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Starter Nitrogen Source and Preflood Nitrogen Rate Effects on Rice Grown on Clay Soils

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Abstract

Seedling rice (*Oryza sativa* L.) grown on clayey-textured soils generally develops slowly as compared to loamy-textured soils. Our research examined the effects of starter-N source and preflood-N rates on canopy closure, total aboveground N uptake, and grain yield of rice grown on clayey-textured soils. Eleven field trials were established in Arkansas and Mississippi including five trials with a hybrid cultivar and six trials using a pure-line cultivar. Starter-N sources included no starter-N (NONE), ammonium sulfate (AMS), diammonium phosphate (DAP), and urea (UREA) applied at 24 kg N ha^{-1} at the rice 2-leaf stage and five preflood-N rates ranging from 0-224 kg N ha^{-1} at the 5-leaf stage. Canopy cover was measured weekly on trials conducted in Arkansas for 5 wk after starter-N application. Rice that received no starter-N produced less canopy coverage than rice receiving starter-N as AMS, DAP, and UREA and AMS, DAP, and UREA produced no differences in canopy coverage. Aboveground total-N uptake was affected only by the preflood-N rate for each site-year with maximum N uptake ranging from 139-196 kg N ha^{-1}. The preflood urea-N recovery efficiency for rice receiving no starter-N ranged from 54-78% among trials. For the Arkansas trials, rice that received the three starter-N sources produced 3.4-5.0% greater relative yield compared to rice receiving no starter. Relative yield for the Mississippi trials was not affected by starter-N source. Results show that starter-N can benefit early season growth and grain yield of rice grown on clayey soils but the benefits are not consistent.

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Chapter 1

Literature Review

Introduction

Rice (*Oryza sativa L.*) has been a major commodity in Arkansas since the early 1900's thanks to the pioneering efforts by entrepreneur W. H. Fuller (Delthloff, 2003). In 2017, Arkansas farmers harvested 450,000 ha of the 1 million ha of rice harvested in the United States (USDA-NASS, 2017). Arkansas accounts for more than 40% of the total US rice production and, the 2016 rice crop, was valued at almost $1 billion [USDA-Economic Research Service (ERS), 2018a]. Rice is grown in more than 27 of the 75 counties in Arkansas with production primarily in the eastern one-half of the state.

In Arkansas, rice is typically grown on poorly drained soils having textures classified as silt loam (48%), clay loam (21%), and clay (24%) with each textural group presenting different management challenges to farmers (Hardke, 2018). Clayey and clay loam soils in Arkansas are generally fertile soils with poor internal drainage that make them well suited for flood-irrigated rice production. The high clay content of these soils often presents growers with crop management challenges for seedbed preparation, timely stand establishment, and, in general, clay soils require greater fertilizer-N rates to produce high-yielding crops as compared to loamy-textured soils.

Early-season growth of rice seedlings in clayey soils is reported to be slow resulting in smaller seedlings at the five-leaf stage than rice grown on loamy soils. Increasing the seedling vigor and early-season seedling growth of rice on clayey soils is of interest to growers. Larger, more vigorous rice seedlings would possibly allow growers to apply preflood urea and the permanent flood earlier and potentially reduce the duration required for weed control, reduce or prevent algal blooms from covering seedling rice after flooding, increase tillering in thin stands, and perhaps hasten maturity allowing for a more timely harvest. This literature review will examine how starter or early-season fertilizer N aids crop growth and yield in various crop production systems and how this information might be used to aid the management of rice grown in the dry-seeded, delayed-flood production system used in Arkansas and other mid-South USA rice-growing states.

Overview of Rice Nitrogen Management on Clay Soils in Arkansas

Fertilizer is a costly input for rice production. The USDA-ERS (2018b) estimated the total operating cost for Arkansas rice production was $1,178.64 ha^{-1} while fertilizer cost inputs were $242.53 ha^{-1} or 21% of the total production cost. An effective and precise N management plan allows producers to use the minimum N rate to produce maximum yield potential, minimize N loss and optimize crop profitability. Historically, the recommended N rates for rice have been based on cultivar, soil texture, and previous crop. Research in Arkansas indicates the N requirement for producing maximal yield differs among cultivars and ranges from 100 to 135 kg total N ha^{-1} on silt loam and 135 to 200 kg total N ha^{-1} on clayey soils (Norman, Wilson, Slaton, Moldenhauer, & Cox, 1999; Norman et al., 2005; Norman et al., 2006). Recommendations suggest rice grown on clayey soils requires, on average, 34 kg N ha^{-1} more fertilizer N than rice grown on silt loams (Norman, Slaton, & Roberts, 2013). The greater N rate needed for rice grown on clayey soils is thought to be caused by ammonium (NH_4^+) fixation and slow diffusion of NH_4-N due to the small pore size present in clayey soils (Norman, Wilson, & Slaton, 2003). Ammonium fixation occurs when NH_4^+ ions become trapped by 2:1 clay minerals (Beauchamp & Drury, 1991). The entrapped NH_4-N is unavailable for immediate plant uptake. Diffusion is the primary mechanism by which NH_4-N moves in the soil towards plant roots and can be very slow in clayey soils (Tisdale, Nelson, Beaton, & Havlin, 1993). Trostle, Tarpley, Turner, and Dou (2011) found diffusion coefficients (D_e) and NH_4^+ diffusion distance per day ranged from

4.6×10^{-5} cm^2 d^{-1} and 1.5 cm d^{-1} for a Katy sandy loam (fine-loamy, siliceous, active, hyperthermic Typic Paleudalfs) to 2.9×10^{-7} cm^2 d^{-1} and 0.11 cm d^{-1} for a League clay (fine, smectitic, hyperthermic Oxyaquic Hapluderts), respectively. The results from Trostle et al. (2011) demonstrate that as clay content increases the NH_4^+ movement decreases.

The Nitrogen Soil Test for Rice (N-STaR) was developed in Arkansas to provide field-specific N rates for mid-South USA rice production (Roberts et al., 2012) and serves as a more precise alternative to the standard recommendation (Norman et al., 2013). The N-STaR recommendations require ten composite soil samples field^{-1} collected from the 0-to 45-cm depth for loamy-textured soils or the 0-to 30-cm depth for clayey soils (Fulford et al., 2013; Norman et al., 2013; Fulford, 2014). The soil samples are analyzed for alkaline hydrolyzable-N, which quantifies amino sugar-N, amino acid-N, and NH_4-N, to determine N that is available or will become available to rice during the growing season (Roberts et al., 2009). The proper soil sample depth is critical to receiving the correct recommendation as soil samples taken at shallower-than-recommended depths likely result in under-application of N and deeper-than-recommended sample depths result in applying excess fertilizer N (Roberts et al., 2012; Davidson et al., 2014).

Rice grown in the dry-seeded, delayed-flood production system has two main strategies for applying fertilizer N, the two-way split and optimum-preflood-N methods (Norman et al., 2013). The two-way split method involves applying a large quantity of fertilizer N immediately before rice is flooded at the five-leaf stage followed by a much smaller N rate applied at the midseason (pure-line varieties) or late boot (hybrid) stage. The optimum preflood strategy involves applying a single application of N at the five-leaf stage immediately before the permanent flood is established (no midseason or boot application),but is recommended only for fields with sufficient irrigation capacity to establish and maintain the flood. The preflood urea N is recommended to be applied to a dry soil surface so that the flood water will move the urea beneath the soil surface to minimize the NH_3 volatilization and nitrification-denitrification processes (Savin, Fuller, Tomlinson, Brye, & Norman, 2007; Del Moro, Sullivan, & Horneck, 2017). Applying the correct N rate and proper management following application (i.e., to prevent N loss) are essential for obtaining high fertilizer-N recovery efficiency (FNRE) and setting high grain yield potential in the delayed-flood production system (Reddy & Patrick, 1978; Norman et al., 2003)

In the delayed-flood production system, rice producers have increased the amount of hectarage of hybrid (*Oryza sativa* L.) cultivars in Arkansas. In the southern United States, hybrid rice was first commercialized by RiceTec Inc. (Alvin, TX) in 2000. Differences exist between hybrid and pure-line cultivar management including seeding rate and N management. Hybrid rice seeding rates vary from 108 to 151 seeds m^{-2} (Hutchens, 2017; Hardke, 2019) while pure-line seeding rates range from 269 to 485 seeds m^{-2} (Hardke, 2019) and depend on soil texture where the recommended seeding rate is increased the clay-textured soils. In Central China, Sun et al. (2015) investigated the yield responses of three hybrid varieties with diverse sowing rates along with investigating the physiological basis for grain yield in a dry, direct-seeded rice system with results suggesting sowing rates of hybrid varieties could be reduced to 60 seeds m^{-2} without influencing grain yields. Similarly, Gravois & Helms (1992) and Ottis & Talbert (2005) showed grain yields were not lowered when seeding rates were decreased in hybrids compared to pure-line varieties, supporting that rice compensates for voids in the canopy by producing more reproductive tillers at lower seeding densities.

Accurate N fertilizer rates are critical in producing optimal grain yields in rice and can vary by cultivar. Arkansas's recommendations of total N for hybrid cultivars range from 134 to 168 kg N ha^{-1} for rice produced on silt loam soils, but an increase of 34 kg N ha^{-1} is required when rice is grown on a clayey textured soil (Hardke et al., 2019). With the proper N fertilization rates, hybrid rice cultivars can produce 17 to 20% (Walker, Bond, & Harrell, 2008) higher grain yields than pure-line cultivars. Norman et al. (2005; 2006) showed higher hybrid grain yields were produced with each increase of N fertilizer and suggested hybrids use fertilizer N, soil N, or both more efficiently than pure-line cultivars (Norman, Roberts, Slaton, & Fulford, 2013). Hybrid rice plants generate a more extensive root system (Yang & Sun, 1989; Yang & Sun, 1992) that could allow for more efficient uptake of fertilizer and soil nutrients and have greater aerobic respiration and energy metabolism (Yang & Sun, 1989) compared to pure-line cultivars.

Nitrogen Uptake by Rice

The 4R Nutrient Stewardship program is encouraged by the world's fertilizer institutes as the core strategy of maximizing N use efficiency and reducing N losses (The Fertilizer Institute, 2018). The 4R concept relates to applying the right source of nutrients at the right rate, right time, and right place and embraces economic, social, and environmental stewardship considerations that influence the perception of policies governing agricultural nutrient management (Arnall & Phillips, 2015). The right source is determined by specific crop and soil properties allowing for balanced fertilization to increase nutrient use efficiency. The right rate, time, and place account for crop need to synchronize availability with demand along with placement and application method to allow efficient fertilizer usage (Dutta, Majumdar, Satyanarayana, & Singh, 2015).

Nitrogen fertilizer is applied to the greatest percentage of rice acreage and the highest rates of all fertilizers because nearly all soils require fertilizer N to achieve maximal yield potential. The most recent estimates on rice fertilization indicate that 96% of Arkansas rice receives fertilizer N at an average rate of 190 kg N ha^{-1} (USDA-NASS, 2013). Rice takes up both soil and fertilizer N for vegetative and reproductive growth. Guindo, Wells, Wilson, and Norman (1992) reported increases in total N accumulation by rice between the five-leaf stage and the onset of reproductive growth from preflood fertilizer N, but native soil N accounted for most of the N taken up during reproductive growth. Maximum rice grain yields are usually achieved by rice that accumulates 150 to 200 kg N ha^{-1} (Guindo, Wells, & Norman, 1994a; Bufogle, Bollich, Kovar, Macchivelli, & Lindau, 1997; Wilson, Bollich, & Norman, 1998).

The FNRE of flood-irrigated rice can be among the most efficient or inefficient crop production systems depending on management and timing. In the delayed-flood, dry-seeded rice system, the timeline from seeding to flooding (five-leaf stage) fluctuates from 25 to 35 d depending on planting dates and environmental circumstances (Norman, Wells, & Helms, 1988). This interval is recognized for having low FNRE (20-30% of applied N recovered) when compared to upland crop production systems due to rapid N loss mechanisms that include denitrification, ammonia volatilization, and immobilization in the soil (Broadbent & Nakashima, 1970; Craswell, De Datta, Weerarantne, & Vlek, 1985; Vlek & Byrnes, 1986). Norman, Wells, Helms, Wolf, and Beyrouty (1993) and Norman et al. (1994b) conducted research that determined the influence of N from fertilizers, soil, and crop residues along with different fertilizer-N application timings and soil moisture conditions. When fertilizer ^{15}N was applied preplant or preflush, the rice FNRE was low (27-40% and 53-57%, respectively) compared to preflood-applied urea (76-80%) and grain yields were reflective of the measured FNRE.

Application of fertilizer ^{15}N to wet soil conditions prior to preflood-N applications consistently produced low FNRE and high ammonia volatilization losses, which corresponded to decreased grain yields as well.

During the physiological development of rice, the majority of N needed is required during active tillering (five-leaf stage) and early reproduction stages (Wada, Shoji, & Mae, 1986; Wilson, Norman, & Wells, 1989). Extensive research has been conducted to evaluate FNRE with N application timings and plant development. Guindo, Norman, and Wells (1994b) conducted field experiments using ^{15}N-labeled urea applied as a single preflood and midseason N application to determine the growth stage for maximum FNRE under the dry-seeded, delayed-flood rice management system. The fertilizer N recovery of preflood-applied urea was reported to reach a maximum of 62% 21 d after application then declined 10% by maturity. The FNRE of the midseason-applied urea peaked at 75% 7 d after application and declined 18% by maturity. Studies with similar objectives have determined different application timings and N management strategies provide FNRE ranging from 49 to 93% of the preflood-applied fertilizer N when plant samples were taken at the R2-R3 stage (late boot) to 50% heading; (Cassman, Kropff, Gaunt, & Peng, 1993; Norman et al., 2003; Richmond, 2017).

Urea, an NH_4-forming fertilizer, is the most commonly used N fertilizer within Arkansas rice production. Urea is utilized due to its high N content (460 g N kg^{-1}) along with the low cost per unit of N (Bufogle, Bollich, Kovar, Lindau, & Macchiavelli, 1998; Griggs, Norman, Wilson, & Slaton, 2007). An undesirable trait of urea is its rapid transformation and potential for NH_3 loss, especially when it is applied to and left on the soil surface. When urea reacts with urease, the pH in the vicinity of the dissolved urea granule increases as the amine-N in urea ($-NH_2$) obtains one H^+ from the soil solution and another from water to form NH_4^+ (Ferguson, Kissel, Koelliker, & Basel, 1984). If the rate of urea is large, the soil is alkaline, the soil has low buffering capacity, or combinations of these issues the potential for NH_3 loss increases. Sunderlage and Cook (2018) reported that soil total cation exchange capacity was the single most important soil property influencing NH_3 volatilization from surface-applied urea. The potential loss of NH_3 is the reason for applying urea to dry soil and quickly flooding the soil to push the urea fertilizer beneath the soil surface where NH_3 is more likely to find an H^+ before escaping into the atmosphere. Urea application to dry soil followed by immediate flooding minimizes NH_3 volatilization losses and nitrification allowing for efficient plant uptake of fertilizer N (Griggs et al., 2007).

Urea is commonly treated with a urease inhibitor to delay hydrolysis of urea and reduce ammonia volatilization loss thereby increasing FNRE and N use efficiency (Abalos, Jeffery, Sanz-Cobena, Guardia, & Vallejo, 2014; Cantarella, Otto, Soares, & Brito Silva, 2018). Dempsey, Slaton, Norman, and Roberts (2017a) reported that urea treated with N-(n-butyl) thiophosphoric triamide (NBPT) urease inhibitor compared to non-treated urea produced 8.9 to 18.1% higher grain yields across a range of simulated rainfall amounts following urea application to dry soil. Dempsey, Slaton, Roberts, and Norman (2017b) reported that urea treated with the nitrapyrin nitrification inhibitor produced similar yield as untreated urea but lower yield than NBPT-treated urea suggesting the nitrification inhibitor had little or no benefit for rice N management. In the dry-seeded, delayed-flooded rice system, fertilization with NBPT-treated urea resulted in less NH_3 volatilization on silt loam and clayey soils when the flood was established 2 to 7 d after urea application (Dillon et al., 2012). Sunderlage et al. (2018) reported NBPT-treated urea reduced NH_3 volatilization from 6.3 to 24.5% of the applied N ($P<0.0001$), averaged from 79 agricultural fields with various cropping systems, tillage practices, and soil textures throughout the United States.

Ammonium sulfate (AMS, 210 g N, and 240 g S kg^{-1}) is another popular N fertilizer used for rice production. Both AMS and urea can be equally effective preflood-N sources for delayed-flooded rice (Bufogle et al., 1998; Griggs et al., 2007). Ammonium sulfate possesses both positive and negative attributes. Ammonium sulfate contains NH_4-N rather than the NH_2-N in urea fertilizer making NH_3 volatilization losses less problematic than for urea (Sommer, Schjorring, & Denmead, 2004; Kissel, Cabrera, & Paramasivam, 2008). A meta-analysis performed on 171 research reports showed that ammonium-based fertilizers decreased NH_3 loss from 31 to 75% when compared to urea (Pan, Lam, Mosier, Luo, & Chen, 2016). The major disadvantage of AMS is the higher cost per unit of N (\$2.79 kg^{-1} AMS-N vs \$1.36 kg^{-1} urea-N) and the low N analysis makes it more expensive to apply via airplane than urea (Norman et al., 2009; USDA-ESR, 2014). Therefore, AMS is typically used as a starter-N source between emergence and flooding to stimulate seedling growth.

Diammonium phosphate (DAP, 180 g N and 206 g P kg^{-1}) is a common N-containing, preplant-P source used for upland grain crops like corn (*Zea mays* L.). However, DAP is less commonly used for rice because of the low FNRE associated with preplant-applied fertilizer N (Norman et al., 1988; Norman, Wells, & Moldenhauer, 1989). Triple superphosphate (206 g P kg^{-1}) has been the most common preplant P source for rice, but DAP is sometimes used as a postemergence P and N source for rice (Slaton, Wilson, Norman, Ntamatungiro, & Frizzell, 2002).

Starter Nitrogen for Crop Production

Research has been conducted on corn, cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* (L.) Merr.), and rice to investigate whether starter-N provides growth, management, and yield benefits. For this literature review, starter fertilizer will be defined as a small amount of an N-including fertilizer that is usually applied at planting or post-emergence during an early crop growth stage. This definition is different from that provided by Hergert, Wortmann, Ferguson, Shapiro, and Shaver (2012) who summarized starter fertilizer as the placement of a small amount of nutrients close to where the seed is placed at planting. A different definition is needed because the primary focus of our research objectives concerns flood-irrigated rice, which is planted and managed differently than most other crops.

The literature provides multiple examples of research showing that starter-N, applied at planting, can sometimes increase corn biomass, N uptake, and grain yield but the efficacy of starter-N is dependent on many factors. In Illinois, researchers determined that starter fertilizers involving different combinations of N, P, and/or K increased corn grain yields consistently for later plantings and when adverse growing conditions were encountered (Ritchie et al., 1996). Corn hybrids in a no-till, dryland environment showed a positive response to starter-N (34 kg N and 15 kg P ha^{-1}) towards early season growth and nutrient uptake, but grain yields didn’t consistently and significantly increase for all hybrids (Gordon, Fjell, & Whitney, 1997). Scharf (1999) conducted six on-farm experiments with no-till corn where starter-N treatments consisted of no starter, low N/high P_2O_5, medium N/P_2O_5, and N only. Corn receiving the starter treatments, when averaged across the six experiments, produced statistically higher yields (807-875 kg ha^{-1}) relative to corn receiving no starter. Niehues, Lamond, Godsey, and Olsen (2004) observed that starter-N, regardless of placement, increased corn early season dry matter (3-155 kg ha^{-1}) and grain yield (0.68-1.59 Mg ha^{-1}). The literature suggests that starter-N applied to corn may increase early-season biomass and yield but the increases are not consistent. Lofton, Arnall, Sharma, and Nisly (2019) concluded that starter fertilizer application resulted in a yield increase at only one of five trials with grain sorghum (*Sorghum bicolor* (L.) Moench) in Oklahoma, with the positive response occurring on soil with low soil-test P.

Cotton research has investigated the interactions of starter fertilizer applied at planting involving different nutrient combinations (N only, N and S, N and P, and N and Ca) alongside planting dates (Guthrie, 1991), tillage systems (Touchton, Rickerl, Burmester, & Reeves, 1986), and placement (Hodges & Baker, 1990; Stewart & Edmisten, 1998). Among these trials, starter fertilizer showed inconsistent cotton yield benefits among most site-years. Other factors, like the weather, may affect how a crop responds to starter fertilizer resulting in sporadic benefits. Bednarz, Harris, and Shurley (2000) showed that starter-N improved cotton lint yields only when cool, wet soil conditions occurred after planting compared to the warmer soil environment. The published research suggests that starter-N may increase cotton lint yields, but the yield increases are not consistent unless unfavorable weather conditions occur early in the season.

Soybeans can produce N from symbiotic N_2 fixation, but research has examined the potential for benefits from starter-N. In the Northern Great Plains, trials were conducted to assess whether starter-N influenced soybean yield and quality. Osborne and Riedell (2006) showed that soybean yield was increased by 50 to 100 kg ha^{-1} by starter-N in South Dakota and suggested that the response might be related to the cool temperatures common to the Northern Great Plains. Starling, Wood, and Weaver (1998) studied the effects of starter-N on the growth habits of late-planted soybeans and concluded that starter-N increased plant-N concentration (R1 stage), dry matter yield (R1 stage), and grain yield by an average of 0.15 Mg ha^{-1}.

A limited amount of research has been conducted on starter-N in direct-seeded, delayed-flooded rice production. Golden, Lawrence, Bond, Edwards, and Walker (2017) concluded that 24 kg N ha^{-1} applied at the rice two-leaf stage was beneficial for overcoming early-season clomazone injury by increased plant height and grain yields. A significant (P=0.0094) and positive early-season response from starter-N increased plant height 3 wk after emergence and grain yields were increased by 150 to 860 kg ha^{-1} when clomazone rates of 0, 420, and 672 g ai ha^{-1} were applied. Walker et al. (2008) reported that 22 kg N ha^{-1} of starter-N applied to a range of seeding density rates of 'Cheniere' and 'Wells' rice on clay soils increased rice yields by 200 kg ha^{-1} compared to rice that received no starter-N. Satterfield, Kaur, Golden, Orlowski, and Walker (2018) examined the effect of starter-N, applied as ammonium sulfate, on the growth, N uptake, and grain yield response of rice grown on clayey soils applied at the two-leaf stage. Starter-N did not increase rice plant height or grain yield but did increase total dry matter and total N uptake in one of two years. The aforementioned research shows that postemergence-applied starter-N may have nominal and significant, albeit inconsistent, benefits on rice yield. The literature lacks information on whether different N sources might influence rice growth, N uptake, and yield response to starter-N.

Summary

Starter fertilizer can be defined as a small amount of fertilizer placed near the seed at planting so that nutrients are positionally available for the seedling. For traditional row crops, the literature suggests that the yield of corn, cotton, grain sorghum, and soybean respond inconsistently to starter fertilizer. Positive responses to starter fertilizer are most frequently associated with selected soil properties (low soil-test P), late planting date, and adverse weather conditions that limit seedling growth. For rice, the literature suggests that starter-N applied at planting or during early season plant growth, may increase rice grain yield but the response is not consistent in the published literature. Rice grown on clayey soils tends to have slow growth and seedling vigor compared to rice produced on coarser-textured soil (silt loam). Broadcast application of starter-N after seedling emergence could promote increased seedling vigor, which in return could provide benefits in management (earlier flood times, weed suppression) and production (N uptake, grain yield). Research has shown starter-N applied to row crops can increase biomass and grain yield, but the benefits are somewhat inconsistent. We could find no published information regarding hybrid rice response to starter-N.

The objectives of the proposed research are to evaluate the effect of different starter-N fertilizer sources applied at an early growth stage (2-3 leaf) on early-season growth, cumulative N uptake, and grain yield of two rice cultivars, one pure-line, and one hybrid, across a range of urea-N rates, applied preflood. Based on the cited research, we hypothesized that starter-N would i) enhance early-season crop growth and vigor, ii) increase N uptake and yield when less-than-optimal preflood-N rates were applied and iii) do not affect grain yield when the preflood-N rate was sufficient to maximize yield. We also expected that hybrid rice would benefit more from starter-N than the pure-line rice cultivar because hybrid rice is seeded at a much lower density than pure-line rice.

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Chapter 2

Effect of Starter Nitrogen Source and Preflood Nitrogen Rate on Canopy Cover, Aboveground N Content, and Grain Yield

Abstract

Seedling rice (*Oryza sativa* L.) grown on clayey-textured soils generally develops slowly as compared to loamy-textured soils. Our research examined the effects of starter-N source and preflood-N rates on canopy closure, total aboveground N uptake, and grain yield of rice grown on clayey-textured soils. Eleven field trials were established in Arkansas and Mississippi including five trials with a hybrid cultivar and six trials using a pure-line cultivar. Starter-N sources included no starter-N (NONE), ammonium sulfate (AMS), diammonium phosphate (DAP), and urea (UREA) applied at 24 kg N ha^{-1} at the rice 2-leaf stage and five preflood-N rates ranging from 0-224 kg N ha^{-1} at the 5-leaf stage. Canopy cover was measured weekly on trials conducted in Arkansas for 5 wk after starter-N application. Rice that received no starter-N produced less canopy coverage than rice receiving starter-N as AMS, DAP, and UREA and AMS, DAP, and UREA produced no differences in canopy coverage. Aboveground total-N uptake was affected only by the preflood-N rate for each site-year with maximum N uptake ranging from 139-196 kg N ha^{-1}. The preflood urea-N recovery efficiency for rice receiving no starter-N ranged from 54-78% among trials. For the Arkansas trials, rice that received the three starter-N sources produced 3.4-5.0% greater relative yield compared to rice receiving no starter. Relative yield for the Mississippi trials was not affected by starter-N source. Results show that starter-N can benefit early season growth and grain yield of rice grown on clayey soils but the benefits are not consistent.

Introduction

Starter fertilizer is generally defined as small quantities of fertilizer applied near the seed at planting and generally involves production systems of crops grown in wide rows like corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and soybean [*Glycine max* (L.) Merr.]. The effects of starter fertilizer nutrient sources (Mallarino, Bergman, & Kaiser, 2011; Scharf, 1999) and placement (Guthrie, 1991; Randall and Hoeft, 1988) and their interaction with planting date (Guthrie, 1991; Kaiser, Coulter, & Vetch, 2016; Mascagni & Boquet, 1996), production system (Niehaus, Lamond, Godsey, & Olsen, 2004; Vetsch & Randall, 2002), with and without broadcast fertilization (Kaiser, Mallarino, & Bermudaz, 2005; Kim. Kaiser, & Lamb, 2013), and soil properties (Bundry & Andraski, 1999, Kaiser & Rubin, 2013; Roth, Beegle, Heinbaugh, & Antle, 2006) have received substantial research attention. The literature includes a considerable amount of information about the benefits or lack of benefits of starter fertilizer for crops grown in wide rows.

The available literature describing the response to starter fertilization by crops grown in narrow-row production systems (e.g., drill seeded) like wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) is scarce. Relatively low rates of N-containing fertilizers applied to crops at or shortly after planting is often referred to as starter fertilizer (Forrestal, Meisinger, & Kratochvil, 2014; Hankinson, Lindsey, & Culman, 2016; Starling, Wood, & Weaver, 1998; Walker, Bond, Ottis, & Harrell, 2008a) and is intended to stimulate early-season crop growth. For this paper, starter fertilizer will refer to broadcast fertilizer that would not normally be applied to supply nutrients recommended by soil tests or the crop's standard fertilizer-N rate recommendation.

The benefits of starter fertilizer are often realized when crops are planted in cool, moist conditions common to early planting dates (Ketcheson, 1968; Cromely et al., 2006) where increased nutrient availability from starter fertilizer facilitates more rapid crop development, increased crop biomass, nutrient uptake and tissue nutrient concentrations (Kaiser & Rubin, 2013; Kaiser et al., 2005; Mengel, Hawkins & Walker, 1988). The early season growth benefits from starter fertilizer are partially attributed to the increased root growth where starter fertilizers are placed (Qin, Stamp, & Richner, 2005). A meta-analysis by Quinn, Lee, & Poffenbarger (2020) summarized that corn yield increases to starter fertilizer were most frequent on soils having below optimal soil-test P and K, where corn stand density was low, and in fields with high yield potential. On average, the meta-analysis showed that subsurface starter fertilizer increased corn yield by an average of 5.2%. Pettigrew and Molin (2013) reported that starter fertilizer reduced early planted cotton stands by 20% but resulted in a 4% yield increase in two of three years.

Research on the benefits of starter-N on rice is limited. Farmers report that a small amount of starter-N stimulates early-season seedling growth and allows the rice seedlings to reach a size large enough to withstand flooding sooner than when no starter-N is applied. Satterfield, Kaur, Golden, Orlowski, and Walker (2018) showed no effect of starter-N on V5 (5-leaves with collars; Counce, Keisling and Mitchell, 2000) stage seedling height, which averaged 17.0 to 21.6 cm for the two years of the field trial. However, Walker, Norman, Ottis, and Bond (2008c) reported that V2-stage (2-leaves with collars) applied starter-N increased seedling height by 2.0 to 3.3 cm by V5 stage compared to rice receiving no starter-N (20.5 cm tall at V5). Although two of three starter-N sources significantly increased grain yield by about 2.5% compared to rice receiving no starter-N (8847 kg ha^{-1}), grain yield was not affected by starter-N interaction with three different preflood-N rates applied at V5 (5-leaf). Walker et al. (2008b) showed that starter-N (AMS and DAP) applied to V2 stage rice grown on a clayey soil increased rice plant height, total-N uptake, total dry matter, and grain yield when compared to rice receiving no starter-N. Starter-N had no effect on the grain yield of rice grown on silt loam soils, was consistent for the two pure-line cultivars tested, and, regardless of soil texture, did not interact with seeding rate to influence rice yield. Satterfield et al. (2018) reported no effect of starter-N applied to V2 stage rice grown on clay soils on grain yield. Satterfield et al. (2018) reported that the rice recovery of the applied starter-N ranged from 0.5 to 3.0% at the V5 stage, 4.6 to 10.1% at R1 stage (panicle differentiation), and 8.3 to 16.4% at R3 stage (heading).

The few published experiments investigating the effects of early-season starter-N application on rice growth and yield are similar to starter fertilizer work done with corn and cotton in that both suggest starter fertilizer is sometimes beneficial to plant growth and yield. Additional research is needed with rice to help delineate the conditions where starter-N is beneficial. Our research objectives were to examine whether different starter-N sources broadcast to seedling rice would influence early-season growth and interact with preflood-N rate to influence aboveground N content and grain yield of hybrid and pure-line rice cultivars grown on clayey-textured soils in a direct-seeded, delayed-flood rice production system. Based on the aforementioned starter fertilizer research we hypothesized that starter-N applied to rice would nominally increase early-season vegetative growth, aboveground N content, and grain yield.

Material and Methods

Site Description

Eleven individual field trials were established in Arkansas and Mississippi to evaluate the effect of starter-N source and preflood-N rate on rice growth and yield including five trials with a hybrid (H) cultivar and six trials using a pure-line (P) cultivar. The trials will be identified by the site, year, and cultivar designation (H or P). Studies were established in soil mapped as a

Sharkey and Desha clay (very-fine, smectitic, thermic Chromic Epiaquerts and Vertic Hapludolls) at the Rohwer Research Station (RRS) in Rohwer, AR during 2017 (RRS-17P, RRS-17H), 2018 (RRS-18P, RRS-18H), and 2019 (RRS-19P, RRS-19H) and a Commerce silty clay (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) at the Delta Research and Extension Center (DREC) in Stoneville, MS during 2017 (DREC-17P, DREC-17H), 2018 (DREC-18P), and 2019 (DREC-19P, DREC-19H). Before each trial was established, alkaline hydrolyzable-N was determined from composite soil samples collected from the 0-to 45-cm soil depth at the DREC and the 0-to 30-cm soil depth at the RRS as described by Roberts et al. (2011). A composite soil sample from the 0- to 10-cm soil depth was collected from each site prior to the establishment of each trial, oven-dried to 65°C, crushed to pass through a 2-mm diameter sieve, and analyzed for soil pH in a 1:2 soil:water mixture (Sikora & Kissel, 2014), soil organic matter (SOM) (Schulte & Hopkins, 1996), and Mehlich-3 extractable nutrients by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Arcos-160 SOP, Spectro, NJ; Zhang, Hardy, Mylavarapu, & Wang, 2014). Soybean was the crop previously grown at all site-years except DREC-18H, which followed rice in the rotation. Selected soil property means for each site are listed in Table 2.1. Phosphorus, K, and other nutrients were not required or applied based on the University of Arkansas (Hardke, 2013) and Mississippi State University (Miller & Street, 2008) soil-test recommendations for rice.

Rice Cultivars

Pure-line and hybrid rice cultivars were included in these trials because they require vastly different seeding rates that could influence the response to starter-N. Rice was drill-seeded into conventionally tilled seedbeds using the seeding rates and dates listed in Table 2.2. At the RRS, each rice plot contained nine 4.9-m long rows spaced 0.15-m apart with a 1.2-m wide plant-free alley separating plots. At the DREC, plots contained nine, 4.6-m long rows spaced 0.19-m apart with a 1.5-m plant-free alley separating adjacent plots. Crop management for pest control, flood management, and fertilization (except for N) followed recommendations for the direct-seeded, delayed-flood rice production system as recommended for Arkansas (Hardke, 2013) and Mississippi (Miller & Street, 2008).

Treatments

Each trial was a randomized complete block design with a 4 (N source) x 5 (preflood-N rate) factorial treatment structure with four blocks. Nitrogen sources were no starter-N (NONE), ammonium sulfate (AMS), diammonium phosphate (DAP), and urea (UREA) treated with N-(n-butyl) thiophosphoric triamide (NBPT) with each source applied at 24 kg N ha^{-1} near the 2-leaf stage and a flush of irrigation water was applied within 1 d to incorporate starter-N sources. At the 5-leaf stage, five preflood-N rates including 0, 56, 112, 168, 224 kg N ha^{-1} were applied to dry soil and a flood was established within 2 d. The fertilizer N was applied to the soil surface on the dates listed in Table 2.2. The UREA applied as a starter and the preflood urea was treated with an urease inhibitor NBPT (Agrotain Advanced, 299 g NBPT kg^{-1}, Koch Fertilizer, L.L.C., Wichita, KS) at a rate of 1.05 g NBPT kg^{-1} urea.

At RRS, weeds were controlled using 0.75 kg ha^{-1} quinclorac (3, 7-dichloroquinoline-8-carboxylic acid) and 0.79 kg ha^{-1} clomazone [2-(2-chlorobenzyl)-4, 4-dimethylisoxazolidin-3-one] in 2017; 0.75 kg ha^{-1} quinclorac, 0.79 kg ha^{-1} clomazone, and 0.56 kg ha^{-1} glyphosate (N-(phosphonomethyl glycine) in 2018; 0.75 kg ha^{-1} quinclorac and 0.63 kg ha^{-1} clomazone in 2019 were applied to soil surface after planting. After the 5-leaf treatments were applied, 0.07 kg ha^{-1} of halosulfuron-methyl [methyl 3-chloro-5-(4,6-dimethoxypyrimidin-2-ylcarbamoylsulfamoyl], 3.3 kg ha^{-1} propanil (3', 4'-Dichloropropionanilide, thiobencarb 4-chlorophenyl-methyl, diethylcarbamothiate) plus 3.3 kg ha^{-1} thiobencarb (S-[(4-chlorophenyl)methyl] diethylcarbamothiate) and 0.07 kg ha^{-}bensulfuron methyl {methyl 2-[[[[[(4,6-dimethoxypyrimidin-2-yl) amino]-carbonyl] amino] sulfonyl]methyl]benzoate} in 2017, 0.07 kg ha^{-1} halosulfuron-methyl, 3.3 kg ha^{-1} propanil plus 3.3 kg ha^{-1} thiobencarb and 0.14 kg ha^{-1} bensulfuron methyl in 2018, and 0.07 kg ha^{-1} halosulfuron-methyl, 3.3 kg ha^{-1} propanil plus 3.3 kg ha^{-1} thiobencarb, 0.07 kg ha^{-1} bensulfuron methyl, and 0.12 kg ha^{-1} fenoxaprop-p-ethyl {(+)-ethyl 2-[4-[(6-chloro-2-benzoxazolyl) oxy] phenoxy]propanoate} in 2019 was applied before flooding. Weeds were controlled at DREC using 0.42 kg ha^{-1} clomazone, 2.2 kg ha^{-1} glyphosate, 0.1 kg ha^{-1} saflufenacil {N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide}, and 0.04 kg ha^{-1} halosulfuron-methyl were applied to the soil surface on the day of planting.

Measurements

The date of rice emergence (Table 2.2) was entered into a degree day program that uses a base temperature of 10°C for predicting rice development and management (DD50 in °F; Hardke, 2018). The rice emergence date is the day rice begins accumulating growing degree units (GDU). The DD10 program calculates GDU accumulation as the daily average temperature (°C) [(maximum + minimum)/2] less the base temperature of 10°C. The program has maximum and minimum temperature thresholds that limit the maximum number of daily GDU that can be accumulated to 17.8. Daily maximum temperatures that exceed 34.4°C are entered as 34.4°C. Daily minimum temperatures less than 21.1°C are entered as 21.1°C.

The percent of the ground area covered by the rice canopy was measured with the Canopeo mobile device application (http://www.canopeoapp.com). Canopeo was developed for analyzing fractional green canopy cover and is based on color ratios of red to green, blue to green, and excess green index (Patrignani & Ochsner, 2015). An iPad Air 2 (Apple, Cupertino, CA; Software version 12.3.1) was mounted on a tripod to allow pictures to be taken at a uniform height of 0.9 m above the soil surface as described by Coffin and Slaton (2020). Canopy coverage measurements were taken at RRS-18H, RRS-18P, RRS-19H, and RRS-19P beginning 1 wk after starter-N application (WASN) and repeated weekly for 5 wk. The 2 WASN measurement was taken immediately before preflood-N was applied. The final canopy coverage measurement at 5 WASN was taken 3 wk after preflood urea application and flooding.

A 1.8-m section from the second drill row inside each plot was flagged for plant sample collection. Whole plant samples were collected by cutting the stems 3 cm above the soil surface within each flagged area when plants reached the R3 stage (Counce et al., 2000) at DREC-17H, RRS-18P, DREC-18P, RRS-19P, and DREC-19P. Early heading represents the approximate time of maximal N uptake by rice grown in a direct-seeded, delayed-flood system (Guindo, Norman, & Wells, 1994). Plant samples were placed in paper bags, dried at 60°C until a constant weight was achieved, and weighed for aboveground dry matter accumulation. A representative subsample of dried plant tissue was ground to pass through a 1-mm sieve and a weighed subsample was placed into a capsule for total-N concentration determination by combustion (elementar rapid N III, Elementar Analysensysteme GmbH, Hanau, Germany; Campbell, 1992). Aboveground N content (kg N ha^{-1}) was computed as the product of aboveground dry matter and N concentration.

Grain yield was determined by harvesting 4.4-m^2 from the middle five rows at RRS-17H, RRS-17P, RRS-18H, and RRS-18P or the entire plot (6.7 to 7.7 m^2 from all remaining sites). Grain yields were adjusted to 120 g H_2O kg^{-1} for statistical analysis. The relative rice yield of each cultivar was calculated for each trial by first calculating the mean yields for each treatment.

The preflood-N rate receiving no-starter-N (NONE) that produced the greatest numerical yield was used as the denominator to calculate the relative yield of each plot. This calculation method resulted in one preflood-N rate receiving no-starter-N that produced 100% relative yield and allowed for relative yields >100% of other preflood-N and starter-N treatment combinations.

Statistical Analysis

Canopy coverage data from the RRS (RRS-18H, RRS-18P, RRS-19H, and RRS-19P) were regressed across the 5 WASN using block and year as random effects. The model included a repeated measure of time (WASN) and allowed coefficients to depend on the cultivar type (hybrid or pure-line), starter-N source, preflood-N rate, and their interactions. Due to lack of normality, the canopy data were analyzed with a beta distribution, and the degrees of freedom were approximated with the Kenward–Rogers method (Gbur et al., 2012). The residual subject-specific pseudo-likelihood (method=RSPL) estimation technique was used for all analyses. A model containing all fixed terms and their interactions was run and the most complex nonsignificant ANCOVA model term was removed sequentially until the simplest significant model was obtained. Regression coefficients remaining in the final model were considered significant when $P \leq 0.05$. The predicted differences as affected by cultivar type, starter-N source, and preflood-N rate were evaluated using LSMEANS statements with the differences interpreted as significant when $P \leq 0.05$. The studentized residuals distribution ($> \pm 2.5$) was examined to identify and remove potential outliers and Cook's D statistic was examined to identify and remove influential data.

Aboveground-N content for RRS-18P, RRS-19P, DREC-17H, DREC-18P, DREC-19P taken at early heading (R3) development stage was a randomized complete block design with a starter-N source (n=4) and preflood-N rate (n=5) factorial treatment structure replicated four times. Aboveground N content data from each trial were analyzed separately to determine the effect of starter-N source and preflood-N rates on aboveground N content. The ANOVA was performed with the GLIMMIX procedure of SAS v9.4 (SAS Institute, Cary, NC) and significant treatment differences among aboveground N content were compared using LSMEANS (α=0.05). The baseline preflood fertilizer-N apparent recovery efficiency (FNARE) was estimated by regressing the aboveground N content of rice receiving no starter-N (NONE, n=20) against the preflood urea-N rate using the GLIMMIX procedure. The FNARE of other treatments was not calculated since the uptake of fertilizer-N applied with the starter- and preflood-N treatments could not be differentiated based on total-N uptake.

Relative grain yield plot-level data were regressed against preflood-N rate using block nested within the trial as the random effect. Regression was performed by cultivar (hybrid or pure-line) using the site-year as an intercept term. The regression model included the linear and quadratic functions of preflood-N rate and allowed regression coefficients to depend on starter-N source, site-year, and their interaction. All regression analysis was performed using the GLIMMIX procedure of SAS v9.4 (SAS Institute, Cary, NC). Due to lack of normality, the yield data were analyzed with a gamma distribution, and degrees of freedom were approximated with the Kenward–Rogers method (Gbur et al., 2012). The default estimation technique (method=RSPL) was used for all analyses. A model containing all fixed terms and their interactions was run with regression model refinement, data manipulation, and comparison of predicted values were performed as described above.

Results and Discussion

Canopy Cover

Canopy closure was measured only at the RRS and was affected by the cultivar type by starter-N source interaction, the week (repeated measure) by preflood-N rate interaction, and the three-way interaction involving week (repeated measure), cultivar type, and preflood-N rate (Table 2.3). Averaged across trials, preflood-N rates and WASN, the cultivar type by starter-N source interaction showed that, within each cultivar, rice receiving no starter N produced less canopy coverage than rice that received starter N as AMS, DAP, and UREA at the 2-leaf stage (Table 2.4). Within each cultivar type, there were no differences in rice canopy coverage when AMS, DAP, and UREA were the starter-N source. Despite the lower seeding rate, the hybrid rice tended to have numerically higher canopy cover than pure-line rice but the percent canopy coverage was not different between the two cultivar types when the same starter-N source was compared.

As would be expected, the main effects of time (WASN) and preflood-N rate both had a significant effect on canopy coverage with the general trends being that rice canopy coverage tended to increase across time as rice developed tillers and leaf area and tended to increase as preflood-N rate increased (Table 2.3). However, a significant interaction occurred among WASN, preflood-N rate, and cultivar type (Figure 2.1). At 1 WASN, regardless of cultivar type, rice that was to receive no preflood-N had the greatest percent canopy coverage compared to rice scheduled to receive preflood-N. The percent canopy coverage was generally similar between cultivar types and the other preflood-N rates, which was expected since the preflood-N was applied after the 2 WASN measurements were made. The reason for greater canopy coverage at 1 WASN for rice that would receive no preflood-N is unclear, but may be related to the model and data transformation The untransformed actual means for the each of the five sites showed at 1 WASN was applied, canopy cover percentages for rice receiving no preflood N was -0.2 to 1.3% different compared to other preflood-N rates. After the modeling process was completed, the predicted values from GLIMMIX showed percentage of canopy cover for no preflood N was 6.5 to 9.7% greater than other preflood-N rates. At 2 WASN, rice scheduled to receive 56 to 224 kg N ha^{-1} had similar canopy coverage that had increased from 1 WASN, and rice that would receive no preflood-N had the lowest numerical canopy cover that was statistically similar to the 1 WASN values. From 3 (1 week after PFN was applied) to 5 WASN (3 weeks after PFN was applied), the canopy cover of rice receiving each preflood-N rate increased weekly (Figure 2.2) and tended to be similar for the two cultivar types. The pure-line and hybrid rice that received no preflood-N had a maximum canopy coverage of about 40% by 5 WASN and at each week the percent canopy cover was always lower than rice that received preflood-N. For the rice that received 56 to 224 kg N ha^{-1} preflood the percent canopy cover at 3 WASN was generally similar among these preflood-N rates with hybrid rice tending to have greater values than pure-line rice within each rate. By 4 WASN and within each cultivar type, the percent canopy cover of rice receiving 56 kg N ha^{-1} was lower than the percent canopy cover of rice receiving 112 to 224 kg N ha^{-1}. At 4 and 5 WASN, the percent canopy coverage of rice receiving 112 to 224 kg N ha^{-1} preflood was similar within each cultivar type. By 5 WASN, both cultivar types and most preflood-N rates reached almost full canopy coverage (90%; Figure 2.3 and Figure 2.4).

Canopy coverage measurements made with Canopeo pictures are linearly related to the light interception of soybean (Shepard, Lindsey & Lindsey, 2018) and photosynthetically active radiation interception and exponentially related to leaf area index and biomass of Old World bluestem [*Bothriochloa bladhii* (Retz) Blake; Xiong, West, Brown, & Green, 2019]. The effects of the starter-N and the preflood-N rate on the canopy development of the two different cultivar types, hybrid or pure-line, are interesting since the cultivar types were established with vastly different seeding rates and have different growth habits. This is the first research we are aware of to report early-season percent canopy coverage of rice as affected by cultivar and N fertilization. Coffin and Slaton (2020) showed a similar progression of canopy coverage across time for pure-line rice with canopy coverage reaching 70 to 90% 2 to 3 wk after preflood fertilization. Walker et al. (2008c) reported a 2.0-3.3 cm plant height advantage from starter-N for five site-years of research in Arkansas, Missouri, and Mississippi. Satterfield et al. (2018) in Mississippi showed that starter-N did not increase rice seedling height but did increase early-season dry matter and total-N uptake in one of two years suggesting the field conditions as affected by weather events and management practices may influence the rice uptake efficiency of starter-N uptake and whether starter-N benefits are realized.

Research has shown that N accumulation generally parallels rice biomass production (Sims & Place, 1968) and N uptake (Moore, 1981). As plant development progresses across time, N uptake and biomass production both increase with total-N uptake usually peaking at the R3 stage (Norman et al., 2003).. In contrast to our results, Satterfield et al. (2018) reported a pure-line rice cultivar had 36-66% more biomass than a hybrid cultivar at the V5 stage, which they attributed the biomass differences between the two cultivar types to the greater seeding rate used to establish the pure-line cultivar (35 kg seed ha^{-1} vs 90 kg seed ha^{-1} for pure-line). Despite the different seedling densities, the hybrid cultivar seedlings tend to have wider leaves with a sprawling rather than upright growth habit. Hybrid rice displays heterosis that contributes to greater root mass and yield components such as biomass and tillering that are grander in comparison to pure-line cultivars (Dobermann & Fairhurst, 2000; Li & Yaun, 2000). This could give cause to our findings with hybrid rice numerically producing a greater canopy closure compared to the pure-line rice (Figure 2.3).

Aboveground Nitrogen Content

Rice aboveground N content was measured for two site years at the RRS and three site-years at DREC (Table 2.5). For each site-year, the aboveground N content was not significantly affected by starter-N source but preflood-N rate had a significant influence on N content (Table 2.6). The aboveground N content increased as the preflood-N rate increased to 168 or 224 kg N ha^{-1}, depending on the site. The statistical maximum aboveground N content averaged across starter-N sources, was 193 kg N ha^{-1} for RRS-18P, 150 kg N ha^{-1} for DREC-17H, and 196 kg N ha^{-1} for DREC-19P when 224 kg N ha^{-1} of preflood-N was applied and 173 kg N ha^{-1} for RRS-19P and 139 kg N ha^{-1} for DREC-18P when 168 kg N ha^{-1} of preflood-N was applied (Table 2.5). Griggs, Norman, Wilson, and Slaton (2007) and Dillon et al. (2012) reported comparable aboveground N uptake for a pure-line cultivar grown on clay and silt loam soils.

The linear slope coefficient from regressing the aboveground N content against preflood-N rate for rice receiving no starter-N showed fertilizer-N apparent recovery efficiency (FNARE) averaged 69% (±5.1 SE, intercept = 32 kg N ha^{-1}) for RRS-18P, 78% (±4.4 SE, intercept = 39 kg N ha^{-1}) for RRS-19P, 57% (±5.5 SE, intercept = 44 kg N ha^{-1}) for DREC-17H, 54% (±7.2 SE, intercept = 52 kg N ha^{-1}) for DREC-18P, and 71% (±7.2 SE, intercept = 27 kg N ha^{-1}) for DREC-19P. These values for FNARE are comparable to the FNARE values reported by Norman et al. (2003) for rice grown in the direct-seeded delay-flood rice production system common to the mid-South USA. It is interesting to note that the FNARE among the five site-years showed a strong trend to decline as the intercept value increased. Barbieri, Echeverría, Saínz Rozas, and Andrade (2008) showed a decline in recovery efficiency in available N as N rates increased in corn (*Zea mays* L.). Griggs, Norman, Wilson, and Slaton (2007) measured N uptake when urea was applied with the permanent flood established 1 and 14 d after application on a clay soil where plant samples were taken at 50% heading. Rice receiving 84, 168, and 252 kg preflood-N ha^{-1} along with permanent flood established 1 d after application resulted in 73%, 52%, and 42% FNARE which shows a decreasing trend as the preflood-N rate increases. The plant samples used to assess FNARE were collected 41-57 d after the preflood-N was applied (Table 2.2) for all site-years. The FNARE of urea applied to dry soil and followed by establishing a 10-cm deep flood within 2 d and maintaining the flood until maturity results in high FNARE (Norman, Wilson, & Slaton, 2003).

We did not attempt to calculate the FNARE of the starter-N using the difference method. However, Satterfield et al. (2018) measured starter-N uptake using ^{15}N applied at the 2-leaf stage and showed total uptake of the labeled N at the R3 stage ranged from 8.8 to 16.4% with significant differences between years and cultivar type. Furthermore, the FNARE ranged from 0.5-3.0% at the V5 stage and 4.6-10.1% at the R1 stage, which suggests that the majority of starter-N uptake by rice occurs after the R1 stage. The results from Satterfield et al. (2018) combined with the findings of Fitts et al. (2014) suggest that a portion of the starter-N recovered by rice is likely immobilized before flooding, but a large proportion of the starter-N is probably denitrified after flood establishment due to the rapid nitrification rate on clayey soils used for rice production. The results reported by Griggs et al. (2007) and Fitts et al. (2014) suggest that very little of the applied N would be lost via ammonia volatilization on clay soils due to the high cation exchange capacity and use of a urease inhibitor when urea was the starter-N source (Dillon et al., 2007; Fitts et al., 2014).

Rice Grain Yields

The grain yields of rice receiving no-fertilizer N ranged from 3536 to 4957 kg ha^{-1} for hybrid rice and 2081 to 4323 kg ha^{-1} for pure-line cultivars grown in trials conducted at the RRS (Table 2.7). The maximum grain yields ranged from 8043 to 14,214 kg ha^{-1} for hybrid rice and 8458 to 12,291 kg ha^{-1} for pure-line cultivars. At the DREC, the mean grain yields of rice receiving no-fertilizer N ranged from 5800 to 6525 kg ha^{-1} for hybrid rice and 3715 to 6038 kg ha^{-1} for pure-line cultivars. For rice receiving fertilizer N at DREC, the maximum grain yields ranged from 12,044 to 12,234 kg ha^{-1} for hybrid rice and 9189 to 10,785 kg ha^{-1} for pure-line cultivars. The maximum yields produced for both hybrid and pure-line rice in these trials were greater than the mean state yields in Arkansas (8429 kg ha^{-1}; USDA-NASS, 2018a) and Mississippi (8238 kg ha^{-1}; USDA-NASS, 2018b). Hybrid rice maximum yields were on average 17% and 23% greater than the maximum yields produced by pure-line cultivars at the RRS and DREC, respectively, which is consistent with the typical yield difference reported between hybrid and pure-line rice cultivars in the mid-South USA (Walker, Bond, Ottis, Gerard, & Harrell, 2008a). It is interesting to note that the average yield advantage of hybrid rice over the pure-line cultivars averaged 40% and 32% at the RRS and DREC, respectively, when no fertilizer N was applied. Hybrid rice reportedly takes up soil and fertilizer N more efficiently than pure-line rice because hybrid rice has a more extensive root system than pure-line cultivars (Yang & Sun, 1988, 1992; Norman et al., 2013). The difference between the minimum and maximum grain yield averages for each site-year in Table 2.7 shows mean grain yield increases to fertilizer-N of 7195 kg ha^{-1} at the RRS and 5610 kg ha^{-1} at the DREC suggesting the soil at each site-year was suitable for the trial's objectives evaluating the combinations of starter-N sources and preflood-N rates.

Relative Yield – RRS

The relative yield of rice grown at the RRS was a quadratic function of preflood-N rate with hybrid and pure-line rice sharing common linear and quadratic coefficients with intercepts differing among the cultivar type and starter-N source combinations (Tables 2.8 and 2.9). Regardless of cultivar and starter-N source, the preflood-N rate predicted to produce maximal grain yield was 195 kg N ha^{-1} (Figure 2.5). The differences in the predicted relative yields were consistent across the range of preflood-N rates since only the intercepts differed among the equations that describe the relationships (Table 2.9). Although the intercept values differed numerically among the four starter-N sources within each cultivar type, the four intercepts were not statistically different and followed the same numerical rank for each cultivar type. Rice fertilized with NONE starter had the lowest numerical intercept values and the predicted relative yields of rice receiving the AMS, DAP, and UREA starters were numerically higher. Between cultivar types, the intercept value of pure-line rice receiving NONE was significantly lower than hybrid rice regardless of starter-N source. The predicted maximum relative differences (195 kg N ha^{-1} preflood) for rice receiving the three starter-N sources were 3.4-4.6% higher for the pure-line rice and 3.7-5.0% higher for the hybrid rice than each cultivar type receiving NONE starter. The other difference was that the relative yield of hybrid rice receiving NONE starter-N produced similar relative yields as pure-line rice receiving the AMS, DAP, and UREA starters. Despite the non-significant relative yield differences among starter-N sources for each cultivar type, these results suggest that starter-N applied at the V2 development stage to hybrid and pure-line rice grown on clayey soils has slight increasing benefits on rice grain yield.

The six trials conducted on clay soils at the RRS had soil alkaline hydrolyzable-N concentrations in the 0-30 cm depth from 95-110 mg kg^{-1} (Table 2.1, average 102 mg kg^{-1}) with fertilizer-N rates of 199-224 kg N ha^{-1} predicted to produce 95% of maximum yield, which is relatively close to the N rate of 195 kg N ha^{-1} that maximized yield at the RRS, especially when the 24 kg N ha^{-1} applied as starter-N is added to the optimal preflood-N rate (Fulford, Roberts, Norman, Slaton, Greub & Davidson, 2019). At RRS, rice that received starter-N sources tended to show an increase in relative grain yield for both hybrid (3.7-5.0%) and pure-line (3.4-4.6%) cultivars. Walker (2008) reported that the application of 22 kg starter-N ha^{-1} to a pure-line cultivar increased their yields by 2.8% compared to rice receiving no starter-N which is comparable to our results. However, Golden (2017) showed rough rice yield increases from starter-N fertilizer application occurred in only 1 out of 3 years in Mississippi.

Relative Yield – DREC

Relative rice grain yield at the DREC was not affected by the starter-N source (Table 2.8). Relative yield was a quadratic function of preflood-N rate with the hybrid and pure-line cultivars having unique intercept, linear, and quadratic coefficients (Table 2.9 and Figure 2.6). The predicted relative yields were greater for hybrid rice than pure-line rice when 0 to 65 kg N ha^{-1} was applied preflood. The predicted relative yields for the two cultivar types were statistically similar for preflood-N rates >65 kg N ha^{-1} with the predicted maximum relative yields peaking at 100% with similar preflood-N rates of 198 kg N ha^{-1} for pure-line rice and 200 kg-ha^{-1} for hybrid rice. Based on the soil alkaline hydrolyzable-N concentrations (Table 2.1) in the 0-45 cm depth 190-225 kg N ha^{-1} preflood was recommended to maximize yield if the soils are considered clayey soils that fit the clay soil calibration curve (Fulford et al., 2019). The yield results and N rate predicted to maximize relative rice yield for the DREC trials fit the clay soil curve from Fulford et al. (2019) better than the silt loam curve proposed by Roberts et al. (2011).

The alkaline hydrolyzable-N concentration predictions encompass the preflood-N rates 198 and 200 kg N ha^{-1} predicted to maximize yields at the five DREC site years (Figure 2.6).

The inconsistent yield benefits from starter-N were not a surprise since Walker et al. (2008b) also reported inconsistent yield benefits to small N additions at the 2-leaf stage to rice grown in the direct-seeded, delayed-flood production system. However, they did show a yield of 205 kg grain ha^{-1} benefit from starter-N on clayey soil but not silt-loam soil, which is one reason our trials focused on clayey soils. Walker et al. (2008c) reported yield benefits from AMS (218 kg grain ha^{-1}) and DAP (177 kg grain ha^{-1}) but not urea applied at the V2 stage. Satterfield et al. (2018) showed no benefit to the grain yield of rice grown on clayey soils at two site years. Our research shows that at RRS, starter-N sources were significant and AMS, DAP, and UREA produced greater relative yields for both cultivars compared to applying no starter-N, however, relative yields were not affected by starter-N at DREC. The predicted preflood-N rate to produce the maximal grain yield regardless of starter-N, was closely related for both locations and cultivars, being 195 kg N ha^{-1} for RRS and 198-200 kg N ha^{-1} for DREC applied preflood.

Summary

Farmers claim the benefits of starter-N applied to rice grown on clayey soils are increased early-season vigor and larger seedlings at the time the permanent flood is established. These benefits might allow growers to flood fields a few days earlier than they normally would, which could reduce the time for weed emergence and potential herbicide costs and allow them to apply preflood urea fertilizer on dry soil and capture water from predicted rainfall events. While these possible management aspects were not tested our results at the RRS did show starter-N increased rice canopy coverage and grain yields tended to be 3.4-5.0% more for rice compared to where no starter was applied. Canopy closure for each cultivar type was not different when AMS, DAP, and UREA were the starter-N source. Hybrid rice tended to have numerically higher canopy cover compared to the pure-line rice even with hybrid's lower seeding rate but the percent canopy coverage was not different between the cultivar types when the same starter-N source was compared. The aboveground N content was not affected by starter-N source but was significantly affected by preflood-N rate.

The results of this study support the results of prior research assessing the benefits of starter N applied to seedling rice showing that the benefits of increased early-season vigor are measurable but the potential benefit to rice yield is small and not consistent across sites. The novel aspects of this research include the use of canopy coverage rather than height to measure seedling growth following starter-N application and the inclusion of hybrid rice established with low seedings rates. The research showed that while the yield and growth of hybrid and pure-line rice cultivars are different both cultivar types respond similarly to starter N.

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Tables

Table 2.1. Selected soil property means of eleven starter-N trials conducted on clayey soils.

Site-year[a]	Soil pH[b]	Mehlich-3 extractable nutrients[c]						AH-N[d]	SOM[e]	Sand	Silt	Clay	Soil Texture
		P	K	Ca	Mg	S	Zn						
		mg kg -1							g kg-1	%			
RRS-17P	8.0	34	206	4007	785	28	2.0	97	23.0	0.0	54.6	45.4	Silty clay
RRS-17H	8.0	31	239	4431	869	26	2.4	96	27.4	0.4	49.8	49.8	Silty clay
RRS-18P	7.0	45	262	3903	1008	25	1.4	110	25.0	0.4	38.1	61.5	Clay
RRS-18H	8.0	46	292	3999	1039	25	2.2	110	27.4	0.0	36.8	63.2	Clay
RRS-19P	8.0	34	254	4457	804	21	1.5	103	25.2	0.8	48.3	50.9	Silty clay
RRS-19H	8.0	41	254	4265	812	21	1.4	95	25.3	0.7	49.6	49.7	Silty clay
DREC-17P	8.1	35	284	3795	676	18	2.3	101	18.0	6.8	59.3	33.9	Silty clay loam
DREC-17H	8.0	32	288	3773	659	20	2.0	85	20.0	9.4	59.3	31.3	Silty clay loam
DREC-18P	8.1	59	261	4196	601	10	3.3	90	25.4	3.9	60.7	35.4	Silty clay loam
DREC-19P	8.0	48	327	4750	874	11	2.6	107	28.0	0.9	50.8	48.3	Silty clay
DREC-19H	8.0	45	314	4119	802	9	2.8	95	26.2	0.9	49.5	49.6	Silty clay

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid.

[b] Soil pH measured in a 1:2 soil:water mixture (Sikora & Kissel, 2014).

[c] Mehlich-3 soil-test determined by inductively coupled plasma atomic emission spectroscopy (Zhang et al., 2014).

[d] AH-N, alkaline hydrolyzable-N in the top 30 (RRS sites) or 45 cm (DREC sites) soil depth (Roberts et al., 2011).

[e] SOM, soil organic matter by loss on ignition (Schulte & Hopkins, 1996).

Table 2.2 Selected agronomically important dates including seeding rates, planting, emergence, fertilizer applications, permanent flood, and plant sampling with the corresponding cumulative growing degree units, at 11 site-years.

	Agronomic management and sample dates										
Site-year[a]	Planted	Emerged	Starter-N applied	Preflood N applied	Flooded	Week 1[b]	Week 2	Week 3	Week 4	Week 5	Plant Sample
	-------month/day------										
RRS-17H	5/10	5/19	5/31 (153)[c]	6/20 (441)	6/23 (484)	–[d]	–	–	–	–	–
RRS-17P	5/10	5/19	5/31 (153)	6/20 (441)	6/23 (484)	–	–	–	–	–	–
RRS-18H	4/20	5/07	5/14 (118)	5/30 (365)	6/01 (400)	5/24 (274)	5/31 (383)	6/07 (493)	6/14 (612)	6/21 (725)	–
RRS-18P	4/20	5/07	5/14 (118)	5/30 (365)	6/01 (400)	5/24 (274)	5/31 (383)	6/07 (493)	6/14 (612)	6/21 (725)	7/19 (1189)
RRS-19H	4/30	5/20	5/28 (144)	6/12 (363)	6/13 (375)	6/04 (254)	6/10 (341)	6/17 (430)	6/24 (541)	7/02 (662)	–
RRS-19P	4/30	5/20	5/28 (144)	6/12 (363)	6/13 (375)	6/04 (254)	6/10 (341)	6/17 (430)	6/24 (541)	7/02 (662)	7/31 (1119)
DREC-17H	5/10	5/17	5/23 (98)	6/09 (324)	6/12 (368)	–	–	–	–	–	7/26 (1089)
DREC-17P	5/08	5/17	5/23 (98)	6/21 (514)	6/22 (530)	–	–	–	–	–	–
DREC-18P	5/02	5/09	5/21 (212)	5/31 (372)	6/5 (453)	–	–	–	–	–	7/27 (1336)
DREC-19H	5/29	6/07	6/27 (321)	7/03 (419)	7/03 (419)	–	–	–	–	–	–
DREC-19P	5/29	6/07	6/27 (321)	7/03 (419)	7/03 (419)	–	–	–	–	–	8/13 (1108)

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[b] Canopeo, mobile device application used for measuring canopy cover (Patrignani & Ochsner, 2015)

[c] Cumulative growing degree units (DD10)

[d] Measurements not taken

Table 2.3. Analysis of variance p-values for canopy closure as affected by cultivar, (C), starter-N source (SN), preflood-N rates (PFN), week (W), and their interactions averaged across two site-years (2018, 2019) at the Rohwer Research Station (RRS).

Source of variation	Num df	Den df	Canopy closure
			—*P-value*—
C	1	9.712	0.8473
SN	3	1506	<0.0001
C × SN	3	1506	0.5240
PFN	4	1506	<0.0001
C × PFN	4	1506	0.4764
SN × PFN	12	1506	0.8803
C × SN × PFN	12	1506	0.9745
W	1	1507	<0.0001
W × C	1	1507	0.0003
W × SN	3	1506	NS* (0.5652)
W × C × SN	3	1506	NS (0.5789)
W × PFN	4	1506	<0.0001
W × C × PFN	4	1506	0.0208
W × SN × PFN	12	1506	NS (0.8235)
W × C × SN × PFN	12	1506	NS(0.9930)

* NS, not significant (P>0.05) in the final model. Values in () were eliminated from the model.

Table 2.4. Canopy closure of rice cultivars averaged across starter-N sources, for two site-years at the Rohwer Research Station (RRS).

	Cultivar Type	
Starter-N Source	Hybrid	Pure-line
	Percentage (%)	
NONE	42.6cd	38.2d
AMS	59.3a	51.2ab
DAP	57.0ab	49.0bc
UREA	56.8ab	52.4ab

Note. Means followed by different lowercase letters are statistically different at the 0.05 level.

Table 2.5. Aboveground N content of rice sampled at early heading (~R3), averaged across preflood-N rates, for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

Site-year	Preflood-N Rates (kg N ha^{-1})				
	0	56	112	168	224
	——Aboveground N content (kg N ha^{-1})——				
RRS-18P	36e	76d	114c	153b	193a
RRS-19P	43d	88c	142b	173a	190a
DREC-17H	48e	76d	101c	130b	150a
DREC-18P	44d	78c	110b	139a	157a
DREC-19P	37e	72d	109c	146b	196a

Note. Within the same site-year (row), means followed by different lowercase letters are statistically different at the 0.05 level.

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

Table 2.6. Analysis of variance p-values for aboveground N content as affected by starter-N source (NS), preflood-N rates (PFN), and their interactions for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

Site-year[a]	Source of variation	Num df	Den df	N content
				—*P-value*—
RRS-18P	NS	3	57	NS[b] (0.1821)
	PFN	4	57	<0.0001
	NSxPFN	12	57	NS (0.6045
RRS-19P	NS	3	57	NS (0.3482)
	PFN	4	57	<0.0001
	NSxPFN	12	57	NS (0.1955)
DREC-17H	NS	3	57	NS (0.2414)
	PFN	4	57	<0.0001
	NSxPFN	12	57	NS (0.0759)
DREC-18P	NS	3	57	NS (0.9594)
	PFN	4	57	<0.0001
	NSxPFN	12	57	NS (0.8718)
DREC-19P	NS	3	57	NS (0.1494)
	PFN	4	57	<0.0001
	NSxPFN	12	57	NS (0.4566)

[a] DREC, Delta Research and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[b] NS, not significant (P>0.05) in the final model. Values in () were eliminated from the model.

Table 2.7. Rice grain yields for six site-years at Rohwer Research Station (RRS) and five site-years at Delta Research & Extension Center (DREC).

Site-year[a]	No fertilizer-N yield[b]	Maximum yield[c]	Yield difference
		kg ha^{-1}	
RRS-17H	4,771	8,043	3,272
RRS-17P	3,529	8,460	4,931
RRS-18H	3,536	14,214	10,678
RRS-18P	2,081	12,921	10,840
RRS-19H	4,957	13,535	8,578
RRS-19P	4,323	9,194	4,871
DREC-17H	6,525	12,234	5,709
DREC-17P	6,038	10,785	4,747
DREC-18P	3,719	9,380	5,661
DREC-19H	5,800	12,259	6,459
DREC-19P	3,715	9,189	5,474

[a] DREC, Delta Research and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[a] Minimum yield produced by rice receiving no starter-N and no preflood urea.

[b] Maximum yield produced by rice regardless of treatment.

Table 2.8. Analysis of variance p-values for relative rice grain yield as affected by cultivar (C) and starter-N source (SN) regressed across preflood-N rates (PFN) defined by the final model for six site-years at the Rohwer Research Station (RRS) and five site-years at the Delta Research and Extension Center (DREC) in 2017, 2018, and 2019.

			Relative yield		Relative Yield
Source of variation	Num df[a]	Den df	RRS	Den df	DREC
			—P-values—		—P-values—
C	1	21.91	0.0314	33.8	0.0007
SN	3	432.2	0.0758	352.0	NS[b] (0.1906)
C × SN	3	187.4	NS (0.4883)	352.0	NS (0.5082)
PFN	1	432.7	<0.0001	370.1	<0.0001
C × PFN	1	189.7	NS (0.9411)	370.1	0.0007
SN × PFN	3	184.1	NS (0.6976)	351.9	NS (0.5635)
C × SN × PFN	3	184.1	NS (0.7454)	351.9	NS (0.3305)
PFN × PFN	1	432.6	<0.0001	370.0	<0.0001
C × PFN × PFN	1	190.0	NS (0.6113)	370.0	0.0268
SN × PFN × PFN	3	185.5	NS (0.7829	351.9	NS (0.6009)
C × SN × PFN × PFN	3	185.5	NS (0.8679)	351.9	NS (0.3595)

[a] The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.

[b] NS, not significant (P>0.10) in the final model. Values in () were eliminated from the model.

Table 2.9 Regression coefficients for relative rice grain yield as affected by cultivar and starter-N source regressed across preflood-N rates defined by the final model for six site-years at the Rohwer Research Station (RRS) and five site-years at the Delta Research and Extension Center (DREC) in 2017, 2018, and 2019.

			Parameter Estimates[a]					
Location	Cultivar	Starter-N	Intercept	SE	Linear	SE	Quadratic	SE
			Coefficients					
RRS	Pure-line	NONE	3.6866 c	0.03133	0.008734	0.000333	-0.0000224	0.000001413
		AMS	3.7337 bc	0.03151	0.008734	0.000333	-0.0000224	0.000001413
		DAP	3.7221 bc	0.03120	0.008734	0.000333	-0.0000224	0.000001413
		UREA	3.7346 bc	0.03142	0.008734	0.000333	-0.0000224	0.000001413
	Hybrid	NONE	3.7669 ab	0.03113	0.008734	0.000333	-0.0000224	0.000001413
		AMS	3.8140 a	0.03121	0.008734	0.000333	-0.0000224	0.000001413
		DAP	3.8025 a	0.03109	0.008734	0.000333	-0.0000224	0.000001413
		UREA	3.8149 a	0.03132	0.008734	0.000333	-0.0000224	0.000001413
DREC	Pure-line	–	3.8610	0.02157	0.007562	0.000269	-0.0000192	0.000001130
	Hybrid	–	3.9864	0.02582	0.006135	0.000318	-0.0000153	0.000001355

Note. Within the same column, means followed by different lowercase letters are statistically different at the 0.10 level.

[a] Coefficients derived by first dividing each plot yield by the highest no starter-N treatment average yield for each trial and regression in PROC GLIMMIX using a gamma distribution and natural log transformation of relative yield data. Predicted values can be calculated using the following equation: $e^Y = ax^2 + bx + c$, where Y = grain yield (kg ha^{-1}); x = preflood-N rates (kg N ha^{-1}); a = quadratic coefficient, b = linear coefficient, c = intercept; and e = natural exponential function. Coefficients are not significantly different from zero (*Pr*>0.10).

Figures

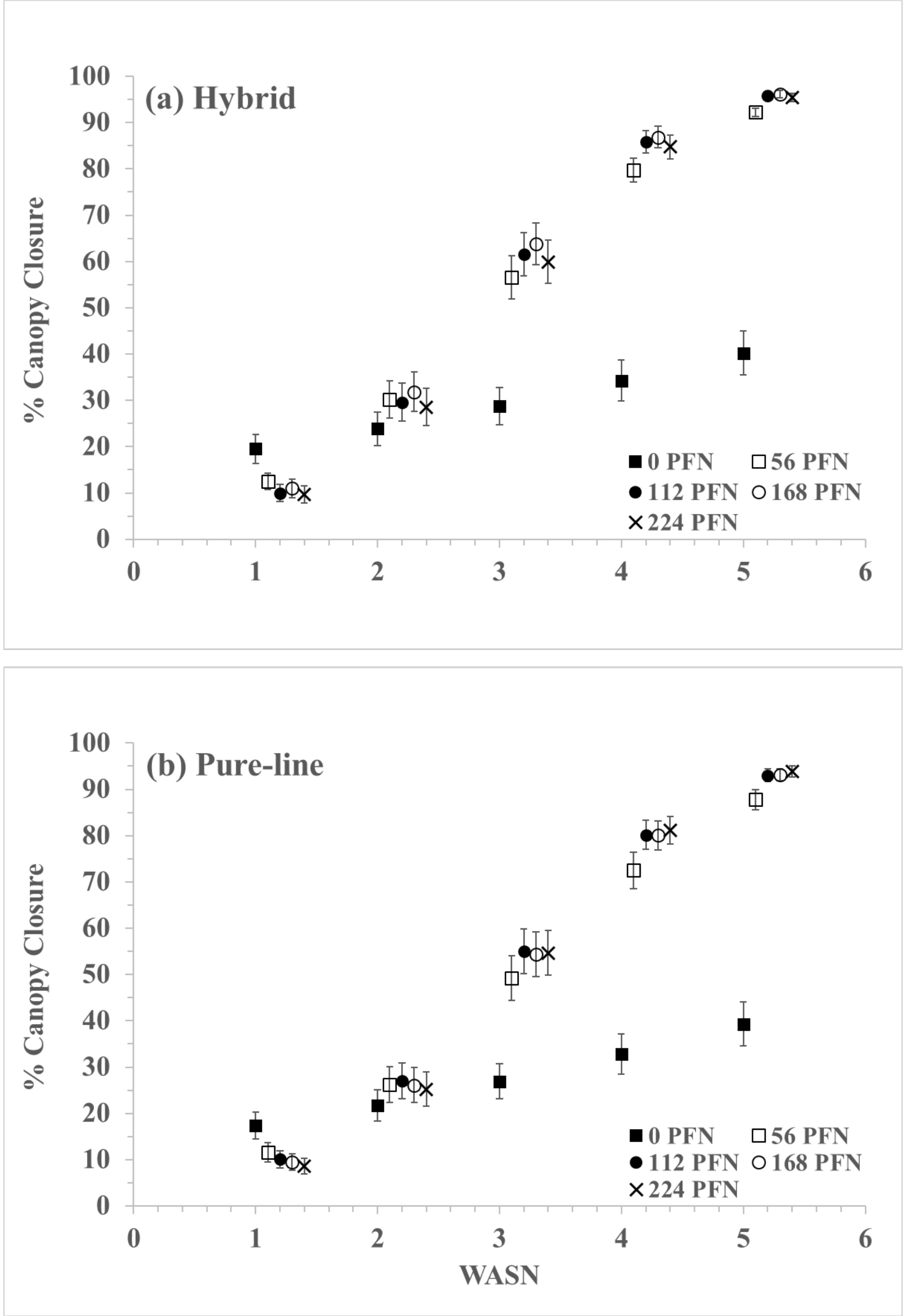


Figure 2.1. Canopy closure for two site-years at the Rohwer Research Station as affected by cultivar (Hybrid; Pure-line), preflood-N rates (PFN), and weeks after starter-N was applied (WASN). The error bars allow comparison among preflood-N rates at each timing and analysis of variance p-values are shown in Table 2.3.

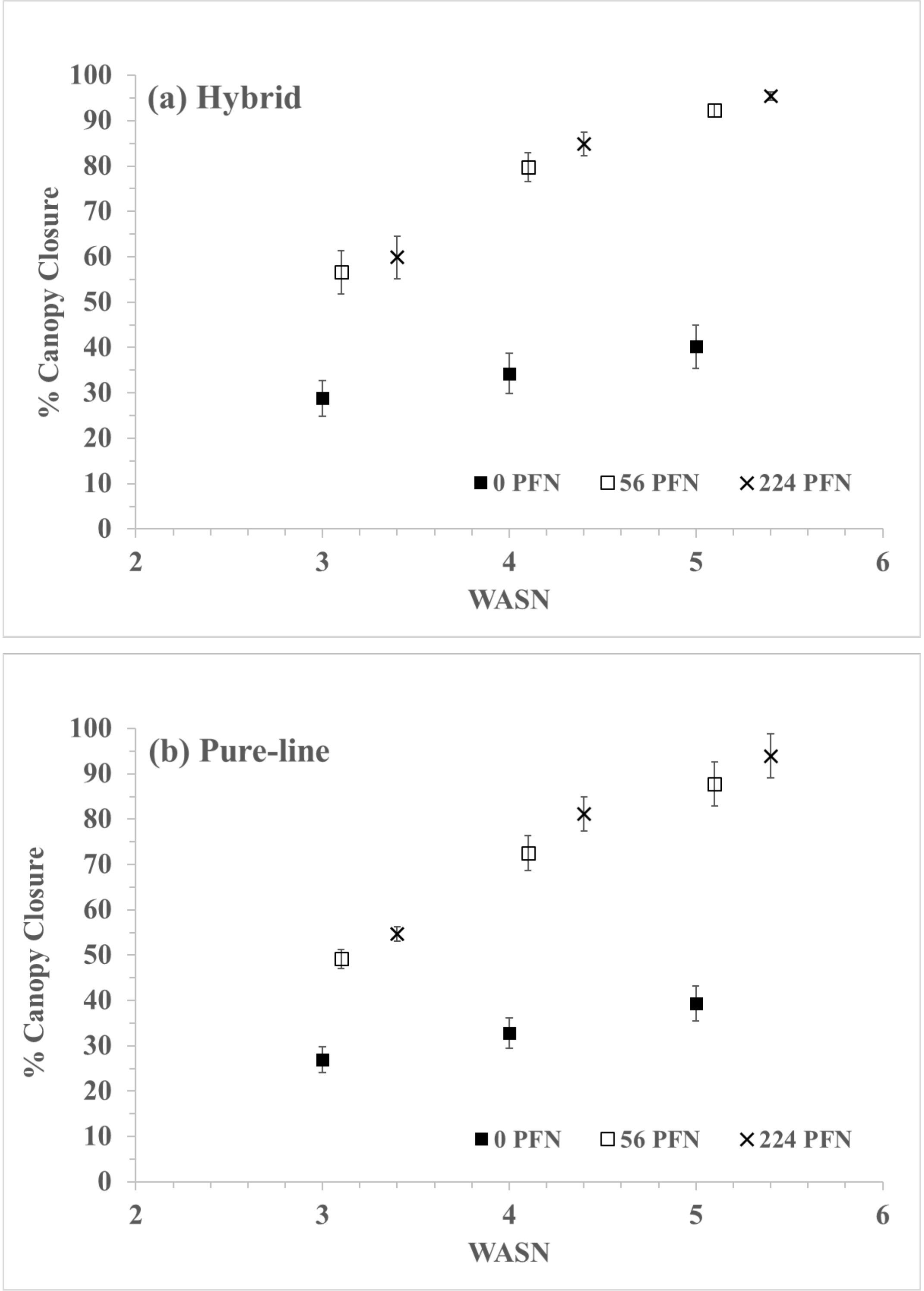
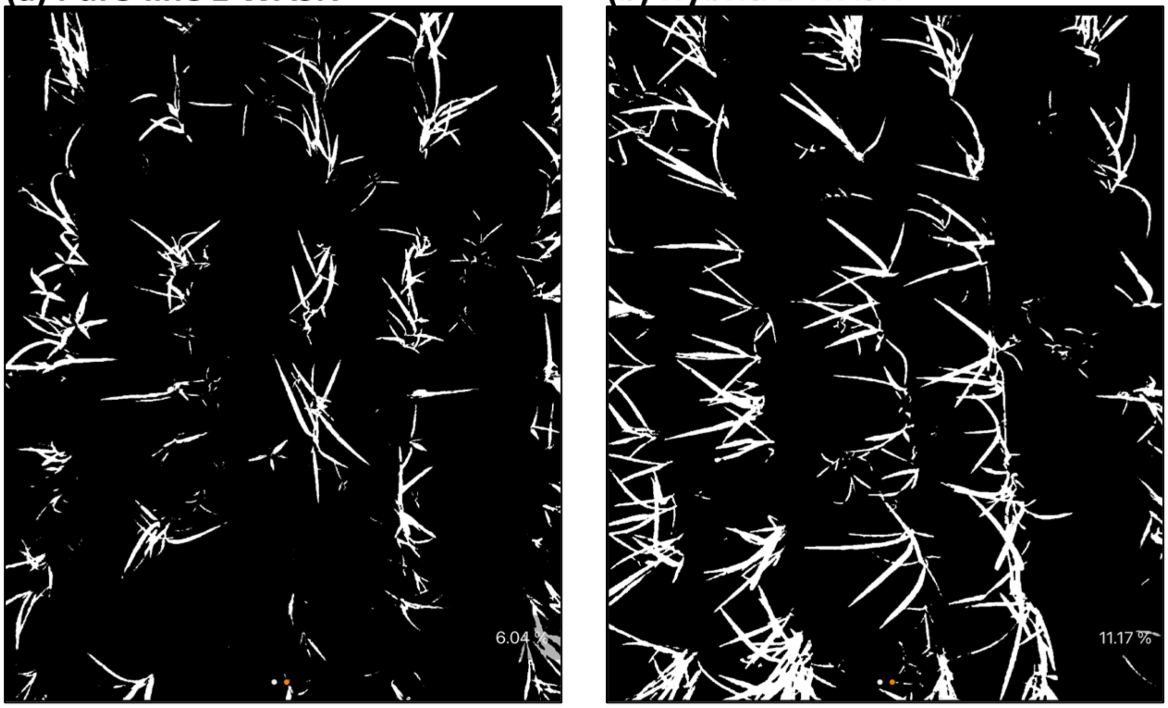
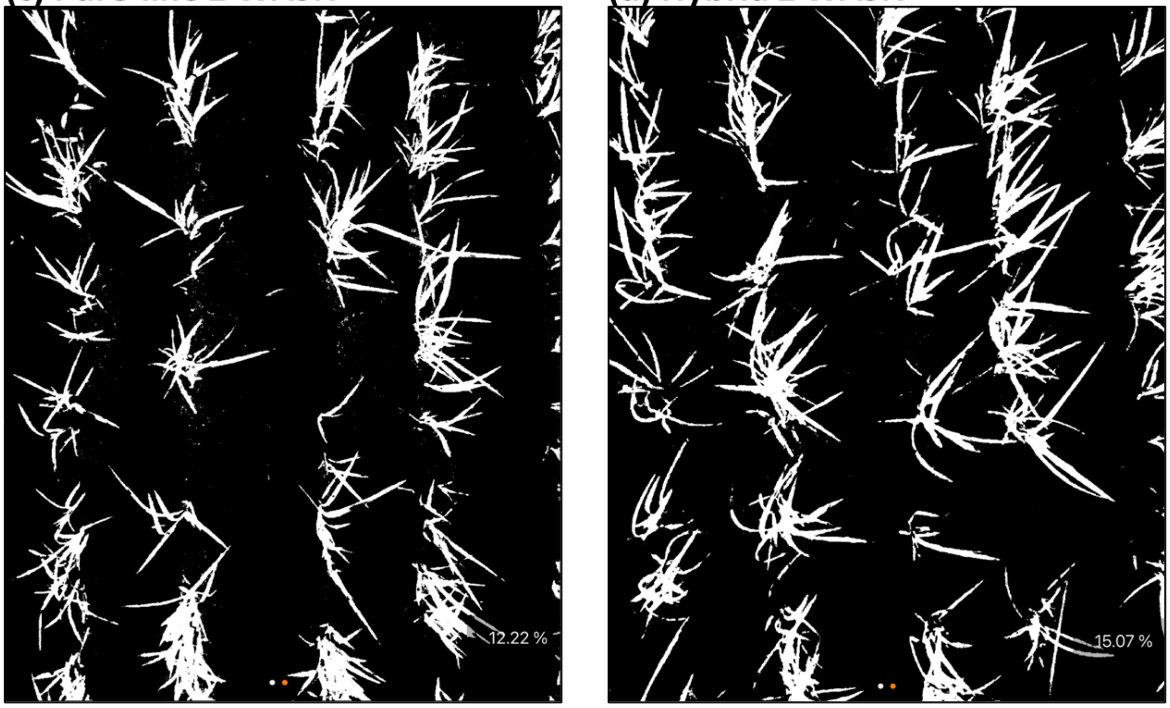


Figure 2.2. Canopy closure for two site years at the Rohwer Research Station as affected by hybrid (a) and pure-line (b) cultivar, preflood-N rates (0, 56, and 224 PFN), and weeks after starter-N was applied (WASN) beginning at 3 WASN (1 week after PFN was applied). The error bars at 0, 56, and 224 kg N ha^{-1} PFN allow comparison among three preflood-N rates and WASN.


(a) Pure-line 1 WASN

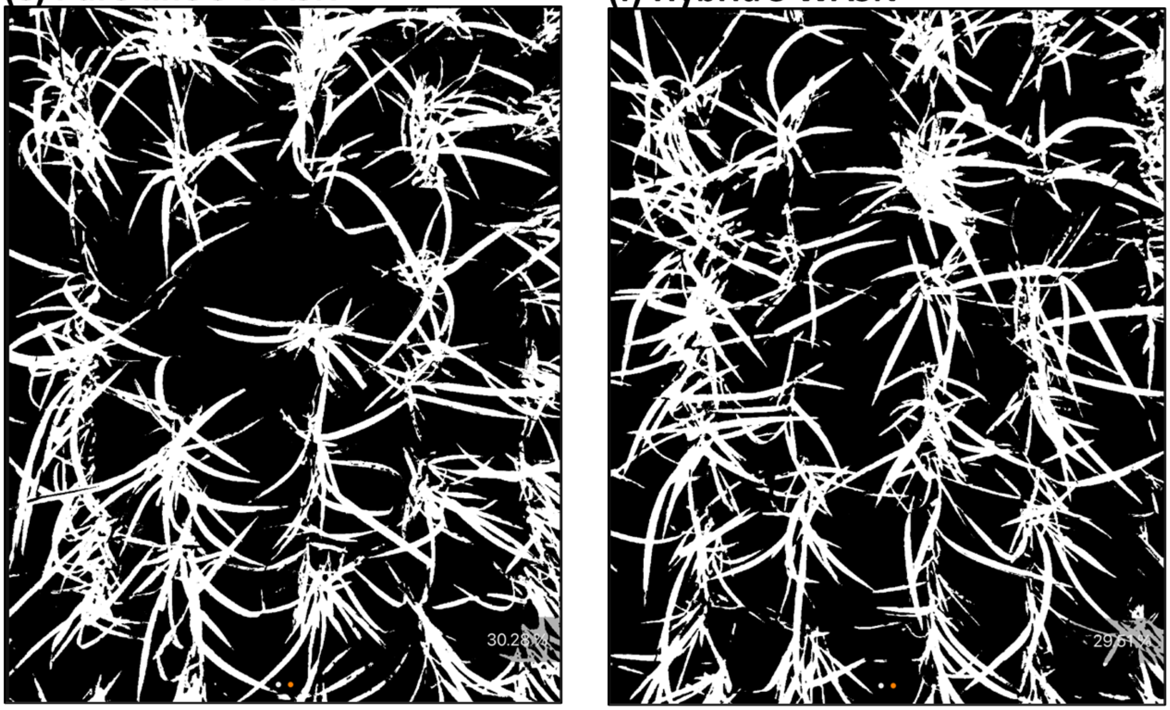
(b) Hybrid 1 WASN


(c) Pure-line 2 WASN

(d) Hybrid 2 WASN

Figure 2.3 Canopeo results at the Rohwer Research Station in 2019 for each cultivar (pure-line and hybrid) including NONE starter-N and 168 kg N ha^{-1} preflood-N for each week after starter-N (WASN) treatments were applied. Canopy closure percentage was 6% (a), 12% (c), 30% (e), 61% (g), and 92% (i) for pure-line rice and 11% (b), 15% (d), 30% (f), 87% (h), and 93% (j) for hybrid rice.

(e) Pure-line 3 WASN **(f) Hybrid 3 WASN**



(g) Pure-line 4 WASN **(h) Hybrid 4 WASN**

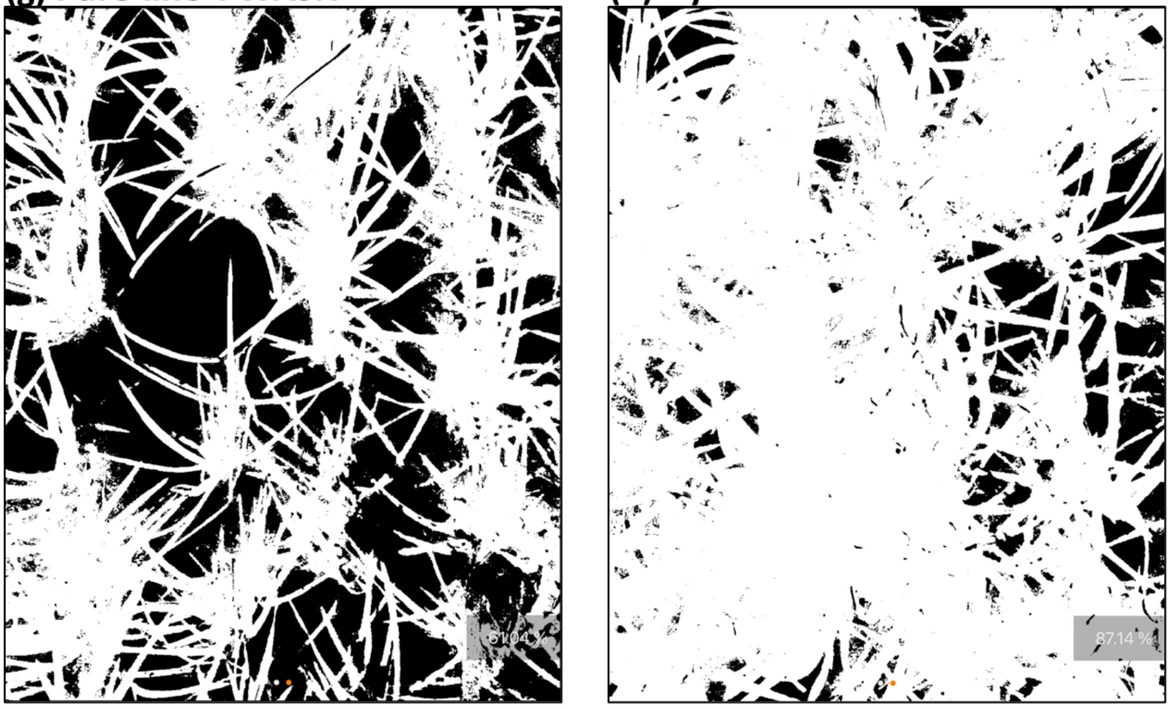
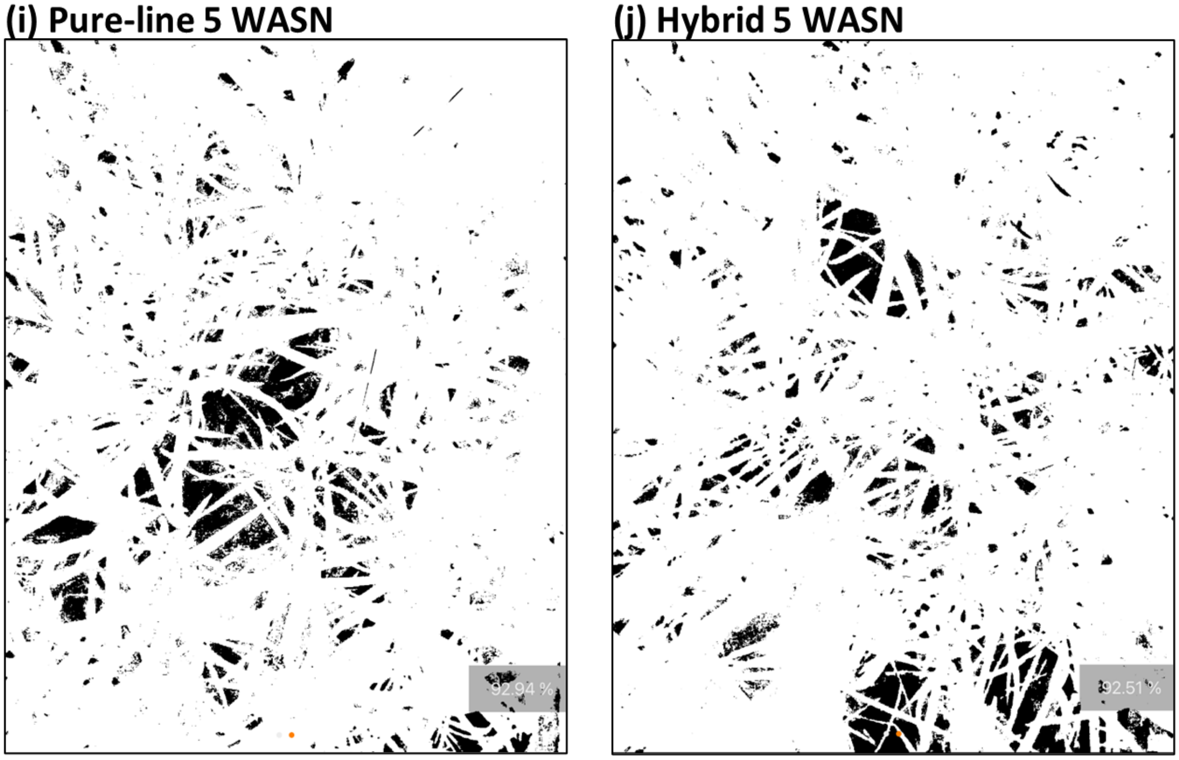
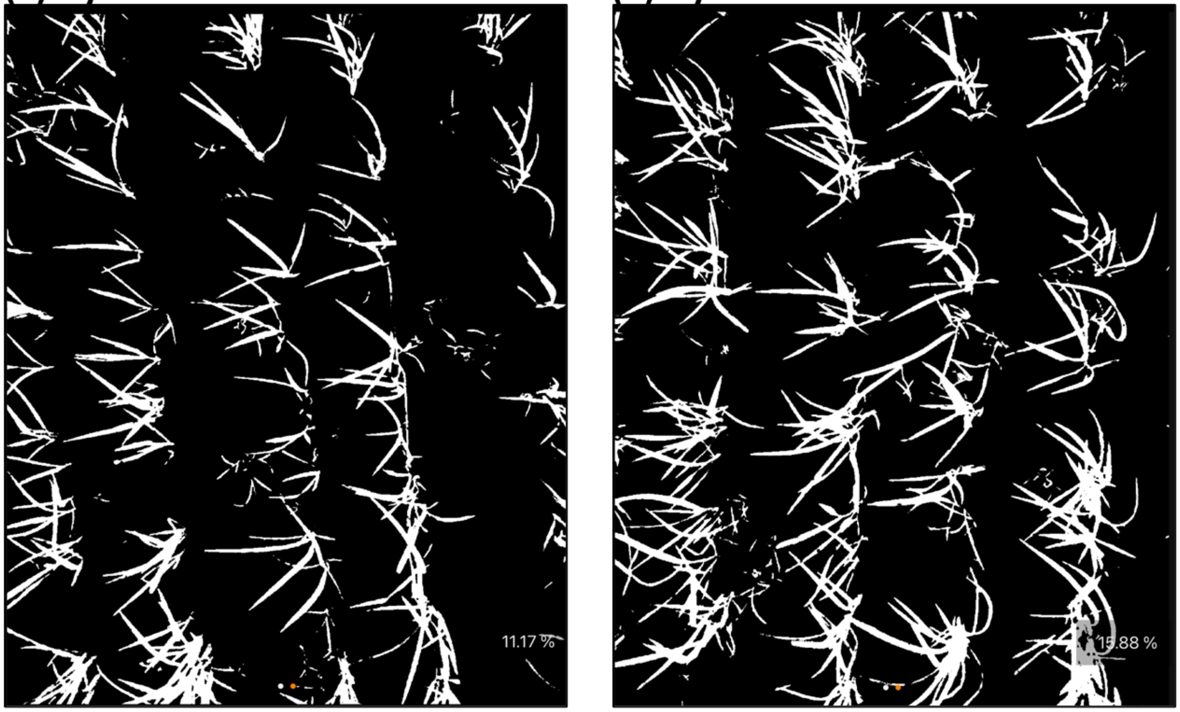


Figure 2.3 (cont.)


(i) Pure-line 5 WASN

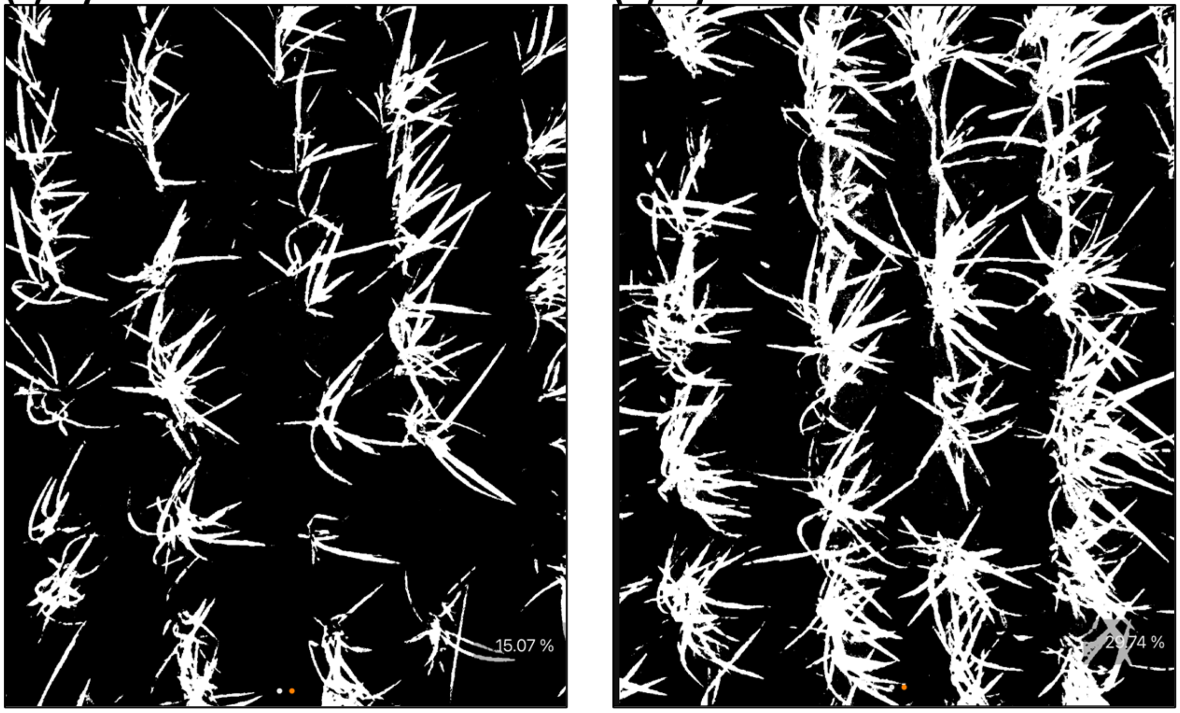
(j) Hybrid 5 WASN

Figure 2.3 (cont.)



(a) Hybrid + None 1 WASN

(b) Hybrid + SN 1 WASN

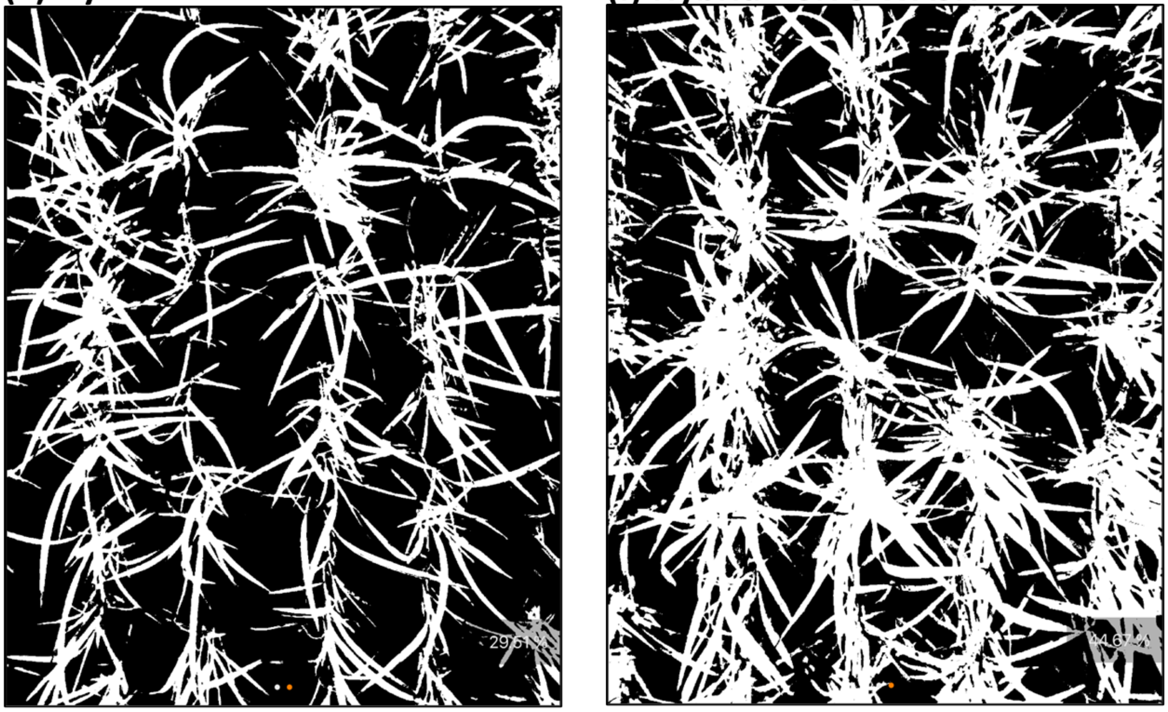


(c) Hybrid + None 2 WASN

(d) Hybrid + SN 2 WASN

Figure 2.4 Canopeo results at the Rohwer Research Station in 2019 for hybrid cultivar including NONE starter-N (SN) along with 168 kg N ha-1 preflood-N and AMS starter-N along with 168 kg N ha^{-1} for each week after starter-N (WASN) treatments were applied. Canopy closure percentage was 11% (a), 15% (c), 30% (e), 87% (g), and 93% (i) for hybrid rice without starter-N and 16% (b), 30% (d), 45% (f), 94% (h), and 99% (j) for hybrid rice with starter-N.

(e) Hybrid + None 3 WASN **(f) Hybrid + SN 3 WASN**



(g) Hybrid + None 4 WASN **(h) Hybrid + SN 4 WASN**

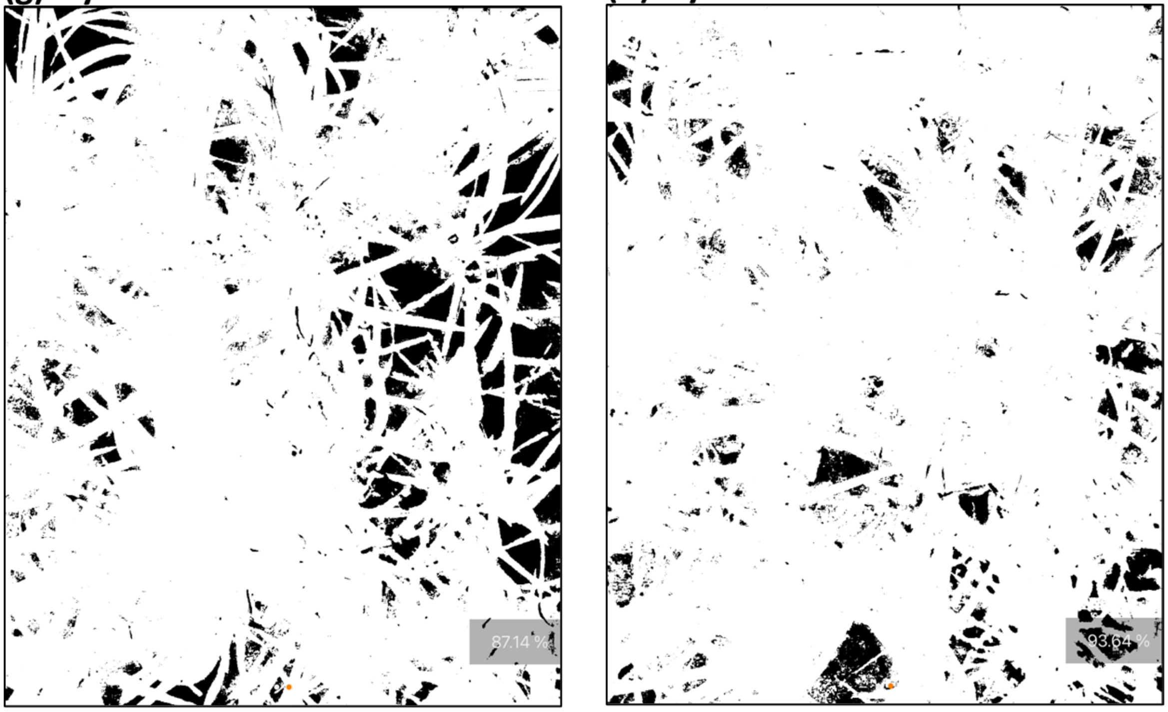
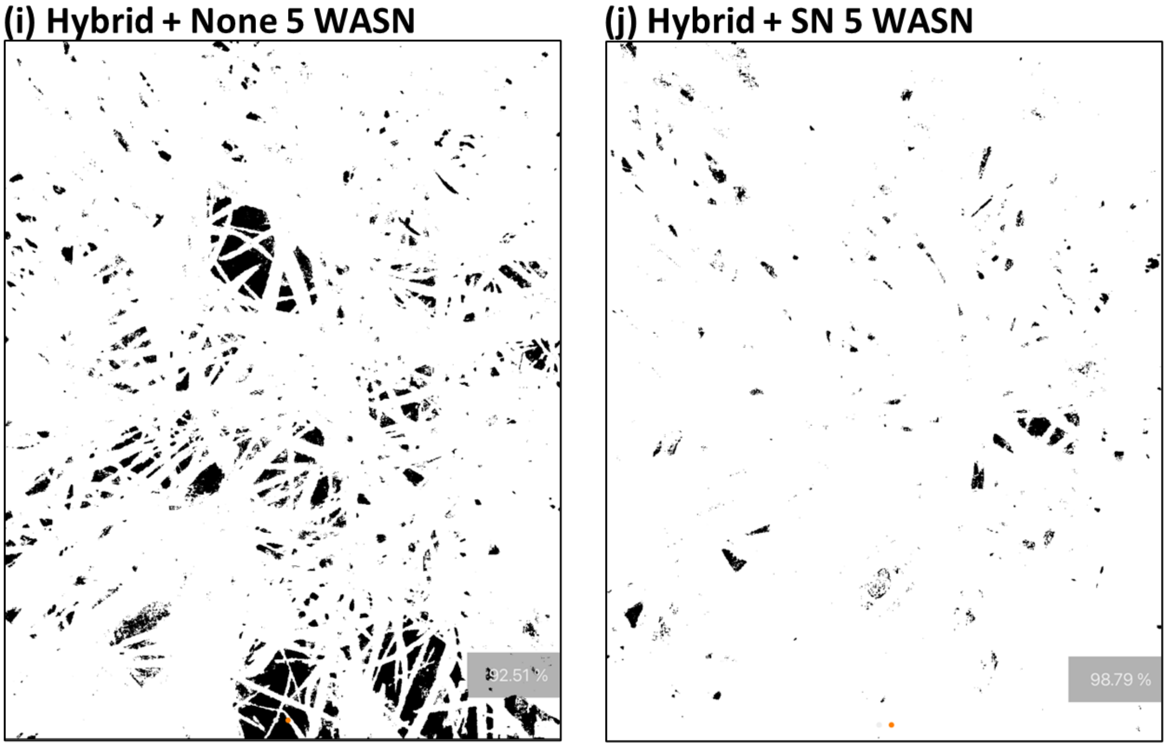


Figure 2.4 (cont.)


(i) Hybrid + None 5 WASN

(j) Hybrid + SN 5 WASN

Figure 2.4 (cont.)

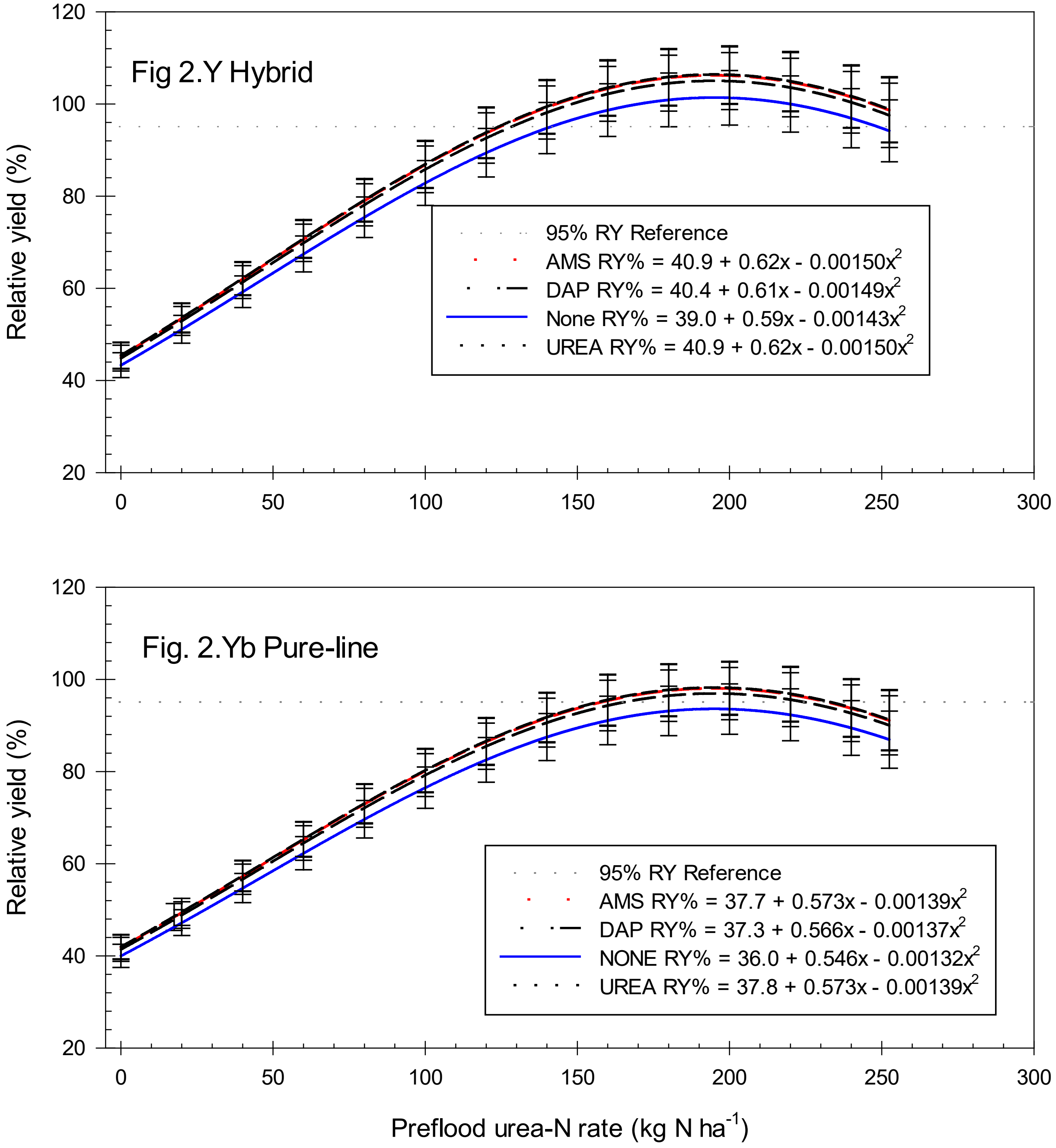


Figure 2.5 Rice relative grain yield predictions as affected by cultivar (hybrid; pure-line), starter-N sources (AMS – ammonium sulfate, DAP – diammonium phosphate, UREA – urea treated with urease inhibitor, and NONE – no starter N), and preflood-N rates using data from three site-years for each cultivar at the Rohwer Research Station (RRS) in Rohwer, AR during 2017, 2018, and 2019. Analysis of covariance p-values listed in Table 2.8 and regression coefficients are listed in Table 2.9.

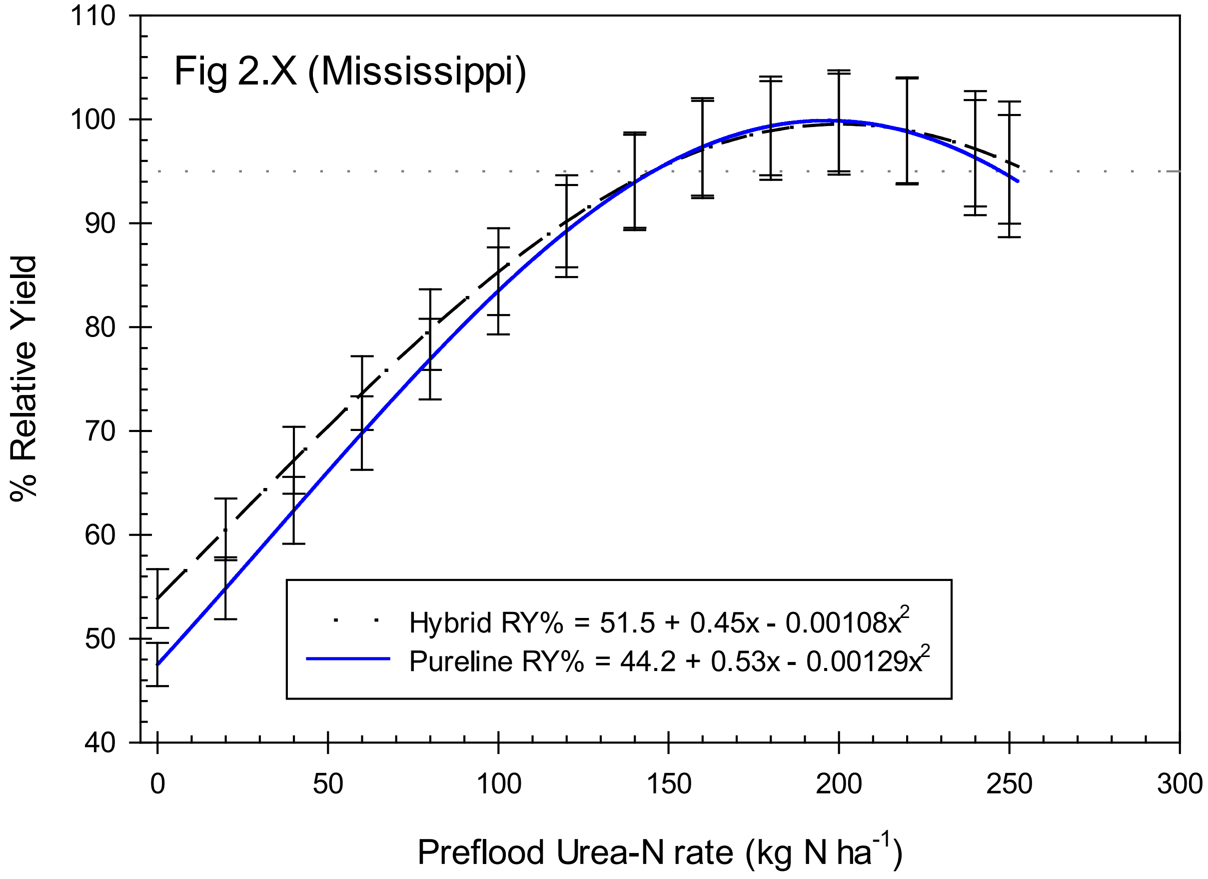


Figure 2.6. Rice relative grain yield predictions as affected by cultivar and preflood-N rates using data from two site-years for hybrid cultivar and three site-years for pure-line cultivar at the Delta Research and Extension Center (DREC) in Stoneville, MS during 2017, 2018, 2019. Analysis of covariance p-values listed in Table 2.8 and regression coefficients are listed in Table 2.9.

Appendixes

Appendix 2.1. Aboveground biomass from plant samples taken at early heading (~R3) averaged across starter-N sources (SN) and preflood-N rates for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

		Biomass					
		Preflood N rates (kg N ha^{-1})					
Site-year[a]	SN	0	56	112	168	224	SN Mean[b]
		Total dry matter (kg ha^{-1})					
RRS-18P	NONE	3,677	8,206	11,170	13,704	13,399	9,085b
	AMS	4,948	9,798	12,426	12,847	14,026	10,165a
	DAP	4,585	8,309	10,761	12,172	14,069	9,317ab
	UREA	4,367	9,161	11,500	14,473	15,753	10,096a
		4,369d[c]	8,845c	11,448b	13,271a	14,286a	
RRS-19P	NONE	3,272	6,677	9,018	9,621	9,285	7,065
	AMS	3,604	7,419	9,624	11,047	9,562	7,706
	DAP	4,387	7,111	9,680	9,214	8,941	7,571
	UREA	4,977	7,263	8,847	9,570	8,418	7,624
		4,005c	7,112b	9,285a	9,839a	9,042a	
DREC-17H	NONE	4,455	7,474	9,575	11,098	11,388	8,338b
	AMS	5,901	9,978	10,081	11,666	12,275	9,680a
	DAP	5,550	8,606	11,363	11,761	12,566	9,569a
	UREA	6,198	8,158	9,177	12,639	11,276	9,206ab
		5,484d	8,506c	10,017b	11,778a	11,864a	
DREC-18P	NONE	4,595	7,876	11,090	11,179	11,239	8,720
	AMS	4,540	7,674	9,122	11,099	10,786	8,243
	DAP	4,459	7,707	8,532	10,987	12,236	8,301
	UREA	5,659	7,690	9,790	9,578	11,784	8,638
		4,790d	7,736c	9,588b	10,690ab	11,498a	
DREC-19P	NONE	4,402	5,895	7,392	8,894	8,565	6,807
	AMS	3,084	7,865	8,460	8,873	10,151	7,134
	DAP	2,986	5,684	7,194	9,478	9,890	6,482
	UREA	4,154	6,941	8,589	9,323	10,770	7,571
		3,602d	6,540c	7,884b	9,138ab	9,810a	

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[b] Within the same column (starter-N mean), means followed by different lowercase letters are statistically different at the 0.05 level.

[c] Within the same row (preflood-N rates), means followed by different lowercase letters are statistically different at the 0.05 level.

Appendix 2.2 Tissue-N content (%) for plant samples taken at early heading (~R3) averaged across starter-N sources (SN) and preflood-N rates for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

		Preflood-N Rates (kg N ha^{-1})					
Site-year[a]	SN	0	56	112	168	224	SN Mean
		Tissue-N Content (%)					
RRS-18P	NONE	0.8351	0.8525	0.9870	1.1300	1.3428	1.0129
	AMS	0.8183	0.8857	0.9763	1.1893	1.2656	1.0127
	DAP	0.8331	0.8686	1.0038	1.1657	1.4518	1.0421
	UREA	0.8285	0.8282	1.0021	1.1418	1.3328	1.0091
		0.8287d[b]	0.8585d	0.9922c	1.1565b	1.3466a	
RRS-19P	NONE	1.1134	1.2216	1.4733	1.7926	2.2648	1.5208
	AMS	1.1351	1.2220	1.4510	1.7501	2.0265	1.4816
	DAP	1.0305	1.2492	1.5063	1.6631	1.9841	1.4495
	UREA	1.0762	1.2151	1.4782	1.8435	2.1734	1.5059
		1.0881e	1.2269d	1.4771c	1.7610b	2.1092a	
DREC-17H	NONE	0.9138efgh[c]	0.9627defhg	1.0029defh	1.2755ab	1.3598a	1.0888a
	AMS	0.8987fgh	0.9582defgh	0.9241efgh	1.0745cd	1.2935ab	1.0204b
	DAP	0.8872gh	0.9212efgh	1.0701cd	1.0200def	1.2346ab	1.0195b
	UREA	0.8524i	0.7659i	1.0397cde	1.0735cd	1.1698bc	0.9686b
		0.8877d	0.8982d	1.0077c	1.1068b	1.2625a	
DREC-18P	NONE	0.9363	0.9460	1.1013	1.2788	1.3510	1.1100
	AMS	0.9753	1.1710	1.1435	1.3025	1.4880	1.2041
	DAP	0.9085	1.0870	1.2333	1.3537	1.3477	1.1731
	UREA	0.8925	0.9557	1.0802	1.2862	1.3348	1.0961
		0.9276c	1.0358b	1.1381b	1.3050a	1.3790a	
DREC-19P	NONE	1.4249	1.1522	1.3142	1.6328	1.8668	1.4575
	AMS	1.0982	1.1676	1.6420	1.6999	1.9323	1.4722
	DAP	1.1937	1.0835	1.4128	1.5990	1.7813	1.3909
	UREA	1.0768	1.1399	1.3453	1.4737	1.8241	1.3473
		1.1909d	1.1354d	1.4231c	1.5992b	1.8503a	

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[b] Within the same row (preflood-N rates), means followed by different lowercase letters are statistically different at the 0.05 level.

[c] Within the same row and column (stater-N source & preflood-N rates), means followed by different lowercase letters are statistically different at the 0.05 level.

Appendix 2.3. Aboveground N content for plant samples taken at early heading (~R3) averaged across starter-N sources (SN) and preflood-N rates for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

		Preflood N Rates (kg N ha^{-1})					
Site-year[a]	SN	0	56	112	168	224	SN Mean
		Total N content (kg N ha^{-1})					
RRS-18P	NONE	31	70	110	155	180	92
	AMS	41	87	122	151	176	103
	DAP	38	72	108	143	204	97
	UREA	36	76	114	165	212	102
		36e[b]	76d	114c	153b	193a	
RRS-19P	NONE	36	81	135	171	210	107
	AMS	41	91	139	192	194	114
	DAP	45	89	146	153	177	110
	UREA	53	90	146	176	181	117
		43d	88c	142b	173a	190a	
DREC-17H	NONE	40	72	97	141	154	90
	AMS	53	96	93	125	159	99
	DAP	49	79	122	120	155	97
	UREA	53	62	95	136	134	89
		48e	76d	101c	130b	150a	
DREC-18P	NONE	42	73	122	143	150	96
	AMS	44	83	106	143	161	98
	DAP	39	82	107	150	163	96
	UREA	50	73	105	122	155	94
		44d	78c	110b	139a	157a	
DREC-19P	NONE	34	68	97	145	195	91
	AMS	34	83	120	149	196	100
	DAP	36	61	103	151	199	92
	UREA	45	78	115	140	196	102
		37e	72d	109c	146b	196a	

[a] DREC, Delta Research, and Extension Center; RRS, Rohwer Research Station; P, pure-line; H, hybrid

[b] Within the same row (preflood-N rates), means followed by different lowercase letters are statistically different at the 0.05 level.

Appendix 2.4. Analysis of variance p-values for aboveground biomass, tissue-N content (%), and aboveground N content as affected by starter-N source (NS), preflood-N rates (PFN), and their interactions for two site-years at the Rohwer Research Station (RRS) and three site-years at the Delta Research and Extension Center (DREC).

Site-year[a]	Source of variation	df	Biomass	N percentage	N content[a]
			Pr>F		
RRS-18P	NS	3	0.0462*	0.6072	0.1821
	PFN	4	<.0001*	<.0001*	<.0001*
	NSxPFN	12	0.5372	0.9121	0.6054
RRS-19P	NS	3	0.2932	0.4398	0.3482
	PFN	4	<.0001*	<.0001*	<.0001*
	NSxPFN	12	0.0785	0.8371	0.1955
DREC-17H	NS	3	0.0378*	0.0037*	0.2414
	PFN	4	<.0001*	<.0001*	<.0001*
	NSxPFN	12	0.5628	0.0356*	0.0759
DREC-18P	NS	3	0.8462	0.1730	0.9594
	PFN	4	<.0001*	<.0001*	<.0001*
	NSxPFN	12	0.9071	0.9625	0.8718
DREC-19P	NS	3	0.2220	0.0917	0.1494
	PFN	4	<.0001*	<.0001*	<.0001*
	NSxPFN	12	0.4417	0.1326	0.4566

[a] For aboveground N content.

*Significant at the 0.05 probability level.

Appendix 2.5. Grain yield for each site-year planted at the Rohwer Research Station (RRS) and the Delta Research and Extension Center (DREC).

		Preflood-N Rates (kg N ha^{-1})				
Site-year	Starter-N	0	56	112	168	224
		Grain yield[a] (kg ha^{-1})				
RRS-17H	NONE	4771	6016	7066	7311	6341
	AMS	5657	6910	6539	6381	7648
	DAP	4718	6556	6791	8043	6127
	UREA	5512	6191	7476	6708	7574
RRS-17P	NONE	3532	5696	6953	7716	8436
	AMS	3717	5850	6747	7671	7990
	DAP	3138	5764	6889	7758	8258
	UREA	3784	5334	7103	7459	8435
RRS-18H	NONE	3537	7172	11091	13015	12844
	AMS	4489	8296	12124	13350	13549
	DAP	4221	8885	11355	13205	14001
	UREA	4327	8563	11858	13404	14212
RRS-18P	NONE	2081	5678	9160	11569	10503
	AMS	2545	7123	9426	11360	11694
	DAP	2508	5924	9098	11172	12919
	UREA	2120	5678	9960	11262	12635
RRS-19H	NONE	4957	8336	11040	12352	13426
	AMS	5692	9185	11886	13023	13217
	DAP	5195	9059	10897	13277	13535
	UREA	6132	8833	11684	13113	12903
RRS-19P	NONE	4319	6395	7410	8071	9195
	AMS	4431	6831	7748	8720	8598
	DAP	4636	6793	7929	8317	8704
	UREA	5296	6559	7891	8265	8723
DREC-17H	NONE	6511	8585	10009	11544	11831
	AMS	6471	9615	10879	11721	12240
	DAP	6807	9303	10898	11305	12063
	UREA	7256	8829	10293	10674	12217
DREC-17P	NONE	6068	9519	9676	10440	10772
	AMS	6938	8597	9697	9932	10213
	DAP	7701	9420	10369	10590	10347
	UREA	7851	9372	9599	10582	10259
DREC-18P	NONE	3716	5806	7449	8823	9236
	AMS	3929	5650	7493	9055	9187
	DAP	3967	5723	7354	8682	9382
	UREA	4207	5552	7563	8357	9118
DREC-19H	NONE	5798	8614	10016	11433	12262
	AMS	6358	9169	11089	11816	11868
	DAP	5691	8953	10597	11859	11837
	UREA	6197	9078	10931	11646	12045
DREC-19P	NONE	3713	5404	7701	8961	8823
	AMS	3701	6080	8145	9186	9051
	DAP	3807	5545	7653	8660	8934
	UREA	3913	5972	7989	9018	9148

[a] Grain yields averaged for each site-year, starter-N source, and preflood-N rates.

Chapter 3

Conclusion

Conclusion

Farmers claim the benefits of starter-N applied to rice grown on clayey soils are increased early-season vigor and larger seedlings at the time the permanent flood is established. These benefits might allow growers to flood fields a few days earlier than they normally would, which could reduce the time for weed emergence and potential herbicide costs and allow them to apply preflood urea fertilizer on dry soil and capture water from predicted rainfall events. While these possible management aspects were not tested our results at the RRS did show starter-N increased rice canopy coverage and grain yields tended to be 3.4-5.0% more for rice compared to where no starter was applied. Canopy closure for each cultivar type was not different when AMS, DAP, and UREA were the starter-N source. Hybrid rice tended to have numerically higher canopy cover compared to the pure-line rice even with hybrid's lower seeding rate but the percent canopy coverage was not different between the cultivar types when the same starter-N source was compared. The aboveground N content was not affected by starter-N source but was significantly affected by preflood-N rate.

The results of this study support the results of prior research assessing the benefits of starter-N applied to seedling rice showing that the benefits of increased early-season vigor are measurable but the potential benefit to rice yield is small and not consistent across sites. The novel aspects of this research include the use of canopy coverage rather than height to measure seedling growth following starter-N application and the inclusion of hybrid rice established with low seedings rates. The research showed that while the yield and growth of hybrid and pure-line rice cultivars are different both cultivar types respond similarly to starter-N.