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Influence of agronomic practices in rice (Oryza sativa L.) and soybean (Glycine max L.) production in midsouthern USA

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INFLUENCE OF AGRONOMIC PRACTICES IN RICE (*Oryza sativa* L.) AND SOYBEAN (*Glycine max* L.) PRODUCTION IN MIDSOUTHERN USA

By

Kevin Alan Dillon

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INFLUENCE OF AGRONOMIC PRACTICES IN RICE (*Oryza sativa* L.) AND SOYBEAN (*Glycine max* L.) PRODUCTION IN MIDSOUTHERN USA

By

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Within Arkansas, Louisiana, Mississippi, Missouri, and Texas, rice acreage is rotated with soybean due to both crops’ adaptability to the clay soils of the midsouthern USA. Two row patterns, two maturity groups, and six seeding rates were examined at Stoneville, MS, in 2009-2010, with respect to soybean growth and yield produced on silt loam soil. Optimal yield for MG IV was 333,000 seed ha^{-1} (297,000 plants ha^{-1}). Twin-row soybean increased seed yield 7 to 10% more than single-row due to greater LAI, NDVI, and node and pod production. Rice field experiments quantified N loss via ammonia volatilization and determined grain yield for various N sources and preflood application timing. Cumulative ammonia volatilization loss on Tunica clay was minimal (10% of applied N). Grain yields were 6% less when fertilizer was applied 10 days before flood (dbf) as compared to 1 dbf; N sources are available to minimize ammonia volatilization loss.

DEDICATION

I would like to dedicate this thesis to my Grandpa Harold L. Dillon and Uncle Kenneth R. Dillon, and to their honorable service to the United States of America while fighting in the Korean War. Crpl. Harold L. Dillon, native of Fairborn, OH, served in Korea from August, 1952 – October, 1953 in the U.S. Army in the 25th Med. Battalion, 25th Inf. Div., Clearing Company, and earned three campaign stars. It was Grandpa Harold who instilled a love for agriculture in my father's heart and in turn passed it on to me. Harold L. Dillon passed away in July, 1964. Kenneth R. Dillon fought in 'Operation Nomad' and served in Korea from June, 1951 – January, 1952 in the U.S. Army, 24th Inf. Div., 19th Inf. Reg., Company E, 3rd platoon, 1st squad. Crpl. Kenneth R. Dillon held all positions of rifle squad including squad leader and was wounded in October, 1951. He received the Purple Heart for his wound in addition to three campaign stars, and the Combat Infantry Badge. Kenneth R. Dillon currently lives happily in Yellow Springs, OH. These two men are just two family members who heeded their country's calling and are joined by numerous men and women who have defended and continue to defend our freedom. Thank you.

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CHAPTER I

INTRODUCTION

Both soybean (*Glycine max* L.) and rice (*Oryza sativa* L.) are crucial to the United States agriculture industry. In the U.S., in 2010, 31.3 million hectares of soybean and 1.5 million hectares of rice were planted (NASS, 2010). Combined U.S soybean and rice production in 2010 resulted in a $34.9 billion value (NASS, 2010). In Mississippi, 2010 soybean and rice production equated to a value of 1.1 billion (NASS, 2010). In the southern United States, rice is commonly grown in rotation with agronomic crops including soybean, grain sorghum (*Sorghum bicolor* L.), and cotton (*Gossypium hirsutum* L.) (Johnson et al., 1995). Crop rotation is a vital component of modern agriculture because continuous monoculture crop production can result in declined yield in most crops (Zhang et al., 2002) Alternating crops can enhance the physical and nutritional properties of soil, and improve control of weeds, insects, and diseases (Delorit et al., 1974). A rice and soybean rotational system is utilized in the midsouthern USA (Kurtz et al., 1993; Heatherly and Spurlock, 2000). Previous research has shown (Kurtz et al., 1993) that when a soybean and rice rotation is implemented, increased yield and net returns for both crops result. Within the states of Arkansas, Louisiana, Mississippi, Missouri, and Texas, a large portion of rice acreage is rotated with soybean due to both crops' adaptability to the clay soils of the midsouthern USA (Heatherly and Spurlock, 2

000). Soybean and rice production interact in the midsouthern USA; many of the production issues addressed by management strategies take into consideration proper growth and yield of both soybean and rice. This research focuses on two entirely different crops, soybean and rice, examines and addresses different production issues and concerns by field experimentation, and reports on approaches midsouthern USA growers can utilize to maximize uptake of nutrients, growth and subsequent seed and grain yield in soybean and rice culture.

Midsouthern USA Production Systems in Soybean

The midsouthern USA has recently experienced drastic changes in agriculture landscapes. Due to increased production costs, many acres traditionally grown to cotton (*Gossypium hirsutum* L.) in the southern USA have shifted to soybean (*Glycine max* L.) production. Higher costs associated with insect management, fertility inputs, and technology fees for current cotton varieties have attributed to increased production costs for producing cotton in the midsouthern USA in recent years. Higher costs associated with producing cotton and increased soybean commodity prices are the primary reasons for the recent landscape shift. In 2001 there were 656,100 hectares of cotton planted in Mississippi compared to 172,000 hectares in 2010. Conversely, 469,800 hectares of soybean were planted in 2001 in Mississippi, and 809,000 were planted in 2010 (NASS, 2010). Within the four state region of Mississippi, Louisiana, Arkansas, and the Missouri Boot heel region (southeastern Missouri), about three million hectares of soybean are produced annually (NASS, 2010). Traditionally, eighty-five percent of the soybean in the midsouthern USA are produced on fine-textured soils (C.H. Koger, personal communication, 2009). Due to the increased amount of soybean hectares grown in the place of cotton, coarser textured soils such as silt loam and sandy loam are now being utilized for soybean production. Currently forty percent of soybean in the midsouthern USA are grown on a coarse textured soil (C.H. Koger, personal communication, 2010). A significant amount of research has dealt with the influence of maturity groups, row pattern, and seeding rate on soybean grown on fine-textured soils (Bowers et al., 2000; Graterol et al., 1996; Alessi and Power, 1982; Janovicek et al., 2006; Ethredge et al., 1989; Holshouser and Whittaker, 2002).

An extensive amount of research has dealt with the effect of row spacing on the growth and yield of soybean; the majority of the research has shown an increased yield for soybean grown in narrow rows as compared to wide rows (>76 cm) (Costa et al., 1980; Alessi and Power, 1982; Beatty et al., 1982; Boquet et al., 1982; Ethredge et al., 1989; Heatherly, 1988; Oplinger and Philbrook, 1992; Heatherly et al., 1999; Bowers et al., 2000; Bertram and Pedersen, 2004; Janovicek et al., 2006; De Bruin and Pedersen, 2008). Greater yield potential for narrow rows can be attributed to soybean’s ability to reach canopy closure quicker in a narrow row pattern (Wilcott et al., 1984; De Bruin and Pedersen, 2008). The advantage of narrow row spacing is more equidistant plant spacing, which increases canopy development and light interception earlier in the growing season (Weber et al., 1966; Alessi and Power, 1982; Dalley et al., 2004). A closed canopy has been shown to decrease weed pressure, lower soil evaporation losses (Shibles and Weber, 1965; Ethredge et al., 1989; Yelverton and Coble, 1991), and subsequently reduce the number of herbicide applications required (Mickelson and Renner, 1997; Nelson and Renner, 1999). Parks and Manning (1980) and Parks et al. (1982) reported a yield increase in narrow rows were the result of increased seed production in the upper portion of the plant. Ethredge et al. (1989) attributed higher seed yield at the narrower spacings to an increased pod number per unit area in the narrower rows (25 and 51 cm) than in the wide rows (76 cm). Ethredge et al. (1989) reported at equal initial plant population, increased natural death of plants occurred with the wide row spacing as compared to the narrow row spacing; the number of plants with active seed production in 76, 51, and 25 cm rows were 77, 93, and 97% of the initial plant population, respectively.

Conventional soybean practice in the midsouthern USA involves planting MG V, VI, VII, and VII varieties during May and June (Bowers et al., 2000). The Early Soybean Production System (ESPS) has been implemented to provide producers with an opportunity to avoid drought stress by planting earlier maturity groups (group IV's and V's) earlier in the growing season (Heatherly et al., 1999). By planting MG IV or early V in early- to mid-April, the grower can avoid drought stress often encountered during summer months and provide the plant with adequate soil moisture during pod fill. Due to the popularity of the ESPS, ninety-five percent of the soybean hectares in the midsouthern USA are planted with MG IV or V variety (C.H. Koger, personal communication, 2010). Maturity group IV varieties have an indeterminate growth pattern, whereas most MG V varieties are determinate. Once anthesis is initiated, soybean with an indeterminate growth habit will continue to grow taller while adding additional nodes and flowers and subsequent pods; soybean with a determinate growth habit stop growing and will flower at one time (Hoeft et al., 2000). Cooper (1981) reported that in a low yield environment, where high temperature and drought stress reduce plant height, lodging, and yield, determinate cultivars were observed to have a lower yield than indeterminate soybean; in a high yield environment, the indeterminate cultivar yielded less than the determinate soybean, due to increased lodging. Graterol et al. (1996) found determinate and indeterminate cultivars yielded the same in the wide-row planting system but determinate cultivars yielded more than indeterminate cultivars in the twin-row planting system.

Thirty percent of the soybean hectares in the midsouthern USA are planted using the twin-row pattern (C.H. Koger, personal communication, 2010). The twin-row planting system uses the narrow row concept in a wide row system. Janovicek et al. (2006) found that a twin row planting pattern, where two 19 cm spaced rows were planted on 76 cm centers, consistently increased yields above those observed with single 76 cm rows. In a year with minimal yield limiting conditions and with a larger amount of total water available for soybean plants during reproductive growth stages, research has shown that the narrow and twin row patterns offer yield advantages over the wide row planting system (Bowers et al., 2000; Graterol et al., 1996). Potential increase in profit exists by utilizing the twin row system; the grower can use the same equipment used for growing other crops such as corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.).

The proper seeding rate varies by field and is dependent upon desired plant population, planting date, soil type, condition of seedbed, planting method (drill vs. planter), percent germination, and seed vigor (Walker et al., 2010). Selecting the proper seeding rate influences yield, lodging potential and economic return. Heatherly et al. (1999) and Heatherly and Elmore (2004) emphasized that a density of 200,000 to 300,000 uniformly distributed plants ha^{-1} is adequate for maximum yield. Research conducted by Bowen and Schapaugh (1989) found no yield differences with seeding rates of 128,000, 259,000, or 385,000 seeds per hectare in 76 cm rows and no observed cultivar x seeding rate interaction. Research conducted by Weber et al. (1966) and Oplinger and Philbrook (1992) showed row spacing by seeding rate interactions with soybean that responded better to higher seeding rates in narrow as opposed to wide rows. Previous research has shown a soybean response to lower seeding rates by producing more branches, biomass, pods, and seed plant^{-1} when compared to higher seeding rates (Egli, 1988; Carpenter and Board, 1997; Board, 2000; Egli and Bruening, 2006; Epler and Staggenberg, 2008; Cox et al., 2010). Boquet (1990) reported that 50 cm row spacing required higher plant densities to maximize yields as compared to 101 cm row spacing, whereas Timmons et al. (1967) concluded that wider rows required higher seeding rates to maximize yield as compared to narrow rows. Bertram and Pedersen (2004) reported that increasing plant population density promoted rapid canopy closure and thus improved light interception and biomass production. Increasing plant population can increase competitive stress (Bowen and Schapaugh, 1989), plant height, plant mortality (Cooper and Lambert, 1971), and usually results in greater yield loss via lodging (Weber and Fehr, 1966; Ethredge et al., 1989). Lee et al. (2008) and De Bruin and Pedersen (2008) reported that due to the high cost associated with soybean seed, economic seeding rates are often less than seeding rates that result in optimum yield.

Limited research in Mississippi has evaluated the influence of maturity group, row pattern, and seeding rate on soybean grown on coarse-textured soils. Due to the combination of increased popularity of the twin row planting system, the planting of MG IV and MG V cultivars, the importance of proper seeding rate, and the shift of a significant amount of cotton hectares to soybean production, research is needed concerning the influence of row pattern, maturity group, and seeding rate on soybean grown on coarse-textured soil. Therefore, the objective of this research was to evaluate the effect of seeding rates on growth and yield for twin-row and single-row maturity group IV and V soybean grown in silt loam soils.

Midsouthern USA Nitrogen Management in Rice

Rice (*Oryza sativa* L.) is grown in more than 100 countries worldwide and accounts for more than 700 million tons of production per year within approximately 160 million hectares (Anonymous, 2011). Rice is considered to be the main food staple for more than 50% of the world's population (Childs, 2004). When the amount of grain used for food is considered, more food energy per hectare is produced from rice as compared to any other cereal (Eggum, 1979; FAO, 2001; Childs, 2004). The United States accounts for only 1.5% of the total rice production in the world; however, in 2005 the U.S. ranked fourth behind Thailand, Vietnam, and India with 14% of the total world exports (Childs, 2005). Childs (2005) reported that the U.S. exports more than 40% of its annual rice production. United States rice production, in 2010, accounted for 243 million hundredweight (cwt) produced on approximately 1.5 million hectares, and was worth approximately 3.1 billion dollars (NASS, 2010). The states of California, Arkansas, Louisiana, Mississippi, Missouri, and Texas produce essentially all of the rice in the USA (Street and Bollich, 2003). In the 2010 growing season in Mississippi, rice production totaled 20.8 million cwt on 123,000 hectares, which ranked as the fourth largest rice producing state, after Arkansas, Louisiana, and California, respectively (NASS, 2010). This 2010 Mississippi rice production increased 27% as compared to 2009 and resulted in a farm-gate value of $226 million value (NASS, 2010). Rice production in the USA is limited to the previously mentioned states due to the requirement for high temperatures throughout the growing season, an ample supply of water that can be applied in a timely manner, a smooth land surface with less than one percent slope, and an impermeable soil pan that is capable to minimizing water loss through leaching. Furthermore, these states have the appropriate infrastructure to dry, store, and process (mill) the paddy rice into a usable form. Additionally, these states have relatively easy access to the Mississippi River/Gulf Coast so that exports can proceed in an economically feasible manner.

High grain yields are greatly controlled by the establishment of an adequate and uniform rice stand (Bond et al., 2005). Rice stand establishment methods are numerous; however, in mechanized rice production such as the case in the USA, rice planting is categorized as either water-seeded or dry-seeded. The rice production system in Mississippi is categorized as drill seeded delayed-flood and is grown on various soil types ranging from sandy loam to clay (Walker et al., 2003). Within this system, seeds are drilled into conventional, minimal, or no-till seedbeds. Most rice in the USA is grown with conventional tillage; however many rice-producing areas, including Mississippi, have adopted conservation tillage (Street and Bollich, 2003; Bond et al., 2005). Within the drill- or water-seeded rice culture, both conventional and reduced tillage fit in well; however, reduced tillage provides producers with the opportunity to plant earlier as compared to conventional tillage (Bond et al., 2005). The use of conservation tillage results in a seed bed that is uniform, weed-free, with optimum conditions for seed emergence (Bond et al., 2005). Reduced tillage involves the use of no-tillage or a stale seedbed (Linscombe et al., 1999; Slaton and Cartwright, 2001). With no-till, rice is planted into the residue of the former year's crop; in stale seedbed, tillage is conducted in the fall, the field is undisturbed throughout the winter months, and herbicide is applied as a burndown prior to spring planting (Bond et al., 2005).

Final seedling population is influenced by seedbed conditions, seedling vigor, planting depth and uniformity, soil temperature, and percent seed germination (Bond et al., 2005). Previous research has reported, for optimal grain yield, plant density of rice at emergence should approximately be 160-215 plants m^{-2} (Wilson et al., 2001; Bond et al., 2005; Saichuk et al, 2005; Wilson et al., 2005). Bond et al. (2005) optimized rough rice yield with a seeding rate of 323 seeds m^{-2}. After germination, emergence will occur in seven to ten days; however, it can be more or less depending on the depth of planting and the soil temperature. If suboptimal plant densities are observed, Counce et al. (1992) reported that additional N fertilizer can be applied in early vegetative growth stages to minimize the loss in yield potential compared to an optimal plant density. Upon emergence, rice is grown aerobically similar to other cereal crops until it reaches the four-to six-leaf growth stage. Days from emergence to flooding will range from twenty to thirty days depending on temperature and other growth contributing factors (Norman et al., 1992). At this stage, rice is typically tall enough to tolerate a shallow flood. The shallow flood (7 to 10 cm) is maintained until approximately two weeks prior to harvest. Growers prefer to harvest fields when they are dry to minimize or eliminate rutting by large commercial combines.

Nutrient uptake by rice is very similar to that of upland row crops such as corn (*Zea mays*) and wheat (*Triticum aestivum*). Due to the flooded environment in which rice is grown, rice production presents challenges for managing nutrients in a manner that allows maximum-availability in the soil. In rice production, the nutrient applied the most frequently and in the greatest amounts is nitrogen (N) (Norman et al., 2003). Watkins et al. (2008a, 2008b) concluded that N is a major input of rice production and accounts for approximately 19 to 25% of total variable production expenses for rice, depending on soil texture. Nitrogen increases plant height, panicle number, leaf size, spikelet number, and number of filled spikelets, ultimately determining the rice plant's yield potential (Dobermann and Fairhurst, 2000). High-yielding rice cultivars require large amounts of N to produce acceptable grain yields. Management of N for maximum availability is a demanding challenge due to its dynamic nature and the associated pathways of loss if not managed properly. Specifically, N can be lost or rendered unavailable to the rice plant by ammonia (NH_3) volatilization, nitrification and the subsequent denitrification, immobilization, fixation, leaching and runoff. The recently high volatility of fertilizer prices has led to increased desire among rice producers to apply N optimally in the most profitable amounts (Watkins et al., 2010). In addition to economic factors, N use efficiency in rice production and the subsequent impacts on environmental quality are under constant scrutiny.

Several forms of N exist in the soil; however, rice utilizes N in the form of ammonium (NH_4^+) and nitrate (NO_3^-). Ammonium is supplied to the rice roots through diffusion. In the flooded, anaerobic environment NH_4^+ is stable and accumulates. Nitrate is supplied to the rice plant via mass flow and diffusion. However, the anaerobic environment renders NO_3^- unstable and subject to loss by denitrification as N_2 (Patrick et al., 1985). Because of the stability of NH_4^+, recommended N fertilizer sources are NH_4^+ or NH_4^+ forming fertilizer (Griggs et al., 2007). The three N fertilizers utilized in dry-seeded, delayed-flood rice culture are urea, ammonium sulfate, and urea-ammonium nitrate. Urea is the most widely used N fertilizer in rice production due to its high N content (45% N) and relatively low cost (Bufogle et al., 1998; Norman et al., 2003; Griggs et al., 2007). Previous research has reported that if urea is not incorporated within a few days after surface application, substantial NH_3 volatilization losses can occur (Mikkelsen et al., 1978; Vlek and Craswell, 1979; Griggs et al., 2007). Ammonium sulfate (21% N) is an excellent source of N, has slightly acidic properties and is subsequently less prone to N loss via NH_3 volatilization, but application costs are greater compared to urea due to its lower N concentration (Vlek and Craswell, 1979). Urea-ammonium nitrate (28-32% N) has as much as 25% of N in the form of NO_3^-. Therefore, UAN should only be used as a topdress application at midseason where the rice plant will absorb the fertilizer in a few days.

Regardless of which type of N fertilizer is used preflood, it is imperative to establish a flood within a few days following fertilizer application (Norman et al., 2009). If the flood is maintained, N losses due to NH_3 volatilization and nitrification and subsequent denitrification are minimized due to the movement of the N fertilizer down into the soil profile by the floodwater (De Datta and Patrick, 1986; Savin et al., 2007). Previous research has shown that in order to observe maximum uptake of preflood N fertilizer, the flood must be maintained for at least 3 to 4 weeks (Wilson et al., 1989; Norman et al., 1992; Guindo et al., 1994). Timeliness of fertilizer application is critical to ensure optimal plant growth and subsequent grain yield (Norman et al., 1992; Norman et al., 2003; Griggs et al., 2007; Norman et al., 2009).

Because of this period without flooding pre-plant fertilizer is not recommended due to the risk of losing the N via denitrification. The optimum preflood (OPF) application method utilizes a large N rate application at preflood and the rice plant is monitored at midseason with N diagnostic techniques developed for rice such as the chlorophyll meter (Wells et al., 1992; Turner and Jund, 1991, 1994), Y-leaf N concentration (Mikkelsen, 1970), and the rice gauge (Wells et al., 1992; Ntamatungiro et al., 1999). At the four to six leaf growth stages, 65 to 100 percent of the total N fertilizer rate is applied onto dry soil surface a few days before flooding (Bollich et al., 1994; Wilson et al., 2001). The floodwater acts to incorporate the preflood N fertilizer, usually urea, into the soil below the oxidized zone at the soil and water interface (Bollich, 2000). The OPF method consistently leads to high N fertilizer uptake efficiency and increased rice grain yields in the dry-seeded rice production system (Norman et al., 2003).

The denitrification loss mechanism is very difficult to pinpoint in the field. Due to the anaerobic environment in the flooded soil, the NO_3^- form of N is used by the soil microbes in place of oxygen. The NO_3^- is quickly transformed to nitrous oxide or N_2 gas and is lost to the atmosphere. Denitrification loss has been estimated as the difference between the unrecovered ^{15}N in a ^{15}N balance and the measured NH_3 loss (De Datta et al., 1991). De Datta et al. (1991) conducted a denitrification study in lowland irrigated rice at Calauan, Laguna, Philippines. The evolved $^{15}N_2$ and $^{15}N_2O$ was collected in a confined atmosphere following application of a highly enriched N source. Denitrification was only a minor loss mechanism for urea broadcast to floodwater in puddle rice fields (De Datta et al., 1991). Denitrification loss, determined by the difference between the total N loss and directly measured NH_3 loss, was 10 and 6% of the applied urea N in 1986 and 1988, respectively (De Datta et al., 1991).

Leaching and runoff of N is a minor loss mechanism in southern rice production (Norman et al., 2003). Most rice is grown on soil with low permeability, which reduces leaching; however, in some instances where rice is grown on sandy soils, leaching of NH_4^+ can prove problematic. Runoff is not a significant loss mechanism due to the low concentration of NH_4^+ in the flood water and minimal loss of water from fields due to land-forming where a permanent levee surrounds the field (Patrick et al., 1985). Furthermore, the fate of N is affected by competition from soil, i.e., CEC, plant uptake, and other N losses, especially NH_3 volatilization.

Ammonia volatilization occurs in the dry-seeded, delayed-flood rice culture when the urea is hydrolyzed to ammonium carbonate $[(NH_4)_2CO_3]$ by the urease enzyme and ammonium carbonate decomposes to produce NH_3 and CO_2. The proportion of NH_3 to NH_4 is determined by the local pH (Boswell et al., 1985). The hydrolysis of urea to NH_3 results in the subsequent NH_3 lost through volatilization. Soil and floodwater pH, soil and air temperature, cation exchange capacity, wind speed, humidity, soil moisture and NH_3 concentrations all affect NH_3 volatilization (Harper et al., 1983; Boswell et al., 1985; Bouwmeester et al., 1985). Previous research has shown that NH_3 volatilization following urea application is an important mechanism for N losses in rice fields (Mikkelsen et al, 1978; Griggs et al., 2007; Li et al., 2008; Norman et al., 2009). The most important factors associated with increasing NH_3 volatilization are a high NH_4^+-N concentration of floodwater combined with high pH (Martin and Chapman, 1951; Chao and Kroontje, 1964; Du Plessis and Kroontje, 1964; Fenn and Kissel, 1973; Mikkelsen et al., 1978;

Vlek and Stumpe, 1978) and high temperature (Fenn and Escarzaga, 1976; Clay et al., 1990).

The primary method to measure NH_3 volatilization in laboratory studies has been a closed chamber method to contain the soil and N fertilizer treatments, force air flow across the treatment surface, and uses an acid trap to capture the volatilized NH_3 (Hargrove and Kissel, 1979; Kissel et al., 2004; Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009). Lab systems using such a method have shown NH_3 recovery values ranging from 72.9 to 103% (Kissel et al., 2004; Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009). Beyrouty et al. (1988), Griggs et al. (2007), and Norman et al. (2009) used a similar semi-open static chamber method that measured NH_3 volatilization in the field. Previous studies have reported that NH_3 volatilization can account for 20 to 80% of total N losses (De Datta et al., 1989; Beyrouty et al., 1988; Freney et al., 1990; Griggs et al., 2007; Norman et al., 2009). Loss of N via NH_3 volatilization can be severe if urea is applied pre-flood and is not incorporated within a few days. Emphasis is put on the rice producer to flood the rice field as soon as possible following pre-flood N fertilizer application. At times it can be difficult for the rice grower to flood the field in a timely fashion due to limited power units, decreased pump outputs, or low water levels. Dry-seeded, delayed-flood rice culture can equate to high yields, but first and foremost the N fertilizer must be stabilized in a plant available form.

Urease enzyme inhibitors have been shown to effectively reduce NH_3 volatilization from urea (Bremner and Chai, 1989; McCarty et al., 1989; Watson, 2000) by slowing the rate of urea hydrolysis and conversion to NH_4^+ (Norman et al., 2009). The compound NBPT, [*N*-(n-butyl) thiophosphoric triamide], has been reported to be an effective urease inhibitor, resulting in minimizing NH_3 volatilization loss of urea (Buresh et al., 1988; Bremner and Chai, 1989; Clay et al., 1990; Al-Kanani et al., 1994; Rawluk et al., 2001; Norman et al., 2009), and increasing N uptake (Freney et al., 1995; Chaiwanakupt et al., 1996; Aly et al., 2001). NBPT [*N*-(n-butyl) thiophosphoric triamide] is the active ingredient in the commercially available Agrotain® (Agrotain International, St. Louis, MO), which is used as a urease inhibitor in the form of treated N fertilizer. Chaiwanakupt et al. (1996) observed an increase in grain yield with NBPT, whereas others have not (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001). Dicyandiamide (DCD) is a nitrification inhibitor that has been shown to increase rice grain yield (Wells and Norman, 1985; Norman et al., 1989). The treated urea product known as Super-U® (Agrotain International, St. Louis, MO) contains the active ingredients DCD and NBPT; the result in theory is dual N loss protection with a nitrification inhibitor and a urease inhibitor, respectively.

To reach optimum grain yield, N rate must be increased by 34 to 67 kg N ha^{-1} when applied to clay soils compared to silt loam soils (Slaton, 2001; Norman et al., 2003). The CEC of the soil influences NH_3 volatilization by acting as a temporary sink for NH_4^+, which reduces the aqueous NH_4^+ concentration and the NH_3 concentration (Boswell et al., 1985). A soil with a low CEC releases a larger portion of the NH_4^+ into solution and is increasingly vulnerable to consequent loss via NH_3 volatilization. Therefore, rice producers can expect higher levels of NH_3 volatilization to occur on low CEC soils (coarse texture, low organic matter) as compared to high CEC soils (fine texture, high organic matter) (Terman, 1979).

The current demand for higher rice yields coupled with the increased popularity of hybrid and high yielding rice cultivars equates to the need for increased N fertilizer efficiency. Only three field experiments have been conducted that examined different N sources and application timing and reported subsequent NH_3 volatilization through the use of the semi-open static chamber method (Beyrouty et al., 1988; Griggs et al., 2007; Norman et al., 2009). Griggs et al. (2007) and Norman et al. (2009) reported grain yield limiting N losses due to NH_3 volatilization on silt loam and clay soils. Previous research conducted by Walker (unpublished) on clay soils in Mississippi, has shown a consistent decrease in grain yield; however, it is uncertain to what extent the yield loss can be explained by NH_3 volatilization losses. Therefore, the objectives of this study were to (1) quantify N loss via NH_3 volatilization for different N sources and N-fertilizer application timings on clay textured soil and (2) determine the grain yield and N uptake as it was affected by NH_3 volatilization losses.

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CHAPTER II

INFLUENCE OF MATURITY GROUP, ROW PATTERN, AND SEEDING RATE ON SOYBEAN (*Glycine max* L.) GROWTH AND YIELD PRODUCED ON SILT LOAM SOILS

Abstract

Significant changes in the agriculture landscape have occurred in the lower Mississippi River Alluvial-flood plain. A large portion of silt loam soils have shifted from cotton to soybean production. Research initiatives are focusing on several key agronomic issues associated with growing soybean on silt loam soils. Field experiments conducted at the Delta Research and Extension Center, Stoneville, MS, in 2009 and 2010, focused on the impact of row pattern (twin-row; 101-cm rows), maturity groups (MG IV; MG V), and six seeding rates (222,000; 259,000; 296,000; 333,000; 370,000; 408,000 seed ha^{-1}) on soybean growth and yield. Experiments were conducted on Bosket and Commerce silt loam soils. Stand count, plant height, NDVI, leaf area index, pod count, node count, seed weight, and yield data were collected each year. Averaged across years, seed yield was significantly influenced by maturity group and row pattern. The MG V yielded 5096 kg ha^{-1}; whereas the MG IV yielded 4347 kg ha^{-1}. The twin-row pattern yielded 4937 kg ha^{-1} as compared to 4506 kg ha^{-1} for the single-row pattern. The yield increase for the twin-row pattern was attributed to combination of increased nodes

plant^{-1}, pods plant^{-1}, and increased number of two-and three-bean pods plant^{-1} compared to the single-row pattern. Higher NDVI and LAI values for the twin-row pattern and MG V variety were observed. The MG V variety and twin-row pattern contribution to NDVI and LAI differences are due to the ability of the MG V variety to shade the row middles quicker, resulting in increased leaf area. The increased leaf area in the twin-row pattern contributed to quicker canopy closure by 7 to 10 days when compared to the single-row pattern. Seeding rate alone had little effect on seed yield; however maturity group and seeding rate interacted to effect seed yield. Seed yield for the MG V variety did not respond to seeding rate. However yield differences associated with varying seeding rates for the MG IV variety were observed. The optimum seeding rate for the MG IV variety with respect to seed yield was 333,000 seed ha^{-1}, which resulted in a plant population of 297,000 plants ha^{-1}. The lack of significant seeding rate response for the MG V variety is due to the soybean plants' ability to compensate for lower plant populations. This research demonstrates how twin-row soybean can provide higher yields (~7 to 10%) when compared to the single-row system (wide-row). Additionally, these higher yields can be obtained without increasing seeding rate. With the drastic shift from cotton to soybean production, approximately forty percent of the soybean acreage in the Mid-South is currently planted in silt loam soils. Regardless of the soil type, soybean growers in the Mid-South have options. Production systems, such as the twin-row pattern, can be applied to optimize yield when soybean is grown on silt loam soils.

Introduction

The midsouthern USA has recently experienced drastic changes in the agriculture landscape. Due to increased production costs, many acres traditionally grown to cotton (*Gossypium hirsutum* L.) in the southern USA have shifted to soybean (*Glycine max* L.). Higher costs associated with insect management, fertility inputs, and technology fees for current cotton varieties have attributed to increased production costs for cotton in the midsouthern USA in recent years. Higher costs associated with producing cotton and increased soybean commodity prices are the primary reasons for the recent landscape shift. In 2001 there were 656,100 hectares of cotton planted in Mississippi compared to 172,000 hectares in 2010. Conversely, 469,800 hectares of soybean were planted in 2001 in Mississippi, and 809,000 were planted in 2010 (NASS, 2010). Within the four state region of Mississippi, Louisiana, Arkansas, and the Missouri Boot heel region (southeastern Missouri), approximately three million hectares of soybean are produced annually (NASS, 2010). Traditionally, eighty-five percent of the soybean hectarage in the Midsouthern USA is produced on fine-textured soils. Due to the increased amount of soybean hectares grown in the place of cotton, coarser textured soils such as silt loam and sandy loam are now being utilized for soybean production. Currently forty percent of the soybean hectares in the midsouth USA are grown in coarse textured soil.

A significant amount of research has been conducted dealing with the influence of maturity groups, row pattern, and seeding rate for soybean grown in fine-textured soils (Alessi and Power, 1982; Ethredge et al., 1989; Graterol et al., 1996; Bowers et al., 2000; Holshouser and Whittaker, 2002; Janovicek et al., 2006). Limited research in Mississippi has evaluated the influence of maturity group, row pattern, and seeding rate on soybean grown on coarse-textured soils.

The majority of the previous research has shown an increased yield for soybean grown in narrow rows as compared to wide rows (>76 cm) (Alessi and Power, 1982; Beatty et al., 1982; Boquet et al., 1982; Heatherly, 1988; Ethredge et al., 1989; Heatherly et al., 1999; Bowers et al., 2000). Greater yield potential for narrow rows can be attributed to soybean's ability to reach canopy closure quicker in a narrow row pattern. The canopy architecture and uniform leaf distribution in a narrow row pattern allows the plant to intercept a larger percentage of solar radiation (Alessi and Power, 1982). The increased amount of solar radiation leads to an increased rate of photosynthesis. A closed canopy has also shown to decrease weed pressure and lower soil moisture evaporation losses (Shibles and Weber, 1966; Ethredge et al., 1989). Research has shown that a soybean yield increase in narrow rows was the result of increased seed production in the upper portion of the plant (Parks and Manning, 1980; Parks et al., 1982). Ethredge et al. (1989) found higher seed yield in narrow row spacings was attributed to an increased pod number per unit area in the narrower rows (25 and 51 cm) when compared to wide rows (76 cm).

The Early Soybean Production System (ESPS) has been implemented to provide producers with an opportunity to typically avoid some drought stress by planting maturity group IV and V soybean varieties earlier in the growing season (Heatherly et al., 1999). The conventional practice in the midsouthern USA, prior to wide-spread adoption of the ESPS, involved planting MG V, VI, VII, and VIII varieties during May through July (Bowers et al., 2000). By planting a MG IV or early V variety in early- to mid-April, soybean typically can avoid some drought stress through summer months, and in most years, provide the plant with more available soil moisture during pod fill. Due to the popularity of the ESPS, ninety-five percent of the soybean hectares in the midsouthern USA are planted with a MG IV or V variety (C.H. Koger, personal communication, 2010). Maturity Group IV varieties have an indeterminate growth pattern, whereas most MG V varieties are determinate in growth habit. Graterol et al. (1996) found determinate and indeterminate varieties yielded the same in the wide-row planting system, however determinate varieties yielded more than indeterminate varieties in the twin-row planting system.

The twin-row planting system uses a narrow row concept in a wide row system. Thirty percent of the soybean hectares in the midsouthern USA are planted using the twin-row pattern (C.H. Koger, personal communication, 2010). Janovicek et al. (2006) concluded that twin row planting pattern, where two 19-cm-spaced rows are planted on 76-cm centers, consistently increased yields above those obtained with single 76-cm rows. In peanut (*Arachis hypogaea* L.), Jaaffar and Gardner (1988) reported that narrow and twin-row patterns (46-cm) had greater ground cover, leaf area indices, canopy light interception, crop growth rates, and higher grain yields when compared to a 91-cm single row pattern. In a year with minimal yield limiting conditions and with a larger amount of total water available for soybean plants during reproductive growth stages, research has shown that the narrow and twin row patterns offer yield advantages over the wide row planting system (Graterol et al., 1996; Bowers et al., 2000). The twin-row planting system provides soybean producers with flexibility concerning equipment. Potential increase in profit exists by utilizing the twin row system; the grower can use the same equipment used for growing other crops such as corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.).

Selecting the proper seeding rate will affect yield, lodging potential and economic return. The proper seeding rate is dependent upon desired plant population, planting date, soil type, condition of seedbed, planting method (drill vs. planter), percent germination, vigor of seed, and variations within a given field. Heatherly et al. (1999) emphasized that a density of 198,000 to 296,000 uniformly distributed plants per hectare is adequate for maximum yield. Research conducted by Bowen and Schapaugh (1989) found no yield differences with seeding rates of 128,000 to 385,000 seeds per hectare in 76-cm rows. Boquet (1990) reported that 50-cm row spacing required higher plant densities to maximize yields as compared to 101-cm row spacing; whereas Timmons et al. (1967) concluded that wider rows required higher seeding rates to maximize yield as compared to narrow rows. Increasing plant population often increases plant height, decreases viable seed production, and may reduce yield due to excessive lodging (Weber and Fehr, 1966; Ethredge et al., 1989). Cooper and Lambert (1971) reported that wide rows resulted in higher plant mortality as compared to narrow rows and as plant population increased, plant mortality also increased. Due to the combination of increased popularity of the twin row planting system and the significant shift from cotton to soybean grown in the midsouthern USA, research is needed concerning the impact of row pattern, maturity group IV and V varieties, and seeding rate on soybean growth and yield when produced on silt loam soils. Therefore, the objective of this research was to evaluate the effect of seeding rates on growth and yield for twin-row and single-row maturity group IV and V soybean grown in silt loam soils.

Materials and Methods

Site Description and Cultural Practices

Irrigated field studies were conducted at the Delta Research and Extension Center, Stoneville, MS, in 2009 and 2010. In 2009, the soil utilized was a Bosket (Fine-silty, mixed, active, thermic Aquic Hapudalf) silt loam (33°24.44.40 N and 90°54.39.05 W) (WSS, 2010). A Commerce (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) silt loam (33°25.59.20 N and 90°54.35.47 W) was utilized in 2010 (WSS, 2010). Soil samples were collected each year prior to planting. The soil texture was determined by conducting particle-size analysis using the hydrometer method (Gee and Bauder, 1986) and soil chemical properties were determined by the Lancaster soil testing method (Cox, 2001) (Table 2.1). In both years, the field utilized for the experiment was disk harrowed, spring-tooth cultivated, and raised beds were formed in the fall each year prior to planting. An Orthman model 504-30B bed shaper (Orthman Mfg. Inc., Lexington, NE 68850) with lister bottom busters was used to construct 101-cm-wide beds approximately 20-cm in height. Glyphosate [N-(phosphonomethyl) glycine] was applied at 1.12 kg ai ha^{-1} in 47 L ha^{-1} water to kill existing vegetation approximately 5 weeks prior to planting.

Experimental Design

The experiment was a split-split plot in a randomized complete block design with 4 replications of each treatment. The main plot unit was maturity group (MG IV & MG V), the sub plot unit was planting system (twin-row vs. single-row), and the sub-sub plot unit was seeding rate (6 rates). A total of twenty-four treatments were tested. The two soybean varieties evaluated were: ‘Delta King 4968’ (MG IV, indeterminate) and ‘Armor GP-500’ (MG V, determinate) (Table 2.2). Seeding rates were 222,300; 259,350; 296,400; 333,450; 370,500; and 407,550 seed ha^{-1} for both planting systems. The single row system consisted of single rows spaced 101-cm apart on a 101-cm-wide bed. The twin-row system constituted two rows spaced 25-cm apart on a 101-cm center pattern on a 101-cm-wide bed. Plots consisted of four (single-row) or eight (twin-row) rows. Each plot was 15-m long. Single-row plots were planted with a 1700 John Deere (Deere & Company, Moline, IL 61265) MaxEmerge™ vacuum planter. Twin-row plots were planted with a Monosem (Monosem Inc., Lenexa, KS 66219) twin-row vacuum planter. Seed treatment consisted of ‘Apron Maxx RTA’ (a.i. Mefenoxam [(R)-2-{2,6-dimethylphenyl)-methoxyacetylamino }-propionic acid methyl ester] and Fludioxonil [4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1*H*-pyrrole-3-carbonitrile]) + ‘Optimize’ (a.i. *Bradyrhizobium japonicum*) at 3.75 g/100 kg seed, 2.5 g/100 kg seed, and 82.8 ml/45.4 kg seed, respectively, and was applied to all seed immediately prior to planting. The experiment was planted early- to mid- April in 2009 and 2010 (Table 2.3). Irrigation was initiated each year just prior to beginning bloom and continued through full seed fill growth stage (Table 2.3). Irrigation water was applied to each furrow (spaced 101 cm apart) using gated rollout poly pipe and amounts were dictated by a watering schedule throughout the summer (Table 2.4).

Data Collection

Plant Population

Plant populations were determined 4 weeks after planting by counting the number of emerged plants in four 1-m lengths of soybean row per plot (Table 2.3). At the time of data collection, soybean were at the V2 growth stage (Fehr and Caviness, 1977). Counts were collected at random from the middle two rows (single-row) and middle four rows (twin-row) of each plot.

Plant Height

Plant height was measured seven weeks after planting by measuring the height of ten plants per plot (Table 2.3). Plant height for each plant was determined by measuring the height from ground level to the uppermost leaf when left in an undisturbed position. The measurements were collected from random plants in the middle two rows (single-row pattern) and middle four rows (twin-row pattern).

Leaf Area Index

Percent light interception was determined with a 1-m-long linear AccuPAR ceptometer (Decagon Devices, Inc., Pullman, WA 99163) when canopy closure was reached in either the twin-row or single-row pattern (Table 2.3). In both 2009 and 2010 canopy closure occurred at approximately the R5 growth stage (Fehr and Caviness, 1977). The ceptometer estimates light intensity (μmol m^{-2} s^{-1}) by measuring photosynthetic active radiation (PAR). Estimates of PAR were measured at the soil level and just above the soybean canopy in each plot. The ceptometer was held perpendicular to the two middle (single-row pattern) or four middle (twin-row pattern) rows of each plot for the soil level and above canopy PAR measurements. Four PAR estimates were collected from the soil level and above the soybean canopy from each plot. Four percent light interception values for each plot were calculated by dividing a soil level PAR estimate by above canopy PAR estimate and multiplying that value by 100. The four percent light interception values for each plot were averaged for analysis purposes.

Normalized Difference Vegetative Index

Amount of sunlight interception was measured by using canopy reflectance (Table 2.3). Vegetative indices are established by wavelengths in the near infrared region (NIR) (750-1300 nm) and visible (400-750 nm) of the light spectrum. The normalized difference vegetative index (NDVI) uses the red (R) region (620-750 nm) and is calculated from the formula NDVI = [(NIR-R) / (NIR+R)]. Normalized difference vegetative index data was collected between the R4 and R5 growth stage (Fehr and Caviness, 1977) by utilizing a GreenSeeker Sensor Model 505 (NTech Industries, Inc., 740 South State Street Ukiah, CA 95482). Normalized difference vegetative index was calculated for each plot by holding the sensor parallel to the plot 76 cm above the top of the soybean canopy between the middle two rows (single-row pattern) and middle four rows (twin-row pattern) and was used for analysis purposes.

Node Count

Ten randomly selected plants were clipped at ground level from the center two (single-row) or four (twin-row) rows per plot and then removed from each plot at 2 wk prior to harvest so that node counts could be collected. The number of nodes per plant was determined by counting the number of nodes beginning at ground level and extending to the uppermost node on each plant.

Pod Count / Percent one, two, three, and four-bean pod plant^{-1}

Pods containing at least one developed seed contributed to the total pod count for each selected plant. The total number of pods plant^{-1} was counted for ten randomly selected plants plot^{-1}(same plants used for node count) and then averaged for the ten plants plot^{-1}. Total pods plant^{-1} was extrapolated into percent one, two, three, and four-bean pods plant^{-1}.

Seed Yield

The two (single-row) or four (twin-row) center rows of each plot were harvested at time of soybean maturity with a Massey Ferguson Kincaid 8XP plot combine (Kincaid Equipment Manufacturing, Haven, KS 67543) (Table 2.3). The combine was equipped with an automated scale, moisture sensor, and data logger. Seed yield was adjusted to 13% moisture.

Seed Weight

At time of harvest, seed samples were obtained from each plot for seed mass measurements. Seed mass was determined by weighing three 100-seed subsamples from each harvest sample and is presented as grams 100-seed^{-1}.

Statistical Analysis

PROC MIXED (SAS, 2008) was used to test fixed effects and interactions among fixed effects. To evaluate the significance of treatment effects on plant growth, light interception, and yield, year, maturity group, row pattern, and seeding rate were considered fixed effects. Replicate of each treatment combination was considered a random variable in all analyses. Least square means at the $P < 0.05$ was used for mean separation. Within results, main effects are discussed unless interactions ($P < 0.05$) were observed.

Results

Growing Conditions

Dates of management inputs were very similar between field experiments in 2009 and 2010 (Table 2.3). The only exception was when harvest occurred in 2009 as compared to 2010. Due to the large amount of rainfall in the fall in 2009 and the extremely wet field conditions, harvest was delayed by approximately two weeks after maturity. The 2010 harvest was concluded without any delay or challenges associated with weather. Drier conditions were more prevalent in 2010 growing season as compared to 2009. The air temperature was on average 2°C higher and significantly less precipitation was observed in 2010 growing season (Table 2.5). Due to the increased heat and decreased rainfall, field experiments were furrow irrigated 7 times in 2010 as compared to 3 times in 2009 (Table 2.4). The intent of a proper irrigation schedule was to ensure that water did not serve as a limiting factor for soybean growth and yield.

Plant Population

Plant population was affected by an interaction between row pattern and seeding rate when averaged across maturity group and year (Table 2.6). When plant populations in the single row pattern were compared to the twin row pattern, there were differences between row pattern at only the two lowest seeding rates (222,000 and 259,000 seed ha^{-1}, respectively) (Table 2.7 and Figure 2.1). The seeding rates of 296,000; 333,000; 370,000; and 408,000 seed ha^{-1} did not increase or decrease plant population when comparing single- and twin-row patterns.

Plant Height

Observed plant height was influenced by the main effects of year, variety, and row pattern (Table 2.6). Plant heights were greater in 2010 as compared to 2009 (Table 2.8). The MG V variety had 7% greater plant height as compared to the MG IV variety (Table 2.9). Row pattern influenced plant height; plants in the single row pattern were 4% taller compared to plants in the twin row pattern (Table 2.10).

Node Production

The number of nodes plant^{-1} was influenced by one 3-way interaction and two 2-way interactions (Table 2.6). An interaction between year, maturity group, and row pattern affected node production. The treatment combination that had the greatest number of nodes plant^{-1} was the MG IV variety in the twin row pattern in 2009 (Table 2.11). Within MG IV, the twin row pattern had the same number of nodes plant^{-1} as the single row pattern. The only exception was the MG IV plants in the twin row pattern in 2009. Maturity group IV plants in the twin-row pattern had more nodes plant^{-1} than the MG IV plants in the single row pattern in 2010. An interaction between maturity group and seeding rate affected number of nodes plant^{-1} (Table 2.6). A trend similar to the interaction between year, maturity group, and row pattern was observed; the MG IV soybean plants had more nodes plant^{-1} than the MG V regardless of seeding rate (Table 2.12). Differences were observed within the different seeding rates. Within MG IV, seeding rates of 222,000 and 259,000 seed ha^{-1} had greater number of nodes plant^{-1} than the seeding rates of 333,000, 370,000, and 408,000 seed ha^{-1}. The highest seeding rate in the MG IV variety (408,000 seed ha^{-1}) had less nodes plant^{-1} than all the other seeding rates. In the MG V variety, the second highest seeding rate of 370,000 seed ha^{-1} had the fewest nodes plant^{-1} (Table 2.12).

An interaction between year and seeding rate affected the number of nodes plant^{-1} (Table 2.6). When years were compared, plants had more nodes plant^{-1} in 2010 when compared to 2009 (Table 2.13). When evaluated within year, seeding rate of 259,000 seed ha^{-1} had the greatest number of nodes plant^{-1} in 2010 as compared to all other seeding rates. However, the seeding rate of 259,000 seed ha^{-1} was not different than the seeding rate of 296,000 seed ha^{-1}. In 2009, the seeding rate of 222,000 seed ha^{-1} resulted in more nodes plant^{-1} as compared to the seeding rates of 333,000, 370,000, and 408,000 seed ha^{-1}, but was not greater than the seeding rates of 259,000 and 296,000 seed ha^{-1}.

Leaf Area Index

The observed leaf area index (LAI) values were influenced by the main effects of year, maturity group, and row pattern (Table 2.6). When averaged across maturity group, row pattern, and seeding rate factors within each year, LAI values were greater in 2010 compared to 2009 (Table 2.8). Leaf area index values were affected by the main effect of maturity group (Table 2.6). When averaged across row pattern, seeding rate, and year, MG V variety plants had a greater LAI value as compared to the MG IV variety plants, 3.81 and 3.09, respectively (Table 2.9). Leaf area index values were affected by the row pattern main effect (Table 2.6). Soybean plants in the twin row pattern had a LAI value of 4.16 compared to 2.74 in the single row pattern (Table 2.10).

Normalized Difference Vegetative Index

The reflectance of the soybean canopy was observed by using the normalized difference vegetative index (NDVI). Normalized difference vegetative index was affected by a 3-way interaction between maturity group, row pattern, and year (Table 2.6). Mean NDVI values were greater in 2010 as compared to 2009, 0.9205 and 0.8867, respectively (Table 2.14). The plants for the treatment combination of MG V in the twin row pattern, in 2010, had the highest NDVI value. Maturity group V plants in the twin row pattern in 2010 had higher NDVI values as compared to all other treatment combinations except the MG IV plants in twin row pattern in 2010. When comparing maturity groups, the MG V variety had greater mean NDVI value as compared to MG IV, 0.913 and 0.894, respectively. When the NDVI results were examined within maturity group, similar trends were observed. Within the MG V variety, in both years the twin row pattern had higher NDVI values as compared to the single row pattern. As mentioned previously, the MG V in the twin row pattern in 2010 had the greatest NDVI value when compared to all other MG V treatment combinations. Within the MG IV, a similar trend was observed; in both years, the twin row pattern had greater NDVI values when compared to the single row pattern. The MG IV, twin row pattern, in 2010, had the highest NDVI value when comparisons are made within the MG IV variety (Table 2.14).

Pod Production

The total number of pods plant^{-1} was affected by two 3-way interactions (year x maturity group x row pattern; year x row pattern x seeding rate). The interaction between year, maturity group, and row pattern affected the total number of pods plant^{-1} (Table 2.6). In general, pod production was greater in 2009 compared to 2010 (Table 2.11). When averaged across years, the MG IV variety had an increased number of pods plant^{-1} as compared to the MG V, 66.1 and 58.0, respectively. When averaged across maturity group and year, the twin row pattern outperformed the single row pattern with respect to pod production plant^{-1}. The MG IV plants in the twin row pattern, in 2009, had the highest number of pods plant^{-1} as compared to all other treatment combinations, except the MG IV variety in the single row pattern in 2009. Within the MG IV variety, the twin-row pattern consistently increased the total number of pods plant^{-1} when compared to the single row pattern. Within the MG V variety, the twin row pattern increased the number of pods plant^{-1} as compared to the single row pattern in 2010, however this trend was not observed in 2009.

The interaction between year, row pattern, and seeding rate affected the total number of pods plant^{-1} (Table 2.6). In 2009, total number of pods plant^{-1} decreased with increasing seeding rates (Table 2.15). Within 2009, the greatest pod production was observed at the lowest seeding rate of 222,000 seed ha^{-1} for both the single- and twin-row patterns. The seeding rate of 222,000 seed ha^{-1} resulted in a plant population of 214,000 plants ha^{-1}. In 2010, a similar trend was observed for the twin row pattern, but not for the single row pattern. The greatest pod production in 2010 in the twin row pattern was observed at the seeding rates of 222,000 and 259,000 seed ha^{-1}, or a plant population of

214,000 and 238,000 plants ha^{-1}, respectively. In the single row pattern, pod production in 2010 reached a plateau at 259,000 seed ha^{-1}. In general, if lower seeding rates were utilized (222,000, 259,000, 296,000 seed ha^{-1}), the increase in pod production from single row to twin row pattern was significant. If higher seeding rates were utilized (333,000, 370,000, 408,000 seed ha^{-1}), the increase in pod production when comparing the single row to the twin row pattern did not occur; instead, a general decrease in pod production plant^{-1} was observed.

Seed Pod^{-1} Production

When soybean pods where counted, they were also separated into mean 1-, 2-, 3-, and 4-bean pods plant^{-1}. The result was the calculation of percent 1-, 2-, 3-, and 4-bean pod plant^{-1}. Percent 1-bean pod plant^{-1} was influenced by the main effects, year and seeding rate, and a 2-way interaction between maturity group and row pattern (Table 2.16). In 2010, the % 1-bean pod plant^{-1} was greater than 2009. In 2010, 10.73 % of the pods plant^{-1} were 1-bean pods; however, in 2009, 6.30 % were 1-bean pods (Table 2.8). Seeding rate influenced percent 1-bean pod plant^{-1} (Table 2.16). Due to time limitations in 2009, only the lowest and highest seeding rates were sampled with respect to percent bean pods plant^{-1}. With the lowest seeding rate (222,000 seed ha^{-1}) a greater percentage of the pods plant^{-1} were 1-bean pods as compared to the highest seeding rate (408,000 seed ha^{-1}), 9.74 and 7.29 %, respectively (Table 2.17). Mean percent 1-bean pod plant^{-1} was affected by an interaction between maturity group and row pattern (Table 2.16). The MG IV twin row pattern and the MG V single row pattern treatment combinations had an increased mean % 1-bean pod plant^{-1} as compared to the MG IV single row pattern treatment combination (Table 2.18).

Mean percent 2-bean pods plant^{-1} was influenced by two 2-way interactions (maturity group x row pattern; year x seeding rate). An interaction between maturity group and row pattern affected percent 2-bean pods plant^{-1} (Table 2.16). The MG V plants in both the single and twin row pattern had greater mean percent 2-bean pod plant^{-1} as compared to the MG IV variety (Table 2.18). For the MG IV variety, the twin row pattern increased the percent 2-bean pods plant^{-1} as compared to single row pattern; within the MG V's, there was no increase due to row pattern. An interaction between year and seeding rate affected the percent 2-bean pods plant^{-1} (Table 2.16). The mean percent 2-bean pod plant^{-1} was greater in 2010 as compared to 2009 (Table 2.19). There were no differences observed between seeding rates in 2010; in 2009 the low seeding rate of 222,000 seed ha^{-1} had increased percent 2-bean pod plant^{-1} as compared to the high seeding rate of 408,000 seed ha^{-1}.

An interaction between year and seeding rate affected the percent 3-bean pod plant^{-1} (Table 2.16). The mean percent 3-bean pod plant^{-1} was greater in 2010 as compared to 2009 (Table 2.19). The high seeding rate of 408,000 seed ha^{-1}, in 2010, had the greatest percent 3-bean pod plant^{-1}, followed by the 2010 low seeding rate of 222,000 seed ha^{-1}, the 2009 low seeding rate, and the 2010 high seeding rate. Mean percent 3-bean pod plant^{-1} was also affected by an interaction between maturity group, row pattern and year (Table 2.16). In 2010, the MG IV plants in the single and twin row pattern had the greatest percent 3-bean pod plant^{-1} as compared to all other treatment combinations of maturity group, row pattern, and year (Table 2.14). In 2009, the MG IV in the twin row pattern increased the percent 3-bean pod plant as compared to the MG IV single row pattern, whereas the MG V twin row pattern did not when compared to the MG V single row pattern. In 2010, the percent 3-bean pod plant^{-1} for the MG IV, single and twin row pattern were not different, however the MG V twin row pattern increased the percent 3-bean pod plant^{-1} as compared to the MG V single row pattern.

Mean percent 4-bean pod plant^{-1} was affected by an interaction between year, maturity group, and seeding rate (Table 2.16). In both 2009 and 2010 the MG IV variety produced an increased percent 4-bean pod plant^{-1} as compared to the MG V (Table 2.20). The 2009 MG IV, at the low seeding rate of 222,000 seed ha^{-1}, had the greatest percent 4-bean pod plant^{-1} when compared to all treatment combinations of maturity group and the low and high seeding rates in 2009 and 2010, but was not greater than the 2010 MG IV at the high seeding rate.

Seed Weight

The weight of 100 soybean seed was influenced solely by a main effect of year (Table 2.6). Seed weight was greater in 2009 as compared to 2010, 15.67 and 13.44 g, respectively (Table 2.8).

Seed Yield

Soybean seed yield was affected by one main effect (row pattern) and two 2-way interactions (year x maturity group; maturity group x seeding rate) (Table 2.6). The twin row pattern increased yield as compared to the single row pattern (Table 2.10). Averaged across year, maturity group, and seeding rate factors, the twin row pattern yielded 4937 kg ha^{-1}; whereas the single row pattern yielded 4506 kg ha^{-1}. An interaction between maturity group and year influenced seed yield (Table 2.6). In both years, soybean seed yield was greater for the MG V variety as compared to the MG IV (Table 2.21). Between years, the MG V seed yield was not different; however the MG IV seed yield was greater in 2010 as compared to 2009. An interaction between maturity group and seeding rate affected seed yield (Table 2.6). Soybean seed yield was greater for the MG V variety as compared to the MG IV variety (Table 2.12). When results are examined within maturity group, seed yield for the MG V variety differed, but was not different across varying seeding rates. Differences due to differing seeding rates were observed within the MG IV variety. The treatment combination of MG IV coupled with the seeding rate of 408,000 seed ha^{-1} resulted in a greater seed yield than the seeding rates of 370,000; 296,000; 259,000; and 222,000 seed ha^{-1}, but was not different than the subsequent seed yield experienced by the MG IV variety at a seeding rate of 333,000 seed ha^{-1}. The plant populations obtained from 333,000 and 408,000 seed ha^{-1} were 297,000 and 353,000 plants ha^{-1} (Table 2.7). For optimum yield, with respect to seeding rates, with a MG IV variety, the plant population was 297,000 plants ha^{-1} and was obtained by a seeding rate of 333,000 seed ha^{-1}.

Discussion

Plant Population

Plant populations were expected to differ based on the associated seeding rate. Seed quality, tillage, residue, soil temperature, and seedbed condition should be considered when seeding rates are selected (Walker et al., 2010). In both years, the entire experiments were planted in one day. Soil moisture conditions were the same for the entire location of the experiment at planting. Previous research, conducted by Helms et al. (1996) showed unsatisfactory emergence for soybean when environmental conditions at planting are dry due to the high water requirement for imbibition. Results show a slightly higher plant population for the soybean plants in the twin row pattern as compared to the single row pattern (Table 2.7). Walker et al. (2010) emphasized that typical estimates of final soybean stand are usually made within a few weeks of emergence and may vary from 50 to 80% of planted seed. The mean emergence of our field experiments was 90%. As different planters were utilized to plant twin- and single-row soybean, differences in seed drop characteristics between the planters may have also affected actual seeding rates and subsequent plant populations.

Plant Height

The increased plant height in 2010 as compared to 2009 could be due in large part to increased air temperature in 2010 (Tables 2.8 and 2.5). Egli and Bruening (1992) reported that soybean development is influenced by temperature. Cooper (1981) determined that stress from high temperature can reduce plant height. The differences in plant height due to maturity group could be explained: the MG V variety was a determinate soybean that had a greater combination of bushy and upright growth as compared to the MG IV soybean variety (Table 2.9). The increase in plant height, due to the effect of row pattern, was influenced by emergence (Table 2.10). As mentioned previously, the twin row pattern had more seedlings emerge than the single row pattern. However, the soybean seedlings in the single row pattern seemed to emerge slightly quicker than the seed planted in the twin row pattern. This decrease in plant height observed for the plants in the twin row pattern could be due to decreased competitiveness among plants as plants were spaced apart at greater distance within individual rows of the twin-row pattern when compared to plants in the single-row pattern, which experienced more intra-row competition. The twin row uses the narrow row concept within the wide row system. Previous research has shown soybean grown in narrow rows deplete soil water more rapidly during vegetative development (Taylor, 1980; Alessi and Power, 1982; Van Doren and Reicosky, 1987; Heatherly and Elmore, 2004).

Vegetative Indices: LAI and NDVI

Plant LAI and NDVI are commonly used vegetative indices (Chen and Wiatrak, 2011). Chen and Wiatrak (2011) reported that production practices such as maturity group, seeding rate, and planting date can influence plant LAI and NDVI, and plant height, and subsequent seed yield. Previous research has demonstrated that optimum crop growth rate and yield result when LAI is sufficient (3 to 3.5) to achieve a 95% light interception by the R5 growth stage (Shibles and Weber, 1966; Board and Harville, 1993; Hunt et al., 1994; Board and Tan, 1995; Haile et al., 1998; Singer, 2001). Plant NDVI has been widely used to measure and monitor plant growth, vegetation cover, and biomass production and yield (Ma et al., 2001; Martin et al., 2005; De Melo et al., 2008; Galvao et al., 2009). Specifically, Ma et al. (2001) concluded that plant NDVI during pod-set stage is closely correlated with soybean yield.

Overall, the environment favored higher LAI and NDVI values in 2010 as compared to 2009. Similar trends were observed between LAI and NDVI values. Soybean plants were taller and contained more growth in 2010 as compared to 2009. The increased plant height and outward growth accounted for increased LAI and NDVI values in 2010 growing season. The MG V variety had an increased LAI and NDVI as compared to the MG IV variety; the MG V grew taller and exhibited increased outward growth (Tables 2.9 and 2.14). Row pattern contributed greatly to LAI and NDVI values. Leaf area index and NDVI values were greater in the twin-row pattern as compared to the single row pattern (Tables 2.10 and 2.14). Taylor et al. (1982) reported plants in narrow rows (<25 cm wide) intercepted more light and often had more uniform leaf distribution than plants in wider rows. Previous research has shown an advantage associated with narrow row spacing of more equidistant plant spacing, which increases canopy development and light interception earlier in the growing season (Weber et al., 1966; Dalley et al., 2004). Our results show that the twin row pattern uses the narrow row concept and combines it with the wide row system. Increasing the plant population density has shown promotion of rapid canopy closure and resulting improved light interception and biomass production (Bertram and Pedersen, 2004). The increase in observed LAI and NDVI values for the twin row pattern resulted in canopy closure occurring approximately 7 to 10 days quicker than in the wide-row system. De Bruin and Pedersen (2009) concluded that soybean yield increases with total dry matter and crop growth rate, which depend on plant canopy development.

Node and Pod Production

The MG IV plants contained more nodes plant^{-1} when compared to the MG V variety (Table 2.11). The twin row pattern also increased node production when compared to the single row pattern (Table 2.11). The increase in node production observed for the twin row pattern was likely due to equidistant spacing; as the plants were spaced farther apart within the twin row pattern as compared to the single row pattern subsequent increase in node production resulted. Soybean have the ability to compensate with more growth when plant populations are decreased. Previous research has shown that soybean responds to lower seeding rates by developing more secondary branches. Secondary branching typically results in increased leaf area, biomass, pods, and seed plant^{-1} compared with soybean plants in fields having higher seeding rates (Egli, 1988; Carpenter and Board, 1997; Board, 2000; Egli and Bruening, 2006; Epler and Staggenborg, 2008). The lower seeding rates consistently had an increased number of nodes plant^{-1} throughout the growing season as compared to the higher seeding rates.

Plant processes that affect yield (photosynthesis, respiration, partitioning, etc.) must ultimately express their effect through the seed (Egli, 2010). Pod production was greater in 2009 as compared to 2010 (Table 2.11); this observation could be due to increased air temperature and decreased rainfall in the 2010 growing season (Table 2.5). Temperature stress has been shown to limit yield by reducing pod set, seed pod^{-1}, and seed size (Specht et al., 1999; Heatherly and Elmore, 2004). Trends similar to node production were observed with pod production. The MG IV produced more pods plant^{-1} as compared to the MG V variety. The twin-row pattern resulted in increased pod production when compared to the single row pattern (Table 2.11). The increased pod production for the MG IV is correlated to an increased number of nodes plant^{-1}. Greater leaf area coverage for plants in the twin-row pattern resulted in greater degree of light interception and quicker canopy closure when compared to the single-row pattern. The increased light interception and subsequent quicker canopy closure resulted in more efficient pod production in the twin row pattern as compared to the single row pattern. Board et al. (1999) reported an increase in pods plant^{-1}, which primarily occurred on the secondary branches, was the secondary yield component most responsible for soybean yield compensation to increased space either within or between rows.

Pod production as influenced by row pattern and seeding rate followed a consistent trend (Table 2.15). If lower seeding rates were utilized (222,000 to 296,000 seed ha^{-1}), pod production was greater with the twin row pattern as compared to the single row pattern. If the higher seeding rates of 333,000 to 408,000 seed ha^{-1} were utilized, pod production per plant did not increase in the twin row pattern. Cox and Cherney (2011) reported soybean produced 27% more pods plant^{-1} at 321,000 compared to 469,000 seed ha^{-1}.

Variation in the number of seeds per unit area is responsible for much of the environmentally induced variation in soybean yield (Egli, 1998; Calvino et al., 2003). Egli (2010) emphasized that the determination of seed number represents the first opportunity for the crop to adjust its productive output to environmental conditions. Mean percent 1, 2, 3, and 4-bean pod definitely had an impact on seed yield. Some trends were observed within the seed pod^{-1} parameter. Total pod production plant^{-1} was greater in 2009. The mean percent 1-, 2-, 3-bean pod were greater in 2010 as compared to 2009 (Tables 2.8 and 2.19). The soybean plants had more 1, 2, and 3-bean pods plant^{-1} in 2010 as compared to 2009. Slightly higher percent 4-bean pod plant^{-1} was observed in 2009 compared to 2010 (Table 2.20). Mean percent of 1-bean pods was greater at lower seeding rates (Table 2.17), whereas percent 3-bean pods were greater at higher seeding rates in 2010 (Table 2.19). There were no observed differences due to seeding rate in

2010 for percent 2-bean pod, however, in 2009, the low seeding rate increased mean percent 2-bean pod plant^{-1} (Table 2.19). There were no observed differences in percent 4-bean pod plant^{-1} with respect to seeding rate (Table 2.20). Maturity group had mixed results with respect to seed pod^{-1}. The treatment combinations of MG IV, twin row pattern and MG V, single row pattern maximized the percent 1-bean pod compared to other MG x row pattern treatment combinations (Table 2.18). An increase in percent 2-bean pods plant^{-1} was observed with the MG V (Table 2.18). Both the percent 3- and 4-bean pods plant^{-1} was greatest with the MG IV variety (Tables 2.14 and 2.20). Row pattern had mixed results across seed pod^{-1} (Tables 2.18 and 2.14). Seed pod^{-1} is a component of yield that has been shown not to respond to seeding rates or row spacing (Egli, 1994; Board, 2000). Epler and Staggenborg (2008) did provide an exception in that they reported a linear decrease in seed pod^{-1} as plant densities increased.

Seed Weight

The yield of grain crops is determined by the dry matter accumulated by the seeds during seed filling. Increased precipitation and decreased air temperature was the trend when environmental conditions in 2009 were compared to 2010 (Table 2.5). Hartwig (1973) concluded that seed size in soybean is under genetic control, although seed of a given variety will fluctuate in size depending on the production environment. The soybean plant was more efficient in seed production in 2009; heavier seed was the result (Table 2.8). Our results are closely associated with what Hartwig (1973) found; seed size of soybean varieties commonly used in commercial production ranges from 12 to 18 g 100 seed^{-1}. Seed size is usually not closely related to yield (Egli et al., 1978).

Seed Yield

The twin row pattern consistently increased seed yield in both 2009 and 2010 when compared to the single row pattern (Table 2.10). Seed yield was increased by 431 kg ha^{-1} when the twin row pattern was utilized as opposed to the single row pattern. As mentioned previously the twin row pattern takes the narrow concept and combines it with the wide row system. Previous research has shown an increased yield for soybean grown in narrow rows (<50 cm) as compared to wide rows (>80 cm) (Alessi and Power, 1982; Beatty et al., 1982; Boquet et al., 1982; Heatherly, 1988; Ethredge et al., 1989; Heatherly et al., 1999; Bowers et al., 2000; Bertram and Pedersen, 2004). Greater yield potential for narrow rows can be attributed to soybean's ability to reach canopy closure quicker in a narrow row pattern. Increased LAI and NDVI values present in the twin row pattern were explained by larger leaf area available for sunlight interception. The twin row pattern closed the canopy approximately 7 to 10 days quicker as compared to the single row pattern. Yelverton and Coble (1991) reported reduced weed competition when soybean was planted in narrow rows. Nelson and Renner (1998, 1999) concluded that soybean produced in narrow rows decreased the amount of herbicide needed, subsequently increasing economic benefits to narrow row soybean. In addition to more efficient canopy closure, the twin row increased yield through increased node and pod production in our experiments. More nodes and pods plant^{-1} were observed in the twin row pattern as compared to the single row pattern.

In a year with no seed yield-limiting conditions and with a larger amount of total water available for soybean plants at early reproductive periods, Graterol et al. (1996)

reported that determinate varieties yielded more than indeterminate varieties in the twin row planting system and yielded similar to indeterminate varieties in the wide row planting system. Research conducted by Elmore et al. (1987) had similar results; determinate varieties yielded more than indeterminate varieties in a low-stress year with enough available water. Our results show an increased seed yield for the MG V's as compared to the MG IV's (Table 2.21). The MG V yielded 981 kg ha^{-1} greater than the MG IV in 2009, and 517 kg ha^{-1} greater in 2010. This yield increase is due in large part to different genetics between varieties with different growth habits of indeterminate and determinate. Maturity group and seeding rate interacted to affect soybean seed yield. Maturity group V's yielded greater than all the MG IV's across all seeding rates (Table 2.12). Previous research has shown minimal response for variety and seeding rate, with respect to seed yield (Costa et al., 1980; Bowen and Schapaugh, 1989). Our results show no differences between MG V and changing seeding rates; however, within the MG IV variety, differences were observed. If planting a MG IV variety, the optimum seeding rate was observed at 333,000 seed ha^{-1}, which resulted in a plant population of 297,000 plants ha^{-1}.

Conclusion

Even with the drastic changes occurring in the agricultural landscapes in the Mississippi River Alluvial-flood plain, producers still have flexibility concerning soybean systems that have been proven to produce excellent soybean yields on fine-textured soils and now have proven to yield as well on silt loam soils. Increase in soybean seed yield was observed for the twin row pattern as compared to the single row pattern. Maturity group V variety had greater seed yield as compared to the MG IV variety. Changing the seeding rate did not influence MG V variety seed yield; however, yield differences were observed with the MG IV variety. The optimal seeding rate for the MG IV variety with respect to seed yield was observed at 333,000 seed ha^{-1}, which resulted in a plant population of 297,000 plants ha^{-1}. Increased LAI and NDVI values and node and pod production were observed for the twin row pattern and explain the associated increase in seed yield when compared to the single-row pattern. Due to the quicker canopy closure in the twin row pattern as compared to the single row pattern, weed competition decreased and leaf area for sunlight interception was maximized. This research has shown that growers producing crops in silt loam soils have production options, such as a twin-row system, that can be utilized to increase yield across maturity groups without increasing seeding rates.

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Table 2.1

Soil chemical properties for soybean study conducted at DREC, Stoneville, MS, 2009-2010.

								Extractable Nutrient Levels[†]						
								kg ha^{-1}						
Year	%OM	%Sand	%Silt	%Clay	Texture[‡]	CEC	pH	P	K	Ca	Mg	Zn	S	Na
2009	0.66	28	55	17	Silt Loam	13.7	6.1	136	479	3896	622	3.02	106	81
2010	0.56	29	54	17	Silt Loam	13.7	5.9	133	466	3873	670	2.13	91	93

† Lancaster soil testing method (Cox, 2001).

‡ Particle size analysis: Hydrometer method (Gee and Bauder, 1986).

Table 2.2

Agronomic ratings for varieties planted in studies conducted at Stoneville, MS, 2009-2010.

Characteristics	Variety	
	Delta King 4968[†]	Armor GP-500[‡]
Maturity	4.9	5.0
Plant type	Indeterminate	Determinate
Plant height	Medium-Tall	Medium
Lodging	Moderate	Moderately resistant
Shatter	Moderately resistant	Resistant
Plant growth	Upright	Bushy
Flower color	Purple	White
Hilum color	Imperfect black	Black
Pubescence	Gray	Brown
Pod color	Tan	Tan
Seed size[Φ]	6167-6828	6388-7048
Water response	Excellent	Excellent
Ease of harvest	Good	Excellent

¥ Resistant implies no or very slight disease when conditions are favorable for development. Moderately resistant implies slight disease presence when conditions are favorable for development. Moderate implies some disease presence when conditions are favorable for development. Moderately susceptible implies significant disease presence when conditions are favorable for development. Susceptible implies very significant disease presence when conditions are favorable for development.

† Ratings available at (Anonymous, 2010a).

‡ Ratings available at (Anonymous, 2010b).

Φ Seed kg^{-1}.

Table 2.3

Calendar dates for agronomic inputs for soybean row pattern x seeding rate x maturity group study conducted at Delta Research Extension Center (DREC), Stoneville, MS, 2009-2010.

Input	2009	2010
Planting	15 April	13 April
Emergence	23 April	21 April
Stand Counts	20 May	12 May
Plant Height	10 June	10 June
LAI†	18 June	24 June
NDVI‡	13 July	12 July
Initiation of Irrigation	11 June	8 June
Harvested MG IV§	18 September	24 August
Harvested MG V¥	2 October	12 September

† LAI, leaf area index

‡ NDVI, normalized difference vegetative index

§ MGIV, ‘Delta King 4968’.

¥ MGV, ‘Armor GP-500’

Table 2.4

Calendar dates for irrigation inputs to soybean study conducted at DREC, Stoneville, MS, 2009-2010.

Input	2009	2010
Furrow Irrigation	11 June	8 June
	24 June	18 June
	6 July	28 June
		7 July
		19 July
		1 August
		13 August

Table 2.5

Total precipitation and average air temperature for months of April – September at DREC, Stoneville, MS, 2009-2010.

	Precipitation[‡]		Air Temperature[¥]	
	2009	2010	2009	2010
Month[†]	-----mm-----		-----°C-----	
April	75	60	23.8	26.8
May	343	134	26.9	30.1
June	7	31	33.7	34.4
July	222	48	32.2	34.0
August	36	6	32.4	37.0
September	129	54	29.9	28.2

[†] Data obtained from Mississippi State University, Delta Research and Extension Center website (DREC, 2011).

[‡] Total precipitation received for indicated month of 2009 and 2010.

[¥] Average air temperature for indicated month of 2009 and 2010.

Table 2.6

Test of fixed effects and interactions for seed yield and weight, stand count, plant height, node count, pod count, LAI, and NDVI across input variables of year, maturity group, row pattern, seeding rate and all interactions for soybean study at DREC, Stoneville, MS, 2009-2010.

	Seed			Plant				
	Yield	Weight	Stand Count	Height	Node	Pod	LAI†	NDVI‡
Source				Pr > F				
Year (YR)	NS¥	0.0016	NS	<.0001	NS	0.0131	0.0003	0.0014
Maturity Group (MG)	0.0002	NS	NS	0.0007	<.0001	0.0080	0.0042	0.0011
Row pattern (RP)	<.0001	NS	0.0004	0.0017	0.0128	0.0364	<.0001	<.0001
Seed rate (SR)	0.0022	NS	<.0001	NS	<.0001	<.0001	NS	NS
YR*MG	0.0507	NS	NS	NS	NS	0.0126	NS	0.0284
YR*RP	NS	NS	NS	NS	NS	0.0284	NS	0.0013
MG*RP	NS	NS	NS	NS	NS	NS	NS	0.0017
YR*SR	NS	NS	NS	NS	0.0227	<.0001	NS	NS
MG*SR	0.0153	NS	NS	NS	0.0474	NS	NS	NS
RP*SR	NS	NS	0.0128	NS	NS	<.0001	NS	NS
YR*MG*RP	NS	NS	NS	NS	0.0295	0.0412	NS	0.0226
YR*MG*SR	NS	NS	NS	NS	NS	NS	NS	NS
YR*RP*SR	NS	NS	NS	NS	NS	0.0009	NS	NS
MG*RP*SR	NS	NS	NS	NS	NS	NS	NS	NS
YR*MG*RP*SR	NS	NS	NS	NS	NS	NS	NS	NS

† LAI, Leaf Area Index.

‡ NDVI, Normalized Difference Vegetative Index.

¥ NS, not significant at the P = 0.05 level of significance. A P value of < 0.05 indicates significant effect or interaction.

Table 2.7

Soybean plant population as affected by row pattern and seeding rate when averaged across maturity group and year at DREC, Stoneville, MS, 2009-2010.

	Plant Population	
	Single[‡]	Twin[†]
Seeding Rate[§]	----------x1000plants ha^{-1}----------	
222,000	201 g[¥]	227 f
259,000	230 f	247 e
296,000	264 d	273 d
333,000	295 c	299 c
370,000	330 b	333 b
408,000	349 a	358 a

§ Seeding Rate, seed ha^{-1}.

‡ Single-row pattern, John Deere® Max-emerge planter.

† Twin-row pattern, Monosem® planter.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.8

Soybean seed weight, plant height, LAI, and % 1-bean pods as affected by year when averaged across maturity group, row pattern, and seeding rate at DREC, Stoneville, MS, 2009-2010.

	Seed Weight	Plant Height	LAI[¥]	1-bean pod
Year	-----grams[‡]-----	-----cm-----		-----%-----
2009	15.67 a[†]	59.0 b	2.33 b	6.30 b
2010	13.44 b	75.1 a	4.57 a	10.73 a

¥ LAI, Leaf Area Index.

‡ grams (100 seed)$^{-1}$

† Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.9

Soybean plant height and LAI as affected by maturity group averaged across row pattern, seeding rate, and year at DREC, Stoneville, MS, 2009-2010.

Maturity Group (MG)	Plant Height	LAI[‡]
	-----cm-----	
MG IV[£]	64.7 b[†]	3.09 b
MG V[β]	69.4 a	3.81 a

‡ LAI, Leaf Area Index.

† Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

£ MG IV, ‘Delta King 4968’.

§ MG V, ‘Armor GP-500’.

Table 2.10

Soybean seed yield, plant height, and LAI as affected by row pattern averaged across maturity group, seeding rate, and year at DREC, Stoneville, MS, 2009-2010.

Row Pattern	Seed Yield	Plant Height	LAI[¥]
	-----kg ha^{-1}-----	-----cm-----	
Single[‡]	4506 b[£]	68.5 a	2.74 b
Twin[†]	4937 a	65.5 b	4.16 a

¥ LAI, Leaf Area Index.

£ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

‡ Single-row, John Deere® Max-emerge planter.

† Twin-row, Monosem® planter.

Table 2.11

Number of nodes and number of pods per plant as affected by maturity group, row pattern, and year when averaged across seeding rate at DREC, Stoneville, MS, 2009-2010.

	Plant							
	Number of nodes plant^{-1}				Number of pods plant^{-1}			
	MG IV[£]		MG V[§]		MG IV		MG V	
Year	Single[‡]	Twin[†]	Single	Twin	Single	Twin	Single	Twin
2009	18.59 ab[¥]	19.33 a	12.06 d	11.93 d	73.2 a	78.4 a	63.1 b	57.5 bc
2010	18.45 b	18.73 ab	12.47 d	13.57 c	53.5 bc	59.4 b	49.9 c	61.4 b

£ MG IV, 'Delta King 4968'.

§ MG V, 'Armor GP-500'.

‡ Single-row pattern, John Deere® Max-emerge planter.

† Twin-row pattern, Monosem® planter.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.12

Soybean seed yield and number of nodes per soybean plant as affected by maturity group (MG) and seeding rate when averaged across row pattern and year at Stoneville, MS, 2009-2010.

	Seed Yield		Nodes plant^{-1}	
	MG IV[£]	MG V[§]	MG IV	MG V
Seeding Rate[†]	------------kg ha^{-1}------------			
222,000	4102 e[¥]	5047 a	19.47 a	12.61 de
259,000	4233 de	5086 a	19.54 a	12.89 d
296,000	4284 de	5094 a	18.96 ab	12.57 de
333,000	4501 bc	5043 a	18.74 b	12.51 de
370,000	4338 cd	5173 a	18.33 b	12.2 e
408,000	4630 b	5132 a	17.63 c	12.26 de

† Seeding Rate, seed ha^{-1}.

£ MG IV, ‘Delta King 4968’.

§ MG V, ‘Armor GP-500’.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.13

Number of nodes per soybean plant as affected by seeding rate and year when averaged across maturity group and row pattern at DREC, Stoneville, MS, 2009-2010.

	Nodes plant^{-1}	
Seeding Rate[†]	2009	2010
222,000	16.33 ab[¥]	15.74 bc
259,000	15.97 a-c	16.45 a
296,000	15.71 bc	15.81 a-c
333,000	15.52 cd	15.73 bc
370,000	14.89 de	15.64 bc
408,000	14.45 e	15.45 cd

† Seeding Rate, seed ha^{-1}.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.14

NDVI and mean percent of all pods that were 3-bean pods per plant as affected by maturity group, row pattern, and year when averaged across seeding rate at DREC, Stoneville, MS, 2009-2010.

	NDVI				3-Bean-pod			
					-------------------------%-------------------------			
	MG IV[£]		MG V[§]		MG IV		MG V	
Year	Single[‡]	Twin[†]	Single	Twin	Single	Twin	Single	Twin
2009	0.850 e[¥]	0.895 d	0.892 d	0.910 bc	24.95 d	32.77 bc	22.07 d	22.72 d
2010	0.907 cd	0.924 ab	0.920 b	0.931 a	51.80 a	46.34 a	32.25 c	38.01 b

£ MG IV, ‘Delta King 4968’.

§ MG V, ‘Armor GP-500’.

‡ Single-row pattern, John Deere® Max-emerge planter.

† Twin-row pattern, Monosem® planter.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.15

Number of pod per soybean plant as affected by row pattern, seeding rate, and year averaged across maturity group at DREC, Stoneville, MS, 2009-2010.

	Year			
	2009		2010	
Seeding Rates[§]	Single[‡]	Twin[†]	Single	Twin
222,000	86.5 ab[¥]	90.0 a	42.3 o	78.2 bc
259,000	73.4 c-e	74.1 cd	59.6 g-m	72.5 c-f
296,000	67.4 c-g	65.9 d-h	53.3 j-n	61.9 g-l
333,000	66.2 d-h	64.3 e-i	56.1 h-n	51.6 l-o
370,000	62.3 f-k	60.0 g-m	48.1 n-o	50.4 m-o
408,000	53.3 l-o	53.5 i-n	51.0 m-o	47.6 no

[§] Seeding Rate, seed ha^{-1}.

[‡] Single-row pattern, John Deere® Max-emerge planter.

[†] Twin-row pattern, Monosem® planter.

[¥] Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.16

Test of fixed effects and interactions for mean percentage of 1, 2, 3 and 4 bean pods plant^{-1} across input variables of year, maturity group, row pattern, seeding rate and all interactions at DREC, Stoneville, MS, 2009-2010.

	Bean pod^{-1}			
	--------------------------%--------------------------			
	1	2	3	4
Source	Pr > F			
Year (YR)	0.0002	<.0001	<.0001	NS
Maturity Group (MG)	NS[†]	0.0002	0.0002	0.0002
Row pattern (RP)	NS	NS	NS	NS
Seed rate (SR)	0.0002	<.0001	0.0024	NS
YR*MG	NS	NS	0.0287	NS
YR*RP	NS	NS	NS	NS
MG*RP	0.0045	0.0349	NS	NS
YR*SR	NS	<.0001	<.0001	0.0012
MG*SR	NS	NS	NS	NS
RP*SR	NS	NS	NS	NS
YR*MG*RP	NS	NS	0.0042	NS
YR*MG*SR	NS	NS	NS	0.0015
YR*RP*SR	NS	NS	NS	NS
MG*RP*SR	NS	NS	NS	NS
YR*MG*RP*SR	NS	NS	NS	NS

† NS, not significant at the P = 0.05 level of significance. A P value of < 0.05 indicates significant effect or interaction.

Table 2.17

Mean percentage of total pods per plant that were 1-bean-pods as affected by seeding rate when averaged over maturity group, row pattern, and year at DREC, Stoneville, MS, 2009-2010.

Seeding Rate[†]	1-bean pod -----%-----
222,000	9.74 a[¥]
408,000	7.29 b

† Seeding Rate, seed ha^{-1}.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.18

Mean percent number of 1-bean and 2-bean pods per plant as affected by maturity group and row pattern when averaged across seeding rate and year at DREC, Stoneville, MS, 2009-2010.

	Bean pod^{-1}			
	1		2	
	-------------------------------%-------------------------------			
Row Pattern	MG IV[£]	MG V[§]	MG IV	MG V
Single[‡]	6.85 b[¥]	9.47 a	28.37 c	42.83 a
Twin[†]	9.49 a	8.24 ab	33.74 b	41.58 a

£ MG IV, ‘Delta King 4968’.

§ MG V, ‘Armor GP-500’.

‡ Single-row pattern, John Deere® Max-emerge planter.

† Twin-row pattern, Monosem® planter.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.19

Mean percent number of 2-bean pods, and mean percent number of 3-bean pods as affected by seeding rate and year when averaged across maturity group and row pattern at DREC, Stoneville, MS, 2009-2010.

	Bean pod^{-1}			
	2		3	
	-------------------------%-------------------------			
Seeding Rate[†]	2009	2010	2009	2010
222,000[Φ]	33.1 b[¥]	48.2 a	31.8 c	40.0 b
408,000	19.6 c	45.7 a	19.4 d	44.2 a

† Seeding Rate, seed ha^{-1}.

¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Φ Due to time constraints only the low and high seeding rates were sampled.

Table 2.20

Mean percent of all pods that were 4-bean pods per plant, as affected by maturity group, seeding rate, and year when averaged across row pattern at DREC, Stoneville, MS, 2009-2010.

	Year			
	2009		2010	
Seeding Rates†	MG IV£	MG V§	MG IV	MG V
	-------------------------%-------------------------			
222,000	0.912 a¥	0.012 c	0.238 c	0.00 c
408,000	0.587 b	0.00 c	0.729 ab	0.00 c

† Seeding Rate, seed ha^{-1}.
£ MG IV, ‘Delta King 4968’.
§ MG V, ‘Armor GP-500’.
¥ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.

Table 2.21

Soybean seed yield as affected by maturity group and year averaged across row pattern and seeding rate at DREC, Stoneville, MS, 2009-2010.

	Seed Yield	
Maturity Group (MG)	2009	2010
	----------kg ha^{-1}----------	
MG IV£	4152b‡	4542b
MG Vβ	5133a	5059a

‡ Means within a column followed by the same letter are not significantly different at P = 0.05 level of significance.
£ MGIV, ‘Delta King 4968’.
β MGV, ‘Armor GP-500’

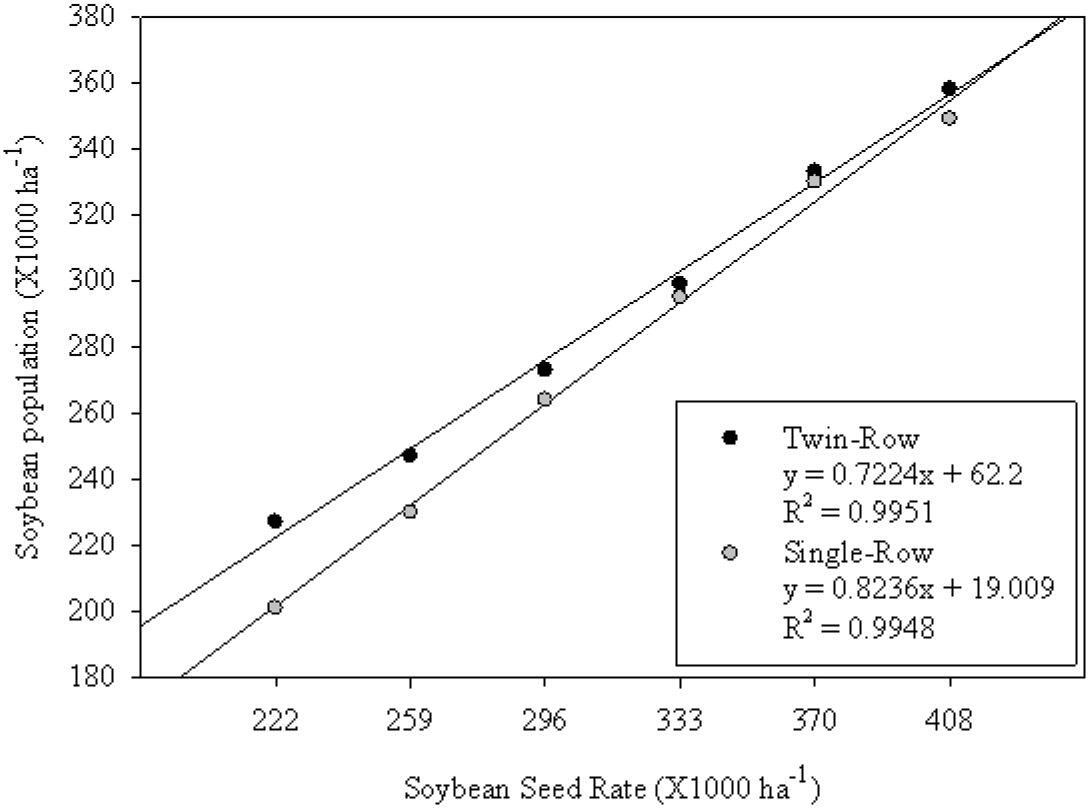

Figure 2.1

Soybean plant populations as affected by seeding rate and row pattern, averaged across maturity group and year at Stoneville, MS, 2009-2010.

CHAPTER III

INFLUENCE OF NITROGEN SOURCE AND APPLICATION TIMING ON GRAIN YIELD AND NITROGEN UPTAKE IN DELAYED-FLOOD RICE (*Oryza sativa* L.) AS AFFECTED BY AMMONIA VOLATILIZATION

Abstract

Sustainable rice production must include a continued effort to increase N use efficiency. Field experiments were conducted in 2009 and 2010 at Stoneville, MS, in a delayed-flood rice system to quantify N loss via ammonia volatilization and determine the grain yield and N uptake for various N sources and application timings on a Tunica clay soil. To evaluate the effects of N source and application timing on grain yield, total N uptake, apparent N recovery efficiency, and agronomic N use efficiency, five N sources including urea, Agrotain® treated urea, Super-U®, ammonium sulfate (AMS), and AMS + urea were applied at 168 kg N ha^{-1} 1, 4, 7, and 10 days before permanent flood establishment. To quantify N loss via ammonia volatilization, the same five sources were applied at the same N rate in a semi-open static chamber 10 days before permanent flood establishment. Sorbers were exchanged on 3 day increments for a total of 6 sample times. Experiments were arranged in an RCB design and replicated four times. Response variables were tested for fixed effects and interactions of fixed effects with PROC MIXED and least square means (P = 0.05) were used to determine mean differences.

Non-linear procedures were used to model cumulative volatilization losses. Cumulative N loss varied by N source. Urea, AMS + urea, AMS, Super-U, and Agrotain resulted in 10.2, 9.6, 5.5, 4.9, and 3.4% loss, respectively. The time at which N loss reached a plateau also was influenced by N source. Nitrogen loss for urea, AMS + urea, AMS, Super-U, and Agrotain reached a plateau at 5.5, 4.2, 4.1, 8.1, 8.4 days, respectively. Nitrogen source did not affect rice grain yield in 2009, however relatively small (< 4%) differences were observed in 2010, with AMS producing 345 and 389 kg ha^{-1} more grain than Super U and AMS + urea, respectively. In 2010, when averaged across all N sources, rice grain yields were approximately 6% less when fertilizer was applied 10 dbf as compared to 1 dbf. Total N uptake, ANRE, and ANUE followed were similar in that they tended to decrease with increasing time of application before permanent flood establishment. These data suggest that N loss via ammonia volatilization on clay textured soil is relatively low compared to silt loam soils in Arkansas rice production; however, Agrotain and Super U proved effective in reducing ammonia volatilization. Furthermore, other loss mechanisms such as nitrification/denitrification should be investigated, quantified, and production practices developed to increase N use efficiency in delayed-flood rice production.

Introduction

Rice (*Oryza sativa* L.) is grown in more than 100 countries worldwide and accounts for more than 700 million tons of production per year within approximately 160 million hectares (Anonymous, 2011). Rice is considered to be the main food staple for more than 50% of the world's population (Childs, 2004). When the amount of grain used for food is considered, more food energy per hectare is produced from rice as compared to any other cereal (Eggum, 1979; FAO, 2001; Childs, 2004). The United States accounts for only 1.5% of the total rice production in the world, however in 2005, the U.S. ranked fourth behind Thailand, Vietnam, and India with 14% of the total world exports (Childs, 2005). Childs (2005) reported that the U.S. exports more than 40% of its annual rice production. United States rice production, in 2010, accounted for 243 million hundredweight (cwt) produced on approximately 1.5 million hectares, and was worth approximately 3.1 billion dollars (NASS, 2010). Rice in the USA is produced by the states of California, Arkansas, Louisiana, Mississippi, Missouri, and Texas. A small amount of rice is produced in Florida (Street and Bollich, 2003). In the 2010 growing season in Mississippi, rice production totaled 20.8 million cwt on 123,000 hectares, which ranked as the fourth largest rice producing state, after Arkansas, Louisiana, and California, respectively (NASS, 2010). Mississippi rice production increased 27% in 2010 as compared to 2009 and resulted in a farm-gate value of $226 million (NASS, 2010). Rice production in the USA is limited to the previously mentioned states due to them having high temperatures throughout the growing season, an ample supply of water that can be applied in a timely manner, a smooth land surface with less than one percent slope, and an impermeable soil pan that is capable of minimizing water loss through leaching. Furthermore, these states have the appropriate infrastructure to dry, store, and process (mill) the paddy rice into a usable form. Additionally, these states have relatively easy access to the Mississippi River/Gulf Coast so that exports can proceed in an economically feasible manner.

In rice production, the nutrient applied the most frequently and in the greatest amount is nitrogen (N) (Norman et al., 2003). Watkins et al. (2008a, 2008b) concluded that N is a major input of rice production and accounts for approximately 19 to 25% of total variable production expenses for rice, depending on soil texture. Nitrogen increases plant height, panicle number, leaf size, spikelet number, and number of filled spikelets, ultimately determining the rice plant's yield potential (Dobermann and Fairhurst, 2000). Management of N for maximum availability is also one of the greatest challenges due to its dynamic nature and the associated pathways of loss if not managed properly. Specifically, N can be lost or rendered unavailable to the rice plant by ammonia (NH_3) volatilization, nitrification and the subsequent denitrification, immobilization, fixation, leaching and runoff. The recently high volatility of fertilizer prices has led to increased desire among rice producers to apply N optimally in the most profitable amounts (Watkins et al., 2010). In addition to economic factors, N use efficiency in rice production and the subsequent impacts on environmental quality are under constant scrutiny.

Several forms of N exist in the soil; however, rice utilizes N in the inorganic forms, ammonium (NH_4^+) and nitrate (NO_3^-). In the flooded, anaerobic environment

NH_4^+ is stable and accumulates. However, the anaerobic environment renders nitrate unstable and subject to loss by denitrification as N_2 (De Datta and Patrick, 1986; Patrick et al., 1985). Because of the stability of NH_4^+, recommended N fertilizer sources are NH_4^+ or NH_4^+ forming fertilizer (Griggs et al., 2007). The three N fertilizers utilized in dry-seeded delay flooded rice culture are urea, ammonium sulfate, and urea-ammonium nitrate. Urea is the most widely used N fertilizer in rice production due to its high N content (45% N) and relatively low cost (Bufogle et al., 1998; Griggs et al., 2007). Ammonium sulfate (21% N) is an excellent source of N but application costs are greater compared to urea due to its lower N concentration. Urea-ammonium nitrate (28-32% N) has as much as 25% of N in the form of nitrate and should only be used as a top-dress application at midseason where the rice plant will absorb the fertilizer in a few days. Regardless of which type of N fertilizer is used preflood, it is imperative to establish a flood within a few days following application.

Ammonia volatilization occurs in the dry-seeded delayed flood rice culture when the urea form of N fertilizer is hydrolyzed to ammonium carbonate [$(NH_4^+)_2CO_3$] by the urease enzyme and ammonium carbonate decomposes to produce NH_3 and CO_2. The proportion of NH_3 to NH_4^+ is determined by the local pH (Boswell et al., 1985). The hydrolysis of urea to NH_3 results in the subsequent NH_3 being lost through volatilization. Soil and floodwater pH, soil and air temperature, cation exchange capacity, wind speed, humidity, soil moisture and NH_3 concentrations all affect NH_3 volatilization (Boswell et al., 1985; Bouwmeester et al., 1985; Harper et al., 1983). Previous research has shown that NH_3 volatilization following urea application is an important mechanism for N losses in rice fields (Mikkelsen et al, 1978; Griggs et al., 2007). Studies have reported that NH_3 volatilization accounts for 20 to 80% of total N losses (Beyrouty et al., 1988; Griggs et al., 2007). The most important factors associated with increasing NH_3 volatilization are a high NH_4^+-N concentration of floodwater combined with high pH (Chao and Kroontje, 1964; Du Plessis and Kroontje, 1964; Vlek and Craswell, 1979) and high temperature (Clay et al., 1990). The pH surrounding the fertilizer reaction zone is crucial; soil pH values > 7.0 increase NH_3 losses by increasing the NH_3 / NH_4^+ ratio (Boswell et al., 1985).

The problem of NH_3 volatilization is not just a rice production problem. Nitrogen losses by volatilization from sources containing urea are a concern especially when N sources are surface-applied to crops (Bandel et al., 1980). Previous research in corn (*Zea mays* L.) has shown that NH_3 volatilization after N fertilization was associated with reduced grain yield and N use efficiency (Fox et al., 1986; Oberle and Bundy, 1987). Ammonia volatilization potential can occur in corn production when a broadcast instead of banding application method of N fertilizer is utilized (Maddux et al., 1984).

If coating or deep placement of the N fertilizer, especially urea, are used, losses can be kept to a minimum (Freney et al., 1985; Mikkelsen et al., 1978; Vlek and Craswell, 1979). The cation exchange capacity (CEC) of the soil influences NH_3 volatilization by acting as a temporary sink for NH_4^+, which reduces the aqueous NH_4^+ concentration and the NH_3 concentration (Boswell et al., 1985). Sommer et al. (2004) emphasized that soil resistance to NH_3 volatilization is associated with rainfall events. Harper et al. (1983) reported rainfall influence was probably the result of rainfall dispersing urea which prevented high concentrations of NH_3 and NH_4^+ from building up around urea-prills. Bouwmeester et al. (1985) reported a 4-cm rainfall decreased N losses by approximately 30% regardless of the initial soil moisture content; the highest losses were observed when wet soil conditions were maintained when air humidity was between 80 and 95% with no rainfall (Bouwmeester et al., (1985).

Urease enzyme inhibitors have been shown to effectively reduce NH_3 volatilization from urea (Bremner and Chai, 1989; McCarty et al., 1989; Watson, 2000). Urease inhibitors accomplish a reduction in NH_3 volatilization by slowing the rate of urea hydrolysis and conversion to NH_4^+ (Norman et al., 2009). [N-(n-butyl) thiophosphoric triamide](NBPT) has been reported to be an effective urease inhibitor and significantly minimize NH_3 volatilization loss of urea (Buresh et al., 1988; Bremner and Chai, 1989; Clay et al., 1990; Al-Kanani et al., 1994; Rawluk et al., 2001). Agrotain® (Agrotain International, St. Louis, MO) contains NBPT as its active ingredient and is (NBPT) extensively used as a urease inhibitor in the form of treated urea fertilizer. In addition to reducing NH_3 volatilization, NBPT has been shown to increase the N uptake of rice (Freney et al., 1995; Chaiwanakupt et al., 1996; Aly et al., 2001). Grain yield with NBPT results have varied; Chaiwanakupt et al. (1996) observed an increase in grain yield with NBPT, whereas others have not reported a grain yield increase with NBPT use (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001).

Woodward et al. (2011) reported that the methods of measuring NH_3 volatilization from N sources, organic amendments, or inorganic fertilizers can be divided into two classes: (1) in situ and (2) in-lab controlled environment experiments. In situ methods of

NH_3 volatilization have been shown to be disadvantaged due to the inability to control climatic factors that directly influence NH_3 volatilization, and fluctuations in season dictate when experiments can be conducted (Woodward et al., 2011). The second class of experiments, in-lab controlled experiments, can maintain environmental factors affecting NH_3 volatilization, analyze multiple treatments and treatment periods, and can be performed year round. The primary method to measure NH_3 volatilization in laboratory studies has used a closed chamber method to contain the soil and N fertilizer treatments, force air flow across the treatment surface, and uses an acid trap to capture the volatilized NH_3 (Hargrove and Kissel, 1979; Kissel et al., 2004; Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009). Lab systems using such a method have shown NH_3 recovery values ranging from 72.9 to 103% (Kissel et al., 2004; Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009).

Field experiments to quantify NH_3 volatilization, using a semi-open static chamber method that uses an in situ approach coupled with a semi-controlled environment, have been conducted by Beyrouty et al. (1988), Griggs et al. (2007), and Norman et al. (2009). Beyrouty et al. (1988) reported that within the first 7 to 10 days after preflood N application, the majority of the N losses due to NH_3 volatilization were observed; cumulative NH_3 volatilization loss for urea was 30% of applied N. Griggs et al. (2007) measured NH_3 volatilization for 21 days after preflood N application and reported losses of 14 to 32% for urea and 1.5 to 7% for ammonium sulfate. Nitrogen losses due to NH_3 volatilization were greatest on a silt loam soil, the majority of N losses occurred within the first 7 to 10 days after application of urea, and grain yields were lower when urea was applied 14 day preflood (Griggs et al., 2007). Griggs et al. (2007) concluded that the flood must be established within 3 days after preflood N application to minimize N loss due to NH_3 volatilization when production occurs on a silt loam soil; however, clay soils will allow a longer (7-10 days) window of opportunity to establish a flood. Norman et al. (2009) measured NH_3 volatilization for 20 days after a preflood N application and reported cumulative loss was greatest for urea, followed by urea + ammonium sulfate, urea + NBPT, and ammonium sulfate, respectively. By 10 days after preflood N application, Norman et al. (2009) observed cumulative NH_3 volatilization losses from urea of 24.4 and 20.5%, in 2003 and 2004, respectively.

Moll et al. (1982) defined N use efficiency as the grain yield produced per unit of N available from the soil and fertilizer. It is the product of two physiological factors: (1) N uptake efficiency, defined as the amount of N uptake by the crop per unit of N available to the crop, and (2) N utilization efficiency, which is defined as the grain yield per unit of N uptake by the crop (Giambalvo et al., 2010). Golden et al. (2009) reported that the most efficient method of N fertilization for rice grown in the direct-seeded, delayed-flood production system is to apply a NH_4^+ or NH_4^+- forming N source to a dry soil surface near the four to five-leaf growth stage of rice and incorporate the N quickly by establishing a flood that is maintained throughout the remainder of the growing season. Rice recovery of properly managed preflood (PF) urea N has been observed to be 60 to 75% of the total applied N. A second application of N fertilizer is then applied into the floodwater near the panicle differentiation (PD) stage 4 to 5 weeks after the PF N application (Norman et al., 2003). The PD growth stage marks the initiation of the reproductive phase, has a high N uptake capacity (Beyrouty et al., 1987, 1992; Bufogle et al., 1997) and is the point at which the number of grains panicle^{-1} and grain weight are determined (Stansel, 1975; Patrick et al., 1985). Bollich et al. (1994) and Wilson et al. (1998) reported that semi-dwarf rice grain yields were affected largely by the PF N application and minimally by N applications at panicle initiation (PI). Wilson et al. (1998) observed that the proper rate of PF N increased the uptake efficiency of N fertilizer top-dressed during the early reproductive stages of growth. Wilson et al. (1998) reported that if 67 kg N ha^{-1} or less is applied at midseason, the entire application can be applied between PI and PD. Rough and whole-grain rice yields have been observed to increase with top-dress (TD) application of N during the latter stages of reproductive growth, which include boot and early heading (HD) stages (Perez et al., 1996). At HD, the conversion of accumulated N utilized through uptake into total dry matter (TDM) occurs and grain production speeds up within the rice plant.

Eagle et al. (2001) reported that total plant and fertilizer N uptake reached a maximum 60 to 80 days after seeding; rice plants were at the panicle initiation growth stage and max tillering was observed. Patrick and Reddy (1976) also reported a large amount of fertilizer N uptake occurred early in the season. Bufogle et al. (1997) and Guindo et al. (1994) concluded N uptake continued much later in the rice growing season. Fertilizer use efficiency for ^{15}N (FUE-^{15}N), in tropical lowland rice production has been reported to be approximately 30 to 50% (Bronson et al., 2000; De Datta et al., 1968; Eagle et al., 2001). Fertilizer use efficiency-^{15}N values for upland crops are usually greater, but are more dependent on crop and soil types, production methods, and timing of fertilizer application (Macdonald et al., 1997). Patrick and Reddy (1976) emphasized that application of fertilizer N later in the growing season increases the FUE-^{15}N. Bronson et al. (2000), however, did not notice any differences in FUE-^{15}N between split fertilizer applications with different times of application. When ^{15}N fertilizer was applied 27 and/or 55 days after emergence, the FUE-^{15}N values were observed to be in the range of 72 to 79% (Norman et al., 1992a). Quanbao et al. (2007) reported significant genetic differences existed among the effect of yield increase with N application, N use efficiency, N accumulation, and distribution of rice under different soil conditions.

The current demand for higher rice yields coupled with the increased popularity of hybrid and high yielding rice cultivars equates to the need for increased N fertilizer efficiency. Factors affecting N losses due to NH_3 volatilization have been extensively studied; however, only three field experiments have been conducted that examined different N sources and application timing and reported subsequent NH_3 volatilization through the use of the semi-open static chamber method (Beyrouty et al., 1988; Griggs et al., 2007; Norman et al., 2009). Griggs et al. (2007) and Norman et al. (2009) reported grain yield limiting N losses due to NH_3 volatilization on silt loam and clay soils. Previous research conducted by Walker (unpublished) on clay soils in Mississippi, has shown a consistent decrease in grain yield; however, it is uncertain to what extent the yield loss can be explained by NH_3 volatilization losses. Therefore, the objectives of this study were to quantify N loss via NH_3 volatilization for different N sources and N-fertilizer application timings on clay textured soil and determine the grain yield and N uptake as it was affected by NH_3 volatilization losses.

Materials and Methods

Site Description and Cultural Practices

Field experiments were conducted at Mississippi State University – Delta Research and Extension Center, located in Stoneville, MS, in 2009 and 2010. The soil type for both years was classified as a Tunica clay (clayey over loamy, mixed, superactive, nonacid, thermic, Vertic Epiaquerts) (33°26.21.31 N and 90°54.27.42 W) (WSS, 2010). Soil samples were collected each year prior to planting. The soil texture was determined by conducting particle-size analysis using the hydrometer method (Gee and Bauder, 1986) and soil chemical properties were determined by the Lancaster soil testing method (Cox, 2001) (Table 3.1). 'Cocodrie', a semi-dwarf, long-grain cultivar (Linscombe et al., 2000), was drill seeded on 17 May in 2009 and 28 April in 2010 at 90 kg ha^{-1} using a Great Plains Drill (Great Plains Mfg., Inc. 1525 E. North Street Salina, Kansas 67401) equipped with double-disk openers (Table 3.2). Experimental units (plot) consisted of eight drill rows spaced 20 cm apart and measuring 4.6 m in length. All replications were separated by 1.6 m alleys. Rice was grown in a delayed-flood culture and flood was established at the 5 to 6 leaf growth stage and maintained throughout the growing season and drained approximately 2 wk prior to harvest (Table 3.2). Pest pressure was minimized and a subsequent high grain yield environment was observed (Buehring et al., 2008). The fertilizer was applied at 168 kg N ha^{-1} with a custom-manufactured, self-propelled distributor equipped with a Hege 80 belt cone

(Wintersteiger, Inc., Salt Lake City, UT) and a zero-max (Zero-Max, Inc., Plymouth, MN) to ensure accuracy and precision.

Experimental Design

Grain Yield and Nitrogen Uptake

Field experiments examining the influence of NH_3 volatilization on grain yield and N uptake were conducted as a factorial arrangement of treatments in a randomized complete block design with four replications. Five N sources and four pre-flood N-fertilizer application timings were tested. Nitrogen sources included: urea (46-0-0), Agrotain® treated urea [a.i. N-(n-butyl) thiophosphoric triamide (NBPT) at 4.17 mL kg^{-1}], Super-U® [combination of a.i. Dicyandiamide (DCD) and a.i. NBPT both at proprietary rates], ammonium sulfate (21-0-0-24S), and ammonium sulfate plus urea (1:1 blend on N weight basis). The pre-flood N-fertilizer application timings were 10, 7, 4, and 1 days before flood (dbf). Treatments were initiated at the 3 to 4 leaf growth stage. Zero N (check) plots were included in each replication.

Ammonia Volatilization

Field experiments designed to measure NH_3 volatilization were conducted as a factorial arrangement of treatment in a randomized complete block design, replicated four times. A factorial combination of five N sources and six collection timings were tested. Nitrogen sources were the same as in the grain yield experiments. The sorber removal timings included: 3, 6, 9, 12, 15, or 18 days after the 10 day preflood N application.

Data Collection

Yield Experiments

Total aboveground biomass from 0.9 m of row from the second inside row was hand harvested at panicle differentiation (PD), and at 5% heading (HD) from each plot (Table 3.2). All biomass was oven-dried at 60°C until a constant weight was obtained (48 to 72 hr) and weighed to determine total dry matter (TDM). Samples were ground through a Wiley Mill with a #40 screen. A dry combustion analyzer (Carlo Erba, Milan, Italy) was used to obtain N concentration. Once TDM and N concentration were determined, total N uptake (TNU) was calculated by multiplying TDM by N concentration.

Rice plots were harvested when grain moisture ranged from 150 to 180 g kg^{-1} with a Wintersteiger Delta Combine (Wintersteiger, Inc., Salt Lake City, UT) equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc., Logan, UT) for measuring weight and moisture (Table 3.2). Grain yields were standardized to 120 g kg^{-1} moisture content.

Nitrogen use efficiency factors ANRE (apparent N recovery efficiency) and ANUE (agronomic N use efficiency) were calculated according to Quanbao et al. (2007). Apparent N recovery efficiency is calculated by the following equation: ANRE = (Total plant N uptake with N application – total plant N uptake without N application) / N application x 100. The focus of ANRE pertains to how the N application influenced the plants' uptake of N. Agronomic N use efficiency is calculated by the following equation:

ANUE = (Grain yield with N application – grain yield without N application) / N application rate. The influence of N application on grain yield is described by ANUE.

Ammonia Volatilization Experiments

A semi-open static system was used to monitor NH_3 volatilization losses, similar to that described by Beyrouty et al. (1988), Griggs et al. (2007), and Norman et al. (2009). Clear plexiglass chambers 13 cm in diameter, 75 cm tall were driven 15 cm deep into the soil. Chambers were protected from rainfall by plastic buckets suspended 5 cm above the top of the chamber by metal rods to allow air circulation. Polyurethane foam sorbers, 2.54 cm thick, were cut to a slightly larger diameter than that of the chambers so that they remained in place when the sorber was expanded against the sides of the chamber. The sorbers were washed with 0.73 M H_3PO_4, rinsed with deionized water, and randomly extracted with 100 mL of 2 M KCl solution. The washed sorbers were impregnated with 20 mL of a 0.73 M H_3PO_4– 33% glycerine (v/v) solution to trap the NH_3. This volume was sufficient to saturate the sorber evenly, but did not drip from the sorber or leach down the sides of the chamber. Two sorbers were used in each chamber. The first sorber was placed 15 cm below the top of the chamber to trap the NH_3 volatilized from the soil surface, and the second sorber was placed level with the top of the chamber to eliminate atmospheric interference. NH_3 volatilization was measured for 18 days following the 10-day pre-flood N-fertilizer application (Table 3.3). The sorbers were changed 3, 6, 9, 12, 15, and 18 days after the 10-day pre-flood N-fertilizer application and inserted into their original plastic Ziploc$^{®}$ bags. To maintain proper flood conditions within the chambers throughout the sampling period, water levels were monitored and replenished by transferring water from the borrow ditches with a bucket. This addition of water to the chambers to maintain flood level was only conducted while changing sorbers in and out of the chambers.

The sorbers were kept in the freezer until they were extracted by saturating with 100 mL of 2 *M* KCl solution and squeezing by hand. An automated segmented flow analyzer (Perstorp Analytical Flow III Analyzer, Wilsonville, OR) was then utilized to determine the concentration of NH_4^+-N sample^{-1}.

Statistical Analysis

PROC MIXED (SAS, 2008) was used to test fixed effects and interactions among fixed effects. For the response variables grain yield, total N uptake at PD and HD, ANRE, and ANUE, year, N source, and application timing were considered fixed effects. Year, N source, and sample timing were considered fixed for N loss. In both experiments, replicate of each treatment combination was considered a random variable in all analyses. Least square means at the $P < 0.05$ was used for mean separation. Means generated in PROC MIXED for N loss were used for nonlinear regression (Gompertz equation) so that inferences could be made regarding the kinetics of the reaction, i.e., the inflection point.

Results

Grain Yield

Rice grain yield was affected by two 2-way interactions (Table 3.4). An interaction between year and N source influenced grain yield (Table 3.4). For each N source, grain yield was greater in 2010 as compared to 2009 (Table 3.5). In 2009, all N sources resulted in similar grain yield. However, in 2010, AMS produced greater yields compared to Super-U and AMS plus urea. Agrotain, AMS, and urea resulted in similar grain yields (Table 3.5). An interaction between year and preflood N application timing also affected rice grain yield (Table 3.4). Application timing did not affect rice grain yield in 2009; however, in 2010, N fertilizer applied 1 day before flood (dbf) produced yields greater than 4 or 10 dbf (3 and 6%, respectively) (Table 3.6). The preflood N application timing of 4 dbf produced 4% greater yield (337 kg ha^{-1} more) than 10 dbf (Table 3.6).

Total N Uptake

Total N uptake at panicle differentiation (PD) was influenced by two 2-way interactions (Table 3.4). An interaction between year and N source affected rice grain yield (Table 3.4). In 2009, urea, Agrotain, Super-U, and AMS plus urea resulted in greater TNU at PD compared to AMS. Furthermore, these sources also resulted in greater TNU at PD compared to all sources in 2010 (Table 3.7). Ammonium sulfate in both years resulted in greater TNU at PD compared to Agrotain, Super-U and AMS plus urea in 2010 (Table 3.7). An interaction between year and preflood N-fertilizer application timing affected TNU at PD (Table 3.4). In 2009, N applied 10 dbf resulted in a total of 117.5 kg N ha^{-1} in the above ground portion of the plant as compared to 106.6 kg N ha^{-1} when N was applied 1 dbf. Furthermore, the 2009 10 dbf application timing resulted in greater TNU at PD than all application timings in 2010 (Table 3.8). In 2010, N applied 1 dbf resulted in greater TNU at PD as compared to 4, 7, 10 dbf. Total N uptake at 1 dbf ranged from 17 to 27 kg N ha^{-1} more compared to other timings (Table 3.8).

Total N uptake at 5% heading (HD) was affected by the same two interactions of main effects observed for TNU at PD (Table 3.4). When Super-U was applied in 2009, TNU at HD was greater compared to AMS plus urea and AMS alone applied in 2009, as well as all N sources in 2010 (Table 3.7). In 2009, Super-U, urea, and Agrotain, resulted in greater TNU at HD compared to AMS applied in 2009, as well as urea, Super-U, AMS plus urea, and Agrotain applied in 2010. Ammonium sulfate plus urea in 2009 resulted in greater TNU at HD than AMS in 2009, and AMS plus urea and Agrotain applied in 2010. In 2010, AMS increased TNU at HD growth stage by 18.2 and 21.6 kg ha^{-1} when compared to AMS plus urea and Agrotain (Table 3.7).

An interaction between year and preflood application timing affected TNU at HD values (Table 3.4). Total N uptake at HD for 10 dbf in 2009 was greater than 4 dbf in 2009 and all four timings in 2010 (Table 3.8). The application timings of 10 and 7 dbf in 2009 resulted in greater TNU at HD compared to 4, 7, and 10 dbf timing in 2010. Total N uptake ranged from 23 to 33 kg ha^{-1} more for the 10 and 7 dbf, in 2009, compared to 4, 7, and 10 dbf in 2010. Timings of 10, 7, 1 dbf, in 2009, had greater TNU at HD than 2010 10 and 4 dbf. In 2009, when N was applied 10, 7, or 1 dbf, an increase of 26.6 to 39.7 kg N ha^{-1} was observed in the above ground portion of the plant compared to the application timings of 10 or 4 dbf in 2010 (Table 3.8).

Apparent Nitrogen Recovery Efficiency

Apparent N recovery efficiency, ANRE, was affected by two 2-way interactions (Table 3.4). An interaction between year and source influenced ANRE (Table 3.4). Super-U, in 2009 was observed to have greater %ANRE than 2009-AMS and AMS plus urea, as well as all N sources in 2010 (Table 3.5). Super-U, Agrotain, and urea, when applied in 2009 resulted in greater %ANRE as compared to AMS applied in 2009, as well as Super-U, urea, AMS plus urea, and Agrotain applied in 2010. Ammonium sulfate plus urea, Super-U, Agrotain, and urea when applied in 2009, produced greater %ANRE than AMS applied in 2009, as well as AMS plus urea and Agrotain applied in 2010. Ammonium sulfate, in 2010, in addition to Super-U, Agrotain, urea, and AMS plus urea, applied in 2009, increased %ANRE as compared to AMS applied the same year and Agrotain applied in 2010 (Table 3.5).

An interaction between year and preflood N-fertilizer application timing affected %ANRE (Table 3.4). The application timing of 10 dbf, in 2009, had a greater %ANRE as compared to 4 dbf in 2009 and all timings in 2010 (Table 3.6). The 10 and 7 dbf application timing in 2009 resulted in a greater %ANRE than the 4 dbf application in 2009, and the 10, 7 and 4 dbf application timing in 2010. Averaged across N sources, when N was applied 1, 7 or 10 dbf in 2009, a greater %ANRE was obtained in comparison to applications made 4 and 10 dbf in 2010 (Table 3.6). In 2009, when N was applied 1, 7, or 10 dbf, the total N uptake was increased by a range of 11.1 to 22.7% more compared to 4 and 10 dbf in 2010. The percent ANRE when N was applied 10 dbf in 2010 was less compared to 1 dbf the same year, as well as 1, 7, and 10 dbf in 2009 (Table 3.6). The application of N at 10 dbf in 2010, resulted in a decrease of 11.8%ANRE compared to when the N-fertilizer was applied at 1 dbf (Table 3.6).

Agronomic Nitrogen Use Efficiency

Agronomic N use efficiency, ANUE, followed the trend, and was affected by two 2-way interactions (Table 3.4). An interaction between year and source influenced ANUE results (Table 3.4). All N sources in 2010 had increased ANUE values as compared to the 2009 growing season (Table 3.5). In 2010, AMS had higher ANUE than Super-U and AMS plus urea. Ammonium sulfate resulted in an 8% increase in ANUE compared to Super-U and AMS plus urea (Table 3.5).

An interaction between year and preflood N-fertilizer application timing influenced ANUE (Table 3.4). All preflood N application timings, in 2010, were observed to have greater ANUE values as compared to 2009 (Table 3.6). In 2010, the application timing of 1 dbf increased ANUE by 6% compared to 4 dbf and 12% compared to 10 dbf. When N was applied 4 dbf, ANUE was 7% greater than 10 dbf (Table 3.6).

Ammonia Volatilization

Ammonia volatilization measured in the semi-open static chambers was affected by two 2-way interactions (Table 3.9). An interaction between year and N source influenced N loss (Table 3.9). In 2009, AMS plus urea had the greatest cumulative N loss (% of applied) followed by urea, AMS, Super-U, and Agrotain (Table 3.10 and Figure 3.1). In 2009, the application of Agrotain reduced NH_3 volatilization loss by 7.4% compared to AMS plus urea and 6.9% compared to urea (Table 3.10 and Figure 3.1). In 2010, urea had the greatest % of applied N loss, followed by AMS plus urea, AMS, Super-U, and Agrotain. In 2010, urea resulted in cumulative NH_3 volatilization losses of 9.95% compared to 3.88% for Agrotain (Table 3.10 and Figure 3.1).

An interaction between N source and sample timing influenced N loss (Table 3.9). Super-U, when compared to urea, AMS plus urea, and AMS, reduced N loss by 52, 49, and 11%, respectively; Agrotain, when compared to urea, AMS plus urea, AMS, and Super-U, reduced N loss due to NH_3 volatilization by 67, 65, 38, and 31%, respectively (Table 3.11 and Figure 3.2). The kinetics of the reaction that resulted in N loss via ammonia volatilization was more rapid for urea (5.5 days), AMS plus urea (4.2 days), AMS (4.1 days), relative to Super-U (8.1 days), and Agrotain (8.4 days) (Figure 3.2).

Discussion

Precipitation

A comparison of precipitation within sampling period at Stoneville, MS, in 2009 and 2010 shows great differences between years, and thus provides insight regarding the results. Rice studies were planted a month earlier in 2010 as compared to 2009 due to drier field conditions in the spring (Table 3.2). Because of this difference in planting date, the sampling period for the yield studies was a month earlier in 2010. In 2009, the sampling period observed a total precipitation of 25 mm and a mean of 0.76 mm day^{-1} (Table 3.12). Precipitation amounts in 2010 differed greatly where the total for the sampling period in 2010 was 134 mm and a mean of 4.3 mm day^{-1}. Precipitation was more than five times greater in 2010 as compared to 2009 (Table 3.12). The lack of precipitation during the 2009 sampling period resulted in minimal NH_3 volatilization conditions. Large amounts of rainfall have been shown to decrease NH_3 volatilization of urea applied in delayed-flood rice (Harper et al., 1983; Bouwmeester et al., 1985). Harper et al. (1983) concluded that rainfall distribution and amount after urea application appeared to control the total NH_3 losses from applied urea. Harper et al. (1983) suggested that rainfall dispersed urea which prevented high concentrations of NH_3 and NH_4^+ from building up around urea granules. Bouwmeester et al. (1985) reported a 4 cm rainfall decreased N losses by approximately thirty percent regardless of the initial soil moisture content, however, the greatest losses were recorded when wet soil conditions were maintained when air humidity was between 80 and 95% with no rainfall. In 2010, approximately 4 cm of precipitation was received over the two days prior to the 10 dbf application and 0.65 cm was received over the three days prior to the 4 dbf application; this resulted in moist soil conditions when 10 and 4 dbf treatments were applied (Table 3.2 and 3.12). The moist nature of the soil surface, combined with the application of urea provided an environment more conducive for NH_3 volatilization loss potential. If large amounts of rainfall had occurred after urea application, the urea granule would have been dissolved, carried into the soil profile, and subsequently hydrolyzed resulting in NH_4^+ and thus minimizing NH_3 volatilization loss potential.

Grain Yield

Rice seeding, in 2009, occurred on 17 May; however, in 2010, rice was planted much earlier on the 28 April (Table 3.2). Rice grain yield has been shown to decrease as seeding date is delayed due to decrease in the number of days spent in vegetative growth (Slaton et al., 2003). Slaton et al. (2003) optimized rice grain yield in Arkansas when seeding date occurred between 29 March and 26 April. The potential for an increase in grain yield was possibly greater in 2010 due to the earlier planting date.

Rice grain yield was lower among all N sources in 2009 (mean = 8344 kg ha^{-1}) compared to 2010 (mean = 9341 kg ha^{-1}) (Table 3.5). Furthermore, in 2009, grain yields were not different among N sources. Additionally, in 2010, AMS produced rice grain yields that were superior to AMS plus urea and Super U, whereas AMS plus urea, Super U, Agrotain, and urea produced similar yields. Finally, AMS produced grain yields that were similar to urea and Agrotain (Table 3.5).

Previous research conducted by Bufogle et al. (1998) reported that urea, when managed correctly, can be as effective as AMS in supplying N to the rice plant. It should be noted however, that Bufogle et al. (1998) findings were reported when the study was flooded within 1 to 2 days after preflood N application and they did not measure NH_3 volatilization. In contrast, Vlek and Craswell (1979) concluded that AMS is an excellent source of N, has slightly acidic properties, and thus is less prone to NH_3 volatilization than urea. Similar results were reported by Griggs et al. (2007) when urea was compared to AMS as a preflood N fertilizer in delayed-flood rice where the flood was delayed up to 14 days after preflood N application. When urea was applied 14 days preflood, observed grain yield decreased compared to application of urea at 1 day preflood; when both urea and AMS were applied 14 days preflood, a reduction in grain yield was observed for urea compared to AMS (Griggs et al., 2007). Minimizing yield loss is ideal; however, AMS can cost substantially more than urea largely because the lower N analysis can result in increased ground and aerial application expense, especially with the N rates required to reach economically optimum yield potential (Norman et al., 2009). When AMS and AMS plus urea were compared, AMS produced greater grain yield (Table 3.5). The AMS proved more stable than AMS plus urea when NH_3 volatilization conditions were prevalent in the field. Norman et al. (2009) reported that AMS consistently yielded more than a blend of urea + AMS. Agrotain did not yield higher than urea or AMS (Table 3.5). Chaiwanakupt et al. (1996) applied urea into floodwater and reported NBPT (a.i. in Agrotain) increased grain yield, while some have not observed a grain yield increase due to NBPT (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001). When preflood N fertilizer was applied to a dry Calloway silt loam soil, Norman et al. (2009) observed a 12.5% grain yield increase for urea + NBPT compared to untreated urea when the flood was delayed 5 days and a 16% yield increase when flood was delayed 10 days. When the flood was delayed 5 days, averaged across 2003 and 2004, N losses due to NH_3 volatilization were 19% (of applied N) for urea and 2% for urea + NBPT; N losses were 22% for urea and 8% for urea +NBPT when the flood was delayed 10 days (Norman et al., 2009).

Walker et al. (2006) reported that the rate and timing of N are critical for optimum rice grain yield. There were no differences observed between N-fertilizer application timing in 2009 with respect to grain yield (Table 3.6); however in 2010, differences did occur between N-fertilizer application timings. When N was applied 10 dbf, grain yields were less than any of the other three application timings. Additionally, when N was applied 1 dbf, grain yields were greater compared to an application at 4 dbf (Table 3.6). Griggs et al. (2007) reported lower grain yields when urea was applied 14 days preflood and emphasized the importance of establishing the flood within 3 days after preflood N application. Norman et al. (2009) concluded that grain yield of rice was at maximum when the flood was established 1 day after preflood N application to minimize NH_3 volatilization loss and maximize the N uptake and grain yield potential of delayed-flood rice. Ammonia volatilization of urea increased substantially between 2 and 5 days after application and resulted in less grain yield as compared to AMS or Agrotain when the flood was delayed for 5 or more days (Norman et al., 2009).

Ammonia volatilization potential was greater in 2010 as compared to 2009; soil pH was 8.2 in 2010 as compared to 7.2 in 2009 (Table 3.1) and precipitation events were probably not large enough to incorporate N fertilizer granules into the soil and minimize NH_3 volatilization (Table 3.12). When the dates of preflood N fertilizer application are examined with respect to rainfall events, the observed NH_3 volatilization conditions can be partially explained (Table 3.2 and 3.12). No rainfall occurred around the application dates in 2009; however in 2010, rainfall events occurred around days of preflood N fertilizer application. The 10 and 4 dbf N fertilizer was applied on May 18, 2010 and May 24, 2010, respectively. At both the 10 and 4 dbf application timings, rainfall had occurred within the previous three days. The result was a moist soil surface which would allow urea hydrolysis to proceed more rapidly than on dry soils. Previous research has shown the application of urea onto moist soil increases NH_3 volatilization losses (Beyrouty et al., 1988; Norman et al., 1992b; Griggs et al., 2007). As noted previously, the 10 dbf N fertilizer application onto damp soil resulted in the lowest grain yield in 2010. Furthermore, in 2010, grain yields produced by N fertilizer applied 4 dbf were less compared to when applications were made 1 dbf (Table 3.6). The preflood N timings of 7 and 1 dbf were applied on May 21, 2010 and May, 27, 2010, respectively. Rainfall events occurred on both days, after preflood N fertilizer was applied. Bouwmeester et al. (1985) reported the highest N losses were observed when wet soil conditions were maintained when air humidity was between 80 and 95% with no rainfall. The subsequent rainfall event after preflood N application limited N loss due to NH_3 volatilization by incorporating the fertilizer into the soil surface. Previous research has shown that incorporation of N fertilizer into the soil surface can minimize N losses (Freney et al., 1985; Mikkelsen et al., 1978; Vlek and Craswell, 1979).

Total N Uptake

High grain yield can be obtained if an adequate amount of N is accumulated in the rice plant throughout the growing season (Ntamatungiro et al., 1999). Nitrogen absorbed by rice during the vegetative growth stage contributes to growth during the reproductive and grain-filling stages through translocation (Bufogle et al., 1997; Norman et al., 1992b). When volatilization conditions were absent, uptake was not greatly affected; however, when conditions were ideal for loss due to NH_3 volatilization, the N source and application timing impacted TNU at PD and HD. Nitrogen sources of urea, Agrotain, Super-U, and AMS plus urea, all in 2009, had greater TNU at PD than 2009 AMS and all N sources in 2010 (Table 3.7). Ammonium sulfate, in both years had greater TNU at PD than 2010 Agrotain, Super-U, and AMS plus urea. The relationship between fertilizer N uptake and total N uptake over the growing season depends on timing of the fertilizer N application (Guindo et al., 1994). In 2009, 10 dbf N-fertilizer application timing had greater TNU at PD as compared to 1 dbf as well as all the timings in 2010 (Table 3.8). Previous research has shown that the maximum total N uptake in rice typically occurs at HD (Norman et al., 1992b; Guindo et al., 1994). Research conducted by Norman et al. (2009) reported a decrease in N uptake when the flood was delayed from 1 to 10 days. Norman et al. (2009) found that at 134 kg N ha^{-1}, AMS plus urea resulted in more N uptake than urea, but less N uptake compared with Agrotain and AMS. At a lower rate of 67 kg N ha^{-1}, rice N uptake was similar for Agrotain, AMS, and AMS plus urea, but greater than that of untreated urea.

Apparent Nitrogen Recovery Efficiency

Ammonia volatilization following urea application is considered to be the major cause of low recovery efficiency of applied N (Tian et al., 2001). Quanbao et al. (2007) utilized the apparent N recovery efficiency (ANRE) as the primary index for describing the characteristics of N uptake and utilization of rice. In this case, ANRE showed how the different N sources and different preflood N-fertilizer application timings influenced N uptake in rice. When Super U was the N source in 2009, ANRE was greater than AMS and AMS + urea in 2009 and all N sources in 2010 (Table 3.5). Furthermore, when comparing the same source across 2009 and 2010, greater ANRE was achieved in 2009 except for AMS where the opposite was true. Observed %ANRE was not different for 2009 10, 7, and 1 dbf application timings, however, 2009 10 dbf had higher %ANRE than 4 dbf in 2009 and all 2010 timings (Table 3.6). In 2010, N fertilizer applied 10 dbf resulted in less %ANRE compared to 1 dbf. Fertilizer use efficiency for ^{15}N (FUE-^{15}N), in tropical lowland rice production has been reported to be approximately 30 to 50%

(Bronson et al., 2000; De Datta et al., 1968; Eagle et al., 2001). Research conducted by Wilson et al. (1989) found that dependent upon the application time, the rice plant had an observed total recovery of 53 to 74% of the applied N. Norman et al. (1992a) reported FUE-^{15}N values for drill-seeded, delayed-flood rice in the range of 72 to 79% when ^{15}N fertilizer was applied 27 and/or 55 days after emergence. Our results show a range of 44 to 71% ANRE for N sources, averaged across both years and preflood N fertilizer application timing and a range of 43 to 65% ANRE for preflood N fertilizer application timing, when averaged across both years and N sources. Percent ANRE values fluctuated greatly due to differing N sources and preflood N fertilizer application timing and associated N loss due to changing NH_3 volatilization conditions in the field.

Agronomic Nitrogen Use Efficiency

No differences were observed for agronomic N use efficiency (ANUE) in 2009 with respect to N source (Table 3.5). All N sources in 2009 resulted in less ANUE compared to 2010. The reduction in ANUE value for 2009 is mostly due to a lower yield potential. Slaton et al. (2003) optimized rice grain yield in Arkansas when seeding date occurred between 29 March and 26 April; in 2009, our rice study was seeded after the planting window for optimal grain yield (Table 3.2). In 2010, AMS resulted in greater ANUE compared to Super-U and AMS plus urea (Table 3.5). All application timings resulted in less ANUE in 2009 as compared to 2010 (Table 3.6). In 2010, N fertilizer applied 10 dbf resulted in the lowest ANUE. Furthermore, ANUE when N fertilizer was applied 4 dbf was less than the application at 1 dbf. Agronomic N use efficiency was used by Quanbao et al. (2007) to describe the capability of yield increase per kilogram of applied N. As mentioned previously, the soil moisture conditions in 2010 posed a large risk of N loss due to NH_3 volatilization. In 2010, the grain increase associated with differing N sources and preflood N-fertilizer application timings was influenced. Ammonia volatilization conditions were prevalent in 2010; however, AMS, urea, and Agrotain increased ANUE compared to all N sources in 2009 (Table 3.5). Minimal NH_3 volatilization conditions occurred in 2009 (Table 3.12), yet the lower yield potential decreased ANUE and grain yield (Tables 3.5). The 10 dbf application timing resulted in decreased ANUE; that is to say that if preflood N-fertilizer is applied 10 days prior to flooding, the efficiency on a yield increase is substantially less than the same rate of preflood N-fertilizer applied at 1, 4, or 7 days prior to flood (Table 3.6). Griggs et al. (2007) emphasized that if rice is produced on clay soil, as is the case of this study (Tunica clay), the producer must establish a flood within 7 days; after that point N loss due to NH_3 volatilization can be severe. If rice is produced on a silt loam soil, flood must be established within 3 days after preflood N application (Griggs et al., 2007).

Ammonia Volatilization Experiments

Previous research has shown that hydrolysis of urea, when applied without a urease inhibitor, requires just a few days to exceed the ability of the soil to buffer the NH_3 formed through conversion to the stable NH_4^+ ion (Beyrouty et al., 1988; Clay et al., 1990; Griggs et al., 2007). Norman et al. (2009) reported significant amounts of NH_3 volatilization from all N sources except Agrotain within two days after N fertilization. Initially, urea and AMS plus urea lost similar amounts of NH_3 and much more than Agrotain (Norman et al., 2009). Ammonia volatilization of urea can be minimized for at least a week after application to the soil with the use of NBPT (Bremner and Chai, 1989; Rawluk et al., 2001). In 2009, AMS plus urea had the greatest N loss (% of applied) followed by urea, AMS, Super-U, and Agrotain (Table 3.10 and Figure 3.1). In 2010, urea had the greatest % of applied N loss, followed by AMS plus urea, AMS, Super-U, and Agrotain (Table 3.10 and Figure 3.1).

Averaged across years, the N sources differed in their N loss due to volatilization when analyzed by time in days after application (DAT) (Table 3.11 and Figure 3.2). Urea and AMS plus urea followed a similar N loss trend; both had exponential losses observed at the first sample timing (3 DAT). Total losses for urea and AMS plus urea were 10.2 and 9.6%, respectively (Table 3.11 and Figure 3.2). Ammonium sulfate and AMS + urea had the greatest amount of N loss due to NH_3 volatilization directly after fertilizer application (Table 3.11 and Figure 3.2). Norman et al. (2009) reported that unlike urea, which requires a few days to hydrolyze, the reaction of AMS is immediate on dissolution; it is not unusual for most of the NH_3 volatilized from AMS to be measured within the first few days after application as the AMS dissolves and acidifies the soil surrounding the granule. Total loss for AMS was 5.5% of applied N (Table 3.11 and Figure 3.2). Ammonia volatilization was observed with Agrotain and Super-U at the first sample timing (3 DAT), but N losses were minimal. Cumulative losses were higher for Super-U than Agrotain, 4.9 and 3.4%, respectively (Table 3.11 and Figure 3.2). Since the amount of NBPT in Super U is proprietary, the difference may be due to a lower concentration than what the Agrotain treated urea contained. The inflection point shows the time (days) it took for each N source's % of applied N loss to plateau (Figure 3.2). Agrotain and

Super-U provided stability with respect to loss compared to untreated urea. Both Agrotain and Super-U are designed to limit the N loss mechanisms at work in the soil and on the soil surface; Agrotain as a urease inhibitor, Super-U as a urease inhibitor and a nitrification inhibitor. Both products decreased fertilizer N loss as compared to urea. Total N loss due to NH_3 volatilization for urea was only 10% of applied. While products such as Super-U and Agrotain minimized NH_3 volatilization, the relatively low cumulative NH_3 losses with respect to the total amount of N applied did not translate into definitive differences among N sources as noted by the lack of a source*time interaction. Furthermore, grain yield, ANRE, and ANUE being less at 10 dbf compared to 1 dbf in 2010 does suggest that other loss mechanisms are in effect that may be greater than the volatilization loss potential on the Tunica clay soil.

Conclusion

The semi-open static chambers provided the opportunity to measure NH_3 volatilization levels in the field while semi-controlling the surrounding environment. The static chambers provided flexibility of sampling location; they can be placed practically anywhere NH_3 volatilization measurements are desired. This flexibility could prove valuable if measurements were conducted in on-farm trials. Due to the very tedious nature of measuring NH_3 volatilization, the static chambers would probably be better suited to a lab controlled-environment. In a lab setting, the static chambers could predict NH_3 volatilization losses from any desired product and could serve useful to defray some of the increased costs and time restraints associated with more advanced methods of measuring NH_3 volatilization. The results obtained from the static chambers in 2009 and

2010 show how much N is actually being lost via NH_3 volatilization on a soil classified as Tunica clay. The static chambers may have over-estimated N loss via NH_3 volatilization in a dry year, as observed in 2009 growing season, but under-estimated N loss in a wet year, such as observed in 2010. Rain events occurred in 2010, yet due to the semi-controlled environment, the chambers were not affected.

Environment largely affected the grain yield and N uptake and efficiency parameters in this study. Fertilizer timing was not critical in 2009 due to the unusually dry conditions that occurred. However, in 2010, grain yield and N uptake and efficiency parameters tended to be less the longer the time between application and flood establishment. Ammonia volatilization losses as measured in the static chamber system were a maximum of 10% for the Tunica clay soil with a high pH. Agrotain and Super U did show an ability to greatly minimize volatilization loss potential as compared to urea. This study confirms that N management in a year like 2010 can be difficult and can result in grain yield loss and lower ANUE. Furthermore, the results from this study indicate that other loss mechanisms, e.g., nitrification/denitrification should be studied further to quantify their contribution to N loss and thus grain yield loss.

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Table 3.1

Soil chemical properties for studies conducted at Stoneville, MS, in 2009 and 2010.

Year	%OM	%Sand	%Silt	%Clay	Texture[‡]	CEC	pH	Extractable Nutrient Levels[†] kg ha^{-1} P	K	Ca	Mg	Zn	S	Na
2009	1.1	7	67	26	Silty clay loam	19.5	7.2	139	310	6562	1193	6.27	180	166
2010	1.2	13	58	29	Silty clay loam	27.8	8.2	195	426	8848	2043	5.49	195	171

[†] Lancaster soil testing method (Cox, 2001).

[‡] Particle size analysis: hydrometer method (Gee and Bauder, 1986).

Table 3.2

Dates of agronomic management and sampling events for yield studies conducted at Stoneville, MS, in 2009 and 2010.

Event	2009	2010
Seeding[¥]	17 May	28 Apr.
Emergence	26 May	6 May
Preflood-N 10dbf [†]	9 June	18 May
Preflood-N 7dbf	11 June	21 May
Preflood-N 4dbf	15 June	24 May
Preflood-N 1dbf	18 June	27 May
Flooded	19 June	28 May
PD tissue samples[‡]	9 July	17 June
HD tissue samples[§]	13 Aug.	21 July
Harvest	21 Sept.	17 Aug.

¥ Seeding, 'Cocodrie' at 90 kg ha^{-1}.

† dbf, days before flood at 168 kg N ha^{-1}.

‡ PD, panicle differentiation growth stage.

§ HD, heading growth stage.

Table 3.3

Dates of agronomic management and sampling events for ammonia volatilization studies conducted at Stoneville, MS, in 2009 and 2010.

Event	2009	2010
Seeding[†]	17 May	28 Apr.
Chamber installation	9 June	18 May
Preflood-N application[‡]	9 June	18 May
A sorbers installed	9 June	18 May
A sorbers removed	12 June	21 May
B sorbers removed	15 June	25 May
C sorbers removed	18 June	28 May
Flooded	19 June	28 May
D sorbers removed	22 June	1 June
E sorbers removed	25 June	4 June
F sorbers removed	29 June	8 June
G sorbers removed	n/a	11 June

† Seeding, 'Cocodrie' at 90 kg ha^{-1}.

‡ Preflood-N application, 168 kg N ha^{-1}.

Table 3.4

Test of fixed effects and interactions for grain yield, total N uptake at PD and HD, ANRE, and ANUE at Stoneville, MS, in 2009 and 2010.

Source	Grain Yield	TNU-PD[†]	TNU-HD[‡]	ANRE[£]	ANUE[§]
			Pr > F		
Year (YR)	<.0001	0.0007	0.0290	NS	<.0001
Pre-flood N (PF)[Θ]	0.0460	NS	NS	NS	0.0460
N Source (SR)	NS[¥]	NS	NS	NS	NS
YR*PF	0.0012	<.0001	0.0235	0.0049	0.0012
YR*SR	0.0447	0.0008	<.0001	<.0001	0.0446
PF*SR	NS	NS	NS	NS	NS
YR*PF*SR	NS	NS	NS	NS	NS

† TNU-PD, total nitrogen (N) uptake at panicle differentiation growth stage.

‡ TNU-HD, total N uptake at heading growth stage.

£ ANRE, Apparent N recovery efficiency, = (total plant N uptake with N application – total plant N uptake without N application) / N application x 100.

§ ANUE, Agronomic N use efficiency, = (grain yield with N application – grain yield without N application) / N application.

¥ NS, not significant at the P = 0.05 level.

Θ Pre-flood N, application timing, 168 kg N ha^{-1}.

Table 3.5

Grain yield, ANRE, and ANUE as affected by an interaction among nitrogen (N) source and year at Stoneville, MS.

	Grain Yield		ANRE[£]		ANUE[†]	
	2009	2010	2009	2010	2009	2010
N Source	--------kg ha^{-1}--------		------------%------------			
Urea	8430 c[¥]	9274 ab	62.2 ab	47.0 c-e	22.1 c	26.8 ab
Agrotain	8459 c	9424 ab	63.7 ab	43.6 e	22.3 c	27.7 ab
Super-U	8358 c	9237 b	70.9 a	49.1 c-e	21.7 c	26.6 b
AMS	8187 c	9582 a	43.3 e	55.6 b-d	20.6 c	28.7 a
AMS+Urea	8287 c	9193 b	56.8 bc	46.3 de	21.2 c	26.3 b

£ ANRE, Apparent N recovery efficiency, = (total plant N uptake with N application – total plant N uptake without N application) / N application x 100.

† ANUE, Agronomic N use efficiency, = (grain yield with N application – grain yield without N application) / N application.

¥ Means followed by a different letter are significant at P = 0.05 level.

Table 3.6

Grain yield, ANRE, and ANUE as affected by an interaction among pre-flood N application timing and year at Stoneville, MS.

Pre-flood N[†]	Grain Yield		ANRE[£]		ANUE[§]	
	2009	2010	2009	2010	2009	2010
	----------kg ha^{-1}----------		------------%------------			
1dbf[‡]	8457 d[¥]	9589 a	57.4 a-c	54.3 b-d	22.3 d	28.7 a
4dbf	8237 d	9321 b	53.5 c-e	46.3 de	20.9 d	27.1 b
7dbf	8243 d	9474 ab	61.3 ab	50.3 c-e	21.0 d	28.0 ab
10dbf	8440 d	8984 c	65.2 a	42.5 e	22.2 d	25.1 c

£ ANRE, Apparent N recovery efficiency, = (total plant N uptake with N application – total plant N uptake without N application) / N application x 100.

§ ANUE, Agronomic N use efficiency, = (grain yield with N application – grain yield without N application) / N application.

† Pre-flood N, application timing rate of 168 kg N ha^{-1}.

‡ dbf, days before flood.

¥ Means followed by a different letter are significant at P = 0.05 level.

Table 3.7

Total N uptake at panicle differentiation (PD) and total N uptake at heading (HD) as affected by an interaction among N source and year at Stoneville, MS.

	TNU-PD		TNU-HD	
	2009	2010	2009	2010
N Source	----------kg ha^{-1}----------			
Urea	113.0 a[¥]	90.1 bc	151.6 ab	124.7 c-e
Agrotain	119.1 a	79.4 c	154.1 ab	115.4 e
Super-U	113.2 a	81.4 c	166.3 a	126.3 c-e
AMS	99.3 b	95.4 b	119.9 de	137.0 b-d
AMS+Urea	113.3 a	79.8 c	142.6 bc	118.8 e

¥ Means followed by a different letter are significant at P = 0.05 level.

Table 3.8

Total N uptake at panicle differentiation (PD) and total N uptake at heading (HD) as affected by an interaction among pre-flood N application timing and year at Stoneville, MS.

	TNU-PD		TNU-HD	
	2009	2010	2009	2010
Pre-flood N[†]	----------kg ha^{-1}----------			
1dbf[‡]	106.5 b[¥]	102.7 b	143.6 a-c	135.2 b-d
4dbf	108.3 ab	83.0 c	137.1 bc	118.5 de
7dbf	114.0 ab	79.3 c	150.1 ab	126.7 c-e
10dbf	117.5 a	75.9 c	156.7 a	117.0 e

† Pre-flood N, application timing rate of 168 kg N ha^{-1}.
‡ dbf, days before flood.
¥ Means followed by a different letter are significant at P = 0.05 level.

Table 3.9

Test of fixed effects and interactions for N loss (% of applied) due to ammonia volatilization with semi-open static chamber rice study at Stoneville, MS in 2009 and 2010.

Source	N Loss (% of applied)
	Pr > F
Year (YR)	NS[¥]
N Source (SR)	<0.0001
Sample Timing (ST)	<0.0001
YR*SR	<0.0001
YR*ST	NS
SR*ST	<0.0001
YR*SR*ST	NS

[¥] NS, not significant at the P = 0.05 level.

Table 3.10

Cumulative ammonia volatilization losses from urea, $(NH_4)_2SO_4$ (AMS), urea + AMS blend (AMS+Urea), urea + dicyandiamide (DCD) + *N*-(n-butyl) thiophosphoric triamide (NBPT) (Super-U®), and urea + NBPT (Agrotain®) as affected by an interaction among N source and year applied to a Tunica clay soil at Stoneville, MS.

Nitrogen Source	Cumulative NH_3 Volatilization Losses[‡]	
	2009	2010
	--------% of applied N--------	
Urea	10.5 a[¥]	9.9 a
AMS	5.1 d	6.3 c
AMS+Urea	11.0 a	8.0 b
Super-U®	3.6 e	6.7 c
Agrotain®	3.5 e	3.9 e

[‡] Cumulative loss was for 18 d after preflood N application of 168 kg ha^{-1}, Flood established 10 DAT.

[¥] Means followed by a different letter are significant at P = 0.05 level.

Table 3.11

Cumulative ammonia volatilization losses from urea, $(NH_4)_2SO_4$ (AMS), urea + AMS blend (AMS+Urea), urea + dicyandiamide (DCD) + *N*-(n-butyl) thiophosphoric triamide (NBPT) (Super-U®), and urea + NBPT (Agrotain®) as affected by an interaction among N source and sample timing applied to a Tunica clay soil at Stoneville, MS, in 2009 and 2010.

Time after application‡	Cumulative NH_3 Volatilization Losses				
	Urea	AMS	AMS+Urea	Super-U®	Agrotain®
	----------	----------	% of applied N	----------	----------
3	0.6 o-r¥	1.7 m-r	1.8 l-r	0.2 qr	0.2 r
6	4.6 f-i	3.1 i-m	6.0 ef	0.8 o-r	0.6 p-r
9†	7.2 de	3.8 h-k	8.0 cd	2.3 k-p	1.5 n-r
12	8.8 bc	4.7 f-h	9.0 a-d	3.8 g-j	2.5 j-o
15	9.9 ab	5.2 fg	9.3 ab	4.6 f-i	3.1 i-m
18	10.2 a	5.5 e-g	9.6 ab	4.9 f-i	3.4 h-m

‡ Sample timing, days after preflood N fertilizer application of 168 kg ha^{-1}.
¥ Means followed by a different letter are significant at $P = 0.05$ level.
† Flood was established at 10 d.

Table 3.12

Precipitation totals and averages for sampling period of ammonia volatilization rice studies at Stoneville, MS, in 2009 and 2010.

2009		2010	
Date	Precipitation	Date	Precipitation
	mm		mm
6/1[†]	0	5/1	5.1
6/2	0	5/2	49.3
6/3	0	5/3	3.6
6/4	1.5	5/4	0
6/5	2.5	5/5	0
6/6	0	5/6	0
6/7	0	5/7	0
6/8	0	5/8	0
6/9	0	5/9	0
6/10	0	5/10	3.8
6/11	0	5/11	0.2
6/12	0	5/12	0
6/13	0	5/13	0
6/14	0	5/14	0
6/15	0	5/15	0
6/16	0	5/16	22.6
6/17	0	5/17	14.0
6/18	0	5/18	0
6/19	0	5/19	0
6/20	0	5/20	0
6/21	0	5/21	6.3
6/22	0	5/22	0.2
6/23	0	5/23	0
6/24	2.8	5/24	0
6/25	0	5/25	0.8
6/26	0	5/26	0
6/27	0	5/27	4.8
6/28	0	5/28	0
6/29	0	5/29	0
6/30	0	5/30	0
7/1	18.3	5/31	23.4
Total	25.1		134.1
Average	0.8		4.3

† Data obtained from Mississippi State University, Delta Research and Extension Center weather website (DREC 2011).

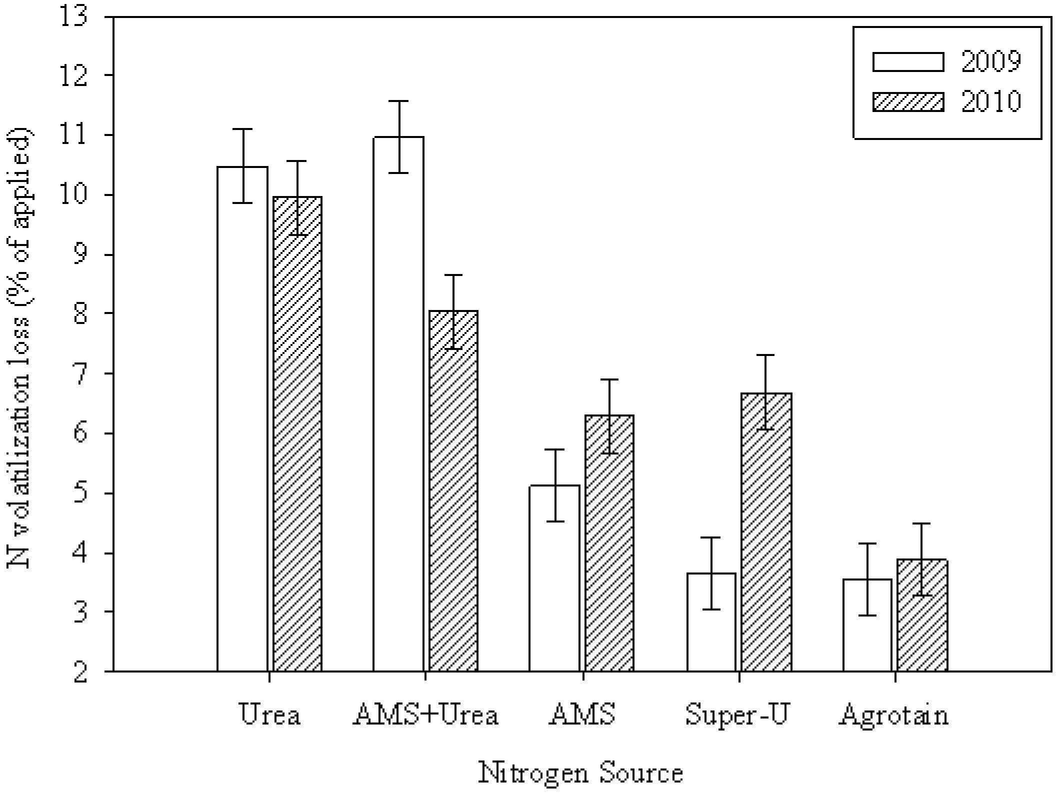
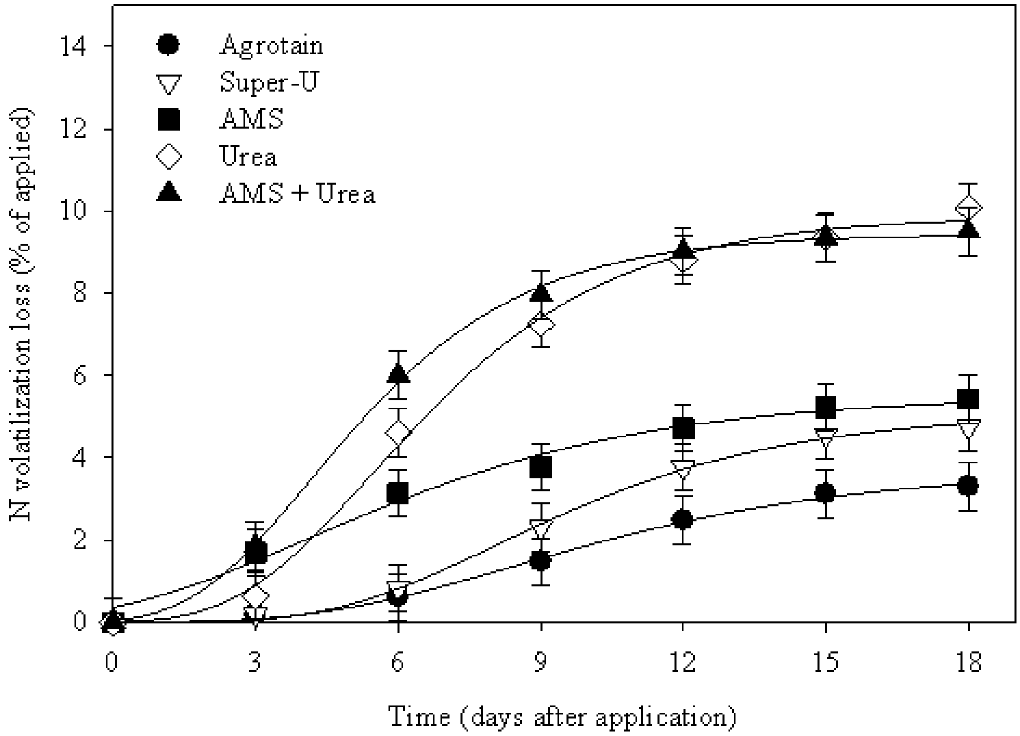


Figure 3.1

N volatilization loss (% of applied) as affected by an interaction among N source and year, averaged over sample time in semi-open static chamber study at Stoneville, MS, in 2009 and 2010.



N Source	Max evolved	Inverse rate constant	Inflection point	R^2	P value
	----%----	-------------day-------------			
Urea	10.1869 (0.2530)†	2.8427 (0.2953)	5.4737 (0.2025)	0.9967	0.0001
AMS + Urea	9.6043 (0.1036)	2.5054 (0.1327)	4.1630 (0.0945)	0.9986	0.0001
AMS	5.5387 (0.3141)	4.0857 (0.7515)	4.0964 (0.4768)	0.9864	0.0002
Super-U	4.8709 (0.1469)	3.4275 (0.2819)	8.0685 (0.1790)	0.9985	0.0001
Agrotain	3.4149 (0.1718)	4.0957 (0.4439)	8.4384 (0.2929)	0.9962	0.0001

† standard deviation.

Figure 3.2

N volatilization loss (% of applied) as affected by N source and sample timing in semi-open static chamber study at Stoneville, MS, in 2009 and 2010.