategies to reduce its occurrence are critical for peanut production.

Inherent B levels in highly weathered southeastern U.S. Coastal Plain soils are often inadequate for proper reproductive growth, requiring supplemental B to overcome deficiency. Soil-applied B amendments are not readily retained in coarse textured, low CEC soils. To guard against B losses due to leaching, B can be applied as a foliar spray. Efficacy of foliar-applied B is dependent on mobility of B within the plant, and evidence suggests that B is able to move from peanut leaf to seed (Konsaeng et al., 2010). In addition to B deficiency concerns, excess B can be toxic to plants and result in yield loss (Hill and Morrill, 1974). This is especially a concern where B is foliar-applied, and lower application rates are often necessary to prevent toxicity.

Detection and correction of hollow heart presents challenges as pods develop belowground, and vegetative B deficiency symptoms might not appear until late in the growing season when B applications are impractical and/or less effective (Hill and Morrill, 1974). Low preplant soil B is related to hollow heart incidence; however, the amount needed to prevent deficiency is highly dependent on soil properties (e.g., texture, pH, CEC, organic carbon content) (Shorrocks, 1997). Leaf B concentration during early reproductive growth stages (30 to 60 days after planting, DAP) is also related to hollow heart incidence, thus providing a way to evaluate and potentially remediate plant B in season (Hill and Morrill, 1974; Rerkasem, 1988).

While yield does not typically respond to B additions, peanut grade often improves with supplemental B when hollow heart is present (Hartzog and Adams, 1973). In Alabama, B recommendations are based on crop (0.28 to 0.56 kg B ha^{-1} for peanut), as opposed to soil or leaf tissue analyses. Current B recommendations were developed using smaller-seeded runner peanut varieties (Cope, 1981), and evidence suggests larger-seeded varieties have different nutrient requirements (Singh et al., 2017). Current recommendations do not specify B source or application timing, and limited research has been conducted on peanut in these areas.

In summary, B management presents challenges to peanut producers, and the objective of this study, therefore, was to evaluate B requirements in larger-seeded runner peanut cultivars. Aspects of B rate, source and timing were investigated.

Materials and Methods

Experimental

Field trials using large-seeded runner type peanut, Georgia-06G, were conducted in 2015, 2016, and 2017 at the Wiregrass Research and Extension Center (WREC) in Headland, AL. Study sites were rotated every year within a Lucy loamy sand map unit (loamy, kaolinitic, thermic Arenic Kandiudult). Sites were composed of four-row experimental plots measuring 3.7 x 12.2 m arranged in a randomized complete block design (RCB) with four replications. Sites were irrigated. Other than B applications, experiments were managed according to Alabama Cooperative Extension System (ACES) recommendations for fertility and pest management. Weather data were provided by Alabama Mesonet (Agricultural Weather Information Service, Inc., Auburn, AL).

Boron Treatments

Boron treatments varied in product, application rate, and timing of applications. Boron products included Borosol 10 (10% B as H_3BO_3, Loveland Products, Inc., Greeley, CO), Solubor (20.5% B as $Na_2B_8O_{13}\cdot 4H_2O$, U.S. Borax, Inc., Boron, CA), and B Xtra (5% B as H_3BO_3, Custom Ag Formulators, Inc., Fresno, CA). All products were mixed according to manufacturer instructions and foliar applied.

Treatments included Borosol 10 applied at 0.28, 0.56, and 1.12 kg B ha^{-1}; Solubor applied at 1.12 and 2.24 kg B ha^{-1}; and B Xtra applied at the product recommended rate of 6 oz. product per acre (0.02 kg B ha^{-1}). Full rates of all products were applied at early bloom (i.e., 30 to 35 DAP), except the 2015 Solubor treatment which was applied at 21 DAP. Two rates of Borosol 10 (0.56 and 1.12 kg B ha^{-1}) were split applied at 35 and 50 DAP, with half of the full rate administered at each application. These eight treatments, in addition to an untreated control, were tested in both 2016 and 2017. Borosol 10 applied at 1.12 kg B ha^{-1} and Solubor applied at 2.24 kg B ha^{-1} were tested in 2016 and 2017 trials but were not tested in 2015. Treatment details are listed in Table 2.1. Growing season dates are provided in Table 2.2.

Sample Collection and Analysis

Soil samples (0–10 cm) were collected from each plot prior to planting and analyzed for pH and Mehlich-1 extractable B. Soils were prepared for analyses by drying at 60°C for 48 h followed by grinding the whole sample to pass through a 2-mm sieve. Soil pH was measured for each sample in a 1:2 soil-water suspension (10 g soil in 20 mL deionized water). Soil samples were prepared for elemental analysis by adding 20 mL of Mehlich-1 (0.05 N HCl + 0.025 N H_2SO_4) extracting solution to 5 g soil, shaking for 5 min, and filtering (Whatman no. 40; G.E. Healthcare, Little Chalfont, England) (Mehlich, 1953). The filtrate was analyzed by inductively-coupled plasma spectroscopy (ICP; Spectro Ciros CCD, SPECTRO Analytical Instruments Inc., Kleve, Germany).

Yield data were obtained using the pod weight from the inner two rows of each four-row plot corrected to 10% moisture. A representative subsample was used to evaluate grade as percentage of total sound mature kernels (TSMK). The TSMK fraction includes both the sound mature kernel (SMK) fraction, which are whole kernels that do not pass through a screen having 6.4 x 19.1 mm openings, and the sound split (SS) fraction, which are similarly sized kernels that are broken or split (U.S. No. 1 Runner, 2018). A subsample from the SMK fraction of each graded sample was used for seed B analyses. Seed samples were finely ground, and 0.1 g sample was prepared using a modification of the EPA 3051A procedure (USEPA, 2007). This modification included an addition of hydrogen peroxide [30% (v/v) H_2O_2, 10 mL] to the prepared sample as a pre-digestion step. The sample was allowed to stand for at least 1 h prior to the addition of nitric acid (conc. HNO_3, 10 mL) and microwave digestion (Mars Xpress, CEM Corporation, Matthews, NC). Following digestion, samples were filtered (Whatman no. 40; G.E. Healthcare, Little Chalfont, England), diluted to volume (50 mL) with deionized water, and analyzed by ICP spectroscopy.

Hollow heart was evaluated using a sample composed of the entire SS fraction and 200 kernels from the SMK fraction of each graded sample. Inner surfaces of kernels were visually inspected for abnormalities. Seed identified as positive for hollow heart had both a concave inner surface and dark brown, yellow, or green discoloration.

Leaf samples were collected and analyzed for total B content in 2016 and 2017. Leaf samples (youngest fully expanded leaves, approximately two per plant) were collected from the outer two rows of experimental plots from at least 10 plants per plot (i.e., samples were not taken from plants used for measurement of yield, grade, and seed B) and combined to obtain a representative sample for each plot. Samples were collected prior to treatment at early bloom (35 DAP); 15 d after early bloom treatment applications, prior to the second split applications (50 DAP); and 15 d following the second sampling and split application (65 DAP). When sample collection and treatment application occurred on the same day, samples were collected prior to treatment application. Leaf samples were rinsed to remove any external residue, dried at 60°C for 48 h, and finely ground. Leaf samples (1 g) were prepared for elemental analysis using a modification of the EPA 3051A procedure described above for seed B and analyzed similarly (USEPA, 2007).

Statistical Analyses

Data were analyzed using the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC). Treatment effects on productivity (i.e., pod yield, grade, and seed B) were evaluated with treatment, year, and their interaction as fixed effects and block (replication) by year as a random effect. Leaf B was analyzed similarly with the inclusion of initial leaf B as a covariate. Simple effects were evaluated using the SLICE statement in SAS. Means were separated using Tukey's HSD test. Significance was determined at the 0.05 level. Pearson linear correlation coefficients (r) between response variables were calculated using the CORR procedure in SAS. Linear regression models relating applied B (independent) to leaf B (dependent) content were generated using the REG procedure in SAS.

Results and Discussion

Site Characteristics

Total rainfall and irrigation amounts were 681, 533, and 490 mm during the 2015, 2016, and 2017 growing seasons, respectively. Initial Mehlich-1 extractable soil B in the pegging zone prior to planting was below 0.1 mg kg^{-1} in all years. Initial soil pH was 6.1, 6.4, and 6.3 in 2015, 2016, and 2017, respectively. Experimental conditions are listed in Table 2.3.

Hollow Heart, Yield, and Grade

Hollow heart was not observed in either 2015 or 2016. In 2017, hollow heart was observed, though incidence was minor (< 1%). Occurrence was localized and appeared to be related to field conditions rather than treatment. Both initial leaf and soil B levels in this area were low, with leaf B prior to treatment below the regional sufficiency range of 20-60 mg B kg^{-1} (Southern Cooperative Series, 2013). Alabama on-farm trials conducted from 1967 to 1986 using runner type peanuts also found low incidence of hollow heart (< 2%) (Hartzog and Adams, 1988). Harzog and Adams (1968) initially conducted their research at WREC but moved to farms after 1967 due to lack of B deficiency.

Average pod yield was 5090, 4493, and 3058 kg ha^{-1} in 2015, 2016, and 2017, respectively. Average percentage TSMK (grade) was 71.4, 69.2, and 74.6 in 2015, 2016, and 2017, respectively. Peanut grade and yield differed by year, but not B treatment, and there was no interaction between year and treatment (Tables 2.4 and 2.5). Previous Alabama field trials had similar results. Hartzog and Adams (1973, 1988) did not observe an improvement in grade or yield with B fertilization even when hollow heart was present. Yield is often unaffected by supplemental B in field studies, whether hollow heart incidence is minor or severe (Hill and Morrill, 1974; Cox et al., 1982; Rerkasem et al., 1988).

Grade was positively correlated with leaf B at 35, 50, and 65 DAP ($r = 0.52$, 0.29, and 0.25, respectively) (Table 2.6). A relationship between grade and leaf B during the early stages of reproductive growth (30–60 DAP) suggests leaf B analyses might have utility for predicting B deficiency during the initial stages of pod development when B requirement is high. Similarly, Hill and Morrill (1974) found leaf B content at 30 and 60 DAP reflected plant B availability. Yield was positively correlated with seed B ($r = 0.53$) and initial Mehlich-1 extractable soil B ($r = 0.35$; Table 2.6). A relationship between yield and soil B suggests pre-season Mehlich-1 extractable soil B could be a useful pre-season indicator of productivity.

Seed Boron

Seed B concentration differed by year, but not B treatment, and there was no interaction of year and treatment (Table 2.7). Average seed B at harvest was 17.4, 19.0, and 15.0 mg kg^{-1} in 2015, 2016, and 2017, respectively. Seed B values were within the range observed by Rerkasem et al. (1988) when spanish type peanuts (cv. Tainan 9) were amended with similar rates of B in a Thailand field study. They found seed B content at harvest was 9.6, 17.9, and 22.8 mg kg^{-1} when plants were supplied with 0, 1.1, and 2.3 kg B ha^{-1}, respectively. In their study, increase in seed B from 9.6 to 17.9 mg kg^{-1} decreased hollow heart incidence from 35 to 0%. In the present study, hollow heart was not observed in 2015 or 2016 when average seed B across treatments were 17.4 and 19.0 mg kg^{-1}, respectively, but was observed in 2017 when average seed B was 15.0 mg kg^{-1} across all treatments. Though average seed B was lower in 2017, hollow heart incidence was minor (<1%) and likely the result of field variability rather than seed B content.

Leaf Boron

Prior to B treatment application at early bloom (35 DAP), average leaf B concentrations were 17.9 and 26.0 mg kg^{-1} in 2016 and 2017, respectively, falling below or within the 20 to 60 mg B kg^{-1} sufficiency range (Southern Cooperative Series, 2013). Post-treatment, leaf B concentration was within or above the sufficiency range. Boron toxicity was not observed when leaf B exceeded 60 mg kg^{-1}. Treatment effects on leaf B were evaluated during early stages of reproductive growth (35–65 DAP). This time frame was observed by Hill and Morrill (1974) to be the growth period in which B deficiency could be detected and remediated. Following foliar B application, leaf B concentrations differed by B treatment and year. In addition, there was an interaction between B treatment and year, thus data are discussed by year (Table 2.8).

Source effects on leaf B content were not observed when products applied at equivalent rates were compared. Borosol 10 (H_3BO_3) and Solubor ($Na_2B_8O_{13}·4H_2O$) applied at a rate of 1.12 kg B ha^{-1} at 35 DAP performed similarly when evaluated at 50 and 65 DAP in both years. Because B Xtra (H_3BO_3) was the only product applied at 0.02 kg B ha^{-1}, source effects could not be compared directly with other products.

Application rate, independent of source, described 83 to 92% of the variability in leaf B concentration 15 and 30 d following application in 2016 and 2017 (Table 2.9). Compared to the untreated control, foliar B applications at an overall rate of at least 1.12 kg B ha^{-1} resulted in higher leaf B levels at both 50 DAP (i.e.,15 days after single and first split applications) and 65 DAP (i.e., 30 days after single and first split applications and 15 days after second split applications). Rates of 0.02, 0.28, and 0.56 kg B ha^{-1} did not result in leaf B levels different from the control, although leaf B was slightly improved with application. Among treated plants, an application of 2.24 kg B ha^{-1} resulted in higher leaf B content than applications of 1.12, 0.56, 0.28, and 0.02 kg B ha^{-1} at both 50 and 65 DAP; applications of 1.12 kg B ha^{-1} resulted in higher leaf B concentrations than applications of 0.28 and 0.02 kg B ha^{-1} at 65 DAP; and applications of 0.56, 0.28, and 0.02 kg B ha^{-1} resulted in leaf B concentrations that were not different from one another at either 50 or 65 DAP. In addition, in 2017, applications of 1.12 kg B ha^{-1} resulted in higher leaf B than applications of 0.56 kg B ha^{-1} at 65 DAP. Overall, applications of 1.12 and 2.24 resulted in higher leaf B than other rates by 65 DAP (Figures 2.1 and 2.2).

Leaf B levels in plants treated with identical B application rates (0.56 or 1.12 kg ha^{-1}) of the same source (Borosol 10) as either one single application at 35 DAP or two split applications at 35 and 50 DAP were not significantly different by 65 DAP in either year. Linear regression analyses of these two treatments showed that leaf B content at 65 DAP was linearly related to amount of B applied ($R^2 > 0.44$) (Table 2.10). Leaf B concentration increased linearly as a function of applied B, regardless of application timing, even though the rate of increase (slope) was greater in 2017 (leaf B increased 18.3 and 15.3 mg kg^{-1} per 1 kg B ha^{-1} applied for single and split applications, respectively) compared to 2016 (leaf B increased 28.7 and 30.2 mg B kg^{-1} per 1 kg B ha^{-1} applied for single and split applications, respectively). The difference in rate of increase between years could be due to environmental conditions affecting plant uptake (e.g., rainfall, temperature, conditions at time of application), differences in plant growth rates, or B translocation within the plant. During plant growth, B moves from older to younger peanut leaves (Konsaeng, 2010). Within years, rates of increase were similar, independent of application timing, suggestive of similar B translocation rates within the plant. Similarities in rates of increase also provide evidence that application rates of 1.12 kg B ha^{-1} at early bloom might not influence the amount of B in younger leaves by mid-bloom (60-70 DAP), a concern with higher foliar B application rates (>1.12 kg B ha^{-1}) (Mortvedt, 1993).

Overall, total rates of 1.12 or 2.24 kg B ha^{-1} applied between 35 and 50 DAP resulted in leaf B levels above the control 15 days following treatment in both years. Furthermore, results suggest application rate is the most important factor affecting leaf B concentration.

Conclusion

Boron rate, source, and application timing had no effect on larger-seeded runner peanut yield, grade, or seed B. Minor incidence of hollow heart was observed in only one year of the study and appeared to be related to field location rather than treatment. The aggregate of these findings suggests that initial Mehlich-1 extractable soil test B levels as low as 0.1 mg kg^{-1} did not cause B deficiency.

Leaf B concentration was affected by B treatment. This appeared to be a function of rate rather than timing or source. Results indicate that sodium borate and boric acid foliar-applied at 1.12 kg B ha^{-1} are absorbed by plant leaves in similar quantities. In addition, rates of 0.56 and 1.12 kg B ha^{-1} applied in full or split applied in early season, result in similar mid-season leaf B concentrations. Higher application rates resulted in higher leaf B concentrations, with 83% of leaf B variability described by applied B rate. High applications of Solubor (2.24 kg B ha^{-1}) increases leaf tissue B while not inducing toxicity.

Correlations among leaf B with grade, and soil B with seed B and yield, warrant further investigation for managing B in season. Similarly, a linear relationship between leaf B and applied B indicates regression models for estimating B application rates to maintain leaf B levels within sufficiency ranges warrant further exploration across growing seasons and soils.

In conclusion, runner peanut productivity was not affected by rate, source, or application timing when initial B levels were sufficient according to state recommendations. Leaf uptake of B was well correlated with B application rate, independent of B source and application timing. Productivity was neither improved nor harmed by increasing application rate when leaf B levels were increased within or above the sufficiency range. Lack of B deficiency symptoms in larger-seeded peanut when B levels recommended for smaller-seeded varieties were met provides evidence that recommendations might prove sufficient for larger- and smaller-seeded runner peanut varieties alike. Further research comparing B fertility in larger- and smaller-seeded runner peanut varieties should aim to test recommendations in areas where hollow heart is known to decrease productivity.

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Table 2.1. Summary of foliar-applied boron (B) treatments on runner peanut (cv. Georgia-06G) during the 2015, 2016, and 2017 growing seasons in Headland, AL.

Source	**Rate**	**Timing†**	**Year**
	kg B ha^{-1}		
Control	0	-	2015, 2016, 2017
B Xtra	0.02	Single	2015, 2016, 2017
Borosol 10	0.28	Single	2015, 2016, 2017
Borosol 10	0.56	Single	2015, 2016, 2017
Borosol 10	0.56	Split	2015, 2016, 2017
Borosol 10	1.12	Single	2016, 2017
Borosol 10	1.12	Split	2015, 2016, 2017
Solubor	1.12	Single	2015, 2016, 2017
Solubor	2.24	Split	2016, 2017

† Single and split application timing details are listed in Table 2.2.

Table 2.2. Planting and harvesting dates for runner peanut (cv. Georgia-06G) B fertility trials conducted in Headland, AL during the 2015, 2016, and 2017 growing seasons. Application dates are listed in relation to planting dates.

			Timing	
Year	**Planting**	**Digging**	**Single**	**Split**
			DAP	
2015	4-June	20-Oct	40†	40, 65
2016	5-May	19-Sept	35	35, 50
2017	31-May	20-Oct	35	35, 50

† 20 DAP for Solubor applied at 1.12 kg B ha^{-1}.

Table 2.3. Initial soil pH, initial Mehlich-1 extractable soil B, total rainfall amount, and total irrigation amount for 2015–17 trials.

Year	**pH**	**Soil B**	**Rainfall**	**Irrigation**
		mg kg^{-1}	mm	
2015	6.1	ND†	567	114
2016	6.4	0.12	483	51
2017	6.3	0.10	439	51

† Not detectable.

Table 2.4. Boron rate, source and application timing effects on runner peanut (cv. Georgia-06G) grade. Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

			Grade			
Source	**Rate**	**Timing†**	**2015**	**2016**	**2017**	**Mean**
	kg B ha^{-1}		% TSMK‡			
Control		-	71.9	71.0	74.8	72.6
B Xtra	0.02	S	72.0	66.5	74.0	70.8
Borosol 10	0.28	S	71.3	69.5	75.0	71.9
Borosol 10	0.56	SP	69.6	70.6	74.3	71.3
Borosol 10	0.56	S	71.1	70.2	73.5	71.6
Borosol 10	1.12	SP	70.4	69.2	74.3	71.0
Borosol 10	1.12	S	-	69.9	74.5	-
Solubor	1.12	S	73.2	68.3	74.8	72.1
Solubor	2.24	S	-	67.9	75.8	-
Standard error treatment means			0.55	0.43	0.26	0.70
			***P* > F**			
Treatment						0.84
Year						< 0.01
Year × Treatment						0.36

† Rate applied in full (single, S) or as two half-rate applications (split, SP).

‡ TSMK = Total sound mature kernels

Table 2.5. Boron rate, source and application timing effects on runner peanut (cv. Georgia-06G) yield. Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

			Yield			
Source	**Rate**	**Timing†**	**2015**	**2016**	**2017**	**Mean**
	kg B ha^{-1}		kg ha^{-1}			
Control		-	5276	4130	3185	4197
B Xtra	0.02	S	4991	4974	3412	3773
Borosol 10	0.28	S	5303	4435	3022	4253
Borosol 10	0.56	SP	5086	4547	2949	4194
Borosol 10	0.56	S	5072	4191	3276	4180
Borosol 10	1.12	SP	5086	4465	2577	4043
Borosol 10	1.12	S	-	4415	3104	-
Solubor	1.12	S	4815	4608	3122	4459
Solubor	2.24	S	-	4669	2877	-
Standard error treatment means			99.9	127.0	92.9	193.9
			***P* > F**			
Treatment						0.92
Year						< 0.01
Year × Treatment						0.76

† Rate applied in full (single, S) or as two half-rate applications (split, SP).

Table 2.6. Pearson linear correlation coefficients (r)† of field measurements collected during and after the 2015, 2016, and 2017 runner peanut (cv. Georgia-06G) growing seasons in Headland, AL.

Variables‡	**Yield**	**Grade**	**Seed B**	**Leaf B_{35}**	**Leaf B_{50}**	**Leaf B_{65}**
Grade	-0.34***	1				
Seed B	0.53***	-0.53***	1			
Leaf B_{35}	-0.51***	0.52***	-0.59***	1		
Leaf B_{50}	-0.26*	0.29*	-0.25*	0.12	1	
Leaf B_{65}	-0.15	0.25*	-0.10	0.02	0.85***	1
Soil B_0§	0.35**	-0.18	0.34**	0.12	-0.10	0.03

*, **, and *** represent significance at the 0.05, 0.01, and 0.001 levels, respectively.

† Yield, grade, and seed B were measured all three years of the study (n > 90); leaf B_{35}, leaf B_{50}, leaf B_{65}, and soil B_0 were measured in 2016 and 2017 only (n = 72).

‡ Subscripts denote days after planting (DAP).

§ Mehlich-1 extractable (0–10 cm).

Table 2.7. Boron rate, source and application timing effects on seed B content in runner peanut (cv. Georgia-06G). Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

			Seed B			
Source	**Rate**	**Timing†**	**2015**	**2016**	**2017**	**Mean**
	kg B ha^{-1}		mg kg^{-1}			
Control		-	16.4	19.6	14.9	17.0
B Xtra	0.02	S	17.2	18.6	14.1	17.5
Borosol 10	0.28	S	17.2	19.0	14.6	16.9
Borosol 10	0.56	SP	18.2	19.1	15.3	17.7
Borosol 10	0.56	S	17.6	18.0	15.1	16.9
Borosol 10	1.12	SP	17.8	19.5	15.0	17.6
Borosol 10	1.12	S	-	18.6	15.2	-
Solubor	1.12	S	17.2	18.9	15.4	16.6
Solubor	2.24	S	-	19.6	15.5	-
Standard error treatment means			0.43	0.19	0.13	0.43
			***P* > F**			
Treatment						0.27
Year						< 0.01
Year × Treatment						0.39

† Rate applied in full (single, S) or as two half-rate applications (split, SP).

Table 2.8. Leaf B content (mg kg^{-1}) at 50 and 65 days after planting (DAP) following foliar B applications during the 2016 and 2017 runner peanut (cv. Georgia-06G) growing season in Headland, AL.

				Leaf B	
Year	**Source**	**Rate**	**Timing†**	**50 DAP**	**65 DAP**
		kg B ha^{-1}		mg kg^{-1}	
2016	Control	0	-	25.0 d‡	30.1 c
	B Xtra	0.02	S	27.5 d	31.4 c
	Borosol 10	0.28	S	29.0 d	33.9 c
	Borosol 10	0.56	SP	28.9 d	39.3 bc
	Borosol 10	0.56	S	35.6 bcd	39.7 bc
	Borosol 10	1.12	SP	32.3 cd	47.0 b
	Borosol 10	1.12	S	47.2 b	49.0 b
	Solubor	1.12	S	45.7 bc	45.5 b
	Solubor	2.24	S	71.5 a	61.2 a
2017	Control	0	-	37.5 d	33.9 c
	B Xtra	0.02	S	35.6 d	31.8 c
	Borosol 10	0.28	S	41.9 d	37.4 c
	Borosol 10	0.56	SP	38.7 d	42.2 c
	Borosol 10	0.56	S	45.1 cd	40.6 c
	Borosol 10	1.12	SP	44.5 cd	57.4 b
	Borosol 10	1.12	S	57.8 bc	55.0 b
	Solubor	1.12	S	63.3 b	56.1 b
	Solubor	2.24	S	107.8 a	82.8 a
				***P* > F**	
Leaf B, initial				0.91	0.83
Treatment				< 0.01	< 0.01
Year				< 0.01	0.10
Year × Treatment				< 0.01	< 0.01

† Rate applied in full at 35 DAP (single, S) or as two half-rate applications at 35 and 50 DAP (split, SP).

‡ Within sampling time (columns) and year, means followed by the same letter are not significantly different at the 0.05 probability level.

Table 2.9. Linear regression relating foliar-applied B rate† to leaf B concentration by year 15 and 30 days after treatment (DAT) in runner peanut (cv. Georgia-06G).

Year	**DAT**	**Equation§**	R^2	**Model** $P > F$
2016	15	Leaf B = 15.4(Applied B) + 31.4	0.85	< 0.01
	30	Leaf B = 22.9(Applied B) + 24.7	0.91	< 0.01
2017	15	Leaf B = 26.0(Applied B) + 29.8	0.84	< 0.01
	30	Leaf B = 36.1(Applied B) + 29.7	0.83	< 0.01

† 0.02, 0.56, 1.12, and 2.24 kg B ha^{-1} applied at 35 days after planting (DAP).

‡ Corresponds to 50 and 65 DAP.

§ Leaf B in mg kg^{-1}; applied B in kg ha^{-1}.

Table 2.10. Linear regression relating foliar-applied B rate† to leaf B concentration by timing by year at 65 days after planting (DAP)‡ in runner peanut (cv. Georgia-06G).

Year	**Timing**	**Equation§**	R^2	**Model *P* > F**
2016	Single	Leaf B = 18.3(Applied B) + 30.8	0.66	0.01
	Split	Leaf B = 15.3(Applied B) + 31.8	0.44	< 0.01
2017	Single	Leaf B = 28.7(Applied B) + 26.1	0.52	0.04
	Split	Leaf B = 30.2(Applied B) + 27.0	0.74	< 0.01

† 0.56 and 1.12 kg B ha^{-1} as boric acid (Borosol 10).

‡ Corresponds to 30 days after treatment (DAT) for single applications, and 30 and 15 DAT for first and second split applications, respectively.

§ Leaf B in mg kg^{-1}; applied B in kg ha^{-1}.

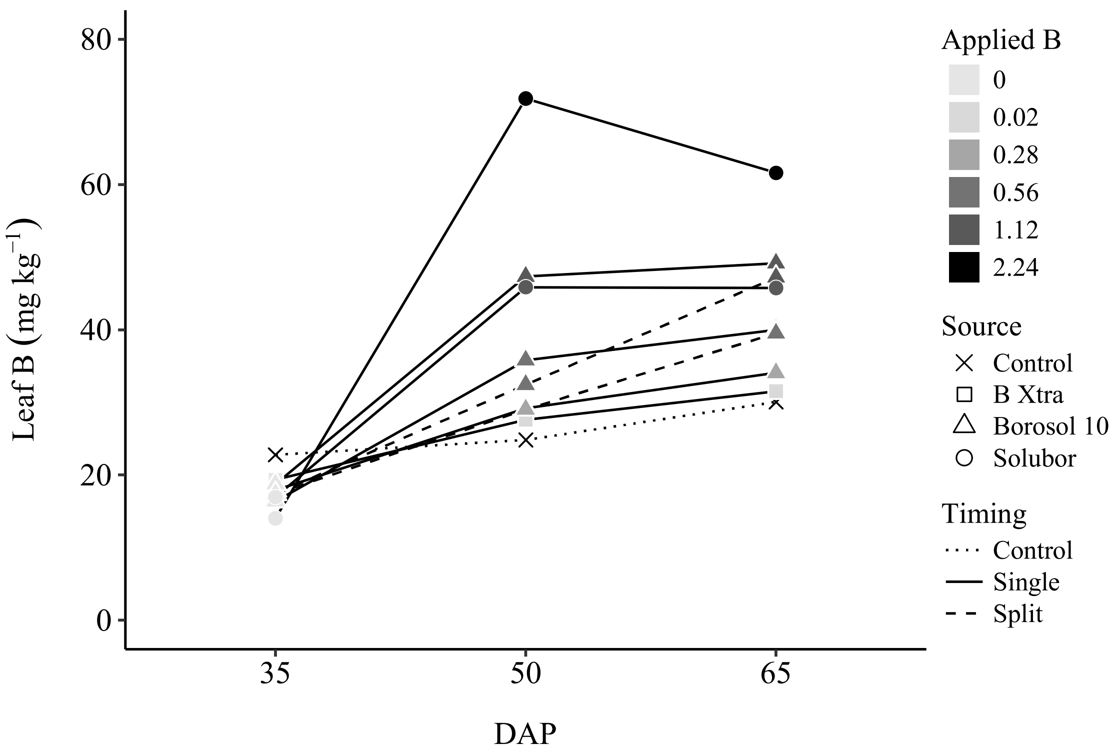

Figure 2.1. Leaf B content (mg kg^{-1}) as a function of applied B (kg B ha^{-1}), B source, and application timing at 35, 50, and 65 days after planting (DAP) during the 2016 runner peanut (cv. Georgia-06G) growing season in Headland, AL. Timing mode consisted of single or split applications at 35 DAP or 35 and 50 DAP, respectively, with data collection preceding treatment application.

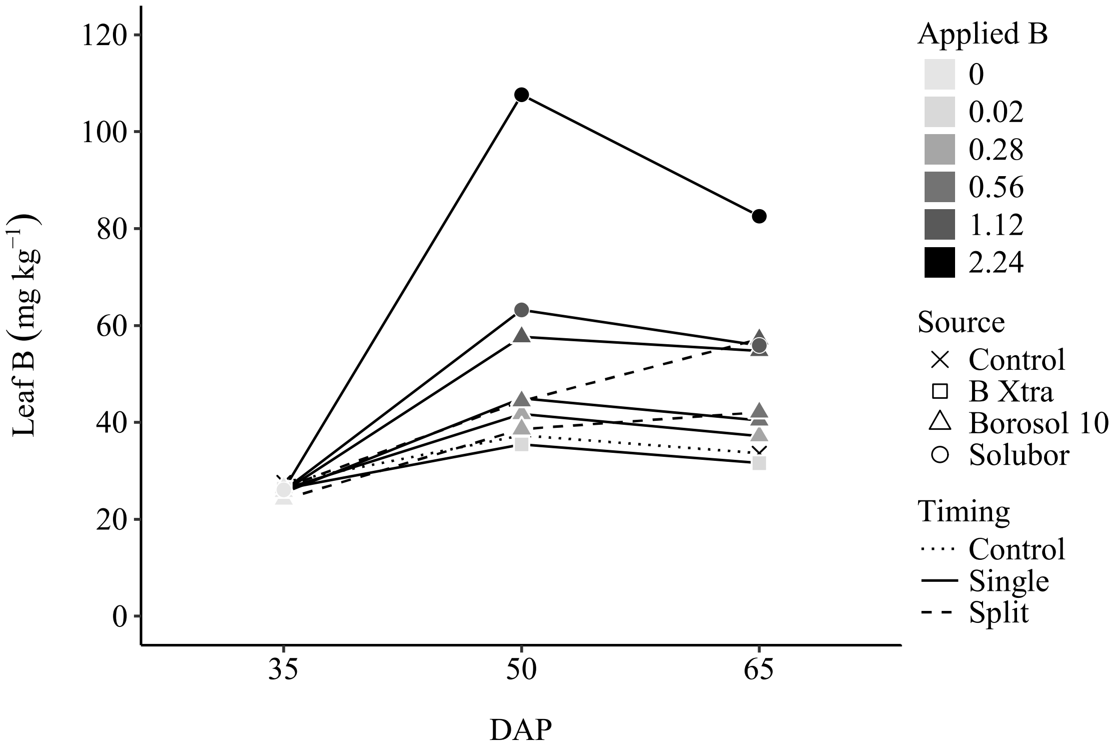

Figure 2.2. Leaf B content (mg kg^{-1}) as a function of applied B (kg B ha^{-1}), B source, and application timing at 35, 50, and 65 days after planting (DAP) during the 2017 runner peanut (cv. Georgia-06G) growing season in Headland, AL. Timing mode consisted of single or split applications at 35 DAP or 35 and 50 DAP, respectively, with data collection preceding treatment application.

III. Calcium Source Effects on Runner Peanut Productivity

Abstract

Insufficient calcium (Ca) during peanut (*Arachis hypogaea* L.) growth and development is a concern for producers in the southeastern U.S. Coastal Plain due to poor Ca retention in soil surface horizons. Calcium is essential for seed development, and a lack of Ca can reduce yield, seed quality, and crop value. The goal of this study was to evaluate Ca products that could potentially increase Ca retention in the pegging zone of coarse textured, low cation exchange capacity (CEC) soils. Calcium source effects on pod yield, seed quality, and soil Ca retention were evaluated over the 2015, 2016, and 2017 growing seasons in Headland, AL, using the runner-type peanut cultivar 'Georgia-06G' grown in a Lucy loamy sand (loamy, kaolinitic, thermic Arenic Kandiudult) soil map unit. Calcium sources included lime ($CaCO_3$, 34% Ca), gypsum ($CaSO_4$, 21% Ca), Black Gypsum ($CaSO_4$, 12% Ca, 21% humate), AgriMend ($CaSO_4$, 11% Ca), and Full Measure Cal ($CaCO_3$, 12.5% Ca, 1% humate) applied at state or product recommended rates. Yield and grade were not increased by Ca treatments, which is likely due to adequate initial soil test Ca levels (>150 mg kg^{-1}). Seed Ca was increased by Ca additions in 2016 and 2017 with 57 and 36% of the variability in seed Ca explained by applied Ca rate in each year, respectively. Lime and gypsum applications of 1120 kg ha^{-1} resulted in seed and soil Ca levels above the untreated control. In addition to lime and gypsum, Black Gypsum increased soil Ca levels above the control to levels comparable to lime and

gypsum in 2016 and 2017, though applied at a lower rate, suggestive of increased soil retention of Ca with humate-containing fertilizers.

Introduction

Calcium is an essential nutrient for peanut (*Arachis hypogaea* L.) development. Insufficient Ca during reproductive growth can result in underdeveloped seed and darkened plumules leading to yield loss and decreased crop value (Colwell and Brady, 1945; Cox and Reid, 1964). In addition, germination percentages are reduced when seed is low in Ca (Harris and Brolmann, 1966b; Adams, 1993). A constant Ca supply is needed throughout reproductive growth for proper seed development (Mizuno, 1959; Howe et al., 2012). Because developing pods obtain Ca directly from soil solution by diffusion (Sumner et al., 1988), soil water content and factors affecting Ca retention and availability (e.g. organic matter content, reactivity) in the pegging zone influence Ca uptake (Wright, 1989).

Calcium availability is a concern for peanut production on southeastern U.S. Coastal Plain soils as coarse textured, permeable, low cation exchange capacity (CEC) surface horizons lack inherent Ca and tend to leach bases (e.g. Ca) with high rainfall. Therefore, these soils require Ca amendments for peanut production. Calcium amendments are soil-applied with application rate, source, and timing recommended as a function of initial soil pH and Ca levels. Lime ($CaCO_3$) and gypsum ($CaSO_4$) are the most commonly applied Ca amendments (Hartzog and Adams, 1988). In the Southeast, lime is recommended to raise soil pH above 6.0 and to increase pegging zone soil Ca levels above 150 mg kg^{-1} for irrigated peanuts, and gypsum is recommended when pH is suitable but soil Ca is low (Mitchell and Huluka, 2012). Alternative fertilizers that could improve soil Ca retention and plant uptake would benefit peanut producers; however, effectiveness of these products is not well-established (Abbott et al., 2018).

Calcium availability is dependent on pegging zone soil Ca levels and water content. To prevent Ca losses due to leaching, products containing humic acid have been developed which aim to increase Ca retention in soils. Because products that potentially increase Ca retention in soils would benefit southeastern peanut producers, a study was designed to compare effectiveness of traditional and alternative Ca sources at state or product recommended rates.

Materials and Methods

Experimental

Field trials using runner type peanut (cv. Georgia-06G) were conducted under irrigation in 2015, 2016, and 2017 at the Wiregrass Research and Extension Center (WREC) in Headland, AL under irrigated conditions. Study sites were rotated each year within a Lucy loamy sand map unit (loamy, kaolinitic, thermic Arenic Kandiudult). Sites were composed of four-row experimental plots measuring 3.7 x 12.2 m arranged in a randomized complete block (RCB) design with four replications. Other than Ca fertilization, plots were managed according to Alabama Cooperative Extension System (ACES) recommendations. Weather data were provided by Alabama Mesonet (Agricultural Weather Information Service, Inc., Auburn, AL).

Calcium Treatments

Calcium source products included lime (34% Ca, Tri-State Lime, LLC, Arlington, GA), gypsum (21% Ca, Kelly Ag of Headland, LLC, Headland, AL), AgriMend (11% Ca, AgriFarm Group, Colorado Springs, CO), Black Gypsum (12% Ca, The Andersons, Inc., Maumee, OH), and Full Measure Cal (12.5% Ca, Miller Chemical & Fertilizer, LLC, Hanover, PA). AgriMend is a granular calcium sulfate product that contains magnesium (1%), iron (1%), boron (0.02%), and cobalt (0.0005%). Black Gypsum is a mined calcium sulfate product containing 21% humate. Full Measure Cal is a liquid Ca fertilizer derived from calcium carbonate and calcium acetate containing 1% humate.

Lime, gypsum, Black gypsum, and AgriMend were applied at a rate of 1120 kg product ha^{-1} corresponding to 381, 235, 134, and 123 kg Ca ha^{-1}, respectively. Gypsum was also applied at 560 kg product ha^{-1} (118 kg Ca ha^{-1}) in 2016 and 2017. Full Measure Cal was applied at the product recommended rate for peanut of 10.7 kg ha^{-1} (1.3 kg Ca ha^{-1}). Treatments were applied at early bloom (30-40 DAP), except for lime which was applied at planting. Granular products were hand-broadcasted evenly over plots. Full Measure Cal was mixed according to manufacturer instructions and soil-applied as a spray. Treatment details are listed in Table 3.1. Growing season dates are provided in Table 3.2.

Sample Collection and Analyses

Soil samples (0-10 cm) were collected during the growing season. Samples were collected prior to planting and treatment applications (0 DAP), during mid- to late-bloom (70-90 DAP), and at harvest (140 DAP). Between years, mid- to late-bloom sampling times differed with samples collected at 90 DAP in 2015 and 70 DAP in 2016 and 2017.

Soil pH and nutrient content were measured for all samples. Soils were prepared for analyses by drying at 60°C for 48 h followed by grinding the whole sample to pass through a 2-mm sieve. Soil pH was measured for each sample in a 1:2 soil-water suspension (10 g soil in 20 mL deionized water). Soil samples were prepared for elemental analysis by adding 20 mL of Mehlich-1 (0.05 N HCl + 0.025 N H_2SO_4) extracting solution to 5 g soil, shaking for 5 min, and filtering (Whatman no. 40; G.E. Healthcare, Little Chalfont, England) (Mehlich, 1953). The filtrate was analyzed by inductively-coupled plasma spectroscopy (ICP; Spectro Ciros CCD, SPECTRO Analytical Instruments Inc., Kleve, Germany).

Yield data were obtained using the pod weight from the inner two rows of each four-row plot corrected to 10% moisture. A representative subsample was used to evaluate grade as percentage of total sound mature kernels (TSMK). The TSMK fraction includes both the sound mature kernel (SMK) fraction, which are whole kernels that do not pass through a screen having 6.4- x 19.1-mm openings, and the sound split (SS) fraction, which are similarly sized kernels that are broken or split (U.S. No. 1 Runner, 2018). A subsample from the SMK fraction of each graded sample was used for seed Ca determination. Seed samples were finely ground and 0.1 g sample was prepared using a modification of the EPA 3051A procedure (USEPA, 2007). This modification included an addition of hydrogen peroxide [30% (v/v) H_2O_2, 10 mL] to the prepared sample as a pre-digestion step. The sample was allowed to react for at least 1 h prior to the addition of nitric acid (conc. HNO_3, 10 mL) and microwave digestion (Mars Xpress, CEM Corporation, Matthews, NC). Following digestion, samples were filtered (Whatman no.

40), diluted to volume (50 mL) with deionized water, and analyzed by ICP spectroscopy (Spectro Ciros CCD, SPECTRO Analytical Instruments Inc., Kleve, Germany).

Statistical Analysis

Data were analyzed using the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC). Treatment effects on productivity (i.e. pod yield, grade, and seed Ca) were evaluated with treatment, year, and their interaction as fixed effects, and block (replication) by year as a random effect. Treatment effects on soil Ca content during the growing season were evaluated by year due to unequal variances among years, treatments, and their interaction as discussed by Dixon et al. (2018). Therefore, treatment effects were analyzed with initial soil Ca as a covariate; treatment, sampling time, and their interaction as fixed effects; block as a random effect; and treatment within block (plot) as repeated observations. Means were separated using Tukey's HSD test. Significance was determined at $\alpha = 0.05$. Linear regression models relating applied Ca (independent) to seed Ca (dependent) content were generated using the REG procedure in SAS.

Results and Discussion

Site Characteristics

Rainfall and irrigation amounts totaled 681, 533, and 490 mm for the 2015, 2016, and 2017 growing seasons, respectively. Initial soil pH was between 6.0 and 6.2 in all years. Experimental conditions are provided in Table 3.3 Pre- and growing season soil Ca in the pegging zone exceeded the critical value for runner peanuts grown under irrigation (150 mg kg^{-1}) in all years. Similarly, soil Ca to K ratios exceeded the recommended 3:1

ratio in 2016 and 2017 (Hallock and Garren, 1968); soil K was not measured in 2015. Calcium deficiency symptoms (e.g., unfilled pods) were not observed in any year of the study.

Yield and Grade

Pod yield was significantly affected by year but not treatment ($P = 0.52$) when averaged across 2015, 2016, and 2017; within years, yields averaged 5099, 6855, and 3783 kg ha^{-1}, respectively (Table 3.4). Similarly, grade was affected by year but not treatment ($P = 0.91$) (Table 3.5). The lack of treatment effects on yield and grade were expected as soil Ca was above the critical value of 150 mg kg^{-1} prior to planting and remained above this value through harvest. Similarly, Hartzog and Adams (1988) also did not observe yield or grade responses to additional Ca on runner peanut grown in Ca-sufficient soil. In the present study, Ca was not limiting in the present study in either a relatively low (2017) or high (2016) yielding year.

Soil Calcium

Calcium source affected late-season (70 and 140 DAP) soil Ca levels in 2016 and 2017 ($p < 0.01$) but not in 2015 ($p = 0.11$) (Table 3.6; Figure 3.1). Rainfall was relatively higher in the early portion of the 2015 growing season (Figure 3.2), which resulted in greater Ca leaching compared to the other years. For example, approximately 400 mm of rainfall occurred within 60 days following early bloom treatment applications in 2015, compared to approximately 250 mm in both 2016 and 2017.

Black Gypsum and lime applied at a rates of 1120 kg ha^{-1} increased soil Ca levels above the untreated control in 2016 and 2017. Additionally, gypsum applied at 1120 kg ha^{-1} resulted in soil Ca levels above the control in 2017. Although Black Gypsum, which contains humic acid, was applied at approximately half the rate of lime and gypsum, resulting soil Ca levels were similar. Humic acids are added to fertilizers because they have potential to increase nutrient (e.g., Ca) soil retention times through the formation of stable humate complexes, which would be beneficial in sandy, highly permeable southeastern Coastal Plain soils (Abbott et al., 2018). Results of this study suggest Ca retention in southeastern Coastal Plain soils is increased using products containing humic acid substances.

AgriMend, gypsum, and Full Measure Cal applied at 1120, 560, and 10.7 kg ha^{-1}, respectively, did not increase soil Ca levels above the control in any year. Interestingly, in 2017, the humate-containing Full Measure Cal applied at 1.3 kg Ca ha^{-1} performed as well as treatments that resulted in higher soil Ca than the control (i.e., gypsum and lime applied at 235 and 381 kg Ca ha^{-1}, respectively), though Full Measure Cal was applied at a much lower Ca rate. This is consistent with the Black Gypsum result suggesting that humic substance fertilizer additions could increase soil Ca retention; however, this trend with Full Measure Cal was only observed in 2017. Further research is necessary to determine effectiveness of this product and to determine if Ca in these humic acid products is plant-available.

<u>Seed Calcium</u>

Seed Ca content at harvest was significantly affected by Ca treatment and year ($p < 0.001$), though the interaction between year and treatment was not significant ($P = 0.10$) (Table 3.7). Across all years, applications of lime and gypsum at 1120 kg ha^{-1} resulted in higher seed Ca compared to the untreated control, while applications of

AgriMend at 1120 kg ha^{-1}, Black Gypsum at 1120 kg ha^{-1}, and Full Measure Cal at 10.7 kg ha^{-1} did not increase seed Ca above the control. Seed Ca in plants treated with AgriMend or Black Gypsum applied at 1120 kg ha^{-1} did not differ from seed Ca levels in plants receiving other treatments. This suggests either Ca application rates were too low or that the organically bound Ca inhibits either diffusion or uptake into the seed.

Though soil Ca remained above the critical level (150 mg kg^{-1}) prior to and throughout the growing season in 2016 and 2017, Ca additions resulted in seed Ca increases. In fact, applied Ca described 57 and 36% of seed Ca variability in 2016 and 2017, respectively (Table 3.8). This is important for peanut seed production as Ca application are recommended, independent of soil-test Ca, due to the effects that low seed Ca can have on germination rates (Harris and Brolmann, 1966a; Adams, 1993).

In contrast to soil Ca, seed Ca increases above the control were not observed with application of products containing humic substances. In addition to soil Ca levels, seed Ca is influenced by several factors including soil water content, nutrient levels, pH, and cultivar; therefore, the relationship between seed and soil Ca levels is complex and beyond the scope of this discussion.

Conclusion

Calcium sources applied at state or product recommended rates did not affect yield or grade. In addition, Ca deficiency symptoms were not observed due to soil Ca levels prior to planting and throughout the season above the Alabama critical value for peanuts grown under irrigation (150 mg kg^{-1}). Thus, the established soil test critical value was sufficient for runner peanut in 2015, 2016, and 2017.

Calcium source affected soil and seed Ca levels in 2016 and 2017, but not in 2015. This is potentially due to differences in rainfall distribution among years with 2015 receiving approximately twice the amount of rainfall within 60 days following treatment application than either 2016 or 2017. Lime applied at 1120 kg ha^{-1} supplied the most Ca to plants (381 kg Ca ha^{-1}), and resulted in soil Ca values above the control in 2016 and 2017. Gypsum performed similar to lime applied at the same rate. Applied Ca described 57 and 36% of seed Ca variability in 2016 and 2017, respectively, suggesting that with additional significant parameters, regression models relating these variables could be developed.

While higher rates of lime and gypsum applications had similar effects on seed and soil Ca, humate-containing products differed in seed and soil Ca effects. Black Gypsum (21% humate) applications resulted in soil Ca levels consistently higher than the control, but seed Ca content that did not differ from the control. In addition, though Full Measure Cal applied at the lowest rate (1.3 kg Ca ha^{-1}) did not result in seed or soil Ca content that differed from the control, soil Ca levels also did not differ from a considerably higher rate of gypsum (235 kg Ca ha^{-1}). Thus, similar soil Ca retention suggests that products containing humic substances could potentially increase soil Ca retention compared at similar Ca rates of commonly applied products. However, a similar trend was not observed with seed uptake making the translation of increased soil Ca retention to plant-available Ca unclear.

Though applied at much lower rates, humate-containing products resulted in similar soil Ca levels to those observed with high application rates of non-humic Ca sources. This suggests that humate additions could increase soil Ca retention, though this does not necessarily translate to increased plant Ca uptake. The aggregate of these findings also supports the validity of established soil test Ca critical values for Alabama market peanut production and previous findings that Ca additions to Ca-sufficient soils increases seed Ca levels.

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Table 3.1. Summary of calcium (Ca) treatments on runner peanut (cv. Georgia-06G) during the 2015, 2016, and 2017 growing seasons in Headland, AL.

		Rate	
Source	**% Ca**	**Product**	**Ca**
		kg ha^{-1}	
Gypsum	21	560	118
Gypsum	21	1120	235
Lime	34	1120	381
Black Gypsum	12	1120	134
AgriMend	11	1120	123
Full Measure Cal	12.5	10.7	1.3

Table 3.2. Planting, harvesting, and application dates for runner peanut (cv. Georgia-06G) Ca fertility trials conducted in Headland, AL during the 2015, 2016, and 2017 growing seasons.

Year	**Planting**	**Digging**	**Application†**
2015	4-June	20-Oct	13-July
2016	5-May	19-Sept	8-June
2017	30-May	20-Oct	12-July

† With the exception of lime, which was applied at or prior to planting.

Table 3.3. Initial soil solution pH, initial Mehlich-1 extractable soil Ca, total rainfall amounts, and total irrigation amounts for 2015–17 trials.

Year	pH	Soil Ca	Rainfall	Irrigation
		mg kg^{-1}	—— mm ——	
2015	6.0	258	567	114
2016	6.2	313	483	51
2017	6.1	258	439	51

Table 3.4. Calcium source and rate effects on runner peanut (cv. Georgia-06G) yield. Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

		Yield			
Source	**Rate**	**2015**	**2016**	**2017**	**Mean**
	kg ha^{-1}	kg ha^{-1}			
Control	0	5506	7107	4079	5564
Gypsum	560	-	6347	4106	-
Gypsum	1120	5004	6754	3686	5148
Lime	1120	4774	6863	3483	5040
Black Gypsum	1120	4598	6971	3605	5058
AgriMend	1120	5221	6795	4025	5347
Full Measure Cal	10.7	5493	7147	3496	5379
Standard error treatment means		206.7	95.4	113.1	291.7
		***P* > F**			
Treatment					0.52
Year					< 0.01
Year × Treatment					0.76

Table 3.5. Calcium source and rate effects on runner peanut (cv. Georgia-06G) grade. Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

		Grade			
Source	**Rate**	**2015**	**2016**	**2017**	**Mean**
	kg ha^{-1}	% TSMK			
Control	0	69.1	74.3	72.8	72.1
Gypsum	560	-	74.0	73.3	-
Gypsum	1120	69.6	73.5	72.5	71.8
Lime	1120	71.3	74.0	73.3	72.8
Black Gypsum	1120	71.1	74.4	71.5	72.3
AgriMend	1120	68.5	74.0	72.8	71.7
Full Measure Cal	10.7	71.1	74.8	72.8	72.9
Standard error treatment means		0.81	0.20	0.33	1.09
		***P* > F**			
Treatment					0.91
Year					< 0.01
Year × Treatment					0.97

Table 3.6. Calcium source and rate effects on mid- to late-season pegging zone (0-10 cm) soil Ca content during the 2015, 2016, and 2017 peanut growing seasons in Headland, AL.

		Soil Ca		
Product	**Rate**	**2015**	**2016**	**2017**
	kg ha^{-1}		mg kg^{-1}	
Control	0	220	285 c†	253 c
Gypsum	560	-	299 c	295 abc
Gypsum	1120	214	357 bc	317 ab
Lime	1120	272	547 a	312 ab
Black Gypsum	1120	207	380 b	325 a
AgriMend	1120	207	297 c	264 bc
Full Measure Cal	10.7	210	291 c	269 bc
			***P* > F**	
Soil Ca, initial		0.65	< 0.01	< 0.01
Treatment		0.11	< 0.01	< 0.01
Sampling Time‡		< 0.01	0.67	0.04
Treatment × Sampling Time		0.02	0.28	0.79

† Within columns, means followed by the same letter are not significantly different at the 0.05 probability level.

‡ 70 and 140 days after planting (DAP)

Table 3.7. Calcium source and rate effects on seed Ca content in runner peanut (cv. Georgia-06G). Field trials were conducted in Headland, AL, during the 2015, 2016, and 2017 growing seasons.

		Seed Ca			
Product	**Rate**	**2015**	**2016**	**2017**	**Mean**
	kg ha^{-1}	mg kg^{-1}			
Control	0	463.9	340.1	372.9	392.3 b
Gypsum	560	-	411.5	390.5	-
Gypsum	1120	564.4	461.3	409.1	478.3 a
Lime	1120	476.2	512.9	476.9	488.7 a
Black Gypsum	1120	527.8	400.4	376.0	434.7 ab
AgriMend	1120	500.5	425.4	378.1	434.7 ab
Full Measure Cal	10.7	453.6	380.0	383.0	405.6 b
Standard error treatment means		16.0	12.7	9.7	21.7
		***P* > F**			
Treatment					< 0.01
Year					< 0.01
Year × Treatment					0.10

† Within columns, means followed by the same letter are not significantly different at the 0.05 probability level.

Table 3.8. Linear regression relating applied Ca rate† to seed Ca concentration by year at in runner peanut (cv. Georgia-06G).

Year	**Equation‡**	R^2	**Model P > F**
2015	Seed Ca = 0.11(Applied Ca) + 481	0.05	NS
2016	Seed Ca = 0.41(Applied Ca) + 361	0.58	< 0.01
2017	Seed Ca = 0.25(Applied Ca) + 363	0.36	< 0.01

† Table 3.1

‡ Leaf B in mg kg^{-1}; applied B in kg ha^{-1}.

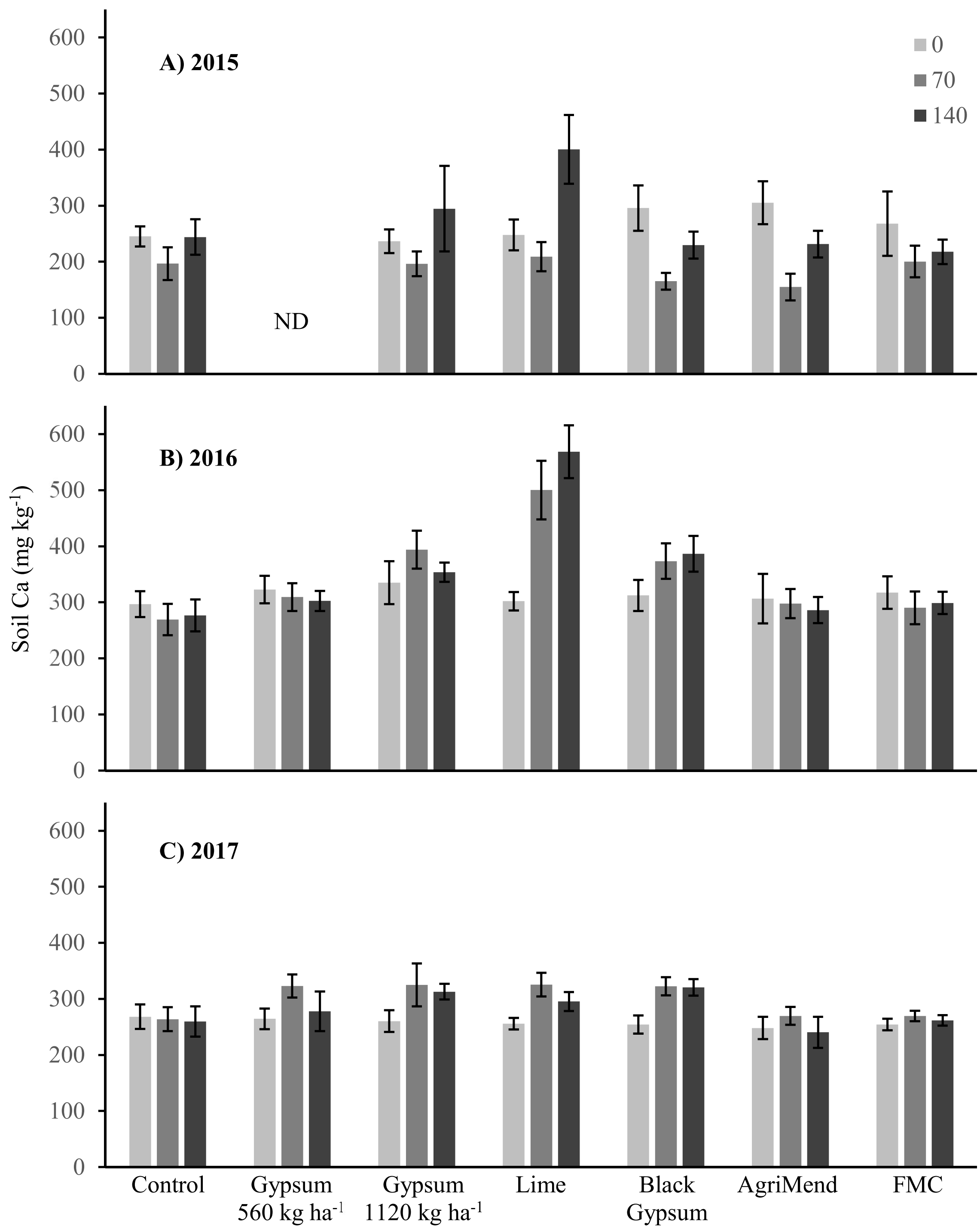

Figure 3.1. Calcium source and rate effects on soil Ca concentration (0-10 cm) at 0, 70, and 140 days after planting during the 2015, 2016, and 2017 peanut growing seasons in Headland, AL. *ND = Not determined

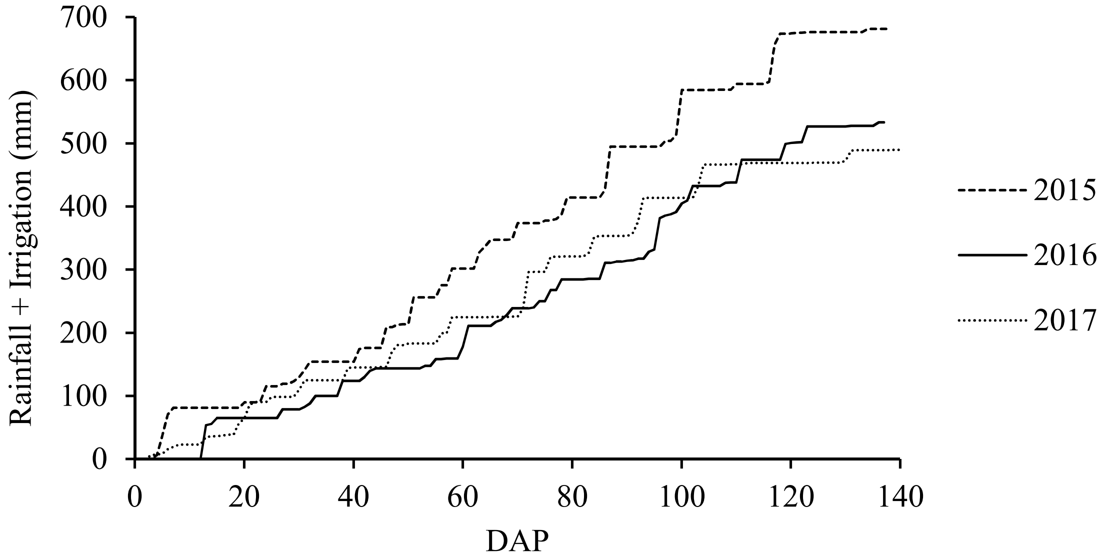

Figure 3.2. Cumulative rainfall and irrigation amounts (mm) at each day after planting (DAP) during the 2015, 2016, and 2017 peanut growing seasons in Headland, AL.

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