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Nitrogen Management in Rice under Suboptimal Soil conditions

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Nitrogen Management in Rice under Suboptimal Soil Conditions

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Abstract

In Mid-South rice (*Oryza sativa,* L.) production, nitrogen (N) fertilizer management for pureline varieties is most often recommended as a single preflood (SPF) or two-way split (2WS) application in a direct-seeded, delayed-flood system. Most of the N fertilizer is typically applied at the four- to six-leaf stage onto dry soil, and the second application, if necessary, into the floodwater during early reproductive growth stages (referred to as midseason). Environmental factors frequently prohibit growers from applying early N fertilizer under optimal dry soil conditions. A study was conducted to determine the best N fertilization management practices to utilize in rice when faced with suboptimal (dry or wet) soil conditions, or an established flood at the early tillering rice growth stage.

Two locations, one a silt loam soil at the Rice Research and Extension Center (RREC) near Stuttgart, AR, and the other a clay soil at the Rohwer Research Station (RRS) near Rohwer, AR, were used to evaluate N fertilizer treatments to the pureline cultivar ‘Diamond’. Treatments included a control receiving no N, SPF and 2WS treatments applied to dry and wet soils, and several treatments using single and multiple N applications into an established flood. Base N fertility rates at each location were determined using the Nitrogen Soil Test for Rice (N-STaR) recommendations of 112 kg N ha^{-1} for SPF on the silt loam and 212 kg N ha^{-1} on the clay. Total N uptake, canopy height, grain yield, and milling yield were among the plant parameters measured at both sites.

Due to a treatment by location interaction data were analyzed independently by site, which is not surprising since season total N rates for silt loams and clay soils differ significantly. On the silt loam soil, N treatments applied to dry soil according to standard recommendations (SPF and 2WS), applied to wet soil with elevated N rates, and those applied in multiple applications into the

flood ("spoon-fed") were the highest yielding treatments, while standard N rates applied to wet soil and single applications of high N rates into an established flood had statistically lower yields. On the clay soil, N treatments applied in a SPF or 2WS application to dry or wet soil, SPF (early) applied during flood initiation, and three of the four spoon-fed treatments were among the highest yielding. The lowest yielding treatments on the clay soil were the 4x52 spoon-fed late and SPF applications applied late (i.e., 7 to 10 days post flood) into the established flood. The different soil textures, accompanying cation exchange capacities, and flood establishment/management may help to partially explain the differences in results among treatments between the two locations. This study shows alternative N management strategies exist for achieving optimum grain yields with extra N fertilizer when faced with wet soil conditions or an established flood at beginning tillering or preflood-N application time.

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Table of Contents

Chapter 1-Literature Review

Chapter 2 – Nitrogen Management in Rice Under Suboptimal Soil Conditions

List of Tables

Chapter 2

CHAPTER 1

Literature Review

Introduction

Rice (Oryza sativa L.) production consumed over one million acres of Arkansas farmland in 2017, which made up approximately 47.1% of the U.S. rice crop (Hardke, 2017). Because of the large acreage rice occupies in Arkansas it is of great importance that Arkansas growers know how to best manage the crop in order to maximize profit. Though it is important to completely understand all aspects of rice production such as land preparation, planting, pesticide applications, irrigation, and harvest practices, one of the largest portions of money spent on rice production is nitrogen (N) fertility (University, 2017). Nitrogen is used by and applied to a rice crop in the largest quantity of any nutrient (Norman, 2003).

Nitrogen is most often applied in Arkansas as a single preflood application, where all of the N is applied prior to flood establishment or as a two-way split where the largest portion of N is applied prior to flood establishment, and another application is made during mid-season. Nitrogen should be applied to the rice crop with optimal soil conditions which include applying the nitrogen fertilizer to a dry soil surface and flooding up in a timely manner of 2 days or less on a silt loam soil and 5 days or less on a clay soil. Optimal soil conditions should be met prior to nitrogen fertilizer application to reduce the amount of N loss via ammonia volatilization and denitrification. Due to weather and irrigation ability it is not always certain that a grower will be able to apply N with these optimal soil conditions.

The goal of the following literature review is to outline information concerning nitrogen fertilization in rice and the issues caused by suboptimal soil conditions.

Introduction to Rice

Rice (*Oryza sativa L.*) is known and recorded as one of the oldest and most consumed foods in the world (Dethloff, 2003) as well as the most important grain from a nutritional, food, and economic perspective (Coats, 2003). Rice is grown universally, in at least 95 countries (Coats, 2003) with approximately 90% grown in Asia (USDA, 2017). Four major types of rice are produced across the globe including Indica (75%), Japonica (8%), Aromatic (15%), and Glutinous, accounting for the remainder. The major rice producing states in the U.S. include Arkansas, California, Louisiana, Mississippi, Missouri, and Texas (Street and Bollich, 2003). Not all states are capable of producing rice due to optimal rice growing conditions such as a readily available supply of water, the ability to apply water in a timely manner, and a significant land area containing less than 1% slope (Street and Bollich, 2003).

U.S. Rice Production

The six rice growing states in the U.S. can be broken up into four main regions: Arkansas Grand Prairie, Mississippi Delta, Gulf Coast, and Sacramento Valley of California (USDA, 2017). According to the USDA (2017) approximately 1 million hectares were planted in 2017 in the U.S.

Long-grain rice accounts for the majority of the rice grown in the U.S., and it is the predominant type grown in the Mid-South. Medium grain accounts for the second largest portion of the rice grown in the U.S. California produces the most medium-grain rice of any state, while Arkansas produces the most of any southern state. Short grain rice can be found in California with limited amounts in the South, but only makes up a small percentage of the rice grown in the U.S (USDA, 2017). Though the majority of rice is grown under permanent, delayed-flood soil conditions, not all is planted or managed in an identical fashion across the rice producing regions of the U.S. Rice production practices vary between U.S. states and regions, and changes in political, environmental, and economic issues result in continually evolving practices of rice production over time (Hardke, 2016).

Arkansas Rice Production

Arkansas is the top rice producer in the U.S., accounting for 47% of the rice production in 2016 (Hardke, 2017). Rice exports from the state of Arkansas were valued at $863 million in 2012. It has also been shown that the rice industry has provided 1 in 6 crop jobs in Arkansas (Division UAEX, 2014). According to Hardke and Wilson (2013), rice was first produced in Arkansas in 1902 in Lonoke County, which remains one of the state's top six rice producing counties (Hardke, 2017). Most rice in the state of Arkansas follows soybean [*Glycine max* (L.) Merr]. in rotation (68.4%) and most often is grown in a direct-seeded, delayed-flood system with only 5.4% using a water-seeded system. With rice primarily being grown in the eastern half of Arkansas, the majority is produced on silt loam soils (55.8%), 19.6% on clay soils, and 21.1% on clay loam soils. Approximately 43% of rice in the state of Arkansas was represented by hybrid cultivars in 2016. Hybrid technology in Arkansas rice production has changed how rice is managed from numerous standpoints such as lower seeding rates, increased yields, and more efficient nitrogen (N) uptake (Walker, 2008; Norman et al., 2013).

Preparation of the soil is a crucial first step in rice production. Tillage, burning, rolling, and winter flooding are all practiced in Arkansas (Hardke, 2017). The typical rice season begins with planting from around the last week of March through early June, approximately 85% of which is drill-seeded each year (Hardke, 2017). A permanent flood is applied in late May through early June at the 4- to 5-leaf growth stage. Irrigation is a key resource for Arkansas rice production with groundwater accounting for the majority (77.4%) of water used, followed by 12.1% coming from surface water collected in reservoirs, and 10.5% streams, and bayous (Hardke, 2017). Due to different land management practices including contour levees (46.2%), precision-level (39.9), and zero-grade (13.8), various irrigation methods are used.   Though the majority of the rice acreage follows a flood/levee irrigation method (62%), other irrigation methods include flood/multiple inlet (33.1%), alternate wetting and drying (AWD) (2.2%), and furrow irrigation systems (2.7%) (Hardke, 2017).

Pest management is also a pivotal component of a successful rice production system, including weed, insect, and disease management. In 2016, 54.8% of Arkansas rice acres received a foliar fungicide, 41% received a foliar insecticide treatment, and 75.9% an insecticide seed treatment (Hardke, 2017). Aside from pest management, nutrient management is also important during the rice crop growing season. Fertilization, especially N application, is one of the most important, concerning, and challenging aspects for rice growers in the state due to frequent suboptimal conditions for proper N applications and a complex growing environment consisting of a flood layer, an oxidized soil layer near the root zone and soil surface, and an anaerobic, oxygen-lacking zone.

DD50 Rice Management Program

The DD50 Rice Management Program is a widely used computer program developed to help growers accurately predict more than 26 management timings in the rice-growing season from criteria such as N fertilizer application timings to dates to check for particular pests and N fertilizer application timings (Hardke et al., 2013). This program is very important in Arkansas rice production and similar programs have been developed by universities in other rice-growing states. The program is based off the degree-day growing concept, including daily high and low air temperatures to calculate thermal accumulations for growth of the plant (Downey et al., 1976; Castaneda-Gonzalez et al., 2017). The program captures temperatures from stations all around the state of Arkansas and bases its predictions off of a 30-year average. The program is set up to be cultivar specific and creates results based off of the plants' emergence date. The DD50 program can be used to provide final preflood and mid-season N fertilizer application timings, though alternative suboptimal condition application timings are not accounted for.

Nitrogen Management in Rice

Improvement in the efficiency of N fertilizer applications in rice requires that agronomists have knowledge of the fate of N and its effect on crop production. It is important to understand all aspects that make up the N budget such as the transformations, transport rates, and effects on the growth rate and yield of the rice. Not only is N the most important nutrient in rice, but also the most difficult to manage (Mikkelsen, 1987). As a result of rice being grown in an established flood, the fertilization practices used in rice are different than in other field crops, due to a depletion of O_2 in the anaerobic soil layer. Norman et al. (2003) states that N typically requires more management than all other nutrients, but no other nutrients can result in the substantial grain yield increase that N produces. Nitrogen is applied more often and in greater quantities than any other nutrient in rice production (Norman et al., 2003). Since most rice crop rotations do not allow for accumulation of N in the soil, coupled with the loss mechanisms and the many chemical, biochemical, and microbial transformations of the nutrient in the established flood, a large amount of N fertilizer is required in U.S. rice production to maximize grain yields

(Norman et al., 2003). Norman et al. (2003) also states there are four key techniques to efficiently applying N to a rice crop including correct N source, rate, application timing, and proper management after application.

Other States

Though most rice producing regions of the U.S. follow similar N management practices, regions such as California differ in their N management methods as a result of their water-seeded planting practices (Street and Bollich, 2003). According to Norman et al. (2003), since the N is being applied preplant instead of preflood at the 4-5 leaf stage using the water-seeded method, it takes the small rice plant up to 7 to 8 weeks for maximum N uptake, which allows a longer time for the NH_4-N diffusion-nitrification-denitrification N loss process. To prevent this from happening, aqua NH_3 fertilizers are banded into the soil at a 10-15 cm depth.

Some states such as Missouri and Mississippi follow similar N fertility practices as Arkansas. Texas N fertility practices most often follow a 3-way application method with the first application being made preplant, and total the N fertilizer applied being greater than Arkansas (Dou et al., 2014). Louisiana N fertility practices differ when applying N in three applications, with the first application (10%) being made during the seedling stage to initiate rapid growth (Harrell et al., 2009).

Evolution of Nitrogen Recommendations in Arkansas

Nitrogen recommendations in Arkansas rice production have evolved over the years from numerous N fertility studies. From 1960 to 1998 the most common N application practice was the "Arkansas 3-way split" (R.J. Norman, personal communication). In 1990, the "Plant

Area Method" or "Rice Gauge" was recommended to be used for decisions related to midseason-N application (Helms et al., 1990; Wells et al., 1992; Slaton et al., 1993; Ntamtungiro et al., 1999). In 1998, the University of Arkansas and Louisiana State University conducted studies (Wilson et al., 1998) that showed that a midseason-N application was effectively taken up by the rice plant if applied in one application instead of two between beginning internode elongation (BIE) and 0.5-inch internode elongation (IE). The midseason N recommendation then was modified to indicate that it could be applied in one or two applications; thus, giving rise to movement away from a three-way split application to a two-way split. In 2003, the midseason recommendation was again changed from 67 kg N ha^{-1} (60 lb N ac^{-1}) applied at midseason to 52 kg N ha^{-1} (46 lb N a^{-1}) applied in a single midseason application with the 17 kg N ha^{-1} (15 lb N a^{-1}) removed from the midseason application added to the preflood application.

Arkansas

There are currently two common N fertilizer application recommendations in Arkansas, one being an optimum single preflood (SPF) application and the other being a standard two-way split application consisting of a large preflood application followed by a midseason application (Norman et al., 2003, 2013). If soil conditions are dry, the flood can be established in a timely manner, and the flood can be maintained for at least 3 weeks, the optimum SPF method is recommended, which can result in similar grain yields compared to the two-way split with less N fertilizer (Bollich et al., 1994, Frizzell et al., 2017). If these conditions cannot be met, the two-way split method provides a similar yield response in most incidences but with a higher total N application rate. Though number and timing of applications vary from state to state in the U.S., a study by Wilson et al., (1989) showed that midseason-N applications were taken up with a slightly higher efficiency than the preflood-N application because of greater plant biomass and smaller amount of N applied at midseason.

Recommendation Details

The majority of cultivars grown in the Mid-South on silt loam soils require 134 to 168 kg N ha^{-1} (120 to 150 lb N a^{-1}) in order to produce a profitable yield for the grower, though soil texture such as clay soils can affect N rate, requiring a 34 kg N ha^{-1} (30 lb N a^{-1}) increase from recommended rates on a silt-loam soil (Norman et al., 2013). The preflood application should account for 65-100% of the season-total N rate and should be applied around the 4-5 leaf stage followed immediately by flood establishment to incorporate the N fertilizer. This preflood application typically requires 3 weeks to be completely taken up by the rice plant (Wilson et al., 1989).

At the time of midseason-N application, noted between BIE and 0.5-inch IE, only 52 kg N ha^{-1} (46 lb N a^{-1}) should be needed, or yield has already probably been reduced (Norman et al., 2013). The midseason-N application can be applied once BIE has occurred and the flood has been established for a minimum of 3 weeks (Hardke et al., 2017). Since the rice plant allows for the midseason-N application to be taken up more quickly and with 65-80% efficacy (Norman et al., 2003), this application is recommended to be applied into the flood with less competition from N loss mechanisms and, if subsequent applications should be made, recommendations suggest to wait a minimum of 7 days later (Norman et al., 2013).

Yield Components/Nitrogen Recommendations

Basic knowledge of yield components in rice production and the timeline upon which they are set is important for rice producers when making N fertilizer applications. According to Stansel (1975), panicles per unit area is the first yield component set in rice production and is set by stand density or tiller development. Norman et al. (2003) stated that the second yield component of grains per panicle is set during early reproduction stages and can be affected by the rice plant's N concentration at that time. The third yield component is generally set by genetics; however, N must be readily available for the plant to take up during vegetative and reproductive stages for the rice plant to achieve maximum grain yield as well. Though the midseason-N application can be taken up by the rice plant in 3 to 7 days compared to 3 weeks for the preflood application, most of the yield is set by the preflood application (Norman et al., 2003).

Nitrogen Soil Test for Rice (N-STaR)

The Nitrogen Soil Test for Rice is a preseason calibration tool developed to predict site or field-specific N rates based on the relative quantity of N that will become available from native soil-N during the rice growing season, and therefore accurately prescribes the amount of N fertilizer needed at an individual site (Roberts et al., 2011). This tool is of great importance in Arkansas rice production because of economic and environmental impact. With N being the most abundantly applied fertilizer in rice production, estimated to account for 30% of total production input, N-STaR is becoming an essential tool for Arkansas rice growers (Roberts et al., 2013). The Nitrogen Soil Test for Rice allows for optimal economic, agronomic, and environmental returns and decisions (Roberts et al., 2013). Soil samples for N-STaR must be taken from the 0-45 cm soil depth in a silt loam soil, while a 0-30 cm sample depth is recommended for a clay soil (Roberts et al., 2011). After soil samples are properly obtained and packaged, the N-STaR lab provides the grower with N fertilizer rate recommendations to consider when making final N fertilization decisions.

Greenseeker Midseason N Recommendations

Greenseeker (Trimble, Sunnyvale, CA) is a handheld midseason-N recommendation tool, measuring normalized difference vegetative index (NDVI) (Hardke et al., 2017), which is being used by rice growers to determine if a midseason-N application is needed to maximize rice yield potential. The NDVI correlates with the amount of above-ground biomass (canopy coverage) and the darkness of the green color (chlorophyll content). Midseason-N applications can be made once the crop has reached BIE and there has been a permanent flood for a minimum of 3 weeks (both criteria must be met). If the single optimum preflood N application rate was made with proper soil conditions, most often midseason-N is not needed to maximize yield, but in other cases such as when the preflood N rate of the two-way split method has been applied or the preflood N was applied on to muddy soil, this tool can be used to make the final and most profitable N fertilizer decisions. A reference plot, measuring 1.52 m by 1.52 m should be formed in each field and should receive an additional 56 to 112 kg N ha^{-1} (50 to 100 lb N a^{-1}) than the remainder of the field to maximize N uptake. The reference plot's Greenseeker reading is then divided by the average field reading. A 50% chance of midseason-N fertilizer response will occur if the result is greater than 1.15. The greater the value over 1.15, the greater the chance of midseason-N response (Hardke et al., 2017).

Nitrogen Forms

Not all forms of N which exist in the soil can be taken up by the rice plant, so transformations of the nutrient in the anaerobic layer can influence the N fertilizer efficiency. To the best of our knowledge only ammonium (NH_4^+-N) and nitrate (NO_3^--N) can be taken up and used by the rice plant, therefore fertilizer applications must contain or be converted to one of these two mineral forms of N. Numerous N transformation processes can occur, resulting in a gain or loss of N from the soil, or solely affect the availability of the nutrient, so an understanding of the N cycle in an established flood is of great importance in a rice production system.

Urea is the primary N source for rice growers in Arkansas because of its high N analysis (46% N) as well as its low cost in comparison to other sources (Norman et al., 2009), but can oftentimes be undesirable because of its tendency to be lost via NH_3 volatilization if not applied to dry ground and incorporated by the flood within a few days (Dempsey et al., 2017a, 2017b). Griggs et al. (2007) also showed that $(NH_4)_2SO_4$ (21% N) resulted in less ammonia (NH_3) volatilization and greater N uptake compared to urea when the N fertilizer was not able to be incorporated by the flood in a timely manner, but instead 14 days later. The issue with this form of N is its higher cost and lower N analysis compared to urea.

For preflood applications, NH_4-N or NH_4-N forming N fertilizers such as urea, urea + NBPT (N-(n-nutyl) thiophosphoric triamide), and $(NH_4)_2SO_4$ are all recommended over NO_3-N based fertilizers to prevent denitrification from occurring once the flood has been established (Norman et al., 2013). Studies by Norman et al. (2009) and Dillon et al. (2012) showed that urea+NBPT and $(NH_4)_2SO_4$ both performed better than urea in terms of actual plant uptake as a result of less NH_3 volatilization. With $(NH_4)_2SO_4$ containing acidic properties, and urease enzyme inhibitors such as NBPT slowing down the urea hydrolysis rate and allowing more time for incorporation into the soil with the flood, these products allow for less NH_3 volatilization and are therefore recommended when a rice grower is unable to apply fertilizer onto dry soil or establish a permanent flood within 2 days of N application.

Nitrogen Gain/Loss Mechanisms

Nitrogen Gains

The major processes resulting in a net gain of N to the soil with standing floodwater include: production of organic-N from N_2 fixation by cyanobacteria, rainfall adding NH_3 and NO_3^-N into the soil, organic-N addition from animal manures and previous plant residues, and synthetic commercial fertilizers (Norman et al., 2003). In Arkansas, most often rice is grown in rotation with soybeans (*Glycine max* L.), although other crops are also rotated with rice and their crop residues often impact the soil N credits available for the following rice. Residues left after soybean harvest often contain higher N concentrations compared to other rotational crops resulting in a difference in the amount of N mineralized due to relatively narrow C:N ratios (Clark et al.,2015). The larger contribution of N to the soil from a previous soybean crop compared to the other rotational crops, necessitates an adjustment of N fertilizer rate for the following rice crop based on the previous crops (Norman et al., 2013).

Denitrification

Loss of N tends to receive attention in rice simply because of its flooded growing conditions initiating N loss. Denitrification is one of the greatest N loss processes occurring from an established flood(Patrick et al., 1985). Denitrification is the anaerobic, microbial process that reduces NO_3-N to N_2 gas, which in turn escapes into the atmosphere. Nitrate becomes an electron acceptor for microorganisms following the removal of oxygen as the soil with standing floodwater becomes reduced (Norman et al., 2003). Nitrification from biological oxidation, converts NH_4-N to NO_3-N which can diffuse from the thin oxidized layer at the soil surface to a thick reduced, oxygen lacking layer in which the NO_3-N becomes an electron acceptor and reduced to N_2 or N_2O gasses and lost to the atmosphere (Mikkelsen, 1987). Since NH_4-N sources are stable in the soon to be reduced zone after flooding, they are preferred over NO_3-N because of its reduction in an established flood leading to a loss of N (Brandon and Wells, 1987). Application of an NH_4-N source on to dry soil at the 4 to 5- leaf growth stage and a flood immediately applied minimizes any nitrification and in turn any denitrification losses in delayed-flood rice (Norman et al., 2003). However, if the NH_4-N fertilizer is applied preplant or weeks prior to flooding then there is ample time for the N fertilizer to nitrify prior to flooding and be quickly denitrified and lost after flooding.

Ammonia Volatilization

Ammonia volatilization is another commonly studied N loss mechanism. Ammonia volatilization occurs when NH_3 is lost from the soil surface or a flood into the atmosphere, this process most commonly occurs when NH_4-N forming fertilizers are applied to a wet or muddy soil prior to flooding or applied to a dry soil and not incorporated with floodwater in 2 days or less (Norman et al., 2003). Numerous factors can increase the rate of volatilization such as high NH_3 concentration, high floodwater pH, high temperature, and high wind speeds (Patrick et al., 1985). To help prevent this type of N loss from occurring in such great amounts, N fertilizer applications preflood onto a dry soil surface are ideal (Norman et al., 2013). Studies show these conditions result in less volatilization than applications on muddy soil where up to 25% volatilization can occur, or into the flood where greater than 40% volatilization can occur from urea fertilizer (Norman et al., 1993, Dempsey et al., 2017a, 2017b). When urea is applied to dry ground and subsequently flooded in 2 or less days, the wetting front initiated by the flood can incorporate the fertilizer to a depth reaching the reduced soil zone (Savin et al., 2006), as opposed to applying into the flood where most of the N fertilizer remains in the flood water or at the soil surface and is subject to NH_3 volatilization and/or denitrification (Brandon and Wells, 1985). When a flood cannot be established in 2 days or less, studies by Norman (2009) show using urea with NBPT or ammonium sulfate result in less ammonia volatilization than urea alone. The risk of N loss via denitrification and/or NH_3 volatilization are much more prone to occur when N fertilizer is applied to the soil at the seedling stage, weeks before flooding, where the rice plant is not capable of taking up and retaining a large amount of N as quickly as it can during active vegetative growth after the flood has been applied (Norman et al., 2003).

Other Processes Preventing Nitrogen Uptake by Rice

Though denitrification and NH_3 volatilization are often the most concerning forms of N loss in rice production systems, other environmental and soil factors can reduce N uptake. These mechanisms include immobilization, NH_4-N fixation by clays, and chemical NH_3 fixation by organic matter, as well as runoff and leaching (Norman et al., 2003).

Immobilization occurs due to organic-matter-decomposing microorganisms in the soil competing with the rice crop for plant available-N. The microbes can tie up the applied N fertilizer and convert it to organic material which cannot be immediately taken up by the rice plant. Because of anaerobic conditions after a flood, organic matter decomposition occurs at a lower rate, requiring less N, in comparison to aerobic conditions (Norman et al., 2003), therefore the immobilization process is not as great a concern to flooded rice as denitrification, NH_3 volatilization, and runoff (Patrick et al., 1985).

Ammonium fixation in clay soil can cause a reduction of N uptake by the rice plant. The NH_4-N fixation process can occur on soils with 2:1 clays containing large amounts of illite or vermiculite which can trap the NH_4-N between the clay layers (Norman et al., 2003). During this fixation process, the NH_4-N takes the place of the K^+ normally fixed between the clay interlayers. Norman and Gilmour (1987) stated that plants taking up 25% of NH_4-N or less of NH_4-N fertilizer fixed by clays is not uncommon, but it can be as high as 70% of the clay fixed N fertilizer. Norman et al., (2003) indicated that the flooded, rice environment probably facilitates the release and plant uptake of N fertilizer fixed by clays. Rice has been shown to be able to take up at least 40% of N fertilizer fixed by clay (Keerthisinghe et al., 1984) Fixation can also occur due to chemical fixation of NH_3 by organic matter, but as stated by Norman et al., (2003) probably only occurs to a small degree (i.e., < 5% of added urea-N) from the urea fertilizer rates used in rice production.

Runoff and leaching are both potential pathways of N loss in rice production although both are regularly minimized with proper management (Patrick et al., 1985). Since NH_4-N is a cation and it is adsorbed to the negatively charged soil colloids where as NO_3-N is an anion and thus, is not, NH_4-N has a lower tendency to leach or percolate through the soil profile out of reach for plant uptake (Mikkelsen, 1987). However, NH_4-N leaching can occur in some circumstances such as sands or waterlogged soil where Fe and Mn take the place of NH_4-N on the cation exchange complex of the soil colloids causing NH_4-N to percolate through the soil with a head of water (Mikkelsen, 1987). Runoff is an additional concern for N loss and can be minimized by not over pumping a field so there is release of water from the bottom levee of the field and making sure the flood is not maintained too deep prior to rain events.

Ideal Soil Conditions for Nitrogen Fertilizer Applications in Rice Production

Nitrogen fertilizer applications to rice involve proper conditions and timely incorporation into the soil with the flood water to be most beneficial to the rice with the greatest yield return. Optimal conditions consist of completely dry ground at the time of preflood N application and a flood established within 2 days after application. This allows the flood to incorporate the N fertilizer into the soil (Savin et al., 2006). Deeper incorporation takes place if the soil is dry versus muddy (Savin et al., 2008) and minimizes the loss of NH_4-N via NH_3 volatilization.

The greatest challenge with N fertilization in delayed-flood rice production is having optimal soil conditions at the correct growth stage of rice for preflood-N applications. According to previous studies (Norman et al., 1993, 2006; Dempsey et al., 2017a, 2017b) focused on suboptimal soil conditions prior to N fertilizer application in delayed-flood rice, when preflood applications cannot be made in the correct time window on dry ground, the use of NBPT with the urea reduced NH_3 volatilization when applied on wet/muddy ground. If at all possible, the wet ground the NBPT treated urea was applied to should be allowed to dry before the flood is established so that the flood can properly incorporate the N fertilizer into the soil (Norman et al., 2013).

Regarding the two-way split method, it is still recommended that the first N application, preflood, be applied to dry ground when the plant is at the 4-5 leaf growth stage. However at the time of midseason-N application it is reasonable to apply the fertilizer into the flood because it is a smaller amount of N fertilizer and the plant is able to take up the fertilizer at a quicker rate due to larger root mass; therefore reducing the amount available for volatilization (Walker et al., 2008). Over time, N fertilizer application into the flood has been a discouraged recommendation to rice growers, but according to Norman et al. (1994), if rainfall has led to a flood at the 4-5 leaf stage, and a grower must apply into the flood, it is recommended to split-apply every week until IE at a 34 to 50 kg N ha^{-1} (30 to 45 lb N a^{-1}) rate. It has been stated by Norman et al. (2013) not to apply a single season-total N application into the flood for any reason.

Summary

It is a common concern among Arkansas rice producers to better understand best N application practices, for the large, early N application that is typically made to dry soil during the early tillering stage of rice, when faced with suboptimal (i.e., wet or flooded) soil conditions. Without better understanding of proper practices when faced with these suboptimal soil conditions growers lose yield and profit. Though parts of this study have been previously performed, no study has covered all aspects and complexities of this one. This study not only covers N fertilization to dry soils, wet soils, and soils with standing floodwater, but also examines the timings and number of applications. The goal of this research is understanding the best N fertilization practices for growers to utilize when faced with suboptimal soil conditions during the early tillering rice growth stage.

Objectives

The objectives of this study include determining best N management practices in rice when faced with dry soil, wet soil, and soil with standing floodwater, during the early tillering rice growth stage, measuring in-season plant N status using Greenseeker, total N (TN) accumulation at heading from aboveground plant samples, nitrogen use efficiency (NUE), applied nitrogen use efficiency (ANUE), and measuring agronomic aspects of each treatment including harvest and milling yield (head rice, total rice), and plant heights at maturity.

CHAPTER 2

Nitrogen Management in Rice under Suboptimal Soil Conditions

Abstract

Environmental factors frequently prohibit direct-seeded, delayed-flood rice (*Oryza sativa,* L.) producers from applying the early, preflood-nitrogen (N) fertilizer onto optimal, dry soil conditions. This study was conducted on a silt loam and clay textured soil to determine possible N fertilization management practices to utilize in rice when faced with suboptimal wet soil conditions or where the flood has already been established. Treatments included a control receiving no N, single preflood (SPF) and two-way split (2WS) treatments applied to dry and wet soils, and several treatments using single and multiple N applications into an established flood. Total N uptake, NUE, ANUE, canopy height, grain yield, and milling yield were determined. Data were analyzed independently by site year because two soil textures were evaluated. In general, N treatments applied to dry soil according to standard recommendations, applied to wet soil with elevated N rates, and most of the treatments at elevated N rates applied in multiple applications into the flood ("spoon-fed") were the highest yielding treatments on both soil textures. Where the N treatments differed between the soil textures was when the SPF and 2WS methods applied to wet soil, with or without extra N, were among the highest yielding on the clay, but not on the silt loam without extra N. In addition, the SPF treatments applied into the flood water were the lowest yielding treatments on the silt loam, but on the clay soil only if they were applied late were the lowest yielding. This study shows alternative N management strategies exist for achieving optimum grain yields with extra N when faced with wet soil conditions or an established flood.

Introduction

Rice hectarage in the state of Arkansas makes up 46.4% of total U.S. rice production, making it the leading rice producer in the U.S. (Hardke, 2018). Nitrogen fertility is one of the largest expenses in rice production and is used by and applied to a rice crop in the largest quantity of any nutrient (Norman et al., 2003; University of Arkansas Division of Agriculture, 2018).

Nitrogen is most often applied to rice in Arkansas as urea (460 g N kg^{-1}) either as a single preflood application, where all of the N is applied prior to flood establishment, or as a two-way split, where the largest portion of N is applied prior to flood establishment, termed preflood, and another application is made during early reproductive growth, termed mid-season. If additional N applications must be made throughout the season, it is suggested to wait at least 7 days between applications (Norman et al., 2013). The only forms of N that can be taken up by the rice plant are ammonium (NH_4^+-N) and nitrate (NO_3^--N). Surveys show that urease inhibitors [e.g., N-(n-butyl) thiophosphoric triamide (NBPT)] are used on approximately 77.7% of rice acres in Arkansas (Hardke, 2018). Urea fertilizer should be applied to the rice crop when optimal soil conditions are present, which include applying the N fertilizer to a dry soil surface and flooding up in a timely manner of 2 days or less on a silt loam soil and 5 days or less on a clay soil. When suboptimal soil conditions (i.e., wet or an established flood) for proper urea application occur, denitrification and/or ammonia (NH_3) volatilization most often result in N loss which leads to a decline in yield.

Denitrification is one of the greatest N loss processes that occur in rice production (Patrick et al., 1985). Denitrification is the anaerobic, microbial process that reduces NO_3-N to N_2O or N_2 gas, which in turn escapes into the atmosphere. Application of an NH_4-N source onto dry soil at the 4- to 5-leaf growth stage and immediately flooded minimizes nitrification potential and in turn denitrification losses in delayed-flood rice production systems (Norman et al., 2003). If the NH_4-N fertilizer is applied preplant or weeks prior to flooding, the N fertilizer has time to nitrify prior to flooding and be quickly denitrified and lost after flooding.

Ammonia volatilization is another concern for N loss in rice production, occurring when NH_3 is lost from the soil surface or a flood into the atmosphere (Norman et al., 2003). This process most commonly occurs when NH_4-N forming fertilizers such as urea are applied to a wet or muddy soil prior to flooding or applied to a dry soil and not incorporated with floodwater in 2 days or less (Norman et al., 2013). Rate of volatilization increases with high NH_3 concentration, high soil or floodwater pH, high temperature, and high wind speeds (Patrick et al., 1985). Urea-N fertilizer applications preflood onto a dry soil surface are ideal to help minimize NH_3 volatilization (Norman et al., 2013). Studies show these conditions result in less volatilization than applications on muddy soil where up to 25% volatilization can occur, or into the flood where greater than 40% volatilization can occur from urea fertilizer (Norman et al., 1993, Dempsey et al., 2017a, 2017b). When urea is applied to dry ground and subsequently flooded in 2 or less days, the wetting front initiated by the flood can incorporate the fertilizer to a depth reaching the reduced soil zone (Savin et al., 2006), as opposed to applying into the flood where most of the fertilizer remains in the floodwater or at the soil surface and is subject to NH_3 volatilization (Brandon and Wells, 1985).

The goal of this research is to determine the differences in N application techniques in Arkansas rice production, varying from treatments onto dry and wet soils at standard and elevated urea fertilizer rates, as well as treatments into the floodwater.

Materials and Methods

Studies involving N management of rice under suboptimal soil conditions in 2017 and 2018 were located at the University of Arkansas System Division of Agriculture's Rice Research and Extension Center (RREC) near Stuttgart, AR., on a DeWitt silt loam (Fine, smectitic, thermic Typic Albaqualfs), and the Rohwer Research Station (RRS) near Rohwer, AR, on a Sharkey clay (Very-fine, smectitic, thermic Chromic Epiaquerts). Each location and year had a composite soil sample taken from the 0- to 10-cm depth for routine soil analysis (i.e., pH, total N [Nelson and Summers, 1996] and Mehlich-3 extractable [Helmke and Sparks, 1996] phosphorus [P], potassium [K], and zinc [Zn] by the University of Arkansas diagnostic Laboratory Fayetteville, AR). A second composite soil sample was taken from the 0- to 30-cm depth for the clay soil site (RRS) and 0- to 45-cm depth for the silt loam site (RREC) for alkaline hydrolyzable N analysis (Roberts et al., 2013). The composite soil samples were formed by randomly sampling each replication. The soil samples were dried at 65°C and ground to pass a 2-mm sieve. Selected soil properties and chemical characteristics at the RREC and RRS are shown in Table (2.1). According to the University of Arkansas Cooperative Extension Service (Norman et al., 2013) the soil test results of the soil at the RREC called for the same recommendations both years of P, K, and Zn fertilizer recommendation of 72 kg P_2O_5 ha^{-1}, 102 kg K_2O ha^{-1} and 11.2 kg Zn ha^{-1}. The soil test results in 2017 and 2018 at RRS for P, K and Zn indicated these nutrients were adequate to produce optimum rice yields and therefore no additional P, K or Zn were applied. There was a rice-soybean [*Glycine max* (L.) Merr.] crop rotation at each location for the past few decades.

At RREC, the rice cultivar 'Diamond', treated with NipsIt Suite [Nipsit Inside 1.11 ml kg^{-1}, Spriato 480 0.05 ml kg^{-1}, Sebring 318 0.23 ml kg^{-1}] (Valent USA) as drill-seeded at a rate of

2.79 seed m^{-2} into a conventionally tilled seedbed. At RRS, Diamond was drill-seeded at a rate of 3.34 seed m^{-2} into a conventionally tilled seedbed. Plots at both locations were 8 rows wide on 19-cm spacing and 2.3-m in length. Each plot was surrounded by a 1.1-m plant free alley. Management of the rice studies was according to the practices recommended for direct-seeded, delayed-flood rice culture as outlined by Hardke (2013). Weeds, insects, and diseases were controlled according to the University of Arkansas Cooperative Extension Service recommendations using best management practices for direct-seeded, delayed-flood rice (Hardke, 2013).

All N fertilizer application dates were determined using heat accumulation units in the Arkansas DD50 Rice Management Program (Hardke et al., 2013). Each location consisted of fifteen treatments with four replications arranged in a randomized complete block design. All other cultural practices followed the University of Arkansas System Division of Agriculture's Cooperative Extension Service recommended practices for optimal rice production. Standard treatments applied to dry soil at RREC included both the single preflood ('SPF-dry'; 112 kg N ha^{-1}) and two-way split ('2WS-dry'; 84 kg N ha^{-1} followed by (fb) 52 kg N ha^{-1} at midseason) methods based on N-STaR recommendations (Roberts et al., 2013) (Table 2.2). Treatments applied to wet soil included the SPF and 2WS rates described above referred to as 'SPF-wet' and '2WS-wet', as well as SPF and 2WS onto wet soil at elevated preflood N rates of 145 and 117 kg N ha^{-1}, respectively, referred to as 'SPF-wet+' and '2WS-wet+'. Treatments applied directly into standing floodwater ("spoon-fed") included: 1) 52 kg N ha^{-1} applied to wet, muddy soil preflood fb by three weekly applications of 52 kg N ha^{-1} beginning 1 wk after flood initiation referred to as 'wet fb spoon', 2) five weekly applications of 52 kg N ha^{-1} beginning at flood initiation referred to as '5x52-spoon-early', 3) five weekly applications of 52 kg N ha^{-1} beginning 7-10 days after flood initiation referred to as ‘5x52-spoon-late’, and 4) four weekly applications of 52 kg N ha^{-1} beginning 7-10 days after flood initiation referred to as ‘4x52-spoon-late’. All spoon-fed treatments were applied at 7 d intervals. While not normally recommended, single applications of 112 and 145 kg N ha^{-1} (RREC) or 201 and 235 kg N ha^{-1} (RRS) were made into the floodwater at both flood initiation (referred to as ‘SPF-flood’ and ‘SPF-flood+’) and at 7-10 d after flood initiation (referred to as ‘SPF-flood-late’ and ‘SPF-flood-late+’). A control plot, receiving 0 kg N ha^{-1}, as well as a high N reference plot receiving an elevated single preflood application (201 kg N ha^{-1} at RREC and 235 kg N ha^{-1} at RRS) were included in the study and used as references for maximum N uptake. The elevated single preflood application allowed for comparison of response index (RI) when using the Greenseeker, while even with significant N loss this would allow more than enough N to maximize yields. All treatments except those receiving spoon-fed applications had rates increased by kg N ha^{-1} at the RRS site due to clay soil recommendations by N-STAR (Table 2.3). All N as urea applied to dry or muddy soil was treated with N-(n-butyl) thiophosphoric triamide (NBPT) [Agrotain Ultra (285 g NBPT L^{-1}) Koch Fertilizer LLC., Wichita, KS] to minimize N losses associated with ammonia volatilization.

Wet, muddy ground was generated on individual plots via sprinkler system. Portable PVC cages, (1.8 m wide x 5 m long x 0.76 m tall), designed with Rainbird SQ Series sprinkler systems (Rain Bird Corp., Azusa, CA and Tuscon, AZ) were used to simulate a 2.54 cm rainfall until the ground was saturated based on the procedures outlined by Dempsey et al. (2017). All sides of the PVC cages were enclosed by tarps to help mitigate water movement by wind. The system was attached to two water tanks and evenly distributed 212 L of water within the rainfall simulator (8.3 m^2). Immediately after all rain simulations were complete, preflood-N fertilizer was applied followed by flood initiation. Rain simulation, preflood-N fertilization, and permanent flood initiation occurred within 2 d at each location. Flood initiation treatments began 1-2 d following flood establishment at each location.

All plots that received N applications directly into the floodwater including those at midseason, were surrounded by galvanized metal frames. The frames rested on the soil surface and extended to 20 cm in height to minimize N fertilizer movement in the floodwater to adjacent plots. The goal of the frames was to limit water movement in order to minimize fertilizer disturbance within the plot area. In addition, the frames were used to simulate fertilizer applications to an individual grower's field by making individual plots more self-contained.

GreenSeeker Handheld Crop Sensors (Trimble, Sunnyvale, CA) were used throughout the growing season as a reference for treatments and their response to N fertilizer. These measurements were taken 1 wk after the final N fertilizer spoon fed applications were made. The readings were used to generate a RI according to University of Arkansas System Division of Agriculture recommendations where the GreenSeeker reading from a high N area is divided by the GreenSeeker reading from a low N area to provide a value of 1.0 or greater (Hardke et al., 2019). The greater the RI value, the greater the chance of a response to midseason-N fertilization. For the purposes of this study, the RI value was used as a general gauge of the likelihood of plant response to additional N fertilizer.

Plant canopy height and total N uptake were measured at 50% heading for each treatment. Plant canopy height was measured by allowing a 0.09 m^{-2} poster board to rest on the canopy and the height above the soil surface recorded. Total-N accumulation was measured by collecting aboveground plant biomass at 50% heading from 1-m of a bordered row of each plot (Norman et al., 1992; Guindo et al., 1994). Aboveground biomass samples were bagged and placed in driers for approximately 1 week at 60°C to reach a constant weight. Each sample was weighed for accumulation of dry matter, then ground to pass a 1-mm sieve and evaluated for total N concentration in the Fayetteville Agricultural Diagnostic Laboratory by high-temperature combustion of a subsample of ground plant material using VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Campbell, 1992). Aboveground N accumulation was calculated as the product of the aboveground biomass and the total N concentration of the plant material. At maturity, the center four rows of each plot were harvested using a Wintersteiger Classic equipped Juniper Systems Harvest Master Grain Gage (Wintersteiger Ag, Austria, Dimmelstrasse), and the moisture content and weight of grain measured. Subsamples were taken from harvested grain and dried to approximately 12% grain moisture and weighed into 100 g samples to run through a Zaccaria mill (ZaccariaUSA, Brazil) to determine and compare milling yields expressed as percent whole kernel rice (head rice; %HR) and percent total rice (total milled rice; %TR). Grain yields were adjusted to 120 g H_2O kg^{-1} grain moisture.

Nitrogen use efficiency (NUE) and agronomic N use efficiency (ANUE) were determined at each location. Nitrogen use efficiency was calculated using the difference method which compares the total aboveground N uptake of the fertilized plots to the unfertilized plots and then divides by the fertilizer rate applied. Equation 2.1 was adapted from Fixen et al. (2014) to describe how NUE was determined.

$$NUE = \frac{(\{TNU-Fertilized\} - \{TNU-Unfertilized\})}{Fertilizer\ Rate\ Applied} \times 100 \qquad \text{Equation 2.1}$$

Agronomic N use efficiency is a similar metric, but compares yield differences from fertilized and unfertilized plots to relate yield gains to fertilization rates. Equation 2.2 was adapted from Fixen et al. (2014) to describe how NUE was determined.

$$ANUE = \frac{(\{Yield - Fertilized\} - \{Yield - Unfertilized\})}{Fertilizer\ Rate\ Applied}$$ Equation 2.2

Four site years, including two locations containing two different soil textures with 15 total treatments were analyzed independently by location because of difference in soil texture. Each treatment was replicated four times at each location. Plots were arranged as a randomized complete block design with four blocks and one replication in each block. All treatments were compared using analysis of variance (ANOVA) by location for all variables including grain yield, milling yield (head rice and total rice), canopy height, Greenseeker RI reading, N uptake, NUE, and ANUE using PROC Glimmix, SAS v. 9.4 (SAS Institute, Inc., Cary, NC) with means separated using Fisher's least significant difference test, where appropriate (P=0.1). Not assuming normality, PROC Glimmix was used, assuming each positive and continuous variable such as Greenseeker RI value, grain yield, height, and N uptake followed gamma distribution, while all other variables followed beta distribution.

Results

A treatment by location interaction ($p<0.1$) resulted in the analysis data averaged across years at each location. All factors except milling yields on the silt loam soil at the RREC and GreenSeeker on the clay soil at the RRS resulted in a $p< 0.1$ for a treatment by location interaction. Therefore, data were analyzed by location.

Total Aboveground N Uptake

The 5x52-spoon-late treatment resulted in the greatest amount of total N uptake of all the treatments at RREC (Table 2.4). Among SPF treatments, the SPF-wet+ treatment resulted in numerically the greatest amount of N uptake but was not significantly different compared to the SPF-dry or SPF-wet treatments. When comparing the 2WS treatments, the 2WS-wet+ treatment resulted in the greatest N uptake with the 2WS-dry and 2WS-wet being similar. The 5x52-spoon-late treatment was statistically greater than all other spoon-fed treatments which were statistically similar to each other. All SPF applications into the floodwater, whether early or late, resulted in the lowest amount of N uptake of all the treatments and were only greater than when no N fertilizer was applied (control).

Most of the N fertilizer treatments at the RRS were similar in N uptake to each other with only the 2WS-wet+ on the high side and the control on the low side standing out (Table 2.5). The 2WS-wet+ treatment resulted in the greatest numerical amount of N uptake of all the treatments, but was not significantly greater than any of the other 2WS or SPF treatments applied to wet or dry soil; which were similar to each other at RRS (Table 2.5). Also, the N uptake of the 2WS-wet+ treatment was not significantly different from the SPF-flood-early+ or the 5x52-spoon-early treatment. All of the spoon-fed treatments were similar in N uptake to each other.

The SPF-flood-early+ treatment was similar to SPF and 2WS treatments applied to dry and wet soil and greater than the SPF-flood-late treatments, but not the SPF-flood-early treatment.

Canopy Height

Canopy heights were influenced by the different N fertilizer treatments at the RREC (Table 2.4). The treatments producing the greatest canopy heights included both treatments receiving five applications (5x52-spoon) into the floodwater (one initiated at flood, the other initiated at a later timing) and the standard 2WS-dry treatment which also resulted in some of the greatest amount of N uptake among the treatments. The 4x52-spoon-late and the wet fb by spoon treatments had some of the highest N uptakes, but this was not necessarily reflected in the canopy height data as for the 5x52 spoon treatments. All SPF applications into the floodwater resulted in the shortest canopy heights of the treatments receiving N fertilizer, as they also resulted in the lowest numerical amount of N uptake by the rice, excluding the control. All other treatments at the RREC had intermediate canopy heights as well as intermediate N uptakes. Overall, with less amounts of N taken up by the rice, less growth was seen by the rice in respect to plant canopy height. The control which received no N had the shortest canopy height and the lowest N uptake.

In general, most of the canopy heights of the different N fertilizer treatments at the RRS were reflective of the N taken up by the rice (Table 2.5). The 2WS-dry, 2WS-wet, SPF-dry and SPF-flood-early+ treatments with the greatest canopy heights also had some of the largest N uptakes. The SPF-wet, SPF-wet+, 2WS-wet, 5X52 spoon-early, and SPF-flood-early treatments were in the second highest tier of canopy heights of all the treatments and they were also mostly in the second tier of N uptakes among the treatments. The remaining five treatments (i.e., wet fb by spoon, 5x52-spoon-late, 4x52-spoon-late, and the two SPF-flood-late) had some of the shortest canopy heights and lowest N uptakes among the fertilizer treatments. The control, receiving no N, had the lowest N uptake and shortest canopy height.

GreenSeeker

GreenSeeker readings resulting in high RI values indicate low amounts of N have been taken up by the rice plants at the time of measurement (Hardke et al., 2017). The majority of treatments resulted in a GreenSeeker RI value less than 1.1, suggesting a low chance of response to additional N fertilization at the RREC (Table 2.4). Generally, the RI values were reflective of the total N uptake values whereby the treatments with the lowest RI values had the greatest N uptake values. Spoon-fed applications, along with SPF and 2WS treatments, resulted in some of the lowest RI values and at least numerically the greatest amounts of N uptake. The control receiving no N and the SPF-flood treatments had the greatest RI values of all the treatments and some of the lowest N uptakes of all the treatments.

The majority of treatments resulted in a GreenSeeker RI of less than 1.1 at the RRS (Table 2.5). The control with no N resulted in the greatest RI value which was significantly greater than all other treatments and had the least N uptake. All SPF and 2WS treatments applied to dry and wet soil as well as the 5x52-spoon-early and SPF-flood early treatments resulted in the lowest RIs and generally had the greater N uptake values. The two SPF-flood-late and the 5x52 and 4x52-spoon-late treatments had RI values >1.15 and generally had the lowest N uptake values of the treatments that received N fertilizer.

Grain Yield

In general, all of the SPF and 2WS treatments applied to wet or dry soil and the spoon-fed treatments resulted in a similar grain yield at the RREC (Table 2.6). The exception to this generality was the SPF-wet that had a numerically lower yield than all the aforementioned treatments (significantly lower than 2WS-wet+ and 2WS-dry). The lowest grain yields were observed for the four different SPF-flood treatments which were applied into the floodwater, as well as the no N fertilizer control. The GreenSeeker RI values for the treatments mirrored closely the grain yields with the treatments having the highest yields also having the lowest RI values and those with the highest RI values having the lowest yields (Tables 2.5 and 2.6). Comparison of the grain yields and N uptakes among the treatments was not quite as clear as the comparison of grain yields and GreenSeeker RI values for the treatments. The treatments with highest N uptakes, 2WS-wet+, Wet fb Spoon, 5x52-spoon-early and -late, and 4x52-spoon-late, were certainly among the treatments with the highest grain yields, but there were also treatments among those with the highest yields that were not among the treatments with the highest N uptakes. The treatments with some of the highest yields but intermediate in N uptake were SPF-dry, SPF-wet+, and 2WS-dry and -wet. All SPF applications into the flood produced significantly lower yields compared to all the other treatments receiving N fertilizer and they also had the highest GreenSeeker RI values and the lowest N uptakes of all the treatments. The no N fertilizer treatment (control) had the lowest grain yield and N uptake and highest RI of all the treatments at the RREC.

Ten of the fourteen treatments that received N fertilizer at the RRS produced statistically similar and the highest grain yields (Table 2.7). For instance, the 2WS-dry treatment produced the top numerical yield among all treatments, but was similar to (not significantly different) nine other treatments and only significantly greater than the 4x52-spoon-late, SPF-flood-early, the two SPF-flood-late, and control treatments. In general, the lowest GreenSeeker RI values and highest N uptake values were mostly associated with the highest grain yields for most of the treatments at the RRS with those being the three SPF and three 2WS treatments applied to dry and wet soil, the 5x52 spoon-early, and SPF-flood-early+ treatments (Tables 2.5 and 2.7). The two exceptions that had some of the highest yields, but high RI values (> 1.15) and low N uptake values < 150 kg N ha^{-1} were the Wet fb Spoon and the 5x52-spoon-late treatments. The lowest yielding treatments were the 4x52-spoon-late and the two SPF-flood-late treatments that also had high RI values greater 1.15 and some of the lowest N uptakes among the treatments. The SPF-flood-early treatment was a little conflicting in that it had a rather intermediate yield and N uptake, but a low RI of 1.07. As at the RREC, the no N fertilizer treatment (control) had the lowest grain and N uptake and highest RI of all the treatments at the RRS.

Milling Yield

The milling yields, whether head rice or total white rice, were not significantly different among the N fertilizer treatments at RREC even though the head rice ranged from 51.3% for the SPF-flood-early treatment to 59.6% for the 5x52-spoon-early treatment (Table 2.6). The total white rice at the RREC only ranged among the treatments from 69.8% for the 5x52-spoon-late treatment to 72.6% for the SPF-flood-early+ treatment. Likewise, neither head rice nor total white rice was significantly different among the N fertilizer treatments at the RRS even though the head rice ranged from 54.4% for the 4x52-spoon-late treatment to 60.5% for the 2WS-wet+ treatment (Table 2.7). The range of the total white rice among the treatments at the RRS was even narrower than at the RREC and only ranged from 70.4 for the SPF-flood early+ treatment to 72.0% for the 2WS-wet+ treatment.

NUE/ANUE

The SPF-wet treatment resulted in the highest NUE value of all the treatments at RREC (Table 2.4). Among SPF treatments, the SPF-wet treatment resulted in numerically the greatest percentage of NUE but was not significantly different compared to the SPF-dry or SPF-wet^{+}

treatments. When comparing the 2WS treatments, the 2WS-wet treatment resulted in the greatest percentage of NUE with the 2WS-dry and 2WS-wet^{+} being similar. The 5x52-spoon-late treatment was statistically greater than all other spoon-fed treatments which were statistically similar to each other. All SPF applications into the floodwater, whether early or late, resulted in the lowest percentage of NUE of all the treatments. Among SPF treatments, the SPF-dry treatment resulted in numerically the greatest ANUE, though the SPF-wet and SPF-wet^{+} treatments were not statistically different from one another. When comparing the 2WS treatments, the 2WS-dry treatment resulted in the greatest ANUE with the 2WS-dry and 2WS-wet^{+} being similar. The 4x52-spoon-late treatment was greater than all other spoon-fed treatments which were statistically similar to each other. All SPF applications into the floodwater, whether early or late, resulted in the lowest ANUE of all the treatments.

The SPF-flood-early^{+} treatment resulted in the greatest amount of NUE of all the treatments at RRS (Table 2.4). Among SPF treatments, the SPF-dry treatment resulted in numerically the greatest percentage of NUE but was not significantly different compared to the SPF-dry or SPF-wet^{+} treatments. When comparing the 2WS treatments, the 2WS-wet^{+} treatment resulted in the greatest percentage of NUE with the 2WS-dry being similar. The 5x52-spoon-early treatment was statistically greater than all other spoon-fed treatments which were statistically similar to each other. SPF-flood-early^{+} resulted in the greatest percentage of NUE of all SPF treatments into the floodwater, though when applied early and late without excess nitrogen the results were similar. The ANUE showed no significant differences among treatments at RRS.

Discussion

Research has shown that rice grown on clay soils requires more N fertilizer than when grown on silt loam soils to achieve similar yields, though clay soils generally contain greater native soil N (Norman et al., 1999, Chen et al., 1989) and have generally less potential for ammonia volatilization loss (Mikkelsen, 1987, Griggs et al., 2007). Two reasons rice grown on clay soils compared to silt loams typically require greater amounts of N are due to NH_4-N fixation along with less diffusion in clay soils (Norman et al., 1987, Chen et al., 1989, Trostle et al., 1998). It was expected that fertilizer N loss via ammonia volatilization would be greater on the silt loam due to a lower CEC compared to the clay soil. Because the silt loam soil has a lower CEC compared to the clay it adsorbs less amounts of NH_4-N on the soil exchange sites resulting in more to be subject to loss via ammonia volatilization (Norman et al., 2003).

RREC

The recommended SPF-dry and 2WS-dry methods resulted in some of the highest grain yields which was expected because previous studies (Norman et al., 1993, Norman et al., 2006) showed that when the preflood N fertilizer is applied properly to dry soil and a flood applied timely there is less NH_3 volatilization loss and in turn greater N uptake and grain yields. Results of this study have shown that when applying the preflood N fertilizer in a SPF or 2WS method onto wet soil yields decreased at least numerically and at times significantly. When the preflood N of the SPF and 2WS treatments was applied to wet soil conditions with an increased rate of N fertilizer (i.e., SPF-wet+ and 2WS-wet+) rice grain yields were more similar to those measured with the recommended SPF-dry and 2WS-dry methods. Studies done by Dempsey et al. (2017a, 2017b) show a decrease in grain yield when N fertilizers were applied onto wet soils with no increased N fertilizer rate to compensate for N loss. All spoon-fed treatments at the RREC are contrary to the most similar previous literature (Norman et al., 1988; 1994) because they resulted in some of the highest grain yields, comparable to the recommended SPF-dry and 2WS dry methods, and show they are a viable alternative N strategy when the preflood N fertilizer cannot be applied to dry soil because of rainy weather. However, the spoon-fed treatments do require considerably more N fertilizer, therefore every effort should be made to apply N fertilizer preflood onto dry soil and the flood applied timely. Norman et al. (1988, 1994) studied applying three and four split applications of the same rate of N fertilizer from preflood to ½-in. internode elongation and found that as less N was applied into the floodwater during vegetative growth and more onto dry soil preflood the greater the grain yields produced. We found no previous studies in the literature concerning spoon-fed treatments with an elevated N rate producing rice yields similar to the recommended N rate applied with the SPF and 2WS methods where the preflood N was applied to dry soil. Although R.J. Norman has stated that “one can apply the N fertilizer anyway they want and produce a top rice yield if they apply enough N fertilizer”.

The lowest yielding N treatments at the RREC were the SPF-flood treatments whether they were applied early or late or if they had the N rate increased by 33 kg N ha^{-1}. Studies conducted by Norman et al. showed that applying N into the floodwater resulted in increased ammonia volatilization loss (Norman et al., 1993), decreased N uptake (Norman et al., 1988), and decreased grain yields (Norman et al., 1988; 1993; 1994) of the rice crop compared to N applied onto dry soil.

Nitrogen uptake is affected by rate and source of fertilizer applied as well at the timing of application, soil conditions and the growth stage of the rice plant (Norman et al., 2003). The N uptake was not as uniform as expected with SPF-dry and 2WS-dry treatments; though they had some of the greatest yields, they had only intermediate amounts of N uptake in comparison to the other treatments. When applying the same treatments to wet soils (SPF-wet, 2WS-wet) N uptake did increase when N fertilizer amounts were increased (SPF-wet+, 2WS-wet+) to compensate for N loss when applied to wet soils. Spoon-fed treatments resulted in the greatest amounts of N uptake. This was expected since these treatments had the greatest amounts of N-fertilizer applied of all treatments, while the SPF applications into the floodwater resulted in the least amounts of N uptake, which was expected because of extreme loss of N via ammonia volatilization when applying N into flood water (Norman et al., 1993).

GreenSeeker RI values of the various treatments generally corresponded well with the respective grain yields and to a lesser degree with the N uptake values measured; in that when grain yields and N uptakes increased then GreenSeeker values typically decreased. The SPF and 2WS treatments applied to dry soil or wet soil with extra N, as well as the spoon-fed treatments had some of the greatest grain yields and N uptakes. These treatments also had some of the lowest RI values indicating low expectancy of a yield increase if midseason N had been applied (Hardke et al., 2019). Treatments using SPF applications into the floodwater which resulted in the lowest grain yields and N uptakes had the greatest RI values indicating additional N uptake from a midseason N application would likely have been beneficial to increasing their grain yields.

Significant differences in canopy height occurred due to wide variation of N fertilizer rates and timings among each treatment. It was expected that treatments with greatest canopy heights would come from treatments with greatest N uptake because of studies showing total N uptake and total dry matter nearly parallel each other throughout the growing season until the plant has reached heading (Guindo et al., 1994, Bufogle et al., 1997). The majority of treatments studied resulted in canopy height mirroring N uptake, therefore treatments with the greatest N uptake were also the treatments with the greatest canopy height.

RRS

The recommended SPF-dry and 2WS-dry where preflood N was applied onto dry soil produced the greatest numerical yields at RRS of any treatments. When these treatments were applied on to wet soil (i.e., SPF-wet and 2WS-wet) there was a numerical decrease in yield, though no significant decrease in yield was observed. Increasing the preflood N rate by 33 kg N ha^{-1} with the SPF and 2WS treatments when applied on to wet soil (SPF-wet+ 2WS-wet+) showed a very slight numerical increase in grain yield for the SPF method and an over 1,000 kg ha^{-1} increase with the 2WS method to result in a yield numerically very similar to the SPF-dry and 2WS-dry. All spoon-fed treatments, some with a much larger N rate, proved to be a viable option when the clay soil is not dry enough for the preflood N to be applied, except for 4x52-spoon-late which had a significantly lower yield compared to the SPF-dry and 2WS-dry. The studies by Norman et al. (1988; 1994) would have suggested the 4x52-spoon-late treatment with the same N rate as the SPF-dry and 2WS-dry treatments would have produced a lower N uptake and grain yield. The majority of spoon-fed treatments (i.e., Wet fb Spoon, 5x52-spoon-early, 5x52-spoon-late) in this study showed no significant difference compared to the top yielding treatments of SPF-dry and 2WS-dry, although the Wet fb Spoon treatment did result in a rice yield over 1,500 kg ha^{-1} less than the SPF-dry and 2WS-dry treatments.

Though the SPF-flood-late and SPF-flood-late^{+} treatments produced some of the lowest yielding rice, the SPF-flood-early and SPF-flood-early^{+} treatments produced some of the top numerical yielding rice of all the treatments with the SPF-flood-early^{+} treatment having yield not significantly different from the SPF-dry, 2WS-dry and other top yielding treatments. This finding on the clay soil is contrary to our findings on the silt loam soil at the RREC where the SPF treatments applied into the floodwater early or late and with and without extra N produced the lowest yields of all the treatments. The only explanations we can give to explain this contradiction are based on the differing soil textures as follows: i) Clay soils have a greater CEC than silt loams. It is possible the NH_4-N hydrolyzed from the urea was, in spite of the floodwater, able to be retained on the exchange complex of the clay soil to a greater degree than the silt loam and not be as subject to ammonia volatilization loss resulting in greater N uptake and consequently greater grain yield. Griggs et al. (2007) did show that urea is much less subject to ammonia volatilization loss when applied to the clay soil at the RRS than the silt loam soil at the RREC. However, if this was the case the SPF-flood-late treatments with and without the extra N should have somewhat similar grain yields to the SPF-flood-early treatments because they were only applied a week later and Norman et al. (1994) measured very little difference in N uptake and grain yield when a portion of the preflood N fertilizer was applied into the floodwater a week apart. ii) The field where the study was located at the RRS is quite large and takes several days to flood; perhaps the day after the flooding was initiated and the N fertilizer applied the soil with standing floodwater had not yet reached field capacity and most of the solubilized urea in the floodwater was adequately moved into the soil preventing little to no ammonia volatilization resulting in greater N uptake and consequently greater grain yield. iii) Lastly, it could have simply been an anomaly and more research is needed to confirm or deny this finding.

Nitrogen uptake was similar for the SPF and 2WS treatments, being among the treatments with the greatest yields, they also resulted in the greatest N uptake, which was expected. Both recommended treatments, SPF-dry and 2WS-dry, resulted in less N uptake when the fertilizer was applied to wet soil (SPF-wet, 2WS-wet), but was increased when applied to wet soil at an elevated fertilizer rate (SPF-wet+, 2WS-wet+) which may have compensated for the N loss. Studies conducted by Norman et al. (2006) compared urea loss to NH_3 volatilization under different soil conditions and suggested a much more rapid and extensive rate of N loss when applied to wet soil. Therefore, to help offset that N loss, compensation must take place by increasing the N fertilizer rate. Spoon-fed treatments into the floodwater resulted in intermediate amounts of N uptake. The spoon-fed treatment 5x52-spoon-early resulted in one of the greater amounts of N uptake on the clay soil. Other spoon-fed treatments had numerically less N accumulation, but not significantly less.

Single applications into the floodwater generally resulted in the lowest amounts of N uptake, which agrees with the previous study by Norman et al. (1993), stating single applications into the floodwater decrease N uptake and yield. The only exception was the SPF-flood-early^{+} treatment which had an N uptake similar to the SPF-dry and 2WS-dry treatments perhaps due to the extra N compensating for the N loss. As we stated earlier, this could be due to the infiltration of the floodwater not being complete when the N was applied or just an anomaly. What does draw this N uptake into question is that the SPF-flood-early^{+} treatment had only 33 kg N ha^{-1} extra N applied compared to the other SPF-flood-early treatment yet had 48.4 kg N ha^{-1} greater N uptake. All N uptake results should be interpreted in light of the errors that can occur when a small field sample (~1 m of an inside row) is taken and the N content extrapolated to a kg N ha^{-1} basis.

GreenSeeker responded as expected with SPF and 2WS treatments. Having the greatest grain yields and N uptake, they also resulted in the lowest RI values, indicating low expectancy of a yield increase from midseason N application. The RI value for the 5x52-spoon-early was among the lowest of all the spoon-fed treatments. It had a slightly greater numerical, though not significant, N uptake compared to the other spoon-fed treatments that had similar RI values, N uptakes, and grain yields could possibly have benefited from additional N fertilizer. Single applications of N into the floodwater late (i.e., 7-10 days postflood) resulted in some of the greatest RI values of all the treatments, suggesting a midseason application of N would likely be beneficial in increasing yields of these two treatments. The SPF-flood-early treatments with and without extra N had RI values <1.15, but the grain yield of the SPF-flood-early treatment indicates it could have clearly benefitted from additional N.

Much like silt loam soils, significant and numerical differences in canopy height were evaluated, due to wide variation of N fertilizer rates and timings between each treatment. The SPF and 2WS treatments had some of the greatest canopy heights, N uptakes and grain yields. Canopy heights were among the lowest for the spoon-fed and single applications into the flood water due to their low N uptakes; the exceptions were the 5x52-spoon-early and the two SPF-flood-early treatments that had some of the greater N uptakes.

Milling Yield

Milling yields can be affected by harvest factors such as grain moisture content (Nangju and De Datta, 1970; Siebenmorgan et al., 2007) and N rate (Jongkaewwattana et al., 1993), as well as environmental factors such as nighttime temperatures during the growing season (Cooper et al., 2008). A study conducted by Rogers et al. (2016) showed that N rates used to maximize rough rice yields also maximize milling rice yields when harvested at medium and high moisture contents, though caution should be used when harvesting at low moisture contents where N rate can be more influential. Rice milling yields showed no significance differences among the treatments at either location in this study which might have been expected since the studies were not harvested at low moisture contents. The different N rates and application methods would likely have had a greater effect on milling yields if the rice was harvested at low grain moisture contents as Rogers et al. (2016) showed a greater influence on head rice yields from N fertilization when harvested at a low moisture content.

Conclusions

In conclusion, the standard SPF and 2WS methods of N application involving the preflood N applied onto dry soil are what should be recommended on either soil texture. At each location they were among the treatments that produced the greatest N uptakes and grain yields. If the preflood N of the SPF and 2WS methods are applied on to wet soil, then extra N fertilizer should be recommended. Spoon-fed treatments are a viable option when the “farmer caught a flood” from a rain event. All the spoon-fed treatments on the silt loam at the RREC produced some of the highest yields, but they were also applied at a much greater N rate, some over double the N rate, than the SPF-dry and 2WS-dry treatments and further research needs to be conducted to determine if a lower N rate and fewer spoon-fed applications might be sufficient. On the clay soil at the RRS, the spoon-fed treatments were not applied at such excessive N rates to the other treatments and this resulted in the spoon-fed treatments applied at the highest N rates, 5x52-spoon-early and -late, having the most comparable grain yields to the SPF-dry and 2WS-dry methods. The SPF-flood treatments were the N treatments that resulted in the lowest N uptakes and grain yields on the silt loam soil at the RREC. Similarly, on the clay soil at the RRS, the two SPF-flood-late treatments resulted in some of the lowest N uptakes and grain yields at this location. However, the two SPF-flood-early treatments at the RRS, particularly the treatment with additional N, resulted in similar N uptake and grain yield to the best treatments; possibly due to the infiltration of the floodwater not being complete when the first N was applied or just an anomaly and thus, further research should be conducted in this area. The canopy heights and GreenSeeker RI values of the various treatments were generally reflective of the grain yield results at each location. However, they were not always reflective of the N uptake values of the treatments and we believe this is partially due to the error that can occur when a small field sample (~1 m of an inside row) is taken and the N content extrapolated to a kg N ha^{-1} basis.

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Table 2.1. Selected properties and chemical characteristics of the soils at the Rice Research and Extension Center (RREC) and Rohwer Research Station (RRS) in 2017 and 2018.

Site	Soil Series	Soil Texture	Soil Analyses[†]						
			TN[‡]	AHN[¶]	Soil pH[§]	TN[‡]	P[#]	K[#]	Zn[#]
			-----mg kg^{-1}-----		1:2	--------------mg kg^{-1}--------------			
				RRS					
2017	Sharkey	Clay	-	83	7.6	1091	67	215	9.1
2018	Sharkey	Clay	-	91	7.8	998	55	177	8.2
				RREC					
2017	DeWitt	Silt loam	-	102	6.6	-	17	90	5.0
2018	DeWitt	Silt Loam	-	100	6.6	-	18	102	4.4

[†] A 0-10 cm depth soil sample was utilized for soil pH, total nitrogen, and Mehlich-3 extractable nutrients and a 0-30 cm and 0-45 cm depth soil sample was utilized for alkaline hydrolyzable nitrogen for the clay and silt loam, respectively.

[‡] Total nitrogen (TN) determined by dry combustion, Nelson and Sommers (1996).

[¶] Alkaline hydrolyzable nitrogen (AHN) determined by direct steam distillation, Roberts et al. (2011).

[§] Soil/water ratio, 1:2.

[#] Mehlich-3 extractable nutrients, Helmke and Sparks (1996).

Table 2.2. Description of nitrogen (N) fertilizer treatments for trials on Diamond rice at the Rice Research and Extension Center, Stuttgart, AR in 2017-2018.

Treatment[a]	N applied to dry[a] soil (kg N ha^{-1})	N applied to wet soil (kg N ha^{-1})	N applied into floodwater (kg N ha^{-1})
Control	0	0	0
SPF[b]-dry	112	0	0
SPF-wet	0	112	0
SPF-wet+[c]	0	145	0
2WS-dry	52	0	52
2WS-wet	84	0	52
2WS-wet+	117	0	52
Wet fb Spoon	0	52	3x52
5x52-spoon-early[d]	0	0	5x52
5x52-spoon-late[d]	0	0	5x52
4x52-spoon-late	0	0	4x52
SPF-flood-early	0	0	112
SPF-flood-early+	0	0	145
SPF-flood-late	0	0	112
SPF-flood-late+	0	0	145

[a] Preflood N applied to "dry" or "wet" soil surface or into the flood "flood".
[b] SPF=single preflood, 2WS=two-way split, fb=followed by.
[c] Symbol "+" refers to elevated N rate; "spoon" refers to multiple applications such as 5x52 where 5 separate applications of 52 kg N ha^{-1} were made each week.
[d] Early=1-2 day post flood, Late= 7-10 day post flood.

Table 2.3. Description of nitrogen (N) fertilizer treatments for trials on Diamond rice at the Rohwer Research Station, near Rohwer, AR in 2017-2018.

Treatment[a]	N applied to dry[a] soil **(kg N ha^{-1})**	N applied to wet soil **(kg N ha^{-1})**	N applied into floodwater **(kg N ha^{-1})**
Control	0	0	0
SPF[b]-dry	202	0	0
SPF-wet	0	202	0
SPF-wet+[c]	0	235	0
2WS-dry	174	0	52
2WS-wet	174	0	52
2WS-wet+	202	0	52
Wet fb Spoon	0	52	3x52
5x52-spoon-early[d]	0	0	5x52
5x52-spoon-late[d]	0	0	5x52
4x52-spoon-late	0	0	4x52
SPF-flood-early	0	0	202
SPF-flood-early+	0	0	235
SPF-flood-late	0	0	202
SPF-flood-late+	0	0	235

[a] Preflood N applied to "dry" or "wet" soil surface or into the flood "flood".
[b] SPF=single preflood, 2WS=two-way split, fb=followed by.
[c] Symbol "+" refers to elevated N rate; "spoon" refers to multiple applications such as 5x52 where 5 separate applications of 52 kg N ha^{-1} were made each week.
[d] Early=1-2 day post flood, Late=7-10 day post flood.

Table 2.4. Canopy height, GreenSeeker response index, and nitrogen (N) uptake, grain yield, head rice, and total white rice for Diamond rice with varying nitrogen management averaged over the two years at the Rice Research and Extension Center, Stuttgart, AR.

Treatment[a]	Canopy Height	GreenSeeker Response Index	N Uptake	NUE	ANUE	Grain Yield	Grain Yield	Head Rice	Total Rice
	(cm)	----	(kg N ha^{-1})	%	(kg grain/kg N)	(kg ha^{-1})	(bu a^{-1})	%	%
Control	67.1 h	1.54 a	72.9 g			6416 f	127	52.4	70.0
SPF[b]-dry	92.6 cd	1.09 de	149.7 d	68.6 a	42.5 a	11174 abc	222	58.2	70.6
SPF-wet	91.2 de	1.05 e	166.9 cd	83.9 a	33.7 b	10191 c	202	58.0	70.6
SPF-wet+[c]	95.4 bcd	1.04 e	173.6 bcd	69.4 a	31.2 b	10942 abc	217	58.3	70.3
2WS-dry	98.8 ab	1.04 e	157.6 d	63.2 ab	38.3 ab	11552 ab	229	58.3	70.4
2WS-wet	92.1 d	1.09 de	163.2 d	67.3 a	32.0 b	10710 bc	213	56.0	70.3
2WS-wet+	95.4 bcd	1.03 e	193.2 bc	71.1 ab	32.0 b	11864 a	235	59.1	70.8
Wet fb Spoon[c]	96.9 bc	1.05 e	196.7 b	61.9 ab	22.5 c	10907 abc	216	59.4	70.8
5x52-spoon-early[d]	102.1 a	1.01 e	192.9 bc	48.0 bc	21.0 cd	11678 ab	232	59.6	70.6
5x52-spoon-late[d]	102.2 a	1.01 e	244.1 a	68.5 a	20.5 cd	11552 ab	230	58.9	69.8
4x52-spoon-late	94.5 bcd	1.02 e	196.9 b	62.0 ab	23.8 c	11174 ab	222	58.4	70.0
SPF-flood-early	74.8 g	1.30 b	105.0 ef	28.7 d	13.2 e	7893 e	157	51.4	69.7
SPF-flood-early+	81.8 f	1.17 cd	101.3 f	19.6 d	11.0 f	8014 de	159	53.5	72.6
SPF-flood-late	76.8 g	1.21 bc	107.8 ef	31.2 cd	12.9 de	7862 e	156	53.5	70.2
SPF-flood-late+	87.7 e	1.17 cd	119.6 e	32.2 c	16.2 cde	8765 d	174	55.6	70.5
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	--	NS[f]	NS

[a] Preflood N applied to “dry” or “wet” soil surface or into the flood “flood”.
[b] SPF=single preflood, 2WS=two-way split, fb=followed by.
[c] Symbol “+” refers to elevated N rate; “spoon” refers to multiple applications such as 5x52 where 5 separate applications of 52 kg N ha^{-1} were made each week.
[d] Early=1-2 day post flood, Late= 7-10 day post flood
[e] Means within a column followed by the same letter are not significantly different, LSD (0.10).
[f] NS=not significant.

Table 2.5. Canopy height, GreenSeeker response index, and nitrogen uptake, grain yield, head rice, and total white rice for Diamond rice with varying nitrogen management averaged over the two years at the Rohwer Research Station, near Rohwer, AR.

Treatment[a]	Canopy Height	GreenSeeker Response Index	N Uptake	NUE	ANUE	Grain Yield	Grain Yield	Head Rice	Total Rice
	(cm)	----	(kg N ha^{-1})	%	(kg grain/ kg N)	(kg ha^{-1})	(bu a^{-1})	%	%
Control	69.7 d	1.76 a	69.8 f			5489 f	109	50.3	70.6
SPF[b]-dry	101.7 ab	0.96 d	193.6 abc	61.3 a	28.6	11259 ab	223	59.7	70.8
SPF-wet	94.1 abcd	1.03 d	168.3 abcde	48.8 a	24.6	10458 abc	208	58.9	71.5
SPF-wet+[c]	94.4 abcd	1.01 d	155.7 abcde	36.6 abcd	21.7	10589 abc	210	59.3	71.1
2WS-dry	102.6 a	0.96 d	177.1 abc	47.8 bcde	26.4	11456 a	227	58.8	71.7
2WS-wet	93.1 abcd	1.07 cd	153.5 abcde	37.0 fde	20.4	10090 abcd	200	56.3	71.6
2WS-wet+	101.6 ab	1.00 d	216.9 a	57.9 abc	22.8	11290 ab	224	60.5	72.0
Wet fb Spoon[c]	87.3 d	1.20 bc	142.9 bcde	36.6 fde	21.0	9697 abcd	192	55.9	71.5
5x52-spoon-early[d]	91.2 abcd	1.08 cd	175.2 abcd	42.2 cdef	22.0	10997 ab	218	57.2	71.5
5x52-spoon-late[d]	87.5 d	1.32 b	137.2 cde	27.0 f	18.3	10075 abcd	200	56.2	70.9
4x52-spoon-late	86.1 d	1.27 b	132.1 cde	31.2 fe	18.5	9193 cde	182	54.4	70.7
SPF-flood-early	94.2 abcd	1.07 cd	148.2 bcde	70.0 ab	37.3	9662 bcd	192	56.2	71.0
SPF-flood-early+	100.5 abc	1.03 d	196.6 ab	87.0 a	34.3	10458 abc	208	58.2	70.4
SPF-flood-late	89.8 bcd	1.25 b	124.2 de	48.6 abcd	27.7	8140 e	162	53.3	71.7
SPF-flood-late+	89.3 cd	1.18 bc	119.9 e	34.6 fe	22.1	8699 de	173	53.6	70.4
P-value	0.0014	<0.001	0.0116	<0.001	NS[f]	0.002	--	NS	NS

[a] Preflood N applied to "dry" or "wet" soil surface or into the flood "flood".
[b] SPF=single preflood, pf=preflood, 2WS=two-way split, fb=followed by, ms=mid-season.
[c] Symbol "+" refers to elevated N rate; "spoon" refers to multiple applications such as 5x52 where 5 separate applications of 52 kg N ha^{-1} were made each week.
[d] Early=1-2 day post flood, Late=7-10 day post flood
[e] Means within a column followed by the same letter are not significantly different, LSD (0.10).
[f] NS=not significant.