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Evaluation of Water and Nitrogen Management Practices in Southern Us Rice (Oryza Sativa L.) Production

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Evaluation of water and nitrogen management practices in southern US rice (*Oryza sativa* L.) production

By

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Nitrogen (N) fertility and irrigation costs are the greatest input expenses required for rice production in Mississippi, therefore N management and irrigation should be conducted in efficiently. Field experiments were conducted at the Delta Research and Extension Center in Stoneville, MS, and the LSU AgCenter in Crowley, LA, to evaluate water and nitrogen management practices. Nitrogen use efficiency and yield were not different for alternate wetting and drying (AWD) systems compared to a traditional continuous flood. Additionally, experiments were conducted to test for differences comparing two experimental designs, randomized complete block (RCB) and split-plot (SP), for N-rate response trials in Mississippi. Rice grain yield response to N-rate was similar for RCB and SP designs, therefore either experimental design would be appropriate for N-response experiments in rice. Increasing efficiency of water and N management practices further improves environmental and economic benefits from rice production in Mississippi.

DEDICATION

I would like to dedicate this thesis to my father, Richard Atwill. I would first like to thank him for his dedication to the Lord. Through thick and thin, he has shown a strength of commitment that I can only strive to possess. Through his example I have learned how to rely on faith in Christ during times of joy as well as hardships. I cannot express how much his guidance and support shapes how I walk every day. Secondly, I would like to thank him for the love that he has for his five children. We are truly blessed to have a father that has unconditional love not only every one of us, but everyone who he come into contact with. His persistence and patience has proven to be the rock that our family is built upon. I would also like to thank him for his service to the education of young people. With 28 years of teaching and administration in the public school system, his positive outlook and impact on the lives of students and faculty is a direct reflection of our family. Lastly, the subtle yet important life lessons that emphasized becoming a free thinker has allowed me to remain focused on the job ahead (i.e. don't get "tunnel vision"). I look forward to the coming years, as you will be able to pass these values on to my family. Love You Pop.

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TABLE OF CONTENTS

DEDICATION ii

ACKNOWLEDGEMENTS iii

LIST OF TABLES vi

LIST OF FIGURES viii

CHAPTER

I. WATER MANAGEMENT STRATEGIES AND THEIR EFFECTS ON RICE GRAIN YIELD, NITROGEN USE EFFICIENCY, AND SOIL CHEMICAL PROPERTIES 1

1.1 Abstract 1
1.2 Introduction 2
1.3 Materials and Methods 9
1.3.1 Statistical Analysis 13
1.4 Results and Discussion 14
1.4.1 Soil Chemical Properties 17
1.5 Conclusion 19
1.6 Literature Cited 29

II. EVALUATION OF RANDOM COMPLETE BLOCK AND SPLIT PLOT EXPERIMENTAL DESIGNS FOR NITROGEN RESPONSE TRIALS IN RICE 37

2.1 Abstract 37
2.2 Introduction 38
2.3 Materials and Methods 42
2.4 Results and Discussion 44
2.5 Conclusion 45
2.6 Literature Cited 51

LIST OF TABLES

1.1 Extractable nutrients for an experiment conducted to evaluate rice irrigation strategies in Stoneville, MS, and Crowley, LA in 2013 and 2014....21

1.2 Statistical significance of the main effects tested for grain yield, plant height, days to 50% heading, and AEN† in Louisiana and Mississippi in 2013 and 2014....21

1.3 Rice grain yield, plant height, days to 50% heading, and AEN response to four irrigation treatments in Louisiana and Mississippi in 2013 and 2014†. 21

1.4 Days to 50% heading, mature plant height, AEN, and rice grain yield response of six cultivars in Louisiana and Mississippi in 2013 and 2014†. 22

1.5 Test of fixed effects and interaction among fixed effects for cultivars 'CLXL745' and 'Presidio' for biomass, N-uptake, IEN, and REN in Louisiana and Mississippi in 2013 and 2014†....22

1.6 The effect of irrigation treatment on cultivars 'CLXL745' and 'Presidio' for biomass, N-uptake, and REN in Louisiana and Mississippi in 2013 and 2014†. 23

1.7 The effect of cultivar on biomass, N-uptake, IEN, and REN in Louisiana and Mississippi in 2013 and 2014†....23

1.8 Measured oxidation/reduction potentials in an irrigation experiment conducted at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2013....24

1.9 Measured oxidation/reduction potentials in an irrigation experiment conducted at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2014....25

2.1 Individual site locations, soil series, taxonomic classification and crop rotation information for nitrogen (N) response tests conducted in 2013 and 2014....47

2.2 ANOVA results for rice experimental design experiment on two soil textures in Stoneville, MS in 2013 and 2014. 48

2.3 Response parameters and significance levels for a quadratic response of grain yield to N rate using ANCOVA for an experiment conducted on clay soil type in 2013 and 2014†. 48

LIST OF FIGURES

1.1 Soil redox potential and soil moisture levels from a field experiment conducted on a Sharkey clay soil in Stoneville, MS in 2013..........................26

1.2 Soil oxidation-reduction potential for a rice irrigation experiment at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2013. 27

1.3 Soil oxidation-reduction potential for a rice irrigation experiment at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2014. 28

2.1 Rice grain yield response to N fertilizer rate and economic optimum N rate (EONR) using two experimental designs on clay soils in 2013 and 2014...49

2.2 Rice grain yield response to N fertilizer rate and economic optimum N rate (EONR) using two experimental designs on silt loam soils in 2013 and 2014. 50

CHAPTER I

WATER MANAGEMENT STRATEGIES AND THEIR EFFECTS ON RICE GRAIN YIELD, NITROGEN USE EFFICIENCY, AND SOIL CHEMICAL PROPERTIES

1.1 Abstract

A thirty year decline of aquifer water levels in the Mississippi River Valley Alluvial Aquifer (MRVAA) is primarily due to agricultural water use that exceeds long-term recharge rates, therefore irrigation of crops should be done in the most efficient manner. This study was conducted to determine the impact of irrigation technique for rice (*Oryza sativa* L.) on six cultivars commonly grown in Louisiana and Mississippi. The effects of four irrigation strategies for six rice cultivars on maturity, mature plant height, nitrogen use efficiency, rough rice yield, and soil redox potential were investigated in 2013 and 2014 at LSU AgCenter in Crowley, LA on a Crowley silt loam (fine, smectitic, thermic Typic Albaqualfs) and at Delta Research and Extension Center in Stoneville, MS on a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts). Nitrogen use efficiency and rice grain yield for rice grown in an aerobic environment was reduced at least 20% compared to continuous flood, straighthead-drain management, and alternate wetting and drying (AWD) irrigation. Straightead irrigation and AWD performed similar to the continuously flooded production system for N-use efficiency and rice grain yield. Alternative irrigation strategies to a continuous flood system may promote increased

irrigation efficiency for rice in midsouthern US production systems, and advocate long-term sustainability of the MRVAA.

1.2 Introduction

Rice (*Oryza sativa* L.) is the staple food for over half of the world's population (Johnson et al., 2012). Additionally, at least 3.5 billion people depend on rice for 20% of their daily caloric intake. Although the US accounts for only 2% of world rice production, US exports account for 10% of the global rice volume (Weber and Lee, 2006). In the US, rice production is concentrated in four regions: Arkansas Grand Prairie, Mississippi River Valley Alluvial Floodplain (including parts of Arkansas, Mississippi, Louisiana, and Missouri), Gulf Coast (southwest Louisiana and Texas), and the Sacramento Valley of California (Childs, 2012). Mississippi long grain rice production is ranked fourth in the US, after Arkansas, Louisiana, and Missouri (USDA-NASS, 2015) Seventy five percent of the 1.2 million hectares of rice grown in the US relies on the Mississippi River Valley Alluvial Aquifer (MRVAA) for irrigation (Powers, 2006; USDA-NASS, 2015). Approximately 98% of the total withdrawals from the MRVAA is used for agricultural irrigation (Rashid et al., 2014). Irrigated rice hectarage for the MRVAA region is 52% less than irrigated soybean [*Glycine max* (L.) Merr.] hectarage, but rice irrigation withdrawal is 78% greater than soybean withdrawal (USDA-NASS, 2015). Additionally, average rice water input is three times greater than soybeans and corn (*Zea mays* L.) water-use ha^{-1}. Agricultural water use from the MRVAA exceeds long-term recharge rates, causing a decline in aquifer water levels. The 30-year decline of the MRVAA is cause for concern regarding its sustainability (Wax et al., 2008).

Rice production in Mississippi and Louisiana has progressed towards water-saving techniques (Massey et al., 2014). Levees are constructed in rice production fields to facilitate water management. Contour levees are constructed with the natural slope of the land and are used on fields that are not precision land leveled. Land leveling on rice production fields allows for levees to be constructed straight and perpendicular to the slope of the field. Using straight levees compared with contour levees results in a more uniform flood depth, decreases tillage and harvest cost, and allows for better drainage and weed control. The adoption of straight-levee rice production during the 1980's decreased water use by 17%, compared with contour-levee production (Smith et al., 2007). Using low pressure, thin-walled (225 to 255 μm) disposable irrigation tubing to deliver water independently to each paddy reduces irrigation inputs up to 17% compared with single-point (levee-gate) distribution system (Vories et al., 2005). Fields that are precision leveled with no slope are referred to as zero-grade. No levees are needed to maintain uniform flood depth on zero-grade production fields, and water use is reduced 60% compared with contour levee fields (Watkins, 2007).

Several irrigation strategies are used in the US for rice production. In the midsouthern US drill-seeded delayed-flood production system, a 5- to 10-cm flood is established at the four- to five-leaf rice growth stage and maintained until 2 weeks prior to harvest. This is referred to as continuous flood, and is the most commonly practiced water management system for rice in the US (Street and Bollich, 2003). In addition to continuous flood, three alternate water management approaches have been noted: straighthead irrigation, alternate wetting and drying (AWD), and in an aerobic production. Straighthead disorder is a physiological disorder of rice that causes high (or complete) sterility and results in a panicle that remains upright at maturity (Ou, 1985). The cause of straighthead disorder is unknown; however, prevention may be achieved by removal of floodwater prior to internode elongation (Atkins, 1974). Floodwater is reestablished and maintained as a continuous flood until draining for harvest. An estimated 10 to 20% of the US rice hectarage is drained and dried annually for prevention of straighthead disorder (Wilson et al., 2001).

Alternate wetting and drying, which began in India, is a water management strategy for rice wherein the field is not continuously flooded. (Lampayan et al., 2015; Sandhu et al., 1980). Currently, AWD is the recommended water management practice for rice in Bangladesh, the Philippines, Myanmar, and Vietnam (Lampayan et al., 2014b, 2015; Palis et al., 2014; Rejesus et al., 2013). Reductions in water loss can under AWD varies by region and is determined by research in each respective region. Alternate wetting and drying in rice that does not result in a loss of grain yield is considered "safe" AWD, and must be determined experimentally. The degree of water reduction that is considered "safe" may also depend on crop growth stage, soil type, and depth of groundwater table (Lampayan et al., 2014a, 2015). For example, "safe" AWD was determined for rice production in the Philippines, and was reported that water level within a paddy can be reduced until the groundwater is 15 cm below the soil surface (Lampayan et al., 2015). Determination of "safe" AWD is not yet determined in the US.

Rice grown on continuously unsaturated soil is referred to as aerobic rice. Aerobic rice can maximize water use in terms of yield and is suitable for water-limiting conditions (Xiaoguang et al., 2003). In tropical rice production systems, aerobic rice increases water use efficiency 20 to 40% over continuously flooded systems (Castaneda et al., 2003).

Although aerobic rice production increases water use efficiency, yield reduction and instability of grain yield over time has to be considered before implementation (Farooq et al., 2009). An aerobic environment increases disease pressure, such as rice blast (*Pyricularia grisea*). Cultivars that are moderately resistant to rice blast are less susceptible to yield losses from blast. In the US, aerobic rice is grown under center-pivot irrigation in Missouri and Arkansas, and in a row-crop culture with furrow irrigation (Stevens et al., 2012, Vories et al., 2002). Growing rice under center pivot irrigation results in a yield reduction compared with a conventional continuous flood (Vories et al., 2002, 2012). Additionally, research in the midsouthern US determined that rice produced using furrow and sprinkler irrigation is not economically viable (Nalley et al., 2014; Van der Hoek et al., 2001, Vories et al., 2010).

The effects of alternate irrigation management strategies on agronomic and N dynamics have been evaluated in many rice-producing countries. Tropical rice production in Asia consists of upland and lowland rice (Bouman et al., 2005). Lowland rice is grown under continuous saturated soil conditions (anaerobic), and upland rice is grown in nonflooded and nonsaturated (aerobic) soil with supplemental irrigation. In aerobic conditions, NH_4^+ is supplied to the rice roots primarily by diffusion and NO_3^- by mass flow and diffusion (Keeney and Sahrawat, 1986). When rice is in an anaerobic environment, NH_4^+ is stable and accumulates, but under anaerobic environments NO_3^- is unstable and is converted into N_2 gas by denitrification. The instability of NO_3^- in flooded soils is well documented, and denitrification loss in flooded rice has indirectly been recognized because of its poor performance as an N source in lowland rice (Cabangon et al., 2011; Cassman et al., 2002; DeDatta, 1981; Haefele et al., 2008; Keeney and

Sahrawat, 1986; Ladha et al., 2005; Linquist et al., 2011; Norman et al., 2003; Pirmoradian et al., 2004; Ponnamperuma, 1972, 1978; Shao et al., 2014; Sun et al., 2012).

Reducing the amount of water that is present in the soil solution can affect nutrient availability to rice plants. In the drill-seeded, delayed-flood rice production system, rice is grown upland until the four- to five-leaf growth stage at which time an ammonium-forming nitrogen (N) source is applied, termed preflood N application (Norman et al., 2003). A 5- to 10-cm flood is established and preflood N is immediately incorporated into the soil profile with the floodwater. If this N management strategy is performed correctly, N recovery ranges from 65 to 75%. Several forms of N exist in soil; however, ammonium (NH_4^+) and nitrate (NO_3^-) are the forms used by rice plants (Norman et al., 2003). Alternating between anaerobic and aerobic soil environments in rice production systems can result in reduced yields and increased environmental loading via nitrification and denitrification losses (Cassman et al., 1998; Massey et al., 2014). Under well-aerated (oxidized) conditions, oxygen is the ultimate acceptor of electrons that are produced by microbial oxidation of carbon (C) in organic compounds (Kozlowski, 1984). Redox potential of a soil influences oxygen concentration in the soil, pH, directly and indirectly affects the concentration of nutrients in soil solution, including NH_4 (Ponnamperuma, 1978; DeDatta, 1981). Additionally, nitrification potential on soils used for rice production in Mississippi, such as Sharkey clay (very-fine, smectitic, thermic *Chromic Epiaquerts*), is 22 to 57% higher than light-textured soils commonly used for rice production in the southern US (Fitts et al., 2014). Management of nutrients for rice under AWD or aerobic conditions may differ when compared to traditionally flooded systems and must be considered.

Nitrogen use efficiency (NUE) is defined as the proportion of all N inputs that are removed in harvested crop biomass, contained in recycled crop residues, and incorporated into soil organic matter and inorganic N pools (Cassman et al., 2002). Alternate wetting and drying management is commonly used in rice production to increase water use efficiency (WUI) and NUE in many parts of the world (Cabangon et al., 2001). Alternate wetting/drying increase water-use efficiency 13 to 16% over continuously flooded rice irrigation (Belder et al., 2003). Although AWD reduces water inputs, nitrate-N buildup during field drying can result in up to 60% loss of fertilizer-N applied (Linquist et al., 2011). Average N-fertilizer uptake efficiency, or N-fertilizer recovery efficiency (REN), is defined as the percentage of fertilizer-N recovered in aboveground biomass during the growing season. When methods of irrigation are altered, NUE of the rice plant can be altered. Reduced NUE can decrease yield, and must be considered when changing agronomic practices. Nitrogen fertilizer accounts for the greatest input cost in rice production, and contributes to the greatest economic losses incereal cropping systems. Improving REN reduces the amount of fertilizer-N that is lost to the environment.

Alternate wetting and drying increase NUE of rice compared to continuous flood irrigation (Pirmoradian et al., 2004; Sun et al., 2012). The reduced water input compared with continuous flooding may improve the soil aeration and enhance oxygen supply to the root system, produce and supply more assimilates to the newly emerged leaf, improve the assimilation of inorganic N and the photosynthetic rate, and consequently provide sufficient material for growth (Sun et al., 2012). Alternate wetting and drying has been shown to produce higher (Guo et al., 2009) or similar (Shao et al., 2014) grain yield compared with continuous irrigation. Shao et al. (2014) reported that AWD irrigation enhanced root and panicle dry matter accumulation and partitioning, effective panicles per m^2, spikelets per m^2, grain filling percentage, all of which increased grain yield while reducing water input.

Several issues exist concerning rice irrigation practices. Elliot et al. (2014) reported that although increasing yields 5 to 10% yr^{-1} in the US via irrigation practices is technically possible, it may not be economical due to the cost of irrigation relative to the potential increase in production. The apparent trend in climate models suggest that crop water consumption will rise, thus requiring more irrigation per ha of agricultural land. The adoption of water-saving irrigation practices that maintain or improve yield is necessary to mitigate the low irrigation efficiencies associated with increased irrigation.

The MRVAA is relied on for irrigating intensively managed crops in the Mississippi River Delta region of Mississippi (Powers, 2006). Therefore, irrigation of crops, including rice, should be done in the most efficient manner. Continuous flooding has been the common irrigation scheme used for most rice producers in the US, yet several other established practices exist (Street and Bollich, 2003). Alternate irrigation strategies may reduce irrigation costs; however, producers have expressed concerns regarding the potential negative impacts of AWD flooding (Massey et al., 2014). These concerns include reestablishment of flood in a timely manner, nitrogen dynamics, pest management, and labor associated with changing a management practice. Before adoption of alternate irrigation strategies in the southern US, examining effects on popular rice varieties and hybrids is a priority. The objective of this study was to evaluate the impact of alternate rice irrigation strategies on grain yield and NUE, and to understand the agronomic and physiological performance of six rice cultivars in Louisiana and Mississippi.

1.3 Materials and Methods

An experiment was conducted in 2013 and 2014 in Louisiana and Mississippi to evaluate the response of six rice cultivars to four irrigation treatments. Specific details of each location are reported in Table 1.1. The experimental design was a split plot design with irrigation as the main plot and cultivar as the sub plot. The main plot factor was not replicated within each site and year, therefore two sites and two years were used as replication of the main plot factor. The four irrigation treatments included:

1. Continuous flooding for the drill-seeded, delayed-flood cultural system (Street and Bollich, 2003). For the continuous flood treatment, a 10-cm flood was established at the 1 to 2 tiller growth stage. Flood was maintained until 2 to 3 wk prior to harvest, and drained.
2. Straighthead management system, where flood was established and maintained for 10 to 14 d, then allowed to drain until soil was completely dry and cracked, followed by a continuous flood until 2 to 3 wk prior to harvest (Street and Bollich, 2003; Wilson et al., 2001).
3. Alternate Wetting and Drying, where flood was maintained for 10 to 14 d, then allowed to subside until soil moisture reached field capacity as reported by soil moisture sensor, flooded back to 5 to 10 cm depth and repeated until 2 to 3 wk prior to harvest (Bouman and Tuong, 2001).

4. Aerobic culture, where rice was flooded when soil moisture reached field capacity as reported by soil moisture sensor, maintained for 12 hr then released, and repeated until 2 to 3 wk prior to harvest.

Three inbred long-grain, one inbred medium-grain, and two hybrid long-grain cultivars were evaluated. Inbred long-grain cultivars evaluated were ‘CL151’ (Blanche et al., 2011), ‘Cheniere’ (Linscombe et al., 2006), and ‘Presidio’ (Anonymous, 2005). The inbred medium-grain cultivar was ‘Jupiter’ (Sha et al., 2006). Hybrid long-grain cultivars were ‘CLXL729’ and ‘CLXL745’ (RiceTec, Inc., Alvin, TX). Experimental plots were drill-seeded from late March to late April, with dates corresponding to the optimum planting period for rice from southern Louisiana to north Mississippi (Beuhring et al., 2008; Saichuck et al., 2014).

This experiment was conducted on a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) soil in Mississippi, and on a Crowley silt loam (fine, smectitic, thermic Typic Albaqualfs) soil in Louisiana. Experimental plots were managed according to University recommendations for each respective state to minimize weed and insect pest pressure (Buehring et al., 2008; Saichuck et al., 2014). Experimental main plots in Mississippi measured were separated by two levees to minimize seepage from one irrigation treatment to adjacent main plots. In Mississippi, experimental subplots consisted of 8 rows spaced 20-cm apart and measured 4.6-m in length. Experimental subplots in Louisiana consisted of 12 rows spaced 15.68-cm apart and measured 6.1-m in length. Grain was packaged to plant on a weight basis. Experimental plots were seeded at 80 and 30 kg ha^{-1} for inbred and hybrid cultivars, respectively (Walker et al., 2013). Rice was seeded to a depth of 2 cm with a small-plot grain drill (Great Plains Mfg., Inc., Salina, KS) equipped with double disk openers and press wheels spaced 20-cm apart. In all site years, a 10-cm flood was established at the one- to two-tiller rice growth stage. Flood was maintained for 10 to 14 days before initiating irrigation treatments. Nitrogen fertilizer was applied immediately before flood establishment as urea (46-0-0) at approximately 165 kg ha^{-1} for clay textured soils and 135 kg ha^{-1} for silt loam soils.

Soil moisture for each irrigation treatment was monitored using Irrometer Watermark 200SS (IRROMETER Company, Inc., Riverside, CA) soil moisture sensors placed within a rice plot in the center of the paddy at a 10-cm depth. Data collection occurred every 30 minutes with an Irrometer Watermark 900M Monitor. Field moisture capacity is equal to -33 kPa, at which an irrigation event would occur for AWD and aerobic managed treatments (USDA-NRCS, 2015). Values for volumetric water content at field capacity used were 28.2% and 42.8% for Crowley silt loam and Sharkey clay soil types, respectively.

Soil chemical conditions were monitored using Sensorex Oxidation Reduction Potential (ORP) (Sensorex, Garden Grove, CA) electrodes in each of the irrigation treatments. Sensors were placed within a rice plot in the center of the paddy at 10-cm depth. All ORP data collection in Mississippi was recorded using a Campbell Scientific CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) collecting 30-min averages. Data for the 2014 experiment in Stoneville, MS was not included due to sensor malfunction. Oxidation/Reduction potential was collected in Louisiana weekly in 2013 and 2014. A Fluke 77-IV multi-voltage meter with a calomel electrode reference was used to obtain redox potential (Patrick et al., 1996). In Louisiana, the electrodes were removed prior to harvest of the main-crop and reinstalled before re-flooding for the ratoon-crop. Redox potential was calculated by removing the highest and lowest readings from each water management treatment, and remaining readings were averaged. Final redox potential was reported based on standard hydrogen electrode by adding 245 mV (Patrick et al., 1996). The maximum (Eh_{max}) and minimum (Eh_{min}) reduction potentials were calculated for Louisiana in 2013 and 2014. Linear response analyses were conducted to calculate the rate of reduction from irrigation initiation until 8 to 10 d immediately following flood establishment, and the rate of reduction from 10 days until 5 weeks post-flood establishment.

Phenotypical measurements were collected to monitor rice plant developmental growth across the four irrigation treatments. Days to 50% heading was recorded as an estimation of plant maturity by calculating the time from seedling emergence until 50% of the rice plants in an individual plot had fully emerged panicles. Plant height was measured from the ground surface to the tip of the tallest panicle at maturity.

Rice plots were harvested when the grain moisture reached a range of 150 to 180 g kg^{-1} with a Wintersteiger Delta (Wintersteiger USA, Salt Lake City, UT) small-plot combine equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc., Logan, UT). Yields were adjusted to a moisture content of 120 g kg^{-1} for analysis.

Total above ground biomass was collected for the cultivars CLXL745 and Presidio from 0.9-m of row when rice was at the panicle emergence growth stage. Biomass was oven-dried at 60°C for 48 h until a constant weight was achieved. Tissue was ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) with a #40 screen. Samples were weighed to determine the total dry matter (TDM). Tissue analysis for total N content was conducted at LSU AgCenter RRS using a LECO TruSpec series combustion analyzer (LECO Corp., St. Joseph, MI). The agronomic efficiency of N (AEN; kg grain yield per kg N applied) was calculated based on the yield increase due to N application divided by N rate. Internal (physiological) efficiency of N (IEN; kg grain yield per kg N uptake) was calculated by dividing total grain yield by total aboveground N uptake, and recovery efficiency of applied N (REN; kg fertilizer N uptake per kg N applied) was estimated based on the increase in plant N uptake due to N application divided by the N rate applied (Ladha et al., 2005).

1.3.1 Statistical Analysis

All data were subjected to ANOVA using the Mixed Procedure (Littell et al., 2006; SAS, 2013) in SAS 9.4 (SAS Institute Inc., Cary, NC). Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Replication of cultivar (nested within site-year and irrigation treatment). Considering site-year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al., 2011; Carmer et al., 1989). Treatment means were averaged for each cultivar within each irrigation treatment for rice grain yield, plant height, days to 50% heading, AEN, biomass, N uptake, IEN, and REN. Fixed effects for these parameters were cultivar and irrigation treatment. Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS software, which is a macro for converting mean-separation output letter groupings (Saxton, 1998).

1.4 Results and Discussion

Cultivar and irrigation treatment affected maturity (days to 50% heading), mature plant height, AEN, and rice grain yield (Table 1.2). No interactions among main effects of cultivar and irrigation treatment were detected for maturity, plant height, AEN and Rice grain yield. Pooled over cultivar, aerobic irrigation reduced maturity by 3 d and plant height 13 to 15% compared with other irrigation treatments. Similar studies have reported that rice grown aerobically can exhibit delays in maturity up to 1 wk (Okami et al., 2011). Delay in maturity ≤ 3 d does not directly influence harvestability or rice grain yields, but longer delays in maturity could have negative implications (Bond and Walker, 2012). Declining day length, temperature, and tropical weather frequency during anthesis or harvest can reduce a grower's economic returns (Bond and Walker, 2012; Jones and Synder, 1987; Slaton et al., 2003). Similar to maturity, plant height >70 cm does not directly affect grain yields, but can have negative implications. Plant height influences harvest height of a combine, and lowering harvest height in US production fields increases harvest time and unwanted green material entering harvest equipment (Quick, 2003). Pooled over irrigation treatments, maturity and plant height varied with cultivar (Table 1.4). The hybrid cultivars CLXL729 and CLXL745 matured earlier than the inbred cultivars, Cheniere, Presidio, and Jupiter. Jupiter matured later than all other cultivars tested. Maturity of CL151 was similar to CLXL729 and Presidio less than Cheniere. Plant heights for hybrid cultivars were 9 to 16% greater than all inbred cultivars. CL151 mature plant height was 7, 6, and 2% greater than Cheniere, Presidio, and Juptier, respectively. Jupiter plant height was greater than Cheniere, and no different from Presidio. Cheniere plant height was less than all cultivars.

Aerobic irrigation reduced AEN and rice grain yield compared with other irrigation treatments (Table 1.3). Agronomic efficiency of N for aerobic irrigation was 20 to 25% lower than AWD, straighthead, and continuous irrigation. Pooled over all irrigation treatments, AEN for CLXL729 (73 kg yield kg^{-1} N) was greater than all inbred cultivars, and was no different from CLXL745 (Table 1.4). CLXL745 and CL151 (67 and 65 kg yield kg^{-1} N, respectively) were similar to one another and greater than Cheniere and Presidio (55 and 50 kg yield kg^{-1} N, respectively). Jupiter (60 kg yield kg^{-1} N) AEN was greater than Presidio, and no different from Cheniere. Presidio had the lowest AEN of all cultivars tested, but was not statistically different than Cheniere.

Rough rice yield was 25 to 28% less for aerobic rice compared to all other irrigation treatments (Table 1.3). No difference in grain yield was observed between AWD and continuous flood. Similar studies have also shown no differences in grain yield for AWD and continuous flood (Avila et al., 2015; Belder et al., 2004; Borrel et al., 1997; Tabbal et al., 2002). Grain yield in aerobic production systems can vary, largely depending on water availability during the post-anthesis growth stage that can enhance net assimilation and mean leaf area index (LAI) (Okami et al., 2011). Selecting a cultivar that exhibits rapid early vegetative leaf growth to capture incident radiation efficiently under aerobic conditions is important to maintain yields comparable to continuously flooded production systems (Kato et al., 2009; Katsura et al., 2010; Okami et al., 2011). Pooled across irrigation treatments, CLXL729 produced greater Rice grain yields than other cultivars tested. CL151 and CLXL745 had similar yields to Jupiter, and was these were greater than Cheniere and Presidio. Juptier and Cheniere were similar and produced greater yields than Presidio. Of cultivars tested, the lowest Rice grain yield was observed for Presidio.

The cultivars CLXL745 and Presidio were used to test for plant biomass, N uptake, Internal efficiency of N (IEN), and the Recovery efficiency of N (REN) for all irrigation treatments (Table 1.5). Biomass, N uptake, and REN were affected by irrigation and cultivar (Table 1.6). Internal efficiency of N was affected by cultivar, but no irrigation effect was detected. Recovered biomass at heading and N uptake were less for aerobic irrigated rice compared with other irrigation treatments. Biomass for AWD, straighthead, and continuous irrigation were greater than aerobic rice by 42%, 30%, and 36%, respectively. Nitrogen uptake and recovery efficiency of N (REN) for continuous and AWD irrigation were similar to straighthead irrigation, and were greater than aerobic culture. Aerobic and straighthead N uptake were not different from one another, and could be caused by possible nutrient loss post flood via nitrate loading and losses due to nitrification and subsequent denitrification. This is caused when N in the soil is converted to NO_3^- form when the soil is saturated, and lost to the atmosphere as N gas as aeration in the soil increases.

Recovery efficiency of N was greater for continuous and AWD irrigation than aerobic irrigation by 19 and 20%, respectively (Table 1.6). CLXL745 utilized N more efficiently than Presidio (Table 1.7). Biomass, N uptake, IEN, and REN was greater for CLXL745 compared to Presidio. Walker et al. (2008) reported a yield advantage of 1685 to 2454 kg ha^{-1} for the hybrid long-grain cultivar ‘XL723’ compared with inbred cultivars. Increase in N-use efficiency and subsequent yield increase is associated with greater root mass and number compared with inbred cultivars.

1.4.1 Soil Chemical Properties

Soil Oxidation/Reduction potential was collected from flood establishment until fields were drained for harvest in Mississippi in 2013 and 2014. Data for 2013 is reported in Figure 1.1. Soil Oxidation/Reduction potential for Louisiana in 2013 and 2014 is reported in Figure 1.2 and Figure 1.3, respectively. The maximum (Eh_{max}) and minimum (Eh_{min}) reduction potentials for Louisiana in 2013 and 2014 are shown in Table 1.8 and Table 1.9, respectively. Linear response analyses were conducted to calculate the rate of reduction from irrigation initiation until 8 to 10 d immediately following flood establishment, and the rate of reduction following until 5 wk post flood establishment. Data are reported for the main and ratoon crop in days after initiation of irrigation. The rate of reduction is highest in the first 8 days after flood establishment for both main and ratoon crop compared with the remaining period in which irrigation was maintained. The degree of reduction in the soil was 70 to 75% less in aerobic irrigated rice compared with other irrigation treatments. Similar results were reported by Reddy and Patrick (1975), who reported a three-fold decrease in reduction potential for continuously anaerobic conditions in soil compared with aerobic culture.

Increasing the time between alternating aerobic and anaerobic systems allows redox potentials to reach lower levels. However, Reddy and Patrick (1975) reported that the first decrease in reduction potential was greater than the subsequent decreases when cycling aerobic/anaerobic systems. Our data suggest that the rate and severity of reduction of soil was higher in the ratoon than in the main crop. The amount of fertilizer-N that is converted to nitrate slows the rate of reduction in the soil. Nitrate has been shown to prevent a rapid decline in redox potential (Reddy and Patrick, 1975). The depletion of nitrate in the soil from the rice plants during the main-cropping season may allow for more rapid reduction in subsequent aerobic/anaerobic cycles.

Prolonged aerobic conditions in rice can increase N loss in rice production (DeDatta, 1981; DeLaune and Reddy, 2005). This is because of the predominately aerobic nature of the soil present in aerobic irrigated rice. Our data suggest that aerobic irrigated rice remained aerobic (>200 mV) excluding the 8 days following flood establishment for a ratoon crop in Louisiana. Due to the short amount of time that irrigation water remained in the paddy, the soil was not allowed to become greatly (< -600 mV) reduced. The yield loss in aerobic irrigated rice can be attributed to the presence of O_2 in the soil. In highly reduced soil environments, such as continuously flooded fields, anaerobic conditions cause NH_4 to be stable and accumulate, and NO_3 to be unstable (Norman et al., 2003). The instability of NO_3 is due to its use in the anaerobic environment as an electron acceptor for microbes in place of O_2, and loss to the atmosphere via denitrification as N_2 occurs. When slightly reduced soil begins to turn aerobic as the soil dries, NH_4 can diffuse upward from the reduced soil layer to the oxidized soil layer and be nitrified, and resulting NO_3 can diffuse or leach back to the reduced layer and be denitrified. This diffusion-nitrification-denitrification is not of major significance in dry-seeded, delayed- continuous-flood rice culture due to the rice plant's ability to reach maximum N-uptake in ≤ 3 wk (Norman et al, 2003). Twenty percent of available N in the soil is lost within the first 3 submergence/drying cycles (Patrick and Wyatt, 1964). Therefore, if no drying occurs during the time that rice is actively absorbing fertilizer-N, the amount of N lost can be reduced. The lack of severe reduction in the aerobic irrigated treatment resulted in less stability of NH_4, and perhaps increased the rate at which N loss occurred. Using a continuous flood system increased the severity of reduction late in the season, but did not impact N-uptake. This is due to the rice plant's ability to reach maximum N uptake during the first 2 to 3 wk after the preflood N application. Straighthead management in rice allows soil to become completely dry at the 1- to 2-cm internode elongation growth stage. This could be an advantage to growers applying a mid-season fertilizer application by reducing loss of N via volatilization when applying into floodwater or onto a moist soil surface (Norman et al., 2003). Although AWD flooding irrigation allows for the top layer of the soil to become slightly aerobic, the stability of N in the root zone during maximum N uptake is not different from a continuous- or straighthead-managed irrigation system.

1.5 Conclusion

The objective of this research was to evaluate the impact of alternate rice irrigation strategies on grain yield and NUE for six rice cultivars commonly grown in Louisiana and Mississippi. Rice grown in an aerobic environment performed poorly compared with continuous flood, irrigation managed for straighthead prevention, and AWD irrigation. Moreover, data suggest that when properly managed, use of an alternate irrigation strategy, such as AWD irrigation, does not result in a loss in NUE, plant height, or grain yield compared to a continuously flooded system. Alternate wetting and drying irrigation reduces water usage by up to 50%, and increases N use efficiency in major rice producing countries that currently experience irrigation water scarcity. Alternate wetting and drying is currently the recommended irrigation practice in countries that account for 83% of global rice production and include the Phillipines, Bangladesh, Vietnam, India, China, Laos, Thailand, Myanmar, and Indonesia (Lampayan et al., 2004, 2014b, 2015;

Palis et al., 2004, 2014; Rejesus et al., 2011, 2013; Sibayan et al., 2010). In all countries where AWD is recommended, adoption of AWD resulted in a two-fold return in economic benefit for farmers over the investments made to develop and disseminate the technology (Lampayan et al., 2015). In all areas where AWD has been implemented, the technology was assessed and adapted to incorporate into their own programs. Policy and institutional changes of central and local governments were established encourage farmers to adopt safe AWD as well. Prior to widespread adoption of AWD irrigation in the southern US, best management practices (BMPs) for production size fields should be well defined. Adoption of water saving irrigation strategies provides a long-term solution for sustainability of the MRVAA.

Table 1.1 Extractable nutrients for an experiment conducted to evaluate rice irrigation strategies in Stoneville, MS, and Crowley, LA in 2013 and 2014.

Year	Soil texture‡	Sum of bases	pH	%OM	Extractable Nutrient Levels†				
					P	K	Ca	Mg	Zn
					mg kg^{-1}				
2013	Sharkey clay	42.7	8.3	2.41	194	534	12000	2875	4.2
2013	Crowley silt loam	4.1	7.1	1.13	13	68	1179	254	7.4
2014	Sharkey clay	41.6	8.0	1.60	190	553	11300	3023	4.9
2014	Crowley silt loam	5.7	7.4	1.75	12	66	1744	297	5.9

†Lancaster soil testing method (Cox, 2001).
‡Soil texture classification (USDA-NRCS, 2015).

Table 1.2 Statistical significance of the main effects tested for grain yield, plant height, days to 50% heading, and AEN† in Louisiana and Mississippi in 2013 and 2014.

Source	Days to 50% heading	Mature plant height	AEN	Rice grain yield
	Pr > F			
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation‡	<0.0001	<0.0001	0.0046	0.0053
Cultivar x Irrigation	NS§	NS	NS	NS

† AEN, Agronomic efficiency of N
‡ Irrigation, irrigation treatment.
§ NS, not significant at P = 0.05.

Table 1.3 Rice grain yield, plant height, days to 50% heading, and AEN response to four irrigation treatments in Louisiana and Mississippi in 2013 and 2014†.

Irrigation‡	Days to 50% heading	Mature plant height	AEN§	Rice grain yield
	DAE¶	cm	%	kg ha^{-1}
Continuous	93 b	97 a	67 a	10053 a
Straighthead	93 b	96 a	65 a	9703 a
AWD#	93 b	94 a	65 a	9651 a
Aerobic	96 a	82 b	50 b	7278 b

† Data were pooled across six cultivars and four site-years. Means followed by the same letter for each parameter are not significantly different at P ≤ 0.05.
‡ Irrigation, irrigation treatment.
§ Agronomic Efficiency of Nitrogen (kg grain yield kg^{-1} N applied).
¶ DAE, days after emergence.
# AWD, alternate wetting and drying.

Table 1.4 Days to 50% heading, mature plant height, AEN, and rice grain yield response of six cultivars in Louisiana and Mississippi in 2013 and 2014†.

Cultivar	Days to 50% heading	Mature plant height	AEN‡	Rice grain yield
	DAE§	cm	%	kg ha^{-1}
CLXL729	92 de	99 a	73 a	10809 a
CLXL745	91 e	99 a	67 ab	9795 b
CL151	93 cd	91 b	65 bc	9699 b
Cheniere	95 b	85 d	55 de	8257 c
Presidio	94 bc	87 cd	50 e	7397 d
Jupiter	97 a	89 c	60 cd	9069 bc

† Data were pooled across four irrigation treatments and four site years. Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.
‡ Agronomic efficiency of nitrogen (kg grain yield kg^{-1} N applied).
§ DAE, days after emergence.

Table 1.5 Test of fixed effects and interaction among fixed effects for cultivars ‘CLXL745’ and ‘Presidio’ for biomass, N-uptake, IEN, and REN in Louisiana and Mississippi in 2013 and 2014†.

Source	Biomass	N uptake	IEN‡	REN§
	Pr > F			
Cultivar	<0.0001	0.0119	0.0350	0.0081
Irrigation¶	0.0006	0.0216	NS#	0.0321
Cultivar x Irrigation	NS	NS	NS	NS

† Data were pooled across four irrigation treatments and four site years. Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.
‡ Internal efficiency of N (kg grain yield kg^{-1} N uptake).
§ Recovery efficiency of applied N (kg N uptake kg^{-1} N applied).
¶ Irrigation, irrigation treatment.
# NS, not significant at $P \leq 0.05$.

Table 1.6 The effect of irrigation treatment on cultivars ‘CLXL745’ and ‘Presidio’ for biomass, N-uptake, and REN in Louisiana and Mississippi in 2013 and 2014†.

Irrigation‡	Biomass§	N uptake¶	REN#
	——kg ha^{-1}——		%
Continuous	10541 a	119 a	81 a
Straighthead	10052 a	110 ab	75 ab
AWD††	10934 a	121 a	82 a
Aerobic	7710 b	91 b	62 b

† Data were pooled across six cultivars and four site-years. Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.
‡ Irrigation, irrigation treatment.
§ Biomass, total aboveground biomass (dry weight basis).
¶ N uptake, total N uptake measured at the panicle emergence growth stage.
# REN, recovery efficiency of N (kg N uptake kg^{-1} N applied).
†† AWD, alternate wetting and drying.

Table 1.7 The effect of cultivar on biomass, N-uptake, IEN, and REN in Louisiana and Mississippi in 2013 and 2014†.

Cultivar	Biomass	N uptake	IEN‡	REN§
	—— kg ha^{-1} ——		%	%
CLXL745	10981 a	119 a	88 a	82 a
Presidio	8637 b	101 b	76 b	68 b

† Data were pooled across four irrigation treatments and four site years. Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.
‡ Internal efficiency of N (kg grain yield kg^{-1} N uptake).
§ Recovery efficiency of applied N (kg N uptake kg^{-1} N applied).

Table 1.8 Measured oxidation/reduction potentials in an irrigation experiment conducted at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2013.

		Main-Crop				Ratoon-Crop			
		Continuous†	Straighthead ‡	AWD§	Aerobic¶	Continuous	Straighthead	AWD	Aerobic
	Eh_{max}#	+394	+305	+312	+365	+210	+264	+309	+321
	Eh_{min}††	-132	33	+137	+216	-188	-37	+55	+142
Days 1-8	ΔEh‡‡	-222	-129	-122	-127	-300	-249	-168	-167
	Slope	-33	-19	-18	-18	-44	-37	-25	-25
	r^2	0.83	0.76	0.81	0.99	0.96	0.88	0.94	0.8
Days 8-36	ΔEh	-185	-44	-45	+51	-98	-29	-59	-168
	Slope	-8	-2	-1	+2	-3	-1	-3	+5
	r^2	0.95	0.69	0.49	0.40	0.71	0.90	0.53	0.67

† Continuous, continuous irrigation
‡ Straighthead, straighead managed irrigaiton
§ AWD, Alternate wetting and drying irrigation
¶ Aerobic, rice grown in an aerobic culture
# Eh_{max}, maximum reduction potential (*Eh*) observed in mV.
†† Eh_{min}, minimum reduction potential (*Eh*) observed in mV.
‡‡ ΔEh, change in *Eh* during time period noted (mV)

Table 1.9 Measured oxidation/reduction potentials in an irrigation experiment conducted at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2014.

		Main Crop				Ratoon Crop			
		Continuous[†]	Straighthead[‡]	AWD[§]	Aerobic[¶]	Continuous	Straighthead	AWD	Aerobic
	Eh_{max}[#]	+260	+236	+274	+342	+231	+319	+236	+388
	Eh_{min}[††]	-92	-191	-8	+249	-150	+2	+34	+243
Days 1-10	ΔEh[‡‡]	-44	-53	-102	-16	-274	-242	-202	+76
	Slope	-6	-6	-10	-3	-25	-21	-20	-5
	r^2	0.46	0.95	0.80	0.31	0.87	0.72	0.99	0.20
Days 10-39	ΔEh	-108	-160	-67	+70	-60	-71	+19	+57
	Slope	-4	-7	-3	+3	-2	-3	0	0
	r^2	0.78	0.77	0.64	0.82	0.83	0.99	0.11	0.01

† Continuous, continuous irrigation
‡ Straighthead, straighead managed irrigaiton
§ AWD, Alternate wetting and drying irrigation
¶ Aerobic, rice grown in an aerobic culture
# Eh_{max}, maximum reduction potential (*Eh*) observed in mV.
†† Eh_{min}, minimum reduction potential (*Eh*) observed in mV.
‡‡ ΔEh, change in *Eh* during time period noted (mV)

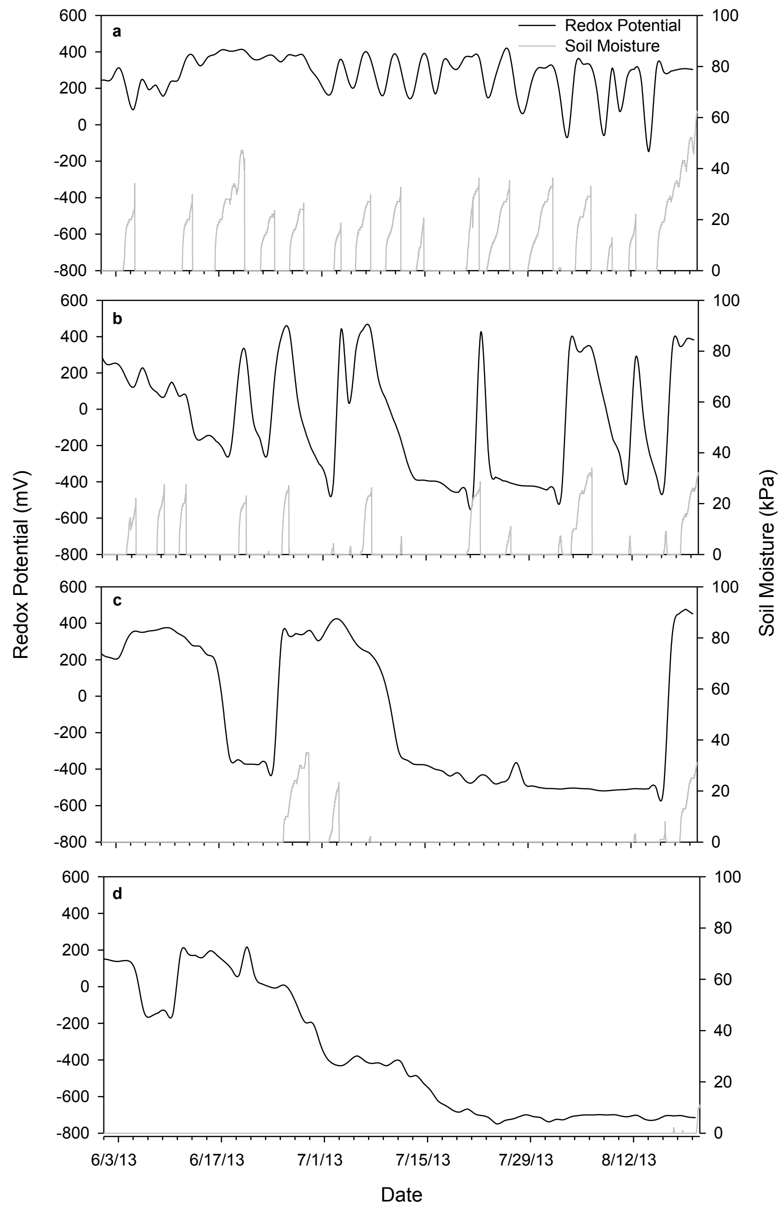

Figure 1.1 Soil redox potential and soil moisture levels from a field experiment conducted on a Sharkey clay soil in Stoneville, MS in 2013.

(a) aerobic irrigated
(b) alternate wet and dry (AWD) irrigated
(c) straighthead managed irrigation
(d) rice grown under a continuous flood

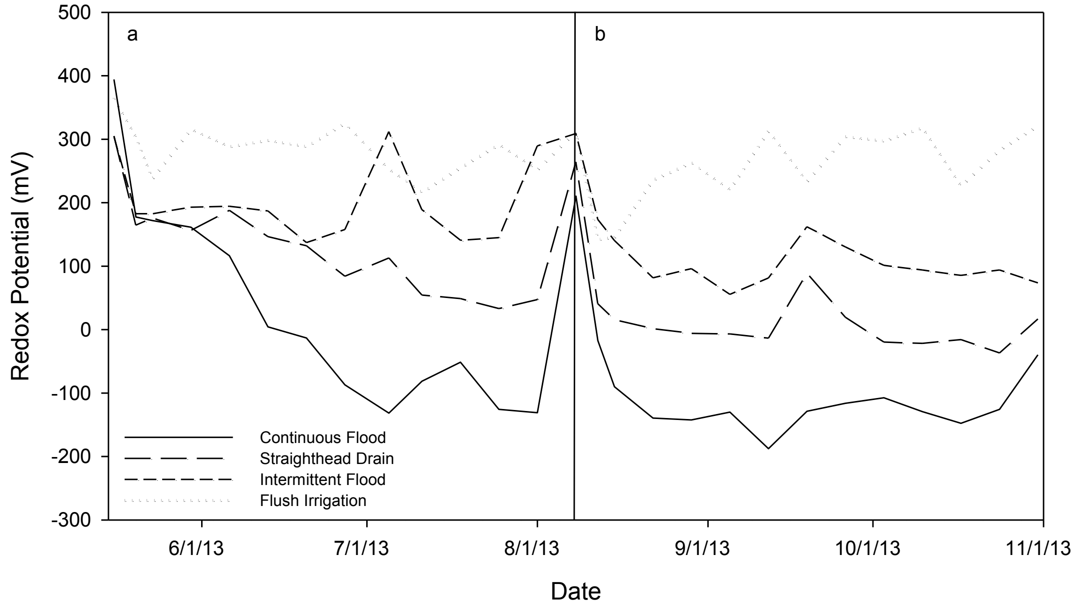

Figure 1.2 Soil oxidation-reduction potential for a rice irrigation experiment at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2013.

(a) Main crop
(b) Ratoon crop

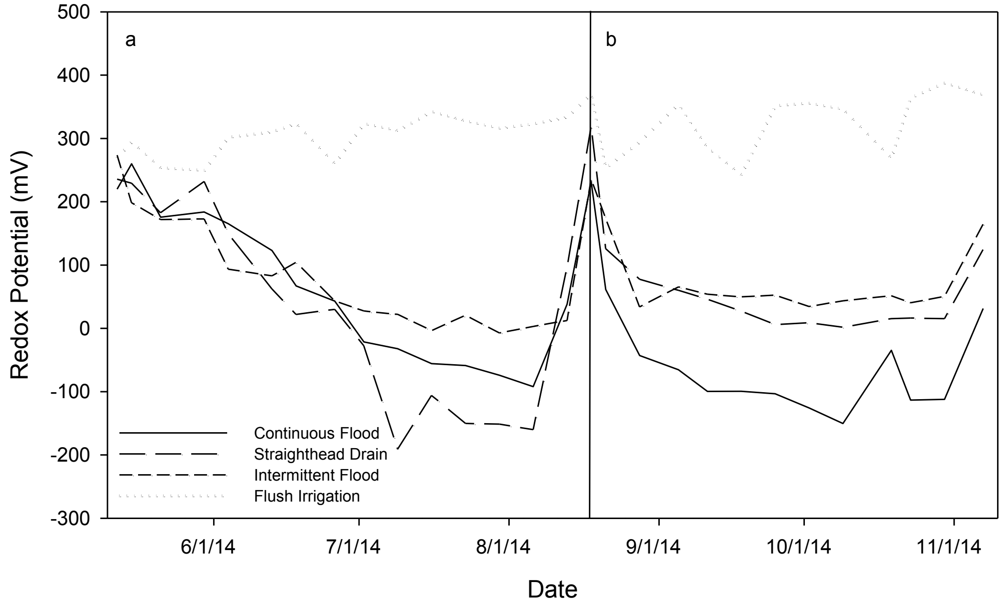

Figure 1.3 Soil oxidation-reduction potential for a rice irrigation experiment at LSU AgCenter in Crowley, LA on a Crowley silt loam soil in 2014.

(a) Main crop
(b) Ratoon crop

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CHAPTER II

EVALUATION OF RANDOM COMPLETE BLOCK AND SPLIT PLOT EXPERIMENTAL DESIGNS FOR NITROGEN RESPONSE TRIALS IN RICE

2.1 Abstract

Nitrogen (N) response studies are conducted for rice (*Oryza sativa* L.) to provide grower recommendations with economical optimum N rates (EONRs) in Mississippi. The objective of this experiment was to determine the effect of randomized complete block (RCB) and split-plot (SP) experimental designs on rice grain yield response to N fertilizer for N response trials in Mississippi, and to determine if one experimental design was superior in predicting EONRs. The effect of RCB and SP experimental design on N-response experiments was investigated on sites with clay and silt loam soils near Stoneville, MS in 2013 and 2014. Rice grain yield response to seven N-fertilizer rates was tested comparing RCB with SP experimental design. Grain yield response data were fitted with a quadratic equation, and differences in response coefficients were tested comparing RCB with SP design. No differences were detected between RCB and SP designs for rice grain yield response to N-rate; therefore either design, RCB or SP, would be appropriate for use in N-response studies for rice.

2.2 Introduction

Historically, rice nitrogen (N) fertilizer recommendations have been defined according to the current inbred or hybrid cultivars being grown and are modified according to soil texture, tillage system, seedbed condition, and previous crop (Buehring et al., 2008; Saichuk et al., 2014). The recommendations are made from N fertilizer response data that are generated each year by university scientists across multiple locations (Harrell et al., 2011). This is perceived to be necessary because of the dynamic nature of N, especially in the dry-seeded, delayed-flood rice culture common to much of the southern US. Effective N management can potentially ensure economic benefits for rice producers. For the majority of land where rice is produced, a large amount of N must be applied to achieve optimum grain yields (Norman et al., 2003). Currently, a soil or plant-based test that can be implemented before or during the growing season to aid in determining site specific N fertilizer application rates for rice does not exist (Harrell et al., 2011). Therefore, N-fertilizer recommendations must be made according to response of popular cultivars subjected to an N-fertilizer response experiment.

Currently, rice N-response experiments are conducted in small-plot trials with a minimum of three replications arranged in a randomized complete block design (Buehring et al., 2008; Harrell et al., 2011; Saichuck et al., 2008). Using this experimental design, rice cultivars and N rates are randomized within each replication, and adjacent plots have different fertilizer treatments. Plots are harvested and yield data subjected to a quadratic response curve (Harrell et al., 2011).

The use of one statistical model over another for N-response experiments can often result in different calculated optimum fertilization rates for rice (Cerrato and

Blackmer, 1990). Different response models have been used to identify economic optimum N fertilization rates (EONRs), and many have noted that these models often conflict (Abraham and Rao, 1965; Anderson and Nelson, 1971, 1975; Nelson et al., 1985; Blackmer and Meisinger, 1990). Alivelu et al. (2006) reported that the quadratic-plateau response model improved the economic benefit of N fertilization rates compared to the quadratic response model in India. Harrell et al (2011) noted that the quadratic response model was superior to both the linear- and quadratic-plateau models when predicting EONRs for rice, and the quadratic response model has since been used for state-based N fertilizer recommendations for newly released rice cultivars in Louisiana and Mississippi. Although several regression models have been tested for predicting EONRs for rice, little research exists that evaluate experimental design of the test units, and the effect experimental design has on N rate recommendations.

Determination of N rate recommendations are derived from N-response equations fitted to data from experiments testing grain yield response to N rate. Specific solutions for the quadratic response equations are determined by taking the first derivatives of the quadratic equations, setting the first-order derivatives equal to zero to estimate the optimal urea-N rate, and substituting the resulting urea-N rate values into the equations to estimate the corresponding maximum yields (Harrell et al., 2011).

Plants that are located within close proximity often compete with one another for sunlight and soil nutrients. For rice experiments, when experimental of plants competing with one another immediately surrounding (i.e. within a plot) or adjacent to (i.e. neighboring experimental units) is referred to as competition effects. for N is re is neighboring experimental units effects can be a major source of experimental error in field experiments and is greater in grain crops where row spacing is narrow (Gomez and Gomez, 1984). Border effect is defined as the difference in performance between plants along the sides or ends of an experimental unit and those in the center. Gomez (1972) reported that when adjacent units receive different fertilizer treatments, border effects can be expected if units are not separated by a levee. Levee construction could reduce the effect of fertilizer treatment on neighboring experimental units, but this practice is currently not practical for most current US rice research programs, primarily due to lack of time for field preparation prior to planting.

However, there are several ways in which experimental error due to competition can be reduced. Gomez and Gomez (1984) reported differences in grain yield between the outermost row of a rice plot and the inner rows for fertilized and non-fertilized plots. An interaction between the adjacent nitrogen rate and the outside rows was detected, however, N rate of adjacent plots did not impact yield on the inner rows. A practical solution to mitigate experimental error associated with outside rows would be to remove the outermost rows of each plot. Several research programs currently exclude the outermost rows from plots prior to analyzing data. For example, nitrogen response trials conducted in Arkansas used a custom built combine header that harvests the middle four rows (Roberts et al., 2014), the middle five rows (Norman et al., 2014a,b; Rogers et al., 2014), or five to eight of nine rows (Slaton et al., 2014). It is also suggested that if border rows are to be removed, it is best to do so prior to harvest to minimize possibility of mixing border plants with inner plants (Gomez and Gomez, 1984). An experiment at the International Rice Research Institute (IRRI) was conducted to test if the method of yield determination, both including and excluding outside rows, had an effect on grain yield.

The determination of grain yield was found to be no different whether outside rows are included or excluded from analysis.

Another route to minimize border effect is to do so through experimental design. Gomez and Gomez (1984) stated that the grouping of homogeneous treatments, as in a split-plot design with fertilizer as the main-plot factor, allows grouping of plots with similar fertilizer rates thus minimizing fertilizer competition. This design, however, potentially allows diffusion of N fertilizer from one experimental plot to another, causing a "border effect." The interaction of adjacent plots can increase error and decrease accuracy of the response model. Using the split-plot experimental design can be a disadvantage as well, particularly due to grouping similar treatments together (Little and Hills, 1978). Allowing like treatments to be arranged side-by-side can violate the first assumption of the analysis of variance, which states that the error terms are randomly, independently, and normally distributed.

In order to evaluate N recommendations supplied by agriculture research stations, different experimental design techniques coupled with response modeling should be analyzed to achieve the most accurate prediction of N-rate requirements. N-rate recommendations that are influenced by "border effect" of neighboring plots due to N diffusion from plot-to-plot in experimental designs may impact recommendations provided for Mississippi rice producers. Therefore, the objective of this research was to compare grain yield response for randomized complete block design with split-plot experimental design for rice N-rate response experiments in Mississippi, and to determine if superiority of one experimental design exists over another.

2.3 Materials and Methods

Replicated N response studies were conducted in Mississippi in 2013 and 2014 on clay and silt loam soils to determine the response of two cultivars to different N fertilizer rates. Specific details of each location appear in Table 2.1. Two newly released cultivars, 'Colorado' (Tabien et al., 2015) and 'Mermentau' (Oard et al., 2014), were evaluated to compare two different experimental designs: randomized complete block and split-plot. For the split-plot design, N rate was the main-plot and cultivar was sub-plot. The two experimental designs were evaluated in each site-year with four replications. The split-plot design was compared to a randomized complete block design separately for each soil type. Experimental units consisted of eight-row plots (20-cm spacing) of 4.6-m in length seeded at 80 kg ha^{-1}. Plots were spaced 40-cm from the outside rows of one plot to the adjacent plot. Each experimental replication was separated by a 1.6-m alley in front of and behind each plot. Rice was grown in an upland condition until the five-leaf growth stage at which time N rates were broadcasted onto dry soil as urea (46-0-0) within 2 d prior to flood establishment. Nitrogen rates used were 0, 67, 100, 135, 170, 200, and 235 kg N ha^{-1} for silt loam soils and 0, 100, 135, 170, 200, 235, and 270 kg N ha^{-1} for clay soils. Fertilizer was applied using a Hege 80 belt cone (Wintersteiger, Inc., Salt Lake City, UT) and a zero-max (Zero-Max, Inc., Plymouth, MN) situated onto a custom manufactured, self-propelled distributor. Standard agronomic and pest management practices were used during the growing season according to University recommendations (Beuhring et al., 2008). Plots were drained at maturity, approximately 2 weeks prior to harvest.

Rice plots were harvested with a Wintersteiger Delta (Wintersteiger USA, Salt Lake City, UT) small-plot combine when grain moisture reached a range of 150 to 180 g kg^{-1}. Plot grain yields were measured using a Harvest Master weighing system (Juniper Systems, Inc., Logan, UT) equipped on the combine. Yields were adjusted to a moisture content of 120 g kg^{-1} for analysis.

Rice grain yield data were subjected to ANOVA using the Mixed Procedure (Littell et al., 2006; SAS, 2013) in SAS 9.4 (SAS Institute Inc., Cary, NC). Rough rice grain yield response was analyzed with experimental design and N rate as fixed effects. Random effects were cultivar, site-year, and replication of cultivar (nested within cultivar and site-year). Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Considering site-year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al., 2011; Carmer et al., 1989). Rice grain yield was regressed on N rate, allowing for both linear and quadratic terms with coefficients. A quadratic response model was selected for use in response analysis due to its superiority of fit over other models in rice small plot experiments (Harrell et al., 2011). The quadratic response is defined by:

$$Y = a + bN + cN^2 \qquad (2.1)$$

where *Y* is rough rice grain yield (kg ha^{-1}) and *N* is the rate of N application (kg ha^{-1}); *a* is the yield when no N is applied (intercept), *b* is the linear coefficient and *c* is the quadratic coefficient (Harrell et al., 2011). Parameters *a*, *b*, *c* are determined by fitting the model to the data. Nonsignificant ($P > 0.05$) model terms were removed sequentially and the analysis of covariance was performed using the GLM procedure in SAS to test for differences in quadratic coefficients for RCB and SP experimental designs. Estimates for each parameter were calculated using the GLM procedure in SAS. Differences in the intercept, linear, and quadratic response parameters comparing RCB and SP designs were determined using single-degree-of-freedom contrasts.

Grain yield response equations to N rate were used to calculate EONR using coefficients derived from Eq. 1. The predicted EONRs of fertilization for each quadratic model were calculated by equating the first derivatives of the response equations to a fertilizer-to-rice price ratio and solving for N (Nelson et al., 1985). The prices of fertilizer (\$1.22 kg^{-1} N) and rice (\$0.30 kg^{-1} rice) were chosen based on 2013 and 2014 planning budgets (Budgets 2013, 2014).

2.4 Results and Discussion

Results for analysis of variance for clay and silt loam soils are presented in Table 2.2. Rough rice grain yield was influenced by N rate, and exhibited a quadratic response to N rate for clay and silt loam soils. For clay soils, an interaction of main effects N rate and design was detected for the linear and quadratic parameters of the quadratic response model. Data for clay soils were then subjected to analysis of covariance to test for differences in RCB and SP designs for the quadratic response parameters *a*, *b*, and *c* (Table 2.3). Single-degree-of-freedom contrasts comparing RCB with SP designs indicate that no differences exist for the intercept, linear, and quadratic parameters on clay soils (Table 2.3). The response of rice grain yield was similar comparing RCB with SP design on clay and silt loam soils (Figure 2.1 and 2.2, respectively). The EONR for rice grown in Mississippi on clay soils in 2013 and 2014 was determined to be 202 kg N ha^{-1}, and predicted rice grain yield at EONR is 11637 kg ha^{-1}. The EONR for rice grown in

Mississippi on silt loam soils for 2013 and 2014 was determined to be 198 kg N ha^{-1}, and the predicted rice grain yield for EONR was 12091 kg ha^{-1}.

2.5 Conclusion

The objective of this experiment was to determine the effect of randomized complete block and split plot experimental designs on rice grain yield response to N fertilizer for N response trials in Mississippi, and to determine if one experimental design was superior in predicting EONRs. The response of rice grain yield to N rate is not influenced by experimental design of test units. These data serve as a validation of prior N-response studies conducted using RCB experimental design in Mississippi. The movement of N-fertilizer from plots with N rates greater compared to adjacent units does not change the quadratic response derived from rice grain yield data. No differences in the intercept coefficient comparing RCB and SP indicates that movement of N from experimental units treated with high N rate, such as 270 kg N ha^{-1}, to a lower N rate (i.e. 0 kg ha^{-1}) is minimal or does not occur. Additionally, grouping similar N rate treatments together, as in SP experimental design, does not violate the analysis of variance and valid statistical inferences can be made under proper management of experimental units. Using a split-plot experimental design for rice N-response trials may reduce the amount of time spent on preparation (i.e. measuring fertilizer) for N-response trials, and help reduce human error during application of fertilizer to individual units in RCB designs. However, experiments arranged in RCB design allows for rice agronomists and breeders to make side-by-side visual comparisons of multiple cultivar and N rate combinations. Visual observation of experimental plots are important for phenotypic response comparisons, as well as pest and disease infestations that may differ among cultivar and N rate. Although both RCB and SP experimental designs provide advantages to research scientists, our data suggest that the use of one experimental design over another does not influence the response of rice grain yield to N rate. This provides research scientists versatility in choosing an experimental design that is appropriate for the research program, without sacrificing accurate rice grain yield response to N-fertilizer rates.

Table 2.1 Individual site locations, soil series, taxonomic classification and crop rotation information for nitrogen (N) response tests conducted in 2013 and 2014

			Soil			
Site	Year	Location	Series	Texture	Taxonomic Classification	Crop Rotation
1	2013	Shaw, MS	Sharkey	Clay	Very-fine, smectic, thermic Chromic Epiaquerts	Rice-soybean
2	2013	Greenville, MS	Commerce	Sandy loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	Rice-soybean
3	2013	Minter City, MS	Dubbs	Loam	Fine-silty, mixed, thermic Typic Hapludalfs	Rice-soybean
4	2014	Shaw, MS	Sharkey	Clay	Very-fine, smectic, thermic Chromic Epiaquerts	Rice-soybean
5	2014	Shaw, MS	Forestdale	Silty clay loam	Fine, smectitic, thermic Typic Endoaqualfs	Rice-soybean
6	2014	Arcola, MS	Sharkey	Clay	Very-fine, smectic, thermic Chromic Epiaquerts	Rice-soybean

Table 2.2 ANOVA results for rice experimental design experiment on two soil textures in Stoneville, MS in 2013 and 2014.

Source	Clay		Silt-Loam	
	F-Value	Pr < F	F-Value	Pr < F
Nitrogen (*N*)				
N linear	70.81	<0.0001	35.70	<0.0001
N quadratic	25.63	0.0001	13.94	0.0018
Design (*D*)	< 1	0.6480	< 1	0.5848
D x N linear	13.14	0.0003	< 1	0.3326
D x N quadratic	14.00	0.0002	< 1	0.6538
RCB vs SP†	1.15	0.3677	< 1	0.4439

†RCB vs SP, Randomized complete block and split-plot experimental design tested using single-degree-of-freedom contrasts for the complete model

Table 2.3 Response parameters and significance levels for a quadratic response of grain yield to N rate using ANCOVA for an experiment conducted on clay soil type in 2013 and 2014†.

	Parameter estimates			RCB vs SP‡	
Source	Estimate	*t-Value*	*Pr > |t|*	*F-value*	*Pr > F*
Intercept (*a*)				0.19	0.6651
RCB	7153.60	19.05	<0.0001		
SP	7384.39	19.66	<0.0001		
Linear (*b*)				1.77	0.1871
RCB	48.24	8.22	<0.0001		
SP	37.20	-5.26	<0.0001		
Quadratic (*c*)				1.57	0.2144
RCB	-0.12	6.34	<0.0001		
SP	-0.08	-3.91	0.0002		

†Data were pooled over two cultivars with four replications and three site-years.

‡Comparison of randomized complete block (RCB) vs split-plot (SP) design using single-degree-of-freedom contrasts

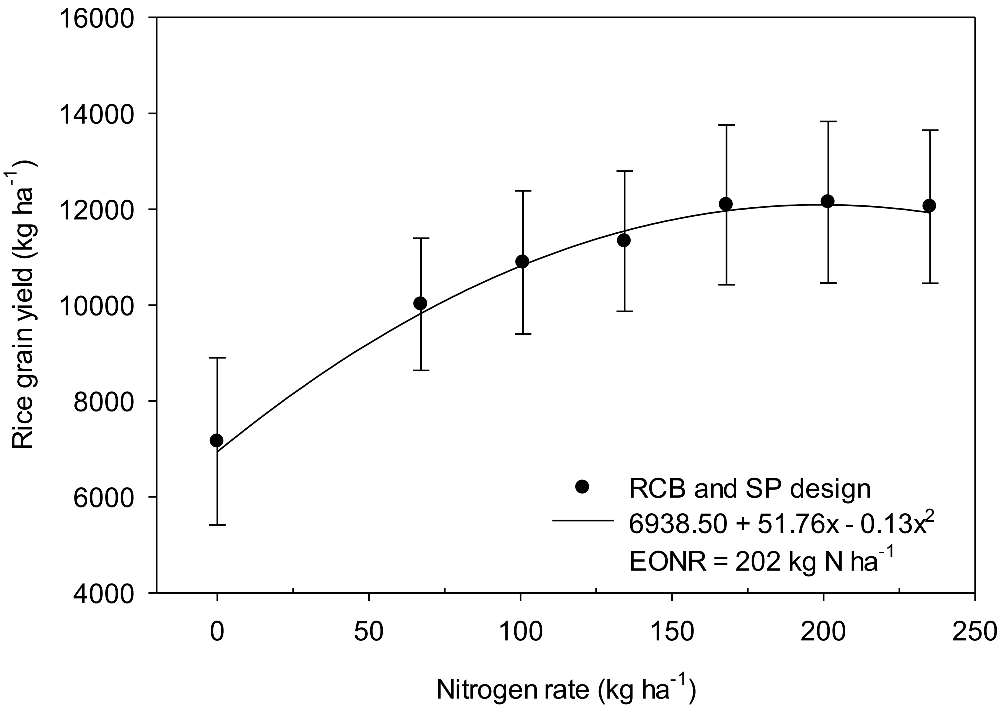

Figure 2.1 Rice grain yield response to N fertilizer rate and economic optimum N rate (EONR) using two experimental designs on clay soils in 2013 and 2014.

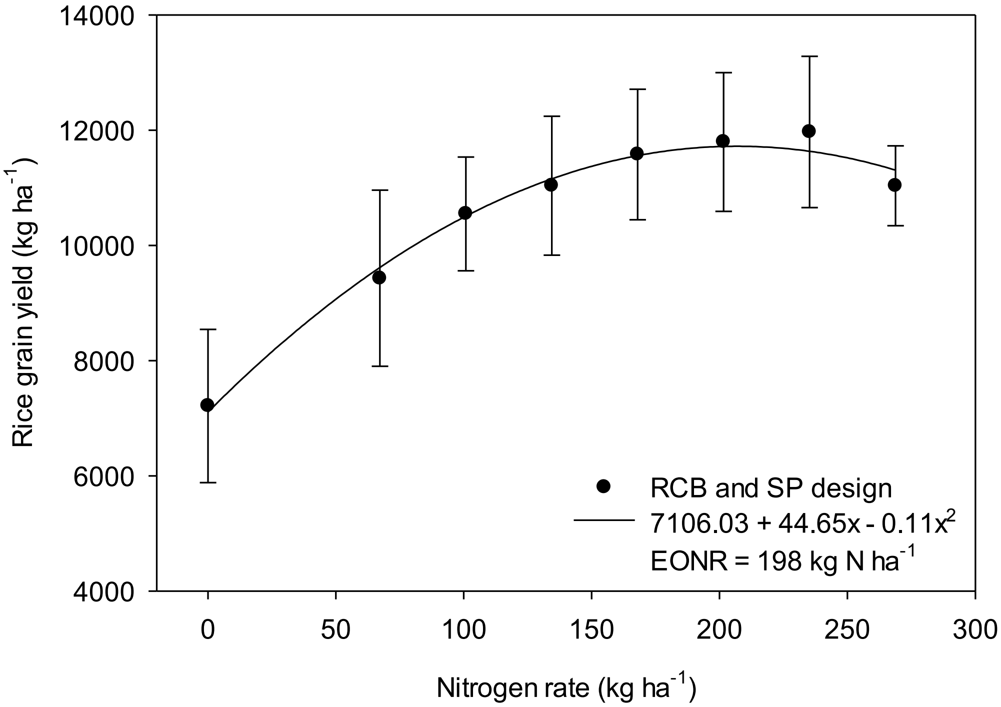

Figure 2.2 Rice grain yield response to N fertilizer rate and economic optimum N rate (EONR) using two experimental designs on silt loam soils in 2013 and 2014.

2.6 Literature Cited

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