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Improving Nitrogen Use Efficiency and Yield in Louisiana Sugarcane Production Systems

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IMPROVING NITROGEN USE EFFICIENCY AND YIELD IN LOUISIANA SUGARCANE PRODUCTION SYSTEMS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
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requirements for the degree of
Master of Science

in

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Daniel Ernesto Forestieri
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Abstract

Proper nitrogen (N) management is essential to optimize crop production. This study was conducted to evaluate different N fertilizer management strategies to improve N use efficiency and yield in sugarcane production in Louisiana. This research was initiated in 2013 at the Sugar Research Station in St. Gabriel, LA and was arranged in a randomized complete block design with four replications consisting of different N rates (0, 45, 90, and 135 kg N ha^{-1}) and sources (urea-46% N, ammonium nitrate [AN]-34% N, and urea-ammonium-nitrate solution [UAN]-32% N dribbled and knifed-in) as treatments. Sensor readings were taken from different N response trials to validate the sugarcane yield potential prediction and N response index (RI) models based on normalized difference vegetation index (NDVI). Soil nitrate (NO_3^-) and ammonium (NH_4^+) at 0-15 and 15-30 cm depths were also measured at different dates after N fertilization. At the grand growth stage, plots which were knifed-in with UAN showed a more even distribution of NO_3^- and NH_4^+ compared to urea- and AN-treated plots for both depths. Among the treatments, the highest sugarcane yield was achieved from plots treated with 90 kg N ha^{-1} as UAN knife-in and 135 kg N ha^{-1} as AN. Yield potential prediction models established in 2012 and 2015 could be used to estimate sugar and cane yield using NDVI readings collected at 21 (r^2=0.30 and r^2=0.51) and 60 (r^2=0.41 and r^2=0.52) days after N fertilization (DANF), respectively. Both RI and modified RI models demonstrated a better level of precision when RI was predicted at 60 DANF (r^2=0.30) for both cane and sugar yield compared to 21 DANF (r^2=0.15). The outcomes of this study demonstrated the effectivity of UAN knife-in as N source and the current N recommendation, but there were indications that application of higher N rate may further maximize yield. This study also revealed some limitations of the models used for predicting the components of remote sensor-based N recommendations for Louisiana sugarcane production.

Apart from strengthening the yield and sensor readings database, areas of focus for future research include the use of different vegetation indices and reflectance readings from different wavebands.

Chapter 1. Introduction

Sugarcane (*Saccharum spp*) is a complex hybrid between *Saccharum officinarum* and *S. spontaneous* (Verheye, 2010). Worldwide cane production is close to 1900 million Mg from around 22 million hectares (Salassi, 2015). Presently, sugarcane is mostly grown in tropical and sub-tropical climates of the world, with Brazil and India as the major producing countries (Fortes, 2013). In the United States, production of sugarcane in 2015 for sugar and seed was estimated at 71 million Mg ha^{-1}, of which 69 million Mg were used for sugar and 2 million Mg for seed. Yield estimated for both sugar and seed was 82 Mg ha^{-1} coming from Florida, Louisiana, Hawaii, and Texas (USDA, 2015). In Louisiana, sugarcane production in 2015 reached 12 million Mg grown on more than 210,000 hectares producing 1.26 million Mg of sugar (USDA, 2015). Sugarcane is cultivated in 23 parishes with an average yield of 74 Mg ha^{-1} and sugar recovery of 10.8% or 109 kg sugar per Mg of cane harvested (Salassi et al., 2015).

Sugarcane is propagated vegetatively from cuttings called billets or stalk which contains eyes or buds that will develop into the first stem and later produce shoots (Bakker, 1999). Mostly, the sugarcane crop cycle is between 12 to 16 months before being harvested (Legendre, 2000). Sugarcane has essentially four growth phases: germination, tillering, grand growth period and ripening, each phase typically requires 1 to 12 weeks (Hunsigi, 1993).

In Louisiana, the cane is planted in fall (early July through October), and the standard planting method uses either whole stalks or billets. If conditions are favorable, the buds will germinate and produce new shoots during the following spring (Bakker, 1999). Three to four whole stalks or billets are planted side-by-side with overlapping of at least two mature joints or more per 14 to 18 cm run to compensate for damage problems to seedlings during planting, stalk rot disease, and winter freeze (Gravois, 2014). Buds in stem cuttings (setts) are expected to germinate in November or December, but because of the winter temperature, seedlings die and remain dormant until the next spring (late March to early April of the following year). During this subsequent growth, the original cuttings produce new mature plant stalks that are harvested in the late fall in December, called plant cane (Bakker, 1999). Two or three weeks after plant cane harvest, the stump shoots are regrown again for two or three additional years after original planting, a procedure termed ratooning or ratoon crop (Glynn, 2004). In 2015, sugarcane growers planted several varieties: the most commonly grown variety was HoCP 96-540, planted on more than 34% of the production areas (Gravois and Legendre, 2015). This was followed by L 01-299 (30%), L 99-226 (11%), L 01-283 (10%), and HoCP 04-838 (9 %). All other varieties each occupied less than 4% of the state's acreage (Gravois, 2015).

Proper nutrient management, efficient cultural practices, and the use of suitable cane varieties positively influenced the growth rate of subsequent ratoon crops (Bakker, 1991). Liebig established the "Law of the Minimum," which states that the growth and development of a particular crop is controlled by the scarcest resource (Salisbury, 1992). If an essential element is not balanced with the requirements of that crop, either present in insufficient quantities or an excessive amount, growth and yield will be diminished (Bakker, 1991). Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are required in the largest amounts by the plant. About 90% of total N on Earth is present in the core and the mantle (Walker, 1977) whereas only 0.03% N on the Earth's crust is available for living organisms (Scharf, 2015). Nitrogen is the main component of chlorophyll pigments, an essential component in photosynthesis process which is responsible for almost 90% of plant dry matter production (Poorter et al., 1990). Nitrogen is the most limiting nutrient in crop production, and its deficiency substantially restricts plant growth (Lea, 1989; Maust and Willianson, 1994).

Nitrogen is present in soil as inorganic and organic forms; nitrate (NO_3^-) and ammonium (NH_4^+) are the two forms of N taken up by the plant. Mass flow and diffusion are the main transport mechanisms of NO_3^- and NH_4^+ in the soil (Havlin et al., 2014). Most of the NH_4^+ is assimilated and incorporated into organic compounds in the root cells while NO_3^- is very mobile in the xylem and can be stored in the vacuoles of roots and shoots (Engels and Marschner, 1995). The amount of NO_3^- taken up by the plant is higher in comparison to NH_4^+, but the plant spends more energy converting NO_3^- to NH_4^+ to amino acids and then to proteins (Havlin et al., 2014). The preference between NO_3^- and NH_4^+ differs between plant species. According to Robinson et al. (2011), the low capacity of sugarcane to store NO_3^- in the shoots during the tillering stage limits its uptake, thus resultings in the accumulation of NO_3^- in the soil. The main sources of NH_4^+ include ammoniacal N fertilizer and mineralization of organic N from plant/animal residues and organic matter in the soil (Myrold and Bottomley, 2008). Nitrate is produced from the oxidation of NH_4^+ also known as the nitrification process (Paul and Clark, 1989; Norton, 2008). The nitrification process always takes place when both the substrate (NH_4^+) and oxygen are present thus NO_3^- is the major form of inorganic N in most agricultural soils (Paul and Clark, 1989; Norton, 2008).

Nitrate is very mobile in soil. Thus, any residual remaining in the soil is prone to los through soil surface runoff, leaching, and denitrification especially in areas prone to flooding and with poor drainage (Power et al., 2000; Bronson, 2008). Nitrate leaching is the downward movement of NO_3^- through the soil profile (Randall and Iragavarapu, 1995). Nitrate losses through runoff (0.3 kg ha^{-1}) are minimal compared with the amount (9.2 kg ha^{-1}) lost by the leaching process when a N fertilizer is applied in excess (Hubbard et al., 1991). Nitrogen lost through ammonia (NH_3) fertilizer volatilization has a negative effects on air quality and likely is an increase risks to human health (Power et al., 2000). NH_3 volatilization in the senescing plant can contribute to N losses (Myrold and Bottomley, 2008).

Fertilizers such as urea and ammonium nitrate (AN) are fertilizers containing NH_4^+ which is the form of N that is prone to volatilization. Thus, proper placement into the soil is one of the key management practices to minimize or prevent N volatilization. Moisture level, chemical properties (e.g., cation exchange capacity), and temperature of soils affect the removal of NH_4^+ from the soil-plant system (Havlin et al., 2014). Volatilization of NH_4^+ can also be affected by soil pH and N sources, i.e., when soil pH is low, NH_3 losses can be <25% of the fertilizer N applied and about double this amount when soil-pH is high (calcareous soils) (Havlin et al., 2014). Another pathway in which NH_4^+ can be lost is through fixation by clay minerals. Ammonium fertilizer fixation is greater in the interlayer spaces of 2:1 type clay minerals like illite, vermiculite, and montmorillonite (Drury and Beauchamp, 1991; Thompson and Blackmer, 1993; Kissell et al., 2008).

The production of sugarcane biomass requires substantial quantities of N fertilizer (Roy et al., 2006). Site-specific management of N fertilizer is essential, considering the large N demand of sugarcane, with each unit of N fertilizer applied will matter not only to meet the yield goal but also to minimize the negative effect of N fertilizer on the environment (Johnson et al., 2002; Beaudoin et al., 2005).

Nitrogen recommendations should be established under the notion that crop productivity, economic advantage, and environmental quality are balanced (Roy et al., 2006; Meyer et al., 2007; Kostka et al., 2009). Nitrogen has a direct impact on the development of sugarcane affecting yield production and sugar content; application of excessive N can delay maturity, increase lodging and reduce sucrose content (Bakker, 1991).

Studies have found that in many cases both cane stalk and sucrose yield can be reduced with high N rates applications (Wiedenfeld, 1997; Fortes et al., 2013). A study by Rattey and Hogarth (2001) showed the effect of high N rates in reducing sugar yield.

A proper N fertilization management program employs N application using the optimal rate, time, placement, and source. Nitrogen recommendation and management schemes vary with crop species, growth cycle, variety, and growing conditions (Shapiro et al., 2006). Implementation of proper management of N fertilizer can reduce N losses and increase the farmers's income (Randall and Iragavarapu, 1995; Owens et al., 1999). In Louisiana sugarcane production systems, N rate recommendations are based on soil type and crop age and applied in a uniform amount in a field (Legendre et al., 2000).

For many years, researchers from USDA-ARS and LSU AgCenter have conducted experiments to test different N sources and rates across different varieties and soil types (Johnson et al., 2005). Current N recommendations for sugarcane were established based on one source, i.e., urea-ammonium-nitrate (UAN), with soil type and crop age being the determining factors (Everingham et al., 2007). According to Johnson et al. (2008), differences in N requirements for plant cane, first and second ratoon crop was observed wherein the first and older ratoon crops requiere slightly more N to maximize yield. Nitrogen fertilizer application in Louisiana is applied one-time between April and the beginning of May before of the highest growth of sugarcane. For all varieties, plant cane on light and heavy textured soil should receive 67-90, and 90-112 kg N ha^{-1}, respectively, but ratoon crops require 90-112 and 112-135 kg N ha^{-1} (Viator et al., 2014).

Nitrogen fertilizer is unquestionably the most valuable nutrient input in sugarcane production and can bring significant returns when managed properly. Given this fact, it is also important to know that the N cycle is very dynamic, particularly the many pathways by which it can be lost from the soil systems. This poses a challenge to efficienty N fertilizer use. The negative impact of mismanagement of N fertilizer is an important issue that should be taken into consideration in crop production to balance environmental and yield goals (Van Miegro et al., 1994). The greatest challenge in agriculture is to improve yield production and quality at a reduced production cost (Rodrigues et al., 2013). The greatest challenge for N management; is to provide guidelines to attain economically optimum N nutrition for crops (Bronson, 2008). Visual observation is still a common practice used by growers to identify the adequacy of N supply for plant growth (Fox et al., 2008). Proper and affordable crop monitoring technologies are needed to assess N status. Visual symptoms and soil-plant tissue analysis are the most common techniques to monitor plant nutrient status (Fagueria et al., 2009). While soil and plant testing are proven, effective diagnostic tools for crop N status monitoring (Schöder et al., 2000), their cost, and high time, and labor requirements prompted the pursuit for development of quick and easy-to-use diagnostic tools.

Research has been done since the 1970s to use remote sensing technology in monitoring crop health and N status (Fox et al., 2008). Investigators began developing a new approach called non-destructive monitoring of plant N health status using canopy spectral reflectance and chlorophyll readings (Fox and Piekielek, 1992; Schepers et al., 1998). In this technology, leaf spectral reflectance from different wavebands is measured and transformed to a vegetation index (Raun et al., 2002; Johnson et al., 2005; Singh et al., 2006). Vegetation index is a surrogate measurement of plant N-related variables such as chlorophyll, biomass, and N content (Raun et al., 2002; Singh et al., 2006; Shanahan et al., 2008; Tubaña et al., 2015). Precision N management became possible with the integration of remote sensing technology with variable rate application systems. Many studies have shown that this remote sensor-based N decision tool has the ability to adjust N rate based on plant needs, improving N use efficiency (NUE), economic return, and environmental quality (Raun et al., 2002; Johnson et al., 2005; Singh et al., 2006; Shanahan et al., 2008).

The implementation of site-specific N management in sugarcane production in Louisiana requires a decision tool which can account for both within field and year-to-year variation in crop growth factors. An on-site, sensor-based N decision tool using a GreenSeeker® Handheld sensor has been recently developed which derives N recommendations based on sugarcane yield potential and response index (estimate of plant-available N at the time of fertilization) (Lofton et al., 2012a and 2012b; Tubaña et al., 2015).

GreenSeeker is an active light sensor that uses a self-contained illumination in both red (670 ± 10 nm) and near infrared (NIR, 780 nm ± 10 nm) bands (Singh et al., 2006; Shanahan et al., 2008). The emitted light is reflected from the leaves to the sensor device where it is later used to calculate normalized difference vegetation indices (NDVI) (Shanahan et al., 2008) using the following equation:

$$\text{NDVI}= (\rho\text{NIR}-\rho\text{Red})/(\rho\text{NIR}+\rho\text{Red}). \qquad (1)$$

Where:

ρNIR = Reflectance at the near-infrared region of the electromagnetic spectrum

ρRed= Reflectance at the red region of the electromagnetic spectrum

Validation of existing N fertilization guidelines is essential to ensure its effectiveness even with changing production technologies and continuous adoption of new high-yielding varieties. To date, UAN remains the common N source that is typically knifed-in for sugarcane production systems in Louisiana. Occasional use of urea was reported mostly associated with delayed N application due to weather interference during the fertilization period. Limited research has been conducted to elucidate the differences in N status both in cane and soil fertilized with different N source in sugarcane production. While the performance of a sensor-based N decision tool for Louisiana has shown promise in improving yield and net return from N application (Tubaña et al., 2015), the models for predicting the components (yield potential and N response index) of this tool have not been validated. For these reasons, this study was designed to address the following objectives: 1) determine the effects of different N sources applied at various rates on sugarcane yield and quality parameters, 2) validate the current N recommendation for Louisiana sugarcane production systems, and 3) validate the models used for predicting sugarcane yield potential and response index .

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Chapter 2. Effect of Nitrogen Rates and Source on Sugarcane (*Saccharum officinarum*) Yield and Quality Components

2.1 Introduction

Sugarcane (*Saccharum officinarum* L.) is grown in the tropics and sub-tropical regions of the world including countries such as Brazil, Philippines, Australia and the United States (Galdas, 2009). There are only a few sugarcane-producing states in the US wherein Florida ranks first in sugarcane production followed by Louisiana, Hawaii, and Texas (Baucum, 1992). In 2015, Louisiana's total cane production area reached 210,527 ha across 23 parishes by from approximately 800 producers with an average production of 12 million Mg of cane with a total sugar recovery of 109 kg per Mg of cane (Gravois and Salassi et al., 2015). The sugarcane industry impacts the state economy with a return of 3 billion dollars annually and generates a total of 16,400 direct and indirect jobs.

To attain maximum productivity, sugarcane requirements for temperature, moisture, and light have to be met. The optimum temperatures for good germination range from 26-33ºC. Below 20ºC, germination is slow coupled with diminished root development. The optimum temperature range for sugarcane growth can is between 30-33ºC (Bakker, 1999). Light intensity, temperature, and rainfall (moisture) received by cane during the crop cycle have a substantial effect on yield and crop quality (Hunsigi, 1993). Sugarcane is grown primarily in areas with rainfall ranging from 50-250 cm per year (Hunsigi, 1993). A very wet cropping season influences timely planting and harvesting and decreases sugar recovery (Hunsigi, 1993).

Sugarcane is propagated using vegetative materials (cane cuttings) called whole stalk or billets (Bakker, 1999). Both planting materials contain "eyes or nodal buds" that have the ability to develop a primary shoot once planted. Typically, whole stalk contains an average of 4 to 8 buds, whereas 2 to 4 nodal buds are found in billets. The quality of the bud on the cane is critical in determining the speed and the germination rate (Bakker, 1999). Moisture, nutrient content, and crop age also have an important effect on the germination rate (Hunsigi, 1993). In Louisiana, sugarcane is planted on beds 1.8-m wide and 0.3 m tall (Richard et al., 1991 and Legendre, 2001). With this row configuration, flooding of planted material is prevented during excessive rainfall events. Building adequate field drainage is critical, as excess water in the soil produces an adverse effect on the survival of stalk-buds and subsequent yield of ratooning crops (Richard et al., 1991).

Whole stalks and billets are usually planted from August to October. Materials are laid with overlaps side-by-side at seeding rates of three to four per run having at least two or more mature joints overlapping to compensate for damage due to planting injury, stalk rot disease, and winter freeze (Gravois, 2014). The stem cuttings germinate in November or December, but because of the winter temperature, they remain dormant until the next spring (late March to early April). The original cuttings will produce new mature plant stalk that is harvested in the late fall called plant cane (Bakker, 1999). After the plant cane has been harvested, the stumps are regrown for two or three additional years from the original planting, a process known as ratooning or ratoon crop (Glynn, 2004). Sugarcane has essentially four growth phases: germination, tillering, grand growth, and maturity (ripening), each of which typically requires 1 to 12 weeks (Hunsigi, 1993).

Cropping seasons with low temperatures and excessive drought conditions delay germination, tillering and canopy development of sugarcane (Gasho and Shih, 1982). A proper nutrient management program including the optimal time, source, rate, and application method influences sugarcane yield and quality parameters (Hunsigi, 1993). Nitrogen (N) fertilizer is one of the nutrients required in the highest amounts by most crops (Hunsigi, 1993).

Nitrogen is present in soil as inorganic and organic form (Havlin et al., 2014). Nitrate (NO_3^-) and ammonium (NH_4^+) are the two forms of N taken up by the plant. Mass flow and diffusion are the main transport mechanisms of NO_3^- and NH_4^+ in the soil to the root rhizosphere (Havlin et al., 2014). Sugarcane absorbs both forms of N but NO_3^- is absorbed in a higher concentration than NH_4^+ because of the higher mobility of NO_3^- than NH_4^+. Most of the NH_4^+ is assimilated and is incorporated into organic compounds in the roots (Engels and Marschner, 1995), while NO_3^- can be stored in the vacuoles of roots and shoots as it is very mobile in the xylem (Engels and Marschner, 1995).

The amount of NO_3^- taken up by the plant is higher in comparison to NH_4^+, but the plant spends more energy converting NO_3^- to NH_4^+ to amino acids and then to proteins (Havlin et al., 2014). The preference between NO_3^- and NH_4^+ differs among plants species, according to Robinson et al. (2011). While NO_3^- is taken up in a larger amount than NH_4^+, sugarcane inherently has low capacity to store NO_3^- in the shoots during tillering limiting the uptake and increasing the accumulation of NO_3^- in the soil.

The most common pathways by which N can be lost from the soil are leaching, volatilization, denitrification, and N uptake by the plant (Dey, 2003). Nitrogen uptake is affected by two factors; N requirement and available soil N, the last factor is also affected by the environment, growth stage, and the crop variety (Hunsigi, 1993). The excessive use of N fertilizer may lead to NO_3^- leaching and underground water contamination (Ersahin, 2001). Lee et al. (2005) verified that applying N fertilizer at rates higher than the optimal rate will increase N lost via leaching. Evidence provided by Thomas and Scott (1990) observed that N fertilization in sugarcane not only has a substantial effect on cane and sugar yield but also produces a positive effect on phosphorus and potassium uptake because N stimulates the growth of roots and shoots increasing the root sorption area. Proper management of N fertilizer has a positive impact on leaf area index, stalk elongation, tillering, and cane and sugar yield.

Liebig's law of the minimum states that the scarcest determines the yield level (Bray, 1953). Yield potential is directly related to the amount of the limiting nutrient present and the plant content of the deficient nutrient (Bray, 1953). On the other hand, the law of diminishing returns states that as the presence of nutrients increases; yield and growth will also increase but likely at a decreasing rate with each additional unit (Mitscherlich, 1909). These two laws are imortant in developing the concept that proper nutrient management supplies enough nutrients to avoid deficiencies while not providing more than can be utilized in order to optimize yield.

The impact of N fertilization differs with sugarcane crop age. Typically plant cane does not respond to N fertilization compared to the followings ratoon crops presenting differences regarding yield, stalk population and biomass production. Currently, in Louisiana, N rate recommendations are based on the type of soil (heavy or light texture) and crop age (plant cane or following ratoons) (Lofton et al., 2012a). According to Srivastava and Suarez (1992), sugarcane requires 45 to 300 kg N ha^{-1}. Sugarcane produced in Louisiana receives N ranging from 67 to 135 kg N ha^{-1}.

Using the optimal amount of N is essential to sugarcane productivity. Previous research has shown that application of high amounts of N resulted in sugar yield reduction as well as caused environmental problems associated with leaching and runoff of N (Borden, 1942; Chapman et al., 1994; Wiedenfeld, 1995). It is known that, nutrient management approaches are critical to maximizing N recovery, climate, soil type, and variety can also impact cane response to N fertilizer. Muchow et al. (1996) showed that using a high N rate (268 kg N ha^{-1}) did not result in a significant reduction in sucrose content, instead cane yield increased recovering the equal amount of sugar which was higher than the plots applied with lower N rate. However, Rattey et al. (2001) reported a reduction in sugar yield with increasing level of N fertilization. This was consistent with the findings of Lofton et al. (2013) showing that N rate had a significant effect on cane tonnage for both years (plant cane and first ratoon). However, sugar yield was significantly affected only at first ratoon. Gawander et al. (2004) indicated that sugarcane yield and quality parameters such as sucrose content are significantly correlated with N fertilization. While sugar yield has a direct relationship with cane yield and TRS (theoretical recoverable sugar), N rate had a significant effect only on cane yield. Other results differ, showing that the effects of rate and split application of N fertilizer did not show a significant effect on sugarcane quality (Koochekzadeh et al., 2009). Koochekzadeh et al. (2009) also found that the highest sugar yield was obtained from cane receiving the lowest N rate (92 kg ha^{-1}).

Another study conducted in St. Gabriel, LA., in 2010 and 2011 using plant cane, first and second ratoon, applied with N at different application times, showed a significant decrease in sugar yield due to a decline in sugar quality components (Lofton et al., 2013). Timing is also the key to maximizing N fertilization in sugarcane production systems. Nitrogen applications before early April or after late May can produce adverse effects on cane yield and sugarcane quality parameters (Wiedenfeld, 1997).

The timing of N fertilizer application for the Louisiana sugarcane production system should be the month of April (1-30) or synchronous with the commencement of the active growth stage of cane (Johnson et al., 2008). Lofton et al. (2013) reported that sugarcane yield did not have a consistent response to different N application time but a positive effect on sugar and cane yield was observed.

They also reported that late May application resulted in significantly lower yields compared to mid-May application. On the other hand, delaying N fertilization to mid-May and the end of May did not show any significant reduction in cane or sugar yield. Using a linear-plateau model to determine the optimum N rate, Lofton et al. (2013) reported that sugarcane could achieve similar yield using lower N rates than the current N recommendation and the timing of application could be delayed without significantly reducing yield or quality parameters.

A proper nutrient management program encompasses the optimal N rate applied at the optimal time and application method using the right source to achieve high yields while reducing threats to environmental quality. Validation of existing N fertilization guidelines is essential to ensure its effectiveness even with changing production technologies and continuous adoption of new high-yielding varieties. To date, UAN remains the common N source that is typically applied via knife-in for sugarcane production systems in Louisiana. Occasional use of urea was reported mostly associated with delayed N application due to weather interference during fertilization period.Limited research has been conducted to elucidate the differences in N status both in cane and soil fertilized with different N sources in sugarcane production specifically the changes in NO_3^- and NH_4^+ content and distribution in the soil along with subsequent N uptake by sugarcane. This study was conducted to 1) determine the effects of different N sources applied at various rates on sugarcane yield and quality parameters, and 2) validate current N fertilizer recommendation for Louisiana sugarcane production systems.

2.2 Materials and Methods

2.2.1 Site Description, Planting Method, Treatment Structure and Trial Establishment

A field experiment was conducted from 2014 to 2016 at the Sugar Research Station in St. Gabriel, LA (Latitude 30°, 15’, 13” N; Longitude 91°, 06’, 05” W). The soil is a mix of Commerce silt loam (94%) and Commerce silty clay loam (6%) (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquept). The field was planted using sugarcane variety HoCP96-540 in 2013. This variety is considered to be a mid-maturing variety with an excellent stalk population making it a superior material for optimal cane and sugar yield.

HoCP 96-540, released in 2003, was obtained from a cross between LCP 86-454 and LCP 85-384. Research has shown that HoCP 96-540 is moderately resistant to sugarcane borer (*Diatraea saccharalis)*.This variety has an excellent yield potential and has been the leading sugarcane variety in Louisiana since 2008 (Legendre, 2001; Gravois, 2013). Using a whole-stalk harvester, stalks of sugarcane with an average length of between 1.2 and 1.8 m were cut and piled into hauling equipment. Whole stalks were planted by hand on a 1.2-m wide bed with approximately 0.3 m height. The planting furrows were opened to about 10 to 15 cm depth, and then three to four stalks were placed side-by-side with 8 cm overlapping ends in a horizontal position. After planting, furrows were covered with 6-8 cm of soil and then compacted using a custom roller packer to conserve the soil moisture during the germination process. The treatment structure included thirteen combinations of different N sources (urea - 46% N, ammonium nitrate [AN]- 34% N, and urea-ammonium nitrate solution [UAN] - 32% N dribble and knife-in) and three different rates (45, 90, and 134 kg N ha^{-1}) including an untreated check plot (Table 2.1). Each treatment was replicated four times and arranged in a randomized complete block design. The experimental units consisted of three 14-m long rows with a 1.5 m alleyway.

Table 2.2 provides details of the major agronomic activities performed during the three cropping years. Granular N fertilizers were applied in the planting furrow by hand, while liquid fertilizer was applied using fertilizer knives and dribble into the shoulder. Furrows were tilled and covered immediately following N application.

Table 2.1. Description of the treatment structure implemented in this study at the Sugar Research Station in St. Gabriel, LA, 2014-2016.

Trt. No	N Source	N Rate‡	Type	Application method
1	Control	0	Control	Control
2	UAN (32-0-0)	45	Liquid	Knife in (15 cm depth)
3	UAN (32-0-0)	90	Liquid	Knife in (15 cm depth)
4	UAN (32-0-0)	134	Liquid	Knife in (15 cm depth)
5	UAN (32-0-0)	45	Liquid	Dribble in (surface)
6	UAN (32-0-0)	90	Liquid	Dribble in (surface)
7	UAN (32-0-0)	134	Liquid	Dribble in (surface)
8	UREA	45	Granular	Broadcast
9	UREA	90	Granular	Broadcast
10	UREA	134	Granular	Broadcast
11	AN	45	Granular	Broadcast
12	AN	90	Granular	Broadcast
13	AN	134	Granular	Broadcast

UAN – urea ammonium nitrate; AN – ammonium nitrate

‡ N rates are expressed in kg ha^{-1}

Table 2.2. Agronomic activities accomplished during the three cropping years at the Sugar Research Station in St. Gabriel, LA, 2014-2016.

Year	Crop age	N application time	Harvest date
2014	Plant cane	7-May-14	12-Dec-14
2015	First ratoon	4-May-15	17-Nov-15
2016	Second ratoon	8-May-16	18-Oct-16

2.2.2 Soil Sampling

Soil samples at 0-15 and 15-30 cm depths were collected using a standard soil probe (JMC; Model No. 641-792-8285). Sixteen soil cores were sampled from each plot and mixed thoroughly before placing in labeled paper bags.

In 2014, soil samples were taken at 21 and 60 days after N fertilization (DANF), and after harvest. In 2015 and 2016, samples were collected 7, 14, 21, and 60 DANF, and after harvest. Soil samples were then oven-dried (Despatch LBB series; model number LBB2-18-1) at 60°C for about three days, processed using a Humboldt electric flail soil grinder, and sieved through a built in 2 mm sieve for NH_4^+ and NO_3^- analysis.

2.2.3 Soil Analysis

Inorganic N content was determined using a standard extraction procedure for NH_4^+ and NO_3^- by weighing 5.0 grams of dried soil into 125 ml plastic bottle and adding 35 ml of 1 M KCl solution using a dispensing bottle. Soil samples were shaken for 1 hour on a reciprocal shaker at high speed and filtered through Whatman No. 42 filter paper. The N content in the form of NH_4^+ and NO_3^- was determined by spectrophotometric measurement using an automated flow injection system (Lachat QuickChem 8500 series 2).

Nitrate and NH_4^+ were measured simultaneously from the same extract. Nitrate was determined using the method established by Keeney and Nelson (1982) where NO_3^- is converted to nitrite while passing through a copper cadmium reduction column and then reacting with the coloring reagent sulfanilamide to produce a reddish pink color under the acidic condition that can be quantified colorimetrically at 520 nm. The ammonium analysis procedure was quite similar to the procedure proposed by Reardon (1966). Exchangeable NH_4^+ was analyzed for ammonia by the salicylate method. When NH_4^+ present in the sample is heated with salicylate and hypochlorite in an alkaline phosphate buffer environment, a blue-green color is produced. The color is intensified by adding sodium nitroprusside with concentration measured colorimetrically at 660 nm.

2.2.4 Cane Tonnage, Sugar Yield, and Quality Components

Plots were harvested with a single-row, chopper harvester (CASE IH Austoft® 8000 series cane harvester) to determine total plot weight. Cut stalks from each plot were weighed with a modified single axle high dump billet wagon fitted with electronic load sensor cells (Cameco Industries, Thibodaux, LA). Before plot harvesting, ten random stalks were harvested by hand from the middle row of each plot, cleaned (leaves were stripped off from the stalk), and the tops cut between 10 to 12 cm below the apical meristem. The total plot cane yield was determined by adding the weight of the ten stalks sampled and the plot harvest weight. Sampled stalk weights were used to establish average stalk weight.

After weighing, the stalks were shredded and analyzed using a SpectraCane automated NIR analyzer (Bruker Corporation, Billerica, Massachusetts) to determine quality components such as sucrose, theoretical recoverable sugar (TRS), brix (total soluble solids), purity, polarity. A sub-sample of the shredded stalk was collected for each plot, oven-dried (Despatch LBB series; model number LBB2-18-1) at 60ºC for at least five days depending on the moisture content of the sample. The dried shredded samples were ground further using a Wiley Mill grinder (Model Nº3, Arthur H. Thomas CO. Philadelphia, USA) to pass through a 1-mm size sieve and then analyzed for total N (%) using a C:N analyzer (Elementar Americas Inc, Vario EL Cube). The total N (%) was used to calculated stalk N uptake and N fertilizer recovery. Nitrogen fertilizer recovery was calculated according to the following equation:

$$\text{N fertilizer recovery (\%)} = [(\text{TN}-\text{TNW})/\text{NR}]*100 \qquad (2)$$

Here TN is the total amount of N uptake by sugarcane from N applied plots (kg ha^{-1}) and TNW is the total amount of N uptake from the check plots (kg ha^{-1}), and NR is the N rate applied (kg ha^{-1}).

Nitrogen uptake was determined in kg ha^{-1} using the following formula:

$$\text{N Uptake (kg ha}^{-1}\text{)} = [(\text{cane yield}) - (\text{cane yield} * (\%\ \text{moisture}/100))] * [\%\ \text{N}/100] \qquad (3)$$

2.2.5 Data Analysis

Two-way analysis of variance (ANOVA) using PROC MIXED in SAS (SAS Institute, 2012) was performed to evaluate the effect of N rate, source, and their interaction on cane tonnage, sugar yield, quality components, N uptake, and N fertilizer recovery.

The fixed effects were crop-year, N source, N rate, and their interactions while random effects were replication and its interaction with fixed effects. All variables were also analyzed by crop-year wherein N source, N rate, and their interaction was set as fixed effects.

Mean separation was done by Tukey-Kramer post-hoc test if the source (main effect) was significant at $p<0.05$. Orthogonal polynomial contrast (linear, quadratic, and cubic) analysis was performed to determine the effect of N rate when a significant effect of treatment was found.

2.3 Results

2.3.1 Climatic Conditions

Average montly precipitation and temperature for the three crop-years (2014, 2015, and 2016) are presented in Figures 2.1 and 2.2., respectively. Sugarcane is a tropical plant thus, climatic factors such as light, temperature, and rainfall impact cane yield and sugar quality.

The highest average montly precipitation was recorded in August 2016 (Figure 2.1). Overall, the year 2016 accumulated more precipitation compared to 2014 and 2015. More than 20 cm of rain was received in May 2014; a few of these major rainfall events took place a few days after N fertilizer was applied (Figure 2.1). This high amount of rainfall could potentially reduce the inorganic N content in the upper soil profile due to NO_3^- leaching.

Due to the heavy rainfall period on 2016, sugarcane operations in Louisiana suffered from many problems brought about by the delayed schedule of planting and harvesting.

In several parishes, sugarcane harvest started at earlier dates (mid to late September) collecting immature cane which caused a reduction in sugar yield due to low sucrose content.

The average monthly temperature from April to October across cropping years was comparable. The temperature in early spring (March) of 2014 was below average (<15°C) and notably wet (>20 cm rain on May) then followed by a dry summer (~ <10 cm, June and July combined). The optimum temperature for optimal growth is between 30-33^{0}C; at temperatures below 16^{0}C sugarcane development is restricted (Bakker, 1999). Low temperature during the cane ripening process promotes the production of sucrose (Bakker, 1999). Dry matter and stalk elongation are observed with a temperature close to 17.2 to 22.2^{0}C (Hunsigi, 1993).

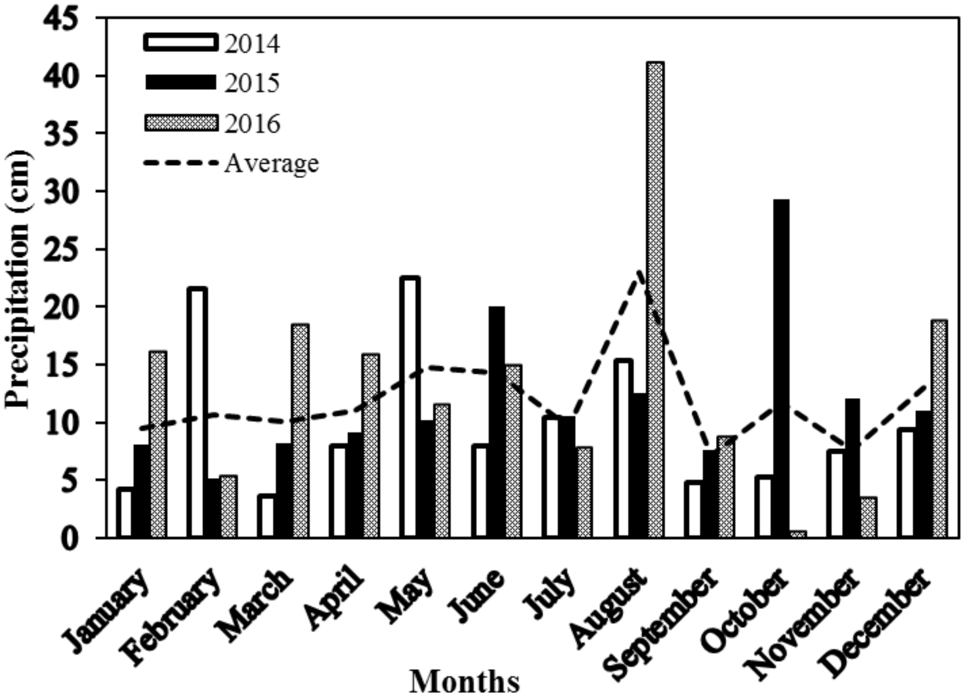

Figure 2.1. Average monthly precipitation from January to December in 2014, 2015, and 2016 at the Sugar Research Station in St. Gabriel, LA.

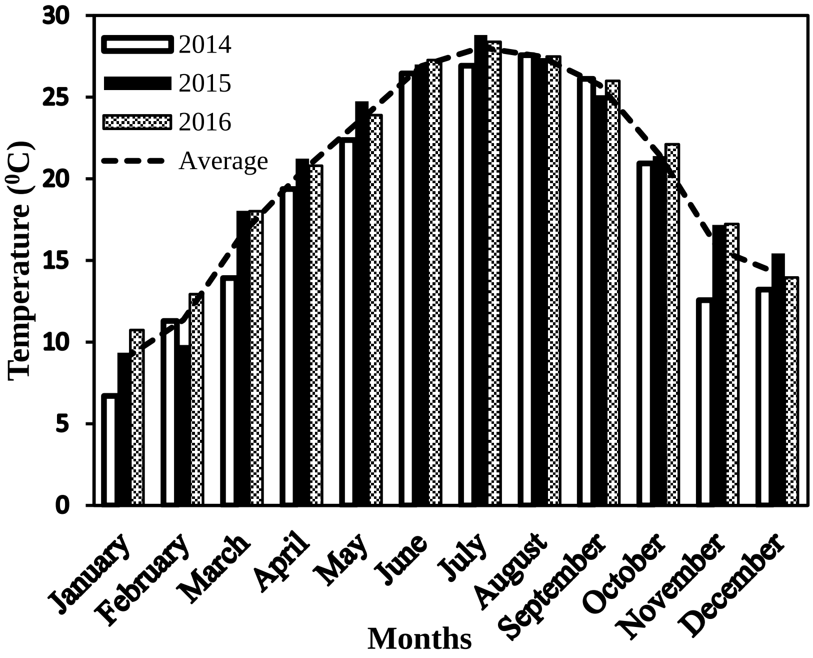

Figure 2.2. Average monthly temperature from January to December in 2014, 2015, and 2016 at the Sugar Research Station in St. Gabriel, LA.

2.3.2 Effect of Crop-Year, N Source and N Rate on All Measured Plant Variables

Table 2.3 shows the effect of crop-year, N source, N rate, and their interactions on yield, quality parameters, N uptake and N fertilizer recovery. Means of all measured variables were significantly different across crop-years (p<0.001). Nitrogen source had no effect while N rate had a significant effect on cane tonnage, sugar yield, and N uptake and fertilizer recovery (p<0.001). The only significant interaction effects were between crop-year and N rate on cane tonnage and sugar yield. There was also a significant crop-year*source*rate interaction effect on brix (p<0.001)

The first ratoon crop (2015) had the highest sugar yield at 9724 kg ha^{-1} followed by plant cane (2016) which had 9288 kg ha^{-1}. The cane tonnage of the first ratoon was lower by 9 Mg ha^{-1} compared to plant cane, but its TRS was significantly higher by 22 kg Mg^{-1}. The first ratoon also had the highest sucrose, brix, and polarity; conversely, both fertilizer recovery and N uptake were the lowest among the crop-year. Sugar yields were significantly affected by N rates, varying sugar yield level from 7727 (0 kg N ha^{-1}) to 9545 kg ha^{-1} (135 kg N ha^{-1}). The rate had a similar linear effect on both sugar yield and cane tonnage, and unlike crop-year, the rate had no effect on quality parameters. Nitrogen uptake linearly increased with N rate. However, the fertilizer N recovery declined in quadratic trend. The significant crop-year and N rate interaction effect on both cane tonnage and sugar yield indicates that N rate effect was not consistent across crop-years.

Tables 2.4, 2.5 and 2.6 detail the effect of N source and rate on all measured plant variables for each crop-year. Nitrogen source had no effect on sugar yield. While sugar yield increased with increasing N rate, this effect was significant only in ratoon crops ($p<0.05$). For the 2015 ratoon crop, sugar yield increased from 6,400 (checks plots) to 10,000 kg ha^{-1} (average of N-treated plots) (Table 2.5). The highest sugar yield was 11,181 kg ha^{-1} achieved from the 135 kg N ha^{-1} treated plots. This was slightly higher than the average (10,352 kg ha^{-1}) sugar yield from other N-treated plots, i.e., 45 and 90 kg N ha^{-1} (Table 2.5). The average sugar yield from the second ratoon crop was lower compared to the first ratoon crop where check plots had a yield of 6,413 kg ha^{-1} and the average sugar yield of N-treated plots was only 7,666 kg ha^{-1} in N-treated plots (Table 2.6). The analysis for 2015 and 2016 showed a significant linear trend between N rate and sugar yield.

Nitrogen source had no effect on cane tonnage across crop-years (Tables 2.4, 2.5, and 2.6). On the other hand, the ANOVA for each crop-year showed that N rate had a significant effect on cane tonnage and this effect was consistent across N source ($p<0.05$). No reduction in cane tonnage was observed using the highest N rate (135 kg N ha^{-1}). The highest yield was attained from 90 and 135 kg N ha^{-1} treated plots.

Table 2.3. Means and analysis of variance for the effect of crop-year, N source, and N rate, and their interactions on sugarcane yield and quality parameters at the Sugar Research Station in St. Gabriel, LA.

Effect	Cane tonnage	Sugar yield	TRS[≠]	Sucrose	Brix	Polarity	Fertilizer recovery	N uptake
	Mg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	%				kg ha^{-1}
Crop-year/Crop age								
2014/Plant Cane	89 A	9288 A	105 B	15 B	18 B	65 B	21 A	75 A
2015 /1st Ratoon	80 B	9724 A	122 A	17 A	20 A	73 A	10 B	39 C
2016/2nd Ratoon	64 C	7343 C	106 B	15 B	18 A	65 B	13 B	44 B
p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Source								
UAN Knife	81	9089	112	16	18	68	14	51
UAN Dribble	78	8688	112	16	18	68	12	51
Urea	79	8673	110	15	19	67	16	54
AN	79	8691	109	15	19	67	17	55
p-value	NS[Ψ]	NS	NS	NS	NS	NS	NS	NS
Rate								
0	70	7727	111	16	18	68		41
45	78	8816	112	15	19	68	25	55
90	82	9053	110	16	18	67	18	55
135	87	9545	110	16	19	67	16	62
p-value	**<0.001**	**<0.001**	NS	NS	NS	NS	**<0.001**	**<0.001**
Linear	**<0.001**	**<0.001**	-[¥]	-	-	-	**<0.001**	**<0.001**
Quadratic	NS	NS	-	-	-	-	**<0.001**	NS
Cubic	NS	NS	-	-	-	-	-	NS

(Table 2.3 continued)

Effect	Cane tonnage	Sugar yield	TRS ≠	Sucrose	Brix	Polarity	Fertilizer recovery	N uptake
	Mg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	%				kg ha^{-1}
Source*Rate	NS	NS	NS	NS	NS	NS	NS	NS
Crop-year*Rate	0.04	**<0.001**	NS	NS	NS	NS	NS	NS
Crop-year*Source	NS	NS	NS	NS	NS	NS	NS	NS
Crop-year*Source*Rate	NS	NS	NS	NS	**<0.001**	NS	NS	NS

UAN: urea-ammonium nitrate

AN: ammonium nitrate

≠ TRS: theoretically recoverable sugar.

Ψ NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis.

¥ Not applicable due to non-significance of the main effect.

± Mean levels within the same column followed by the same letter indicate no significant differences between the treatment means according to the Tukey’s post-hoc analysis.

Table 2.4. Means and analysis of variance for the effect of N source and rate on sugarcane yield and quality parameters in 2014 plant cane at the Sugar Research Station in St. Gabriel, LA.

Effect	Cane tonnage	Sugar yield	TRS$^{\neq}$	Sucrose	Brix	Polarity	Fertilizer recovery	N uptake
	Mg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	%				kg ha^{-1}
Source								
UAN Knife	90	9617	106 AB	15.3 AB	18.4	65	19	73
UAN Dribble	86	9322	108 A$^{\pm}$	15.5 A	19.1	66	12	69
Urea	89	9174	103 B	15.0 BC	18.4	64	21	75
AN	88	9041	102 B	15.0 C	18.2	63	33	83
p-value	NS$^{\Psi}$	NS	0.04	0.02	NS	NS	NS	NS
Rate								
0	84	8929	106	15.2	18.3	65		60
45	86	9374	108	15.4	18.4	66	25	72
90	90	9339	103	15.0	18.6	64	20	79
135	93	9511	102	15.0	18.4	64	21	89
p-value	0.05	NS	NS	NS	NS	NS	NS	**<0.001**
Linear	0.04	-	-$^{¥}$	-	-	-	-	**<0.001**
Quadratic	NS	-	-	-	-	-	-	NS
Cubic	NS	-	-	-	-	-		NS
Source*N Rate	NS	NS	NS	NS	NS	NS	NS	NS

UAN: urea-ammonium nitrate

AN: ammonium nitrate

≠ TRS: theoretically recoverable sugar.

Ψ NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis.

¥ Not applicable due to non-significance of the main effect.

± Mean levels within the same column followed by the same letter indicate no significant differences between the treatment means according to the Tukey’s post-hoc analysis.

Table 2.5. Means and analysis of variance for the effect of N source and rate on sugarcane yield and quality parameters in 2015 first ratoon at the Sugar Research Station in St. Gabriel, LA.

Effect	Cane tonnage	Sugar yield	TRS[≠]	Sucrose	Brix	Polarity	Fertilizer recovery	N uptake
	Mg ha^{-1}	kg ha^{-1}	kg Mg^{-1}			%		kg ha^{-1}
Source								
UAN Knife	84	10232	122	17.0	19.6	73.4	15.5	41
UAN Dribble	79	9612	122	17.2	19.5	73.3	10.9	38
Urea	79	9603	122	17.1	19.6	73.7	10.6	38
AN	78	9447	122	17.0	19.4	73.1	10.8	38
p-value	NS[Ψ]	NS	NS	NS	NS	NS	NS	NS
Rate								
0	64	7839	122	17.1	19.6	73.4		31
45	79	9639	121	17.0	19.4	73.1	15.0	38
90	84	10236	122	17.0	19.5	73.3	9.1	39
135	91	11181	123	17.1	19.7	73.8	13.0	48
p-value	**<0.001**	**<0.001**	NS	NS	NS	NS	**<0.001**	**<0.001**
Linear	**<0.001**	**<0.001**	-[¥]	-	-	-	**<0.001**	**<0.001**
Quadratic	NS[Φ]	NS	-	-	-	-	**<0.001**	NS
Cubic	NS	NS	-	-	-	-		**0.04**
Source*N Rate	NS	NS	NS	NS	NS	NS	NS	NS

UAN: urea-ammonium nitrate

AN: ammonium nitrate

≠ TRS: theoretically recoverable sugar.

Ψ NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis

¥ Not applicable due to non-significance of the main effect.

± Mean levels within the same column followed by the same letter indicate no significant differences between the treatment means according to the Tukey’s post-hoc analysis.

Table 2.6. Means and analysis of variance for the effect of N source and rate on sugarcane yield and quality parameters in 2016 second ratoon at the Sugar Research Station in St. Gabriel, LA.

Effect	Cane tonnage	Sugar yield	TRS[≠]	Sucrose	Brix	Polarity	Fertilizer recovery	N uptake
	Mg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	%				kg ha^{-1}
Source								
UAN Knife	69	7417	107	15.3	18.5	66.0	8.83	34
UAN Dribble	68	7131	105[±]	15.1	18.3	65.0	19.5	44
Urea	69	7240	105	15.1	18.2	65.0	21.2	46
AN	72	7584	106	15.2	18.3	65.0	15.5	40
p-value	NS[Ψ]	NS	NS	NS	NS	NS	NS	NS
Rate								
0	67	6413	106	15.2	18.3	64.8		28
45	69	7444	108	15.4	18.5	65.9	25	38
90	71	7602	107	15.3	18.4	65.5	18	40
135	76	7954	104	15.0	18.2	64.3	13	42
p-value	**<0.001**	NS	NS	NS	NS	NS	**0.02**	**<0.001**
Linear	**<0.001**	**-**	-[¥]	-	-	-	NS	**0.004**
Quadratic	NS	-	-	-	-	-	0.01	NS
Cubic	NS	-	-	-	-	-		NS
Source*N Rate	NS	NS	0.04	0.03	0.01	0.03	NS	NS

UAN: urea-ammonium nitrate

AN: ammonium nitrate

[≠] TRS: theoretically recoverable sugar.

[Ψ] NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis.

[¥] Not applicable due to non-significance of the main effect.

[±] Mean levels within the same column followed by the same letter indicate no significant differences between the treatment means according to the Tukey's post-hoc analysis.

Similar to sugar yield, the trend analysis also showed that cane yield linearly increased with increasing N rate. For plant cane, there was a significant difference in TRS due to N source effect (Table 2.4). The highest TRS content was achieved with the application of UAN dribble (108 kg Mg^{-1}) followed by UAN knife-in (106 kg Mg^{-1}) compared to the granular fertilizer sources; urea (103 kg Mg^{-1}) and ammonium nitrate (102 kg Mg^{-1}). No significant effect of N sources was observed in ratoons crops (Tables 2.5 and 2.6). Nitrogen rate had no effect on TRS, but it is important to note that N applied at higher rates (90 and 135 kg N ha^{-1}) showed a numerical reduction on TRS for plant cane (Table 2.4). This trend of N impact on TRS was similar in 2016 but not consistent among N sources as indicated by the significant interaction effect between source and N rate (Table 2.6). Figure 2.3 shows an evident reduction in TRS with increasing N rate if ammonium nitrate and urea were used as a source, but not for UAN solution.

The response of sucrose, brix and polarity to N source and the N rate was similar to TRS. For 2014 plant cane, sucrose content was affected by N source with UAN dribble having the highest value at 15.5% compared with urea and ammonium nitrate (Table 2.4). A significant interaction effect between source and rate was observed on the levels of sucrose content, brix and polarity in 2016 second ratoon crop (Table 2.6). The values of brix, sucrose, and polarity were significantly reduced using granular fertilizers sources (urea and ammonium nitrate) applied at the highest rate of 135 kg N ha^{-1}. This was not the case for UAN solution: UAN-dribble applied at 45 kg N ha^{-1} recorded the highest sucrose content; the same N rate was needed as UAN knife-in to attain the highest polarity, and brix was the highest in sugarcane treated with 135 kg N ha^{-1} as UAN knife-in.

Consistent across crop-years, N source had no influence on N uptake and fertilizer recovery (Tables 2.4, 2.5, and 2.6). On the other hand, N rate effect on N uptake was significant (*p*<0.05) and consistent across N source (no interaction; *p*>0.05). Also, the trend analysis showed the N rate and N uptake had a significant linear trend (*p*<0.001). The amount of recovered fertilizer was influenced by N rate only in 2015 and 2016 (ratoon crops). Unlike N uptake, the N fertilizer recovery declined with increasing N rate (*p*<0.05).

2.3.3 Monitoring of Ammonium-N and Nitrate-N in the Soil

The concentration of NH_4^+ and NO_3^- (mg kg^{-1}) in the soil treated with different N sources and increasing rates of N shown in Figures 2.4 to 2.9. For the 2014 plant cane (Figures 2.4 and 2.5), a higher amount of NH_4^+ and NO_3^- was measured from plots treated with urea and ammonium nitrate 21 DANF than UAN-treated plots. A significant drop in NH_4^+ and NO_3^- concentration was observed at 60 DANF. The concentration of NH_4^+ and NO_3^- taken from the two depths increased with increasing N rate. The average levels of NH_4^+ and NO_3^- at 60 DANF ranged from between 4 and 6 mg kg^{-1} for all the treated plots. The level of soil NO_3^- concentration across sources and rates for the two depths decreased compared to the fraction of NH_4^+ at 0-15 cm depth at harvest. With an application of 90 and 135 kg N ha^{-1}, a peak level in NO_3^- concentration occurred at 0-15 cm with values between 24 and 27 mg kg^{-1} and NH_4^+ levels with values from 22 to 24 mg kg^{-1} 21 DANF (Figure 2.1). For plant cane, the levels of NH_4^+ and NO_3^- for both knife-in and dribble UAN solution showed the lowest amounts compared to the granular sources (Figures 2.4 and 2.5).

The application of granular N fertilizer (urea and ammonium nitrate) resulted in an evident increase in soil NH_4^+ (0-15 cm) and NO_3^- (0-15 and 15-30 cm) content. The highest concentration of NH_4^+ and NO_3^- in the soil was 23 and 17 mg kg^{-1}, respectively, from plots treated with 135 kg N ha^{-1}.

A lower concentration of NH_4^+ and NO_3^- (12 and 8 mg kg^{-1}) was measured at 15-30 cm than at 0-15 cm, but still, these concentrations were higher when compared to lower N rate treatments (Figure 2.6). Plots treated with urea and ammonium nitrate had the highest level of NH_4^+ and NO_3^- as early as 7 DANF at 0-15 cm (Figure 2.6). At 14 DANF, both urea and UAN (dribble and knife-in) showed an even linear trend distribution and had the highest level of NH_4^+. At the same depth, ammonium nitrate and UAN (dribble and knife-in) recorded the highest level of NO_3^- . The concentration of NH_4^+ and NO_3^- 21 DANF was greater in plots treated with UAN knife-in and ammonium nitrate obtaining values ranging between 20 to 25 mg kg^{-1} for NH_4^+ and from 15 to 20 mg kg^{-1} for NO_3^-.

At 7 and 14 DANF at the 15-30 cm depth, higher levels of NH_4^+ and NO_3^- were obtained from urea and ammonium nitrate treated plots, respectively compared to UAN-treated plots (Figure 2.7). Overall, soil N concentration was lower at this depth by as much as 15 mg kg^{-1} for NH_4^+ and 5 mg kg^{-1} for NO_3^- and steadily declined with sampling time (Figure 2.7).

For the 2016 second ratoon, more uniform levels of NO_3^- and NH_4^+ were observed across the sampling done at 7, 14 and 21 DANF for both depths compared to those of the 2015 first ratoon (Figures 2.8 and 2.9). Ammonium-nitrate treated plots had the highest level of NO_3^- and NH_4^+ followed by urea and UAN (dribble and knife-in) at 0-15 cm, and this pattern went through 14 DANF before levels started declining at 21 DANF (Figure 2.8). Similar to 2014 plant cane and 2015 first ratoon crop, the drastic reduction in NO_3^- and NH_4^+ was observed at 60 DANF across N sources and rates, NH_4^+ was below 10 mg kg^{-1} and 5 mg kg^{-1} for NO_3^- (Figure 2.8). At 15-30 cm depth, the levels of NH_4^+ (4-12 mg kg^{-1}) and NO_3^- (1-5 mg kg^{-1}) across sampling times, i.e. from 7 DANF to harvest, were very similar (Figure 9).

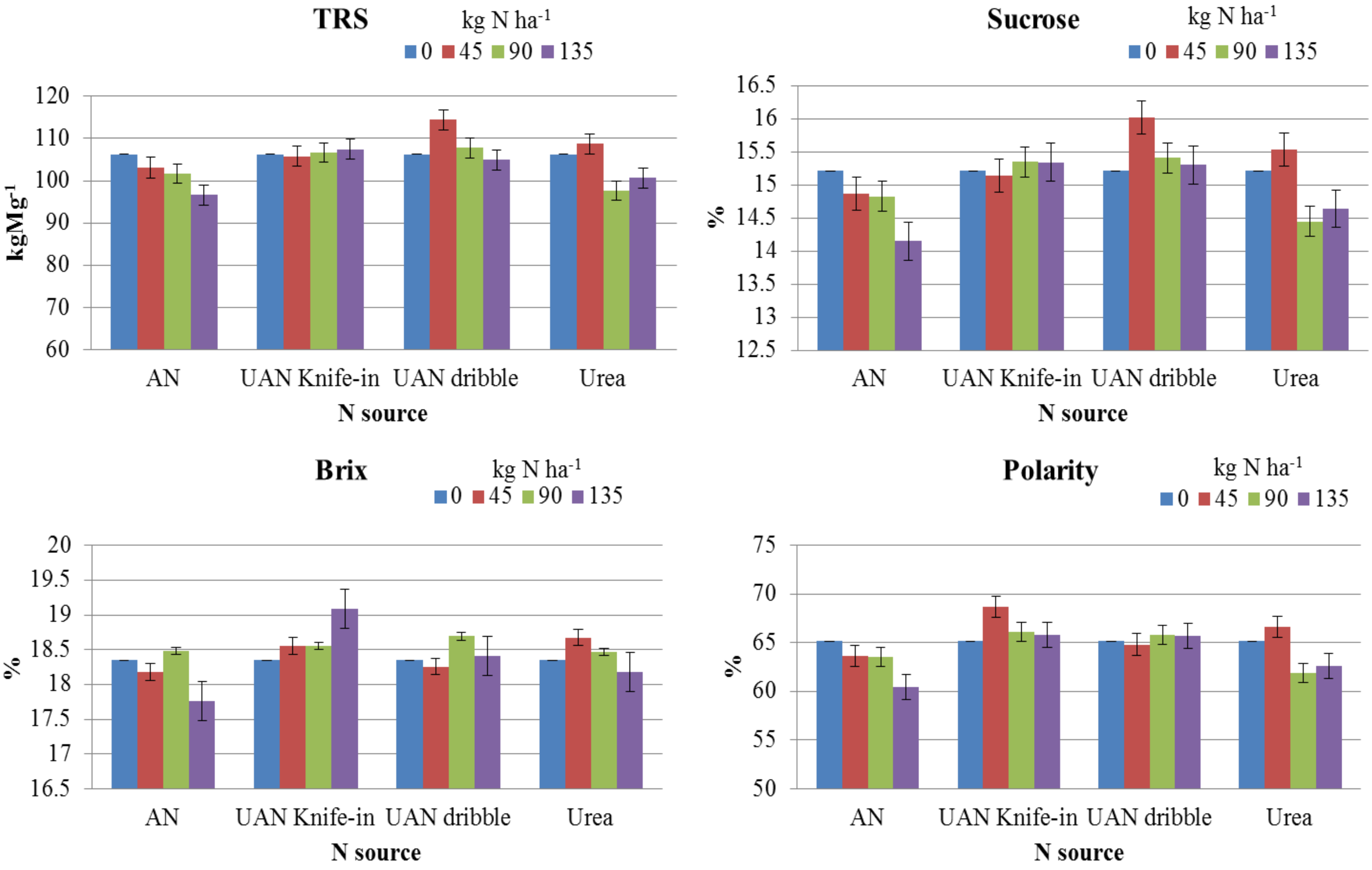

Figure 2.3. Theoretical recoverable sugar (TRS), sucrose content, brix, and polarity of second ratoon applied with different N sources and rates, 2016 at the Sugar Research Station in St. Gabriel, LA.

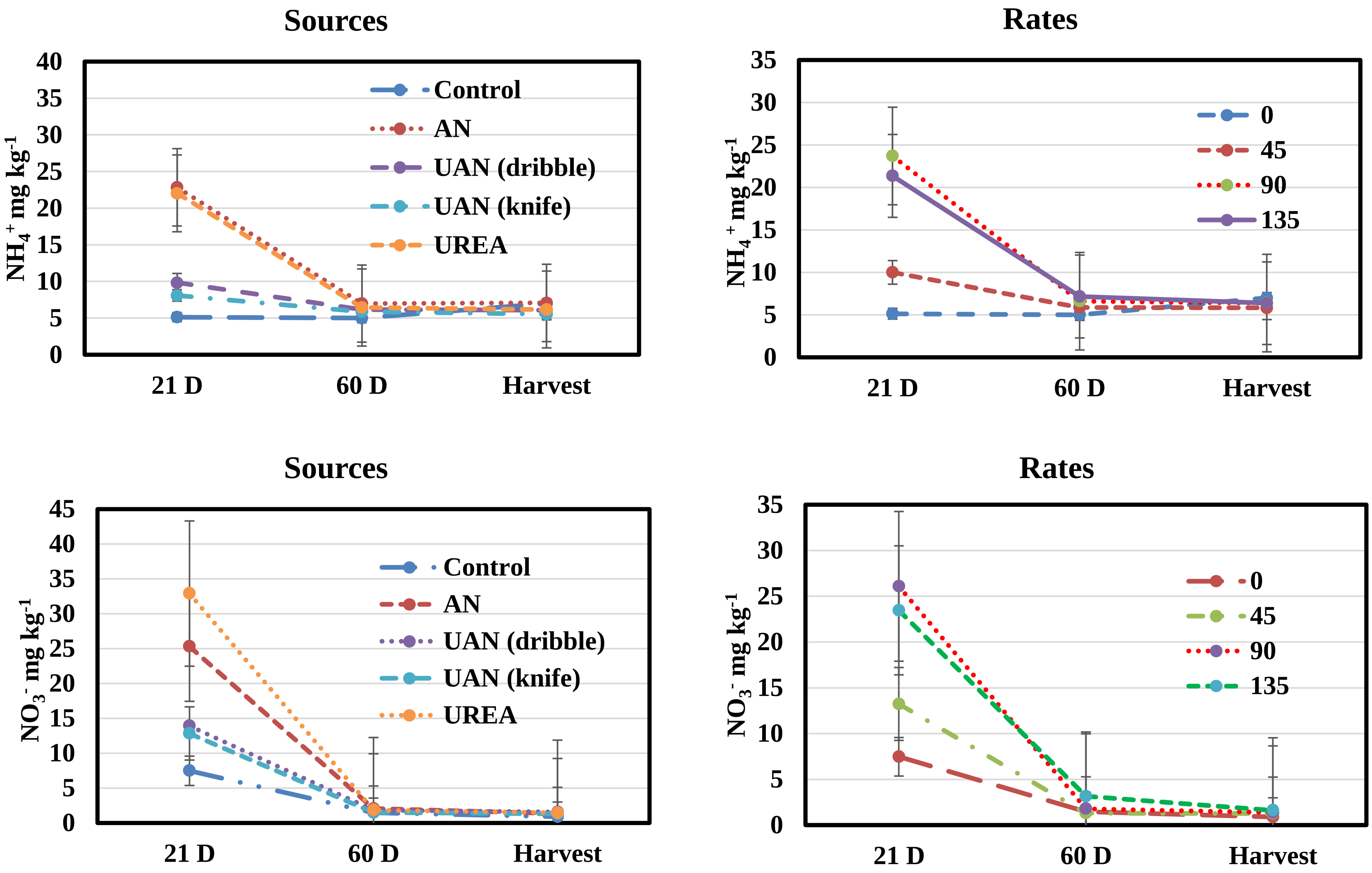

Figure 2.4. Soil NH_4^+ and NO_3^- concentration at 0-15 cm depth at 21 and 60 days after N application and at harvest using different N sources applied at varying rates for plant cane, 2014, Sugar Research Station in St. Gabriel, LA.

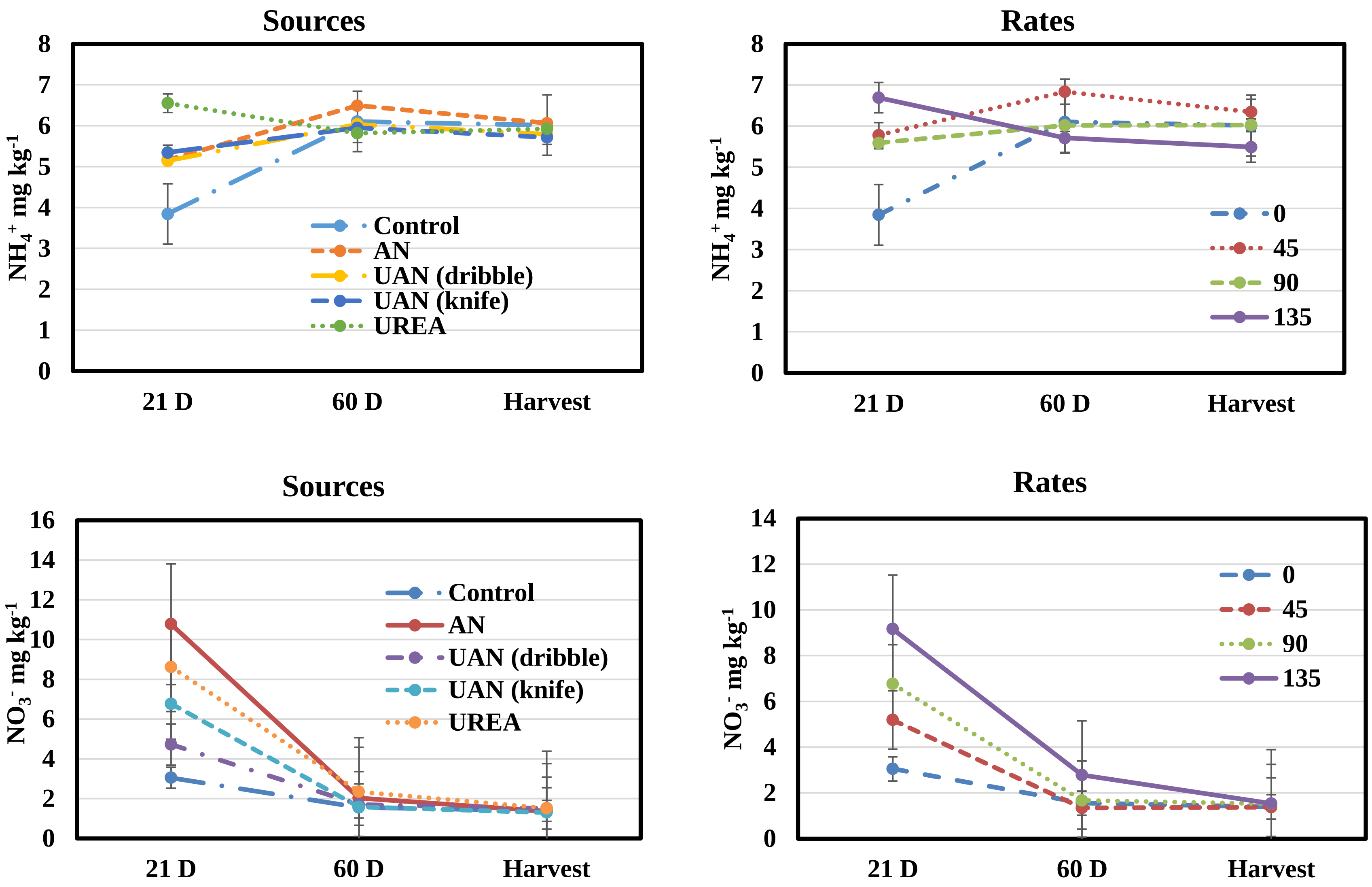

Figure 2.5. Soil NH_4^+ and NO_3^- concentration at 15-30 cm depth at 21 and 60 days after N application and at harvest using different N sources applied at varying rates for plant cane, 2014, Sugar Research Station in St. Gabriel, LA.

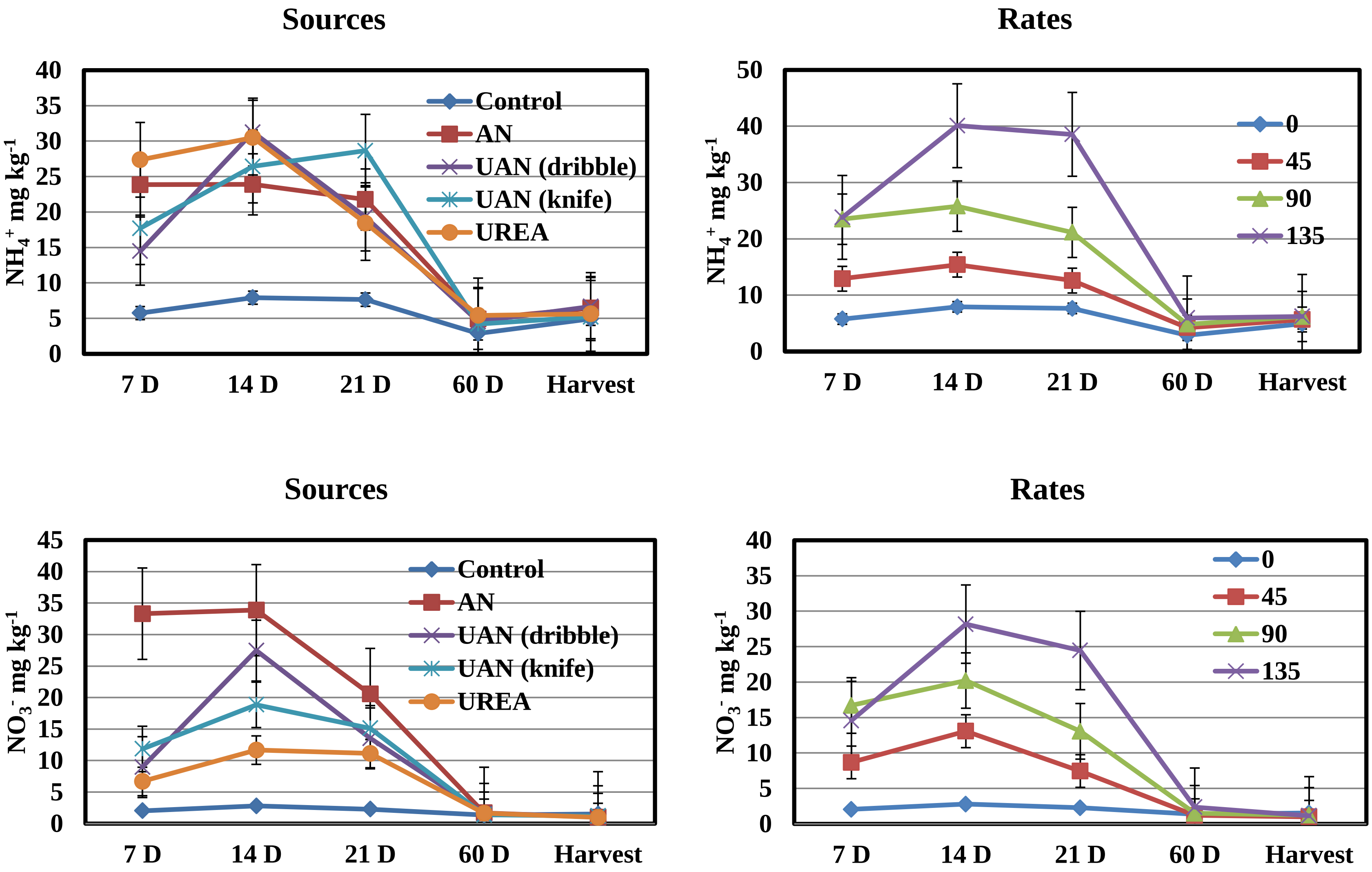

Figure 2.6. Soil NH_4^+ and NO_3^- concentration at 0-15 cm depth at 7, 14, 21, and 60 days after N application and at harvest using different N sources applied at varying rates for first ratoon, 2015, Sugar Research Station in St. Gabriel, LA.

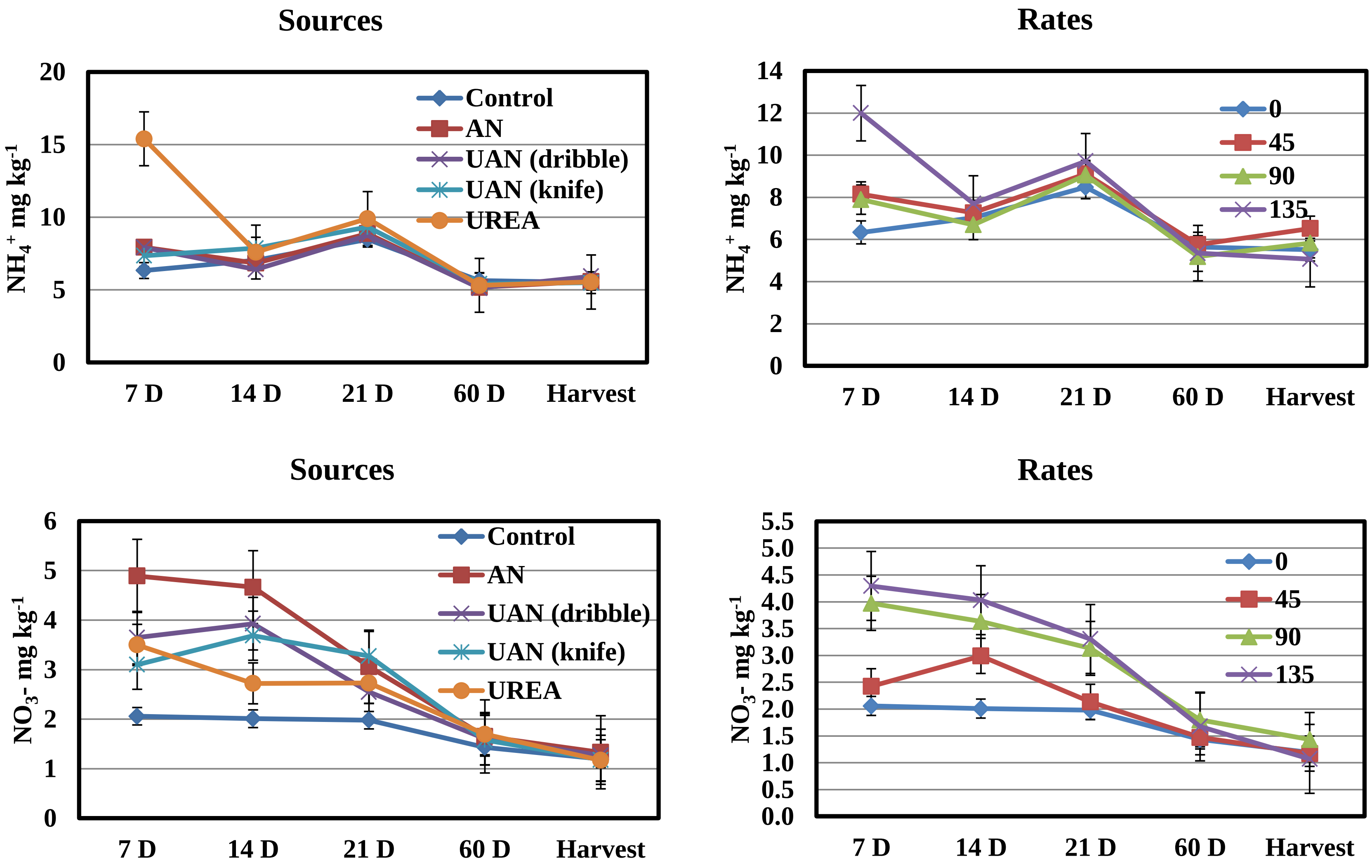

Figure 2.7. Soil NH_4^+ and NO_3^- concentration at 15-30 cm depth at 7, 14, 21, and 60 days after N application and at harvest using different N sources applied at varying rates for first ratoon, 2015, Sugar Research Station in St. Gabriel, LA.

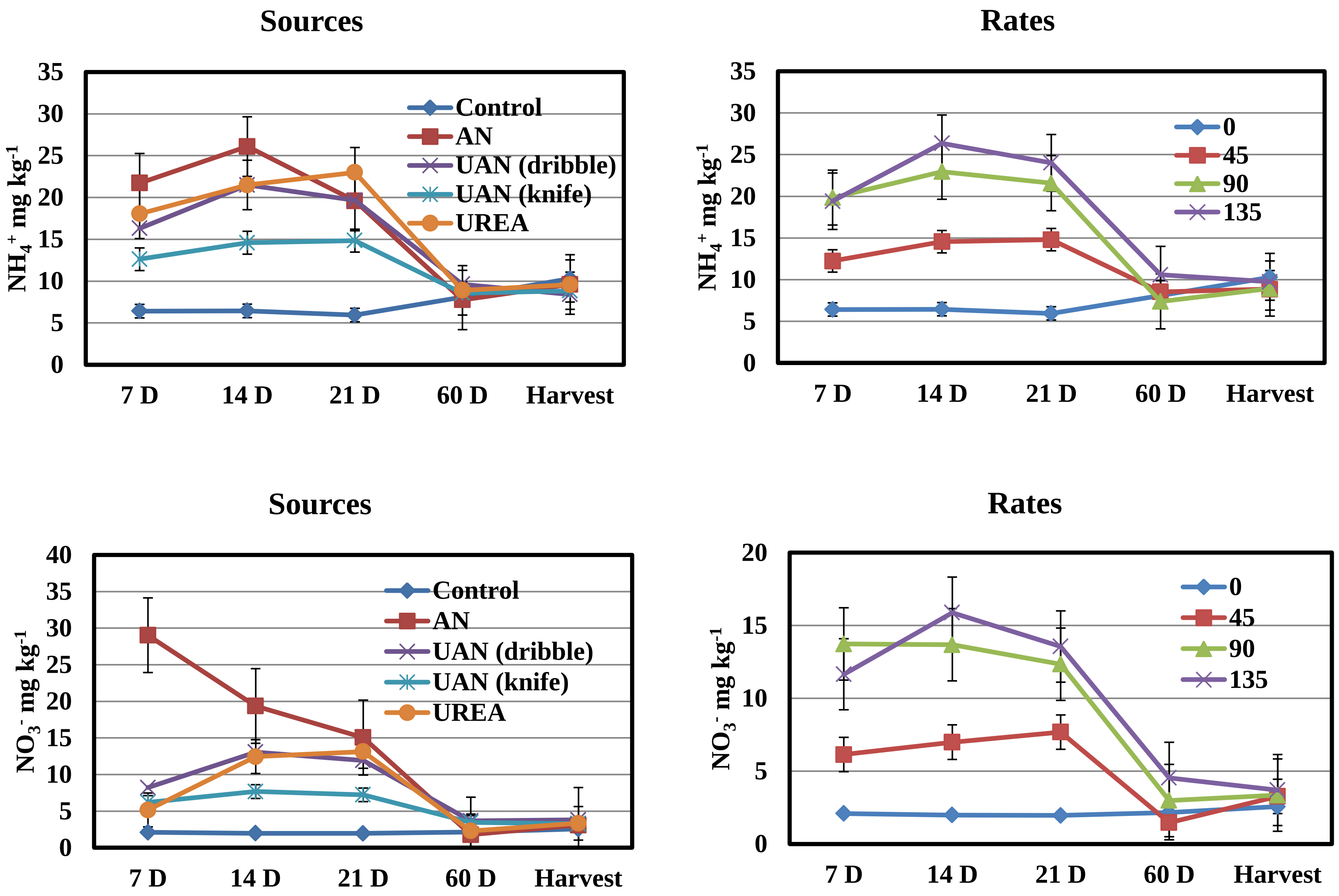

Figure 2.8. Soil NH_4^+ and NO_3^- concentration at 0-15 cm depth at 7, 14, 21, and 60 days after N application and at harvest using different N sources applied at varying rates for second ratoon, 2016, Sugar Research Station in St. Gabriel, LA.

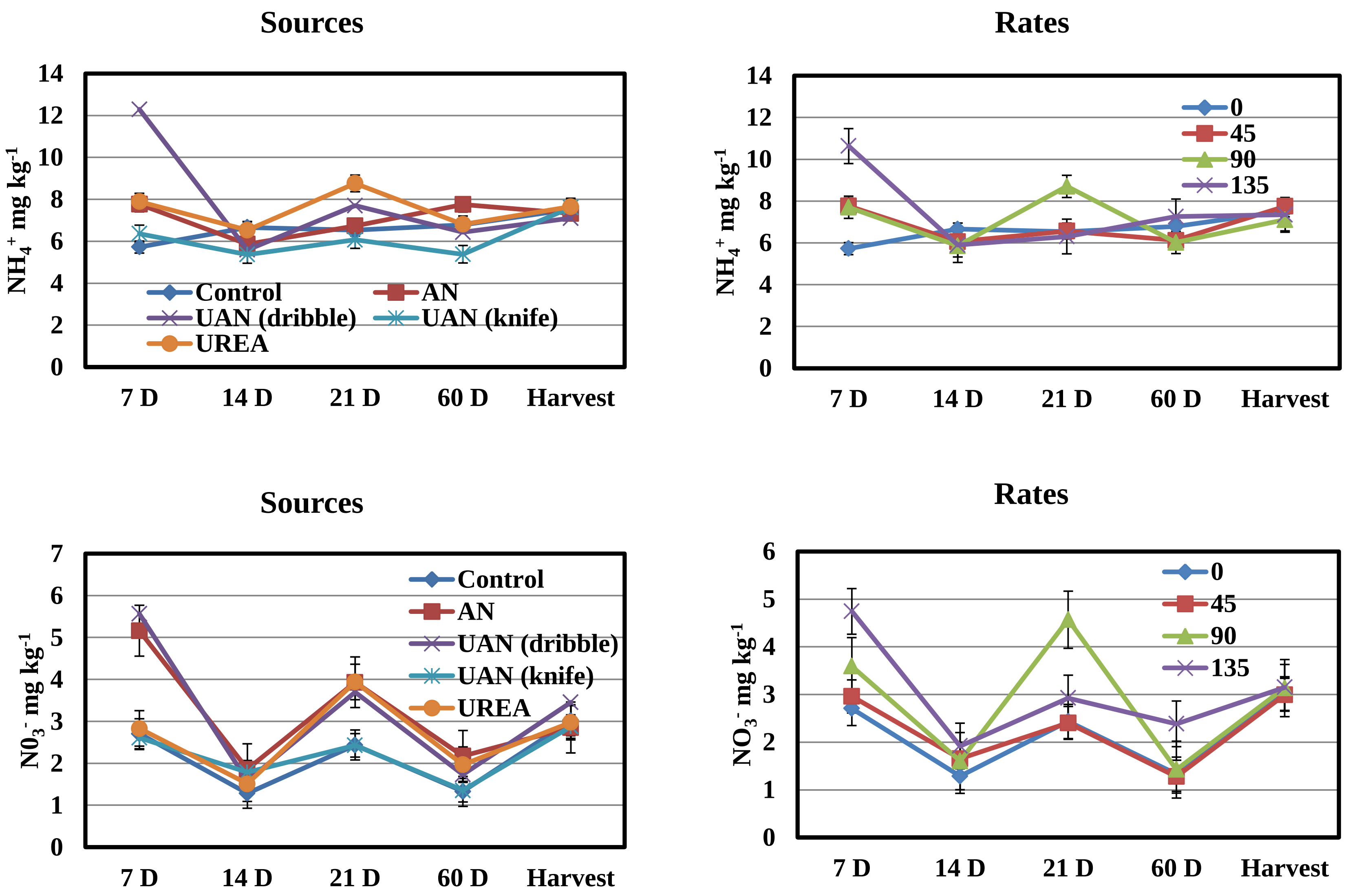

Figure 2.9. Soil NH_4^+ and NO_3^- concentration at 15-30 cm depth at 7, 14, 21, and 60 days after N application and at harvest using different N sources applied at varying rates for second ratoon, 2016, Sugar Research Station in St. Gabriel, LA.

2.4 Discussion

The factors evaluated in this study had different impacts on sugar yield and parameters that determine sugar yield. Among the factors, only crop-year and N rate significantly affected sugar yield. It is notable too that the effect of N rate on sugar yield was not consistent across crop-year (crop age). Sugar yield is computed as the product of TRS and cane tonnage; therefore, N plays an essential role in sugar production as it impacts both quality components of cane and production of the millable stalk. Both late and excessive N application reduces the sugar content of stalks and also lowers juice quality (Gopalasundaram et al., 1994; Srinivasan, 1995; Singh and Yadav, 1996). Using the same N rates, Lofton et al. (2013) found that the effect of N rate on sugar yield was only significant in first ratoon crop. However, sugar yields from 45 to 135 kg N ha^{-1} treated plots were statistically the same. Similar results were observed in this study, where N rates significantly affected sugar yield of the first ratoon crop. Another possible reason as to why sugar yield was reduced in plant cane and second ratoon was due to its respective reduction in TRS by about 15% and 13% compared to the first ratoon crop (Tables 2.4 and 2.6). Muchow et al. (1996) and Rattey and Hogarth (2001) indicated that sugar yield could be reduced by high N rate application, especially for ratoon crops.

According to Lofton et al. (2013) using the linear-plateau model, only 55 kg N ha^{-1} was required to optimize sugar yield. This suggests that for certain crop age, field, and cropping year, the critical N rate could be lower than the rates recommended for sugarcane production in Louisiana. It is important to note that there are some factors that may complicate sugarcane N requirement; for example, soil type, variety, N source, and climatic condition. Sugar yield can also be affected by time of N application; Borden (1948) reported that sugar and cane yield was highly influenced by the total amount of N applied and application time.

Samuels et al. (1952) showed that sugar quality was not affected by N except when N application was delayed by four months. While they indicated that increasing N fertilization rates increased cane tonnage, the excess N delayed the maturity process which led to a negative effect on juice quality especially for cane that was harvested young. This may explain why lower TRS was observed in the second ratoon (Table 2.6) compared to the first ratoon crop (Table 2.5).

Nitrogen treatment applications were all made from April to early May. The second ratoon crop (2016) was harvested five months after N fertilization; it is possible the amount of N in the soil was higher due to residual N from the previous crop year application. Humbert (1963) indicated that when the percentage of reducing sugar is still high and has not transformed to sucrose at harvest, the excess of N applied can produce an adverse effect on the juice quality. Another possible cause of the sugar yield reduction was perhaps due to stalk mortality. Lower stalk population reduces cane tonnage affecting sugar yield; note that sugar yield = cane tonnage x TRS.

The current N recommendation rates in Louisiana for plant cane and ratoons crops in heavy texture soil ranges from 90 to 135 kg N ha^{-1}. Lofton et al. (2013) using a linear-plateau model showed that N rate needed to achieve the optimum yield was lower compared to Louisiana N recommendations. Our results showed that the highest N rate of 135 kg N ha^{-1} did not reduce cane tonnage; a small difference (9 Mg ha^{-1}) in yield levels were observed between 90 and 135 kg N ha^{-1} treated plots across years (Table 2.3). Similar trends were also found by Thourbun et al. (2001) showing that cane yield was not affected by increasing N rate application. Similarly, a study conducted by Wiedenfeld (2000) showed that cane yield was not affected by increasing N rate. La Borde (2000) established a study to evaluate the fertilizer response of first ratoon crop in Vacherie, LA and indicated that N fertilization significantly increased cane tonnage even at high rates ranging from 112 kg N ha^{-1} to 224 kg N ha^{-1}. However, in a different location (Youngsville) N application rates of 112 kg N ha^{-1} to 168 kg N ha^{-1} significantly decreased cane yield. Koochekzadeh et al. (2009) found that the highest cane tonnage (121 Mg ha^{-1}) was obtained from plots applied with 92 kg N ha^{-1}, the lowest N rate in the treatments.

Cane tonnage was lower in the 2015 and 2016 ratoons crops compared to the 2014 plant cane crop (Tables 2.4 and 2.5). One possible explaination for the reduction in cane tonnage observed in ratoon crops was the temporary N immobilization by soil microorganism taking place during the accumulation and decomposition of residues from the previous harvest. Mahendran et al. (1995) established that ratoon crops require 25-50% more N compare to plant cane crop. Therefore, yield response to N fertilization is variable from site to site and from year to year.

Ratoons crops are important because farmers do not invest for field preparation, planting operation and seed. However, for ratooning crops, reduction in cane tonnage can be attributed to the reduced number of tillers due to crop age and annual exposure to physical damage during harvesting (Park et al., 2005). This could also explain the reduction in yield of ratoon crops observed in this study (Table 2.3). On the other hand, Yadav (1992) suggested others reasons for lower yields for ratoon crops. For example, loss of tilth in the root zone, insect attack, ratoon stunting disease, lack of moisture and nutrients, and poor sprouting of eye-buds of under-ground stubbles during low temperatures in winter.

Raun et al. (2010) found that the crop response to N fertilization and yield were not related because both variables are considered independent of one another. Nitrogen transformation processes mediated by microorganisms are affected by climatic factors like precipitation and temperature thus creating temporal and spatial N variability.

Clearly, the temperature and moisture conditions across from 2014 to 2016 had substantial differences especially during the periods which were influential on cane growth and performance (e.g., planting, fertilization) (Figures 2.1 and 2.2). Another study also showed that sugarcane varieties respond differently to the same level of N, suggesting also that variation in day length, light intensity, and temperature contribute to yield variability (Kakde, 1985). He also found that loamy soils are highly productive compared to clay soils, providing better N uptake and higher yields. This was supported by the results obtained from the 2015 Louisiana sugarcane variety development program where the variety HoCP 96-540 obtained superior cane and sugar yield on light vs heavy textured soil from twelve outfield locations in 2015 (Sexton et al., 2015).

The lack of cane tonnage response to N source in this study was consistent with reports from previous studies. Blackburn (1984) showed that sugarcane does not have any preference for a specific source of fertilizers except under special conditions. Similar results were also observed for Salgado Garcia et al. (2001) using isotopic methods; they evaluated the effect of different N sources and concluded that ammonium sulfate, urea, and potassium nitrate had the same effect on yield. However, N source can influence the amount of N in the soil, for example, loss through NO_3^- leaching is lower using slow release N fertilizer and application of urea in saline soils can produce a reduction in the dry matter due to slow N uptake (Isa et al., 2006). Also, preference to certain N source is also influenced by cost and convenience (Singh and Yadav, 1996). The results from this study indicated that cane tonnage linearly increased when N rate increased, suggesting that the application of higher N rates may further maximize yield. Nevertheless, the need of evaluating the reducing effect on the level of TRS and juice quality components are important to identify the optimal N rate.

Overall, reduction in TRS was observed in plots which received higher N rates (90 and 135 kg ha^{-1}) using urea and ammonium nitrate (Tables 2.4, 2.5, and 2.6). The higher cane tonnage in plots treated with higher N rates using granular fertilizers did not offset the reduction in the levels of TRS particularly observed in plant cane subsequently attaining sugar yield numerically lower than plots treated with UAN solution (Table 2.4). Nitrogen fertilization has a major impact on cane tonnage, sugar yield, and TRS. In sugarcane production, the most important factors are the weight of millable cane yield and the amount of commercial sugar that can be recovered from the millable cane stalks (Kumara et al., 2002). Therefore, it is ideal to attain more millable stalk fresh weight with a high level of TRS to maximize sugar production and return from N fertilizer.

The TRS content was higher in the first ratoon by almost 16 kg Mg^{-1} compared to plant cane and second ratoon. Both agronomic and climatic factors can explain these differences in TRS across crop-years. The average low air temperature in 2015 compared to 2014 and 2016 could probably explain the increase in the level of sucrose content, making the levels of TRS also higher (Figure 2.2). Another possibility could be the high amount of rainfall (Figure 2.1) received within the N fertilization period in 2014 and 2016 perhaps negatively affected the ripening process (Tables 2.4, 2.5, and 2.6). Studies have shown that the slower ripening rate in sugarcane was also due to early harvesting schedule. Legendre et al. (1975) pointed out that the accumulation of sucrose might slow down when the air temperature and soil moisture are high. According to Alexander et al. (1973) low air temperature, low soil moisture, and N deficiency are considered the most important ripening agents.

The effect of N source and the interaction effect between N source and rate observed in plant cane and second ratoon suggest the possibility that the higher soil N levels of NH_4^+ and

NO_3^- observed from granular fertilizer especially at the higher rates (90 and 135 kg N ha^{-1}) could explain the reduction on TRS in plant cane and second ratoon (Figures from 2.3 to 2.9).

Crop-year was the only factor that influenced sucrose content, brix and polarity (Table 2.3). The effect of N source and rate on these variables was also observed but not consistent across crop-years. Although not significant, generally lower values of these parameters were associated with the highest N rate (135 kg ha^{-1}) and with cane treated with granular fertilizer. Lofton et al. (2013) indicated that the decrease of sugar quality was the most likely reason behind the lack of sugar yield response to N fertilizer. Hunsigi (1993) and Muchow et al. (1996) indicated that increasing N rate would lead to a reduction in the quality of the juice and sucrose content. This may be explained by the fact that increasing N rate results in the production of high amounts of reducing sugar (Hunsigi, 1993). A similar explanation was presented by Muchow et al. (1996), i.e. increasing N application rate reduced TRS and sucrose content. In this study, increasing N rate tended to decrease quality parameters, and in some cases like the 2014 plant cane, the level of confidence was found at $p<0.10$. There was a significant interaction between source and N rate effect on sucrose, brix, and polarity ($p<0.05$) (Table 2.6). While it is clear as to why high N rate reduces cane quality parameters, there is no literature explaining the differential impact of N rate when applied using different sources. One outstanding observation was the negative effect of high N rates on sucrose, brix, and polarity when ammonium nitrate and urea were used as source (Figure 2.4). The reduction in sucrose content with increasing N rate was may be due to the possible abundance of N in the plant during the ripening phase.

These results are similar to the findings of Rattey and Hogarth (2001) describing the inverse relationship between N levels and polarity, brix and sucrose in juice.

The significant effect of crop-year on N uptake and fertilizer recovery demonstrated the influence of cane crop age on the acquisition of N (subsequently affecting quality parameters) in addition to the factors listed by Vallis et al. (1994). Among the other factors are N source, placement of fertilizer, cultural practices, and varietal performance. Plant cane had taken up 75 kg N ha^{-1} which was about 80% higher than the ratoon crops and recovered 21% of the applied N rate compared to the 10 and 13% recovery of the ratoon crops (Table 2.3). Even with this enhanced N nutrition, the corresponding 9 Mg ha^{-1} increased in cane tonnage did not put plant cane ahead of the 2015 first ratoon crop with respect to sugar yield due to its low TRS level.

In the present study, an evident reduction in N fertilizer recovery with increasing N rate was observed for ratoon crops ($p<0.05$). There was also a decreasing pattern of N fertilizer recovered by plant cane with increasing N rate, but it was not significant. Previous studies showed that sugarcane N recovery rates are between 21 and 40% (Takahashi, 1969; Chang and Weng, 1983; Sampaio et al., 1984). In this study, it is notable that the N uptake consistently increased with increasing N rate. However, higher N uptake associated with high N rate application does not denote high recovery of applied N fertilizer. On average across cropping years, the amount of N fertilizer recovered were 21, 14, and 15% for plots treated with 45, 90, and 135 kg N ha^{-1}, respectively. Raun et al. (1999) noted that at low N rates the microbial activity in the soil could increase mineralization of soil N, making more N available for plants and this may increase the N uptake but not necessarily the N recovery from applied N. There was no significant effect of source on N uptake (Tables 2.4, 2.5, and 2.6) but the choice of N source can affect the amount of N recovered by a crop (Basanta et al., 2003).

Low recovery values of fertilizer are attributed to N losses through volatilization, N-immobilization, and leaching (Basanta et al., 2003). Vallis and Keating (1994) estimated that the total amount of N fertilizer losses from the soil and sugarcane plant system range from 40 to 60 % (Vallis and Keating, 1994). Similarly, sugarcane was also reported to have low (25-40%) recovery of N applied fertilizer (Keating et al., 1993).

There was a reduction of total N uptake (and N fertilizer recovery) by the first ratoon crop (37 kg ha^{-1}) compared to plant cane N uptake (Table 2.5). The N uptake of the second ratoon ranged from 28 to 42 kg ha^{-1} (Table 2.6). On average, these values were slightly lower compared to N uptake obtained by the first ratoon crop probably resulting from lower stalk N concentration, dry matter content and stalk population. A similar reduction in N uptake across crop age was observed by Vallis et al. (1994), Ishikawa et al. (2009), and Franco et al. (2015). These findings are similar to those of Basanta et al. (2003) demonstrating that N uptake often decreases after a plant cane crop, but this will also depend on the source, timing application, and placement of N fertilizers (Keating et al., 1993).

Studies have shown that the recovery of N from crop residues incorporated back to the soil can range from 2 to 15% of the total N content (Basanta et al., 2003). The low N recovery could be caused by N losses through volatilization which is enhanced during residue decomposition. Studies proved that enzymatic activity in residues considerably increased the volatilization of N from applied urea (Denmead et al., 1990; Wood 1991; Cantarella, 1998). There is a possibility that the variables N recoveries across crop age were due to differences in weather conditions (higher evaporation rate or flooding conditions) that may have enhanced N mineralization especially in ratoons crops where higher amounts of rain were received after N application and during periods of high N uptake by sugarcane which may have reduced the amount of N in the soil due to leaching or denitrification. Robert and Thourbun (2007) observed that weather condition had an effect on the correlation between crop residue and N uptake.

Nitrogen fertilizer with NH_4^+ as the main form has higher loss potential in dry years compare to NO_3^- fertilizer. Both nitrification and denitrification are biological processes and are highly influenced by soil temperature. Unlike NH_4^+, NO_3^- is very mobile in the soil. Soil texture and drainage are important for the movement of water and nitrate. In plant cane (2014), the site received more than 20 cm of rain two days after N fertilization, which may have lead to a reduction in the amount of N applied by the leaching of NO_3^-. Overall the amount of rain received during the three cropping years was higher in 2016 compared to 2104 and 2015 (Figure 2.1). In years where moisture is excessive, N loss via leaching will be higher than NH_4^+ losses via volatilization.

Basanta et al. (2003) evaluated the N fertilizer recovered by sugarcane in Brazil from three crop seasons and reported that only 42% was utilized by the crop, 29% remained in the soil, and 29% was lost. Other studies noted that about 80% of the N taken up by sugarcane came from other sources, mainly the soil, and only 20% from fertilizers (Chang and Weng, 1983; Weng and Li, 1992). These low N fertilizer recovery values observed were probably due to mineralization of N in the soil releasing plant-available N for the next ratoon (Basanta et al., 2003).

Our results indicated that NH_4^+ and NO_3^- levels increased when the applied N rate increased. With an application of 90 and 135 kg N ha^{-1} the peak level in NH_4^+ and NO_3^- concentration at 0-15 cm was higher using the granular fertilizers during the grand growth stage of sugarcane. The same pattern was observed by Harada et al. (1996); they noted that NO_3^- concentration level can be reduced during the maturity stage, showing lower levels of NO_3^- before and after harvest. Days with high-temperature followed by drought conditions can lead to NO_3^- accumulation.

These data suggest that the reduction in NO_3^- concentration level was probably caused by leaching following a heavy precipitation (15 cm) received on May 2014 two days after N fertilization (Figure 2.1). However, a significant variation in values between replications was observed (high standard deviation) for plots treated with granular N fertilizer as opposed to UAN solution indicating that even distribution of N using solution was easier to achieve than granular fertilizer at the given sampling time. This could also partly explain the minimal increase in NH_4^+ and NO_3^- concentration in soils treated with UAN.

Results on soil inorganic N monitoring suggest that factors such as rainfall and the presence of sugarcane residue from the previous harvest could influence the levels of NH_4^+ and NO_3^- in the soil. The lower amount of rain received after N fertilization could prevent or reduce leaching process which could explain the high levels of NO_3^- recorded 21 DANF in the 2015 ratoon crop compared to the 2014 plant cane. The presence of crop residue from the previous harvest could lead to N immobilization. Another possible explanation for the lower levels of NH_4^+ and NO_3^- in the soil at 21 DANF could be that it already coincided with the growth stage wherein sugarcane is rapidly taking up N. For the 2015 first ratoon crops, N rates increased NH_4^+ and NO_3^- in the soil 7 DANF for both depths (Figures 2.6 and 2.7).

The direct effect of increasing N fertilization rates on NH_4^+ and NO_3^- was observed at 7 and 21 DANF; however, this was no longer observable at 60 DANF where both forms of N fell below 5 mg kg^{-1} across N sources. Do Vale et al. (2013) also found that concentration of NO_3^- at a depth of 10-20 cm increased with increasing N application rate.

High NO_3^- leaching due to high rainfall after N fertilization is a major loss pathway for N resulting in a significant drop in NO_3^- level at least for the plow layer (0-15 cm). It seems that this was the case for this study especially for the first and second ratoon crops (Figures 2.6, 2.7, 2.8, and 2.9). Many studies have shown that between 54-72% of applied N fertilizer is taken up by the plant, but some can be bound to soil organic matter (8-21%) and lost by leaching (2-8 %) and denitrification process (2-18%) (Owen and Jügens-Gschwind, 1986). An experiment conducted by Füleky (2014) indicated that on average, N losses by leaching in sandy soils were close to 30-40 kg N ha^{-1} and between 20-30 kg N ha^{-1} in loamy soil texture. Overall, our results showed that higher levels of NH_4^+ than NO_3^- were retained between 0-30 cm depth during the entire cropping season regardless of source and rate of N applied. Brum (1975) reported that NH_4^+ is less susceptible to leaching from the soil profile because it is held by the negative charge of soil colloids. Nitrate is very mobile and moves with water in the soil profile, thus can leach faster than NH_4^+ below the root zone causing a reduction in N uptake and possibly, increased risk of contaminating groundwater (Bahmani et al., 2009). Deare et al. (1995) found that higher than recommended N application rates led to greater NO_3^- accumulation below the root zone eventually reducing the % fertilizer recovery and crop N uptake. Under such conditions, N fertilizer becomes more susceptible to losses via leaching, denitrification, and NH_4^+ volatilization.

The higher levels of NO_3^- and NH_4^+ concentration between 0-30 cm depth of soil observed during the first and second ratoon compared to 2014 plant cane could be possibly due to N that remained from N fertilizer applied in the previous year; this was also supported by a study conducted by Wiedenfeld (1995). Large variations in NH_4^+ and NO_3^- levels were observed across replications of urea and ammonium nitrate treated-plots compared to those treated with UAN solution suggesting that the uniform distribution of fertilizer is easier to achieve using UAN solution over granular N fertilizer. This could also partly explain the minimal raise in NH_4^+

and NO_3^- concentration in soils treated with UAN as opposed to those treated with granular fertilizers.

2.5 Conclusions

Crop-year had a significant effect on yield, quality parameters, N uptake and fertilizer N recovery with 2014 plant cane having the highest cane tonnage, N uptake, and amount of recovered N fertilizer. Nitrogen uptake of plant cane was higher than the first ratoon crop but this posed a negative impact on TRS and sucrose content subsequently reducing sugar yield.

The significant effect of N rate on cane tonnage and sugar yield was not consistent across crop-years. For each crop-year, the effect of source and N rate was then evaluated. Nitrogen fertilizer rate significantly affected cane tonnage across cropping years, but for sugar yield, it was observed only in ratoon crops. The highest cane and sugar yield was attained with N application rates of 90 and 135 kg N ha^{-1}. There were no differences in cane and sugar yields of plots treated with different N sources across the cropping years. However, there was a tendency that lower N rate when knifed-in as UAN achieved similar yield levels as those plots receiving higher N rate as urea and ammonium nitrate.

There were significant reductions in TRS, sucrose content, and juice purity (brix and polarity) observed in plots which received higher N rates (90 and 135 kg ha^{-1}) using urea and ammonium nitrate particularly in plant cane. The N fertilizer recovery decreased with increasing N rates and with crop age. On the other hand, N uptake was significantly increased with increasing N rate.

The outcomes of this study demonstrated that N rate had a larger impact on sugarcane yield and quality components than N source. This was also true for soil inorganic N content (NH_4^+ and NO_3^-) and cane N status (fertilizer recovery and N uptake). The significant interaction of N rate and source in 2016 second ratoon showed the potential role of making the right choice of N source to reduce the units of N applied to soil without compromising sugarcane quality parameters. Based on all these results, UAN remains a good N source for sugarcane production systems in Louisiana. With respect to N rate, the present study showed the optimal level varied year to year or essentially with crop age. In fact, the significant linear (positive) trend of N rate with cane tonnage (across years) and sugar yield (2016 second ratoon) suggests the possibilities that in some years, higher N rate can further maximize cane tonnage and sugar yield.

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Chapter 3. Validation of Sugarcane Yield Potential and Response Index Models Based on Normalized Difference Vegetation Index at Different Sampling Dates

3.1 Introduction

Sugarcane (*Saccharum spp*) is a complex hybrid between *Saccharum officinarum and S. spontaneous (*Verheye, 2010*).* The total worldwide production is close to 1900 million Mg of cane from around 22 million hectares (Salassi, 2015). In the United States, the production of sugarcane in 2015 was estimated at 71 million Mg of which 69 million Mg were used for sugar and 2 million Mg for seeds with the yield at 82 Mg ha^{-1} (USDA, 2015). In Louisiana, sugarcane production is estimated at 12 million Mg of the cane on more than 170,000 hectares producing 1.262 million Mg of sugar (USDA, 2015).

The nitrogen (N) cycle is very dynamic, and the negative impact of mismanagement of N fertilizer is an important issue that should be taken into consideration by producers and researchers to balance environmental and production goals (Van Miegro et al., 1994). One of the greatest challenges in agriculture is to improve yield and quality under reduced production cost (Rodrigues et al., 2013). While N is the most limiting nutrient in sugarcane production, typically plant cane does not respond to N fertilization due to the soil available N left from previous crop seasons, presenting differences in yield, stalk population and biomass production compared to the subsequent ratoon crops. Sugarcane biomass formed during the different growths stages requires substantial quantities of N fertilizer (Roy et al., 2006).

Nitrogen fertilizer application in Louisiana is done only once between April and the beginning of May or before sugarcane attains a certain height that limits the entry of fertilizer applicator to the field. The most common N source in Louisiana for sugarcane production is urea-ammonium nitrate (UAN, 28-32% N) solution. Current N rate recommendations are based on crop age and soil type: plant cane on light and heavy textured soils receive 67-90, and 90-112 kg N ha^{-1}, respectively whereas for first ratoon crop rates are 90-112 and 112-135 kg N ha^{-1} (Viator et al., 2014). Nitrogen application guidelines for crop production should be designed to balance productivity, economic, and environmental outputs (Roy et al., 2006; Meyer et al., 2007; Kostka et al., 2009). The increasing fertilizer cost urges Louisiana sugarcane growers to implement N fertilizer management strategies that maximize yield at the lowest cost possible (Johnson et al., 2008).

Nitrogen is present in soil as inorganic and organic forms (Havlin et al., 2014). Nitrate (NO_3^-) and ammonium (NH_4^+) are the two inorganic forms of N taken up by plants. Mass flow and diffusion are the main transport mechanisms of NO_3^- and NH_4^+ from the soil (solution) to the roots rhizosphere (Havlin et al., 2014). Nitrate is very mobile in the soil and any that remains in the soil is prone to losses through leaching and soil surface runoff causing environmental concerns (Bronson, 2008). The excessive use of N fertilizer will lead to NO_3^- leaching and underground water contamination (Ersahin, 2001). Lee et al., (2005) reported that increasing N fertilization above the optimal rate will increase N loss via leaching. Nitrate can be easily lost through leaching in heavy rainfall events for soils with high infiltration rates while flooding conditions in soils with poor drainage or structure can lead to further NO_3^- losses through denitrification or soil surface runoff (Power et al., 2000). Nitrate is the most common form of N associated with runoff loss, but the amount lost by this process (0.3 kg ha^{-1}) is minimal compared with the amount (9.2 kg ha^{-1}) lost by leaching processes (Hubbard et al., 1991). An ammonium-based fertilizer such as urea, ammonium nitrate, and UAN contain a form of N (NH_4^+) that can volatilize in certain environmental conditions.

Thus, proper placement into the soil is one of the key management factors to prevent N volatilization from the soil without incorporation. Moisture, chemical properties (e.g., cation exchange capacity), and temperature of soil affect the amount of NH_4^+ removed from the soil-plant system (Havlin et al., 2014). Another pathway from which NH_4^+ can be lost is through fixation process by clay mineral. Ammonium fixation is greater in the interlayer spaces of 2:1 type clay minerals like illite, vermiculite, and montmorillonite (Drury and Beauchamp, 1991; Thompson and Blackmer, 1993).

Many studies revealed that cane stalk, sucrose content, and sugar yield could be reduced by applying high N rates (Wiedenfeld, 1997; Rattey and Hogarth, 2001; Fortes et al., 2013). According to Srivastava and Suarez (1992), sugarcane needs 45 to 300 kg N ha^{-1}. Using the right amount of N is essential; previous research has shown that high amounts of N will produce negative effects not only reducing sugar yield but also causing environmental problems brought about by NO_3^- leaching and runoff (Borden, 1942; Chapman et al., 1994; Wiedenfeld, 1995).

It is known that not only a nutrient management approach is critical to maximizing N recovery, but climate factor, soil type, and varieties can also impact cane response to N fertilizer. Muchow et al. (1996) showed that using high N rates did not result in a significant reduction in sucrose content; instead cane yield increased recovering the equal amount of sugar which was higher than the plots applied with lower N rate. However, other results differ showing that the effects of rate and split application of N fertilizer did not show a significant effect on sugarcane quality (Koochekzadeh et al., 2009). Rattey et al. (2001) reported a reduction in sugar yield with increasing levels of N fertilization. This was consistent with the findings of Lofton et al. (2013) showing that N rate had a significant effect on cane tonnage for both years (plant cane and first ratoon). However, sugar yield was significantly affected only at first ratoon. Gawander et al.

(2004) indicated that sugarcane yield and quality parameters such as sucrose content are significantly correlated with N fertilization.

A proper N fertilization management program employs N application at the optimal rate, time, placement, and source. Nitrogen recommendation and management scheme varies with crop species, growth cycle, variety, and growing condition (Shapiro et al., 2006). Implementation of proper management practice for N can reduce N losses and increase the farmer's income (Randall and Iragavarapu, 1995; Owens et al., 1999). Site-specific management of N fertilizer has been proposed to improve crop nutrition management practices to meet yield goals and minimize the negative effect on the environment due to non-optimal crop fertilization practices (Johnson et al., 2002; Beaudoin et al., 2005).

Nitrogen fertilizer application in the Louisiana sugarcane production system is accomplished in the month of April (1-30) when cane begins to actively take up nutrients from the soil leaving low amounts of unused N before leaching and/or immobilization process takes begin and the height of cane at this growth stage does not limit entry of farm implements to the field (Johnson et al., 2008). Lofton et al. (2013) reported the varying response of sugarcane yield to different N application timing and delaying N fertilization to mid and late May and found both cane and sugar yield were not significantly affected.

The implementation of site-specific N management in sugarcane production in Louisiana requires a decision tool which can account for both field and year-to-year variation in crop growth factors. Remote sensor-based N recommendation is a promising N decision tool capable of providing an N recommendation based on sugarcane yield potential and estimates of plant available N at the moment of fertilization (Tubaña et al., 2011; Lofton et al., 2012a).

Soil and plant testing have been a valuable decision tool to monitor crop N status (Schröder et al., 2000). However, these decision tools are expensive and labor/time-consuming practices. Investigators began developing technologies to non-destructively monitor plant N health status using canopy spectral reflectance and chlorophyll meters (Fox and Piekielek, 1992; Schepers et al., 1998). These optical sensor technologies are used in determining N rate recommendation by relating the leaf spectral reflectance to the plant N status; because the acquisition of information is fast, this technology can also be used in identifying crop N management zones while providing the correct amount of N on-the-go (Raun et al.,2002; Johnson et al., 2003; Fox et al., 2008; Tubaña et al., 2012).

Application of N on a-need-basis using such technology is essential to improve N use efficiency (NUE) in Louisiana sugarcane production (Johnson et al., 2003). Precision N management using remote sensing technology has proven to be a valuable tool for improving NUE, economic return, and environmental quality for many crops (Raun et al., 2002; Johnson et al., 2003; Singh et al., 2006; Tubaña et al., 2012; Kanke, 2013). The use of crop sensors allows farmers to maximize productivity through more efficient N application (Raun et al., 2002; Singh et al., 2006 and Shanahan et al. 2008).

One of the many crop sensors available on the market is the GreenSeeker® Handheld Sensor (Trimble Navigation, Ltd., Sunnyvale, CA). GreenSeeker® is an active light sensor that uses a self-contained illumination in red (670 ± 10 nm) and near infrared (NIR, 780 ± 10 nm) bands (Singh et al., 2006; Shanahan et al., 2008). The emitted light is reflected from the target surface (e.g. leaves or canopy of crops) to the sensor device where it is used to calculate normalized difference vegetation indices (NDVI; Rouse et al., 1973) using the following equation:

$$NDVI = (\rho NIR - \rho Red)/(\rho NIR + \rho Red). \quad (2.1)$$

Where:

ρNIR = Reflectance at the near-infrared region of the electromagnetic spectrum

ρRed= Reflectance at the red region of the electromagnetic spectrum

Before the introduction of remote sensing technology, N rate application rate was recommended based on a yield goal which is obtained by averaging the most recent 5-year crop yield levels (Johnson et al., 1991; Dahnke et al., 1998; Teal et al., 2006). Yield goal has been defined as the yield per acre that you desired from a crop (Dahnke et al., 1998). However, due to the large yield variability from year to year between and within fields, an excessive N application during fertilization may likely occur (Teal et al., 2006).

To improve N decision management using only yield goal, some changes were made; soil NO_3^- content was incorporated to account for the amount of N available in the soil (Dahnke et al., 1998; Teal et al., 2006). Several researchers began to focus on determining in-season N management based on predicted yield potential (Raun et al.; 2002; Teal et al., 2006; Tubaña et al., 2012). Raun et al. (2001) collected different spectral measurements from winter wheat (*Triticum aestivum*) canopy and developed a non-destructive estimation of yield potential (YP_0) based on the principle that NDVI is correlated with a total above biomass (Teal et al., 2006). A major outcome of their work was the establishment of a predictive model for YP_0 based on the relationship between NDVI and grain yield. Yield potential differs from yield goal because it is highly dependent on the environmental conditions for that particular growing period (Raun et al. 2002). Apart from yield potential, NDVI readings in winter wheat were also used to predict both N uptake and biomass (Solie et al., 1996; Stone et al., 1996). Raun et al. (2001) defined YP_0 as an in-season estimated of yield (INSEY) where INSEY is calculated by dividing NDVI readings by the accumulated positive growing degree days (GDD) from planting to sensing; GDD is calculated as ((Tmax + Tmin)/2) - base temperature) where Tmax = maximum day temperature, Tmin = minimum day temperature and base temperature = minimum temperature required for a crop to grow (Lukina et al., 2001; Raun et al., 2002). Raun et al. (2001) also demonstrated a good correlation between grain yield potential and computed INSEY at two growth stages (Feekes 4 and 5) of winter wheat and from 6 of 9 sites over a 2-year period.

Johnson and Raun (2003) introduced the response index (RI) concept as a way to calculate plant response to additional N requirements. Many studies demonstrated the use of RI to estimate crop N response using NDVI readings collected early in the season (Mullen et al., 2003; Raun et al., 2010; Harrell et al., 2011; Tubaña et al., 2012). The RI is the NDVI ratio of N-treated plots and non-N treated plots (0 N applied). Similarly, Johnson and Raun (2003) described that RI could be used to describe yield response to N fertilization ($RI_{HARVEST}$) calculated as the yield ratio of N-treated plots to the non-N treated plots (0 N applied). Mullen et al. (2003) showed that the ratio of RI_{NDVI} of winter wheat could be used to predict $RI_{HARVEST.}$ Hodgen et al. (2005) reported similar findings in corn (Z*ea mays L.*).

In sugarcane, Lofton et al. (2012b) using an active light sensor showed that the strongest relationship between $RI_{HARVEST}$ and RI_{NDVI} was achieved at four weeks after N fertilization on cane tonnage and sugar yield. Similarly, a strong correlation between agronomic variables and response to N fertilization ($RI_{HARVEST}$) on sugar yield at 4 and five weeks after N fertilization were reported by Kanke et al. (2016). Tubaña et al. (2012) from multiple rice N response trials in Louisiana and Mississippi also found that the RI_{NDVI} measured at panicle initiation (PI) and within three weeks after the onset of PI were significantly correlated and can be used to estimate RI_{YIELD}.

For many years, especially in grain crops, yield goals have been the common method used to estimate pre-plant N rate recommendations (Raun et al., 2001). Unlike predicted YP_0, the yield goal concept does not account for spatial and temporal variability when deriving N rate recommendations. This is especially important for sugarcane that has other sources of variability coming from growing cycle (crop age) and crop longevity. Raun et al. (2011) and Mullen et al. (2003) explained that the low relationship between RI and yield potential (YP_0) was due to the high year-to-year variability of RI and the influence of the environment on YP_0. They emphasized that RI and YP_0 are independent, but both factors are needed for determining the optimal N rate recommendation for a crop. It was in 2002 when Raun et al. established predicted YP_0 and RI as components for an N fertilizer optimization algorithm from which they also developed a sensor-based N rate calculator for a wide array of field crops.

For sugarcane, the models for predicting these components were established recently by Lofton et al. (2012a, 2012b). These components where used by Tubaña et al. (2013) to establish sensor-based N recommendations for Louisiana’s row-crops including sugarcane. Recent evaluations showed that sensor-based N recommendation has the potential of improving the profitability of sugarcane production in Louisiana (Tubaña et al., 2015).

Nitrogen fertilizer is unquestionably the most valuable nutrient input in sugarcane production and can bring significant returns when managed properly. With many pathways by which applied N fertilizer can be lost from the soil and become an environmental concern, the need to implement effective N management practice becomes more evident.

While sensor-based N recommendation has shown promise and is available for implementation on producers’ fields, there is a need for continuous validation of the models that are used for predicting the components (YP_0 and RI) of the optimization N algorithm.

It is for refinement purposes and also to keep in step with the changing production technologies (e.g. use high yield cane variety, use of cover crops and green manuring) the need to validate the components of N working algorithm is essential. Therefore, the main objective of this research was to validate the predictive models for cane yield potential (millable stalk and sugar) and RI using NDVI in-season yield estimates normalized by number of days with positive GDD from January 1 of each year (INSEY-DFY) and INSEY normalized by cumulative growing degree days (INSEY-GDD).

3.2 Materials and Methods

3.2.1 Site Description, Planting method, Treatment Structure and Trial Establishment

The data that were used for this study were collected from 2 sites located at the Sugar Research Station in St. Gabriel, LA (Latitude 30°, 15’, 13” N; Longitude 91°, 06’, 05” W). Site 1 was established in 2013 and data was collected from this site for three years (2014 to 2016).

The cane variety was HoCP 96-540, a mid-maturing variety with an excellent stalk population making it superior for optimal cane and sugar yield. The soil type for site 1 is a mix of Commerce silt loam (94%) and Commerce silty clay loam (6%) (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquept). Site 2 was established in 2015 on a Commerce silt loam soil (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) using cane variety L 01-299.

Using a whole-stalk harvester, whole green stalks of sugarcane an average of 1.2 to 1.8 m in length were cut and piled into hauling equipment to travel around the furrows. Whole stalks were planted by hand on a bed 1.2 m wide and ~0.3 m high.

The planting furrows were opened a depth of between 10 and 15 cm then a total of three to four stalks were placed side by side with 8 cm overlapping ends in a horizontal position.

The planting furrow was covered with 6-8 cm of soil and then compacted using a custom roller packer. Weed management control followed Louisiana State University AgCenter herbicide recommendations with an early spring application that included an application of metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine] after beds were rebuilt in-season (lay-by), approximately in the middle of May.

Site 1 had thirteen treatment combinations of different N sources (urea - 46% N, ammonium nitrate [AN] - 34% N, urea-ammonium nitrate solution [UAN] - 32% N dribble and knife-in) and three different rates (45, 90, and 135 kg N ha^{-1}) including a check plot (Table 3.1). Site 2 had eighteen treatments combinations consisting of different N sources (controlled release polymer-coated N, 31% N - CRF and UAN knife-in, 32% N) applied at 45, 90, and 135 kg N ha^{-1}. For site 1, each treatment was replicated four times and arranged in a randomized complete block design whereas, for site 2, the experiment was arranged in a complete randomized design. The experimental plots consisted of 3 rows 14 m long, with 1.5 m alleys. For both sites (1 and 2), granular N fertilizers (urea, AN, CRF) were applied in the planting furrow by hand, while liquid fertilizer (UAN) was applied using fertilizer knives (sites 1 and 2) and dribble into the shoulder (site 1). Furrows were tilled and covered immediately following N application.

Table 3.1. Agronomic activities accomplished during the three cropping years at the Sugar Research Station in St. Gabriel, LA.

Experiment	Year	Crop age	N application	Harvest	Sensing dates DANF‡	
					21	60
Site 1	2014	Plant cane	7-May	12-Dec	27-May	¥
Site 1	2015	1st ratoon	4-May	17-Nov	30-May	13-Jul
Site 1	2016	2nd ratoon	17-Apr	18-Oct	9-May	17-Jun
Site 2	2016	Plant cane	5-Apr	8-Dec	17-May	26-Jun

‡ Number of days after N fertilization
¥ NDVI readings were not collected

3.2.2 Cane Tonnage, Sugar Yield, and Quality Components

All the experimental plots were harvested with a single-row, chopper harvester (CASE IH Austoft® 8000 series cane harvester) for determination of millable stalk yield. Cut stalks from each plot were loaded into a modified single axle high dump billet wagon fitted with electronic load sensor cells (Cameco Industries, Thibodaux, LA). Before plot harvesting, ten stalks were randomly harvested by hand from the middle row of each plot from both sites and cleaned (leaves were stripped out from the stalk, and 10-12 cm tops were removed). The total plot cane yield was determined by adding the weight of ten stalk sub-samples and the plot harvest weight. Sugar yield was determined as the product of cane yield and theoretical recoverable sugars (TRS). The stalk subsamples were shredded and analyzed for quality components which included TRS (needed for sugar yield computation) using a SpectraCane Automated NIR Analyzer.

3.2.3 Sampling Method and Data Management

Sensor data was collected at 21 and 60 days after N fertilization (DANF) from both sites (1 and 2) using a four-band GreenSeeker® Handheld Optical Active Sensor. The GreenSeeker sensor system measured canopy reflectance readings at Red (670 ± 10nm) and NIR (780 ±

10nm) wavebands of the spectrum. These readings were used to compute NDVI based on equation 2.1.

The sensor system was mounted on an ATV (2013 Honda FourTrax Rancher 4x4 ES TRX420FE) 1 meter above the sugarcane canopy and the readings were collected from the middle row in 2014 and from every row of each plot in 2015 and 2016 at constant speed to obtain an average of reading 185 over 15 m (approximately the plot's length). All the NDVI readings were averaged to obtain one reading per 15 m-row. The RI_{NDVI} was calculated by dividing the NDVI reading of N-fertilized plots with the NDVI reading from a check plot (0 N-treated plots) as proposed by Johnson and Raun (2003).

The $RI_{Harvest}$ was calculated for both cane tonnage and sugar yield similar to RI_{NDVI} by dividing the cane (or sugar) yield from the N-fertilized plots by the yield of the check plot. Due to the high variability of sugarcane response to N fertilization the RI-modified model proposed by Lofton et al. (2012b) was used wherein RIs were computed for all individual applied N rates compared to the check plot using the following equations:

$$RI_{45}\text{= 45 kg N ha}^{-1}\text{ plot/check plot} \qquad (2.2)$$

$$RI_{90}\text{= 90 kg N ha}^{-1}\text{ plot/check plot} \qquad (2.3)$$

$$RI_{135}\text{= 135 kg N ha}^{-1}\text{ plot/check plot} \qquad (2.4)$$

The cumulative growing degree days (CGDD) were computed as the sum of GDD from the beginning of the year until the day of sensing (Raun et al., 2002; Teal et al., 2006). The GDD was calculated as:

$$\text{GDD} = [\left(\frac{\text{Tmax}+\text{Tmin}}{2}\right) - \text{Base temperature}] \qquad (2.5)$$

Where:

Tmax: is the maximum daily atmospheric temperature;
Tmin: is the minimum daily atmospheric temperature;
Base temperature: minimum temperature required for sugarcane growth, 18^{o}C

Yield prediction models that were validated are shown in Table 3.2. There were two models that used NDVI as a predictive variable; one that was established in 2012 and one that was released in 2015 (refined 2012 model). In the 2012 model, there were two predictive variables that were used: the INSEY-DFY which is computed by dividing the NDVI readings by DFY (Raun et al., 2002):

$$\text{INSEY-DFY} = \text{NDVI/DFY} \qquad (2.6)$$

and the INSEY-CGDD calculated by dividing the NDVI by CGDD from the beginning of the year to sensing date:

$$\text{INSEY-GDD} = \text{NDVI/CGDD} \qquad (2.7)$$

Table 3.2. Cane tonnage and sugar yield potential models established in 2012 and 2015 using NDVI, INSEY-DFY, and INSEY-CGDD as predictive variables.

		Cane tonnage	Sugar yield
Year	Plant Index	Equation model	
2012	NDVI	$YP_0Cane = 25.2e^{1.5*NDVI}$	$YP_0Sugar = 2.9e^{1.5*NDVI}$
2012	INSEY-DFY	$YP_0Cane = 39.5e^{59.2*INSEY\text{-}DFY}$	$YP_0Sugar = 3.6e^{87.3*INSEY\text{-}DFY}$
2012	INSEY-GDD	$YP_0Cane = 18.9e^{1280*INSEY\text{-}GDD}$	$YP_0Sugar = 2.1e^{1286*INSEY\text{-}GDD}$
2015	NDVI	$YP_0Cane = 12.07e^{1.47*NDVI}$	$YP_0Sugar = 2354e^{1.7915*NDVI}$

YP_0 = predicted (cane or sugar) yield potential

Table 3.3. Models for predicting yield response using RI_{NDVI} as a predictive variable.

Cane tonnage	Equation Model	Sugar yield
	RI Model	
$RI_{cane} = 1.94*RI_{NDVI}-0.91$		$RI_{sugar} = 1.91*RI_{NDVI}-0.89$
	Modified RI Model	
$RI_{cane} = 2.01*RI_{NDVI}-0.99$		$RI_{sugar} = 2.06*RI_{NDVI}-1.06$

RI_{cane} = predicted cane yield increases due to N fertilization
RI_{sugar} = predicted sugar yield increases due to N fertilization

3.2.4 Data Analysis

Statistical analysis was performed on all data collected in each site-year using SAS 9.4 (SAS Institute, 2012). Two-way analysis of variance (ANOVA) using the PROC MIXED procedure was performed to evaluate the effect of N rate and source on cane tonnage and sugar yield for sites 1 and 2. The fixed effects were N rate, N source, and their interaction while random effects were replications and its interaction with fixed effects. Mean separation was done using Tukey-Kramer posthoc test for any significant effect of N rate and source at $p<0.05$. Orthogonal polynomial contrast (linear, quadratic, and cubic) analysis was performanced to determine the effect of N rate when a significant effect of treatment was found for both sites 1 and 2.

For the validation process, regression analysis was performed using Excel. Cane and sugar yield were predicted using NDVI, INSEY-DFY, and INSEY-CGDD as predictors following the models reported in Table 3.2 for the two sensor sampling dates. With all data combined for the two sites, predicted yield values (cane and sugar) were regressed with the actual cane and sugar yield measured at harvest. A similar procedure was to validate the two RI models. Here, the RI_{cane} and RI_{sugar} were computed based on the RI_{NDVI} collected on two sensor sampling dates using the two RI models. Regression analysis was performed between predicted RI and the actual RI measured at harvest. The coefficients of determination (r^2) of linear regression between the predicted and measured variables were used to evaluate the precision of the models. The accuracy of the models was measured by the slope of the linear regression between the predicted and measured variables.

3.3 Results and Discussion

3.3.1 Climatic Conditions

Sugarcane is a tropical plant that thrives well in regions with high light intensities, warm temperatures, and high average annual rainfall. These factors significantly determine yield and cane quality (Hunsigi, 1993). The average montly temperature and precipitation for 3 years (2014, 2015, and 2016) are presented in Figures 3.1 and 3.2. The 3-year average monthly precipitation for the month of August was higher than what was recorded for the month of May (Figure 3.1). The accumulated precipitation in 2016 was higher compared to 2014 and 2015. A few days after N fertilization in May 2014, site 1 received more than 20 cm of rainfall. Due to the heavy rainfall in 2016, sugarcane operations in Louisiana were challenged by many problems associated with delayed planting and harvest. Temperature influences growth of sugarcane during germination and biomass accumulation.

The average monthly temperature from April to October across the cropping years was comparable. The temperature in early spring (March) of 2014 was below average (<15°C) and notably wet (>20 cm rain in May) followed by a dry summer (~ <10 cm, June and July combined). The optimum temperature for optimal growth is between 30-33°C, while at temperatures below 16°C, sugarcane development is restricted (Bakker, 1999).

Low temperature during the cane ripening process promotes the production of sucrose (Bakker, 1999). Dry matter and stalk elongation are observed with a temperature close to 17.2 to 22.2°C (Hunsigi, 1993). High variability in cane tonnage and sugar yield was observed across the cropping years. The CGDD and precipitation are factors affecting the stalk elongation rate and many physiological processes eventually affecting yield (Thomas et al., 1978; Koehler et al., 1982). The CGDD recorded in 2014 plant cane at 8 WANF was the lowest compared to those recorded in 2015 and 2016 (Figure 3.3). Regarding cane and sugar yields, 2014 plant cane attained a higher level than 2015 and 2016 ratoon crops (only for site 1). Lofton et al. (2013) reported a reduction in yield with increasing crop age. The lower cane and sugar yields in 2015 and 2016 observed in site 1 were expected because of crop age, but it was suspected that high rainfall accumulated in these years compared to 2014 might have partially contributed to yield reduction (Figures 3.1 and 3.2).

It was noted that CGDD is an important parameter of growth phenological stage rate that can be used to standardize NDVI readings collected at different growth stages (Raun et al., 2001). Lofton et al. (2012a) reported that from 601 to 751 CGDD, sugarcane starts to accumulate biomass. The same authors observed that the NDVI readings collected at cane growth stages that fell within this range of CGDD obtained a positive relationship with cane tonnage and sugar yield. In the same study, Lofton et al. (2012a) also indicated that this timeframe corresponded to the last week in May to the first week in June for all cropping years (2008-2011). The relationship between spectral reflectance values and sugarcane yield after 751 CGDD substantially decreased. Conversely, Teal et al. (2006) found that the optimum growth stage for predicting corn yield was at V8 stage or 800 to 1,000 GDD. Similarly, the NDVI readings that were standardized using CGDD did not significantly improve the yield prediction model (r^2=0.76). Several studies have shown that when CGDD is incorporated with NDVI (INSEY-CGDD), the model's r^2 is substantially increased in winter wheat.

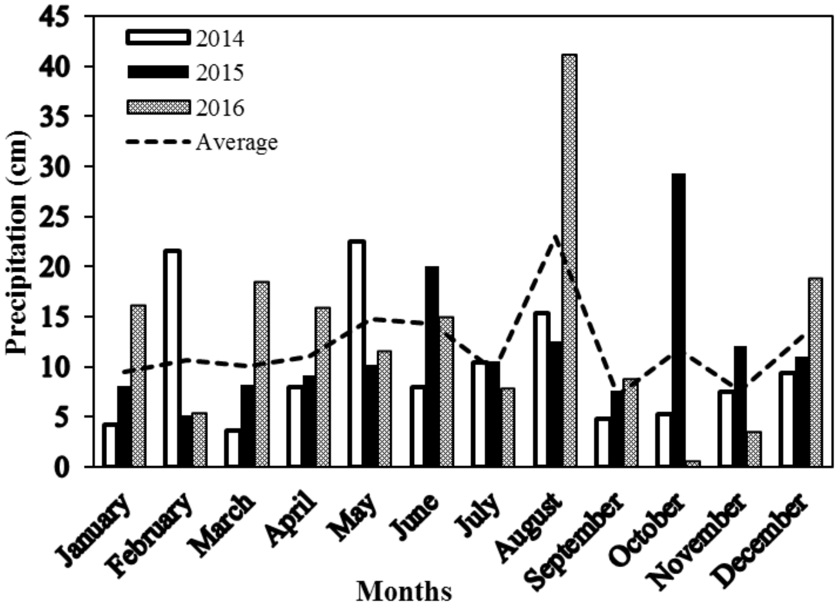

Figure 3.1. Average monthly precipitation from January to December in 2014, 2015, and 2016 at the Sugar Research Station in St. Gabriel, LA.

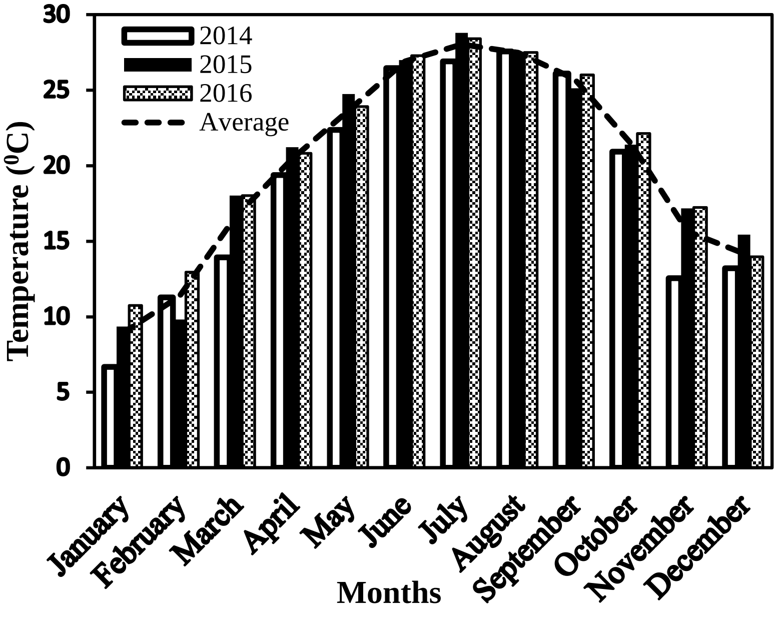

Figure 3.2. Average monthly temperature from January to December in 2014, 2015, and 2016 at the Sugar Research Station in St. Gabriel, LA.

Lukina et al. (2000) and Raun et al. (2002) observed a strong relationship between NDVI and grain yield in winter wheat when NDVI readings values were normalized using CGDD (r^2 = 0.83, p<0.01). Perhaps the use of CGDD is important for winter crops but has limited value for summer crops like corn (Teal et al., 2006) and rice (Harrell et al., 2011). This may be a unique case for semi-perennial crops like sugarcane. Cane is dormant in winter (like winter wheat) but grows actively the entire summer (like summer crops) and completes its growth cycle in late fall. The cumulative growing degree days for three years (2014, 2015, and 2016) for each of the sampling dates are presented in Figure 3.3. The 2015 crop year obtained the highest CGDD where the accumulation increased at an exponential rate at 60 DANF (May to July). The warmer air temperature enhanced the growing conditions in 2015 and led to the faster accumulation of biomass from one growth stage to another. This also coincided with rapid N uptake from late June to early July which explains why the 2015 first ratoon crop had higher TRS than cane harvested in 2014 and 2016 (data not shown).

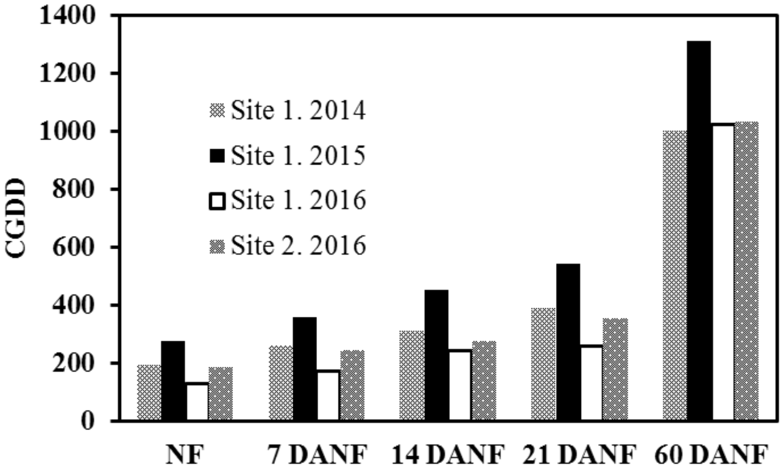

Figure 3.3. Cumulative growing degree days (CGDD) from N fertilization (NF) to 60 days after N fertilization (DANF) from 2014 to 2016 at the Sugar Research Station in St. Gabriel, LA.

3.3.2 Sugarcane Yield Summary

Current N rate recommendations in Louisiana for all varieties of plant cane are 67-90 and 90-112 kg N ha^{-1} in light and heavy textured soils, respectively, but ratoon crops require 90-112 and 112-135 kg N ha^{-1} (Viator et al., 2014). Lofton et al. (2013) using a linear-plateau model showed that N rates needed to achieve optimum yield was lower compared to Louisiana N recommendations. Cane tonnage and sugar yield varied across the sites and years. The effect of N fertilizer sources applied at different rates on cane tonnage and sugar yield from 2014 to 2016 is shown in Table 3.4. Nitrogen rate had a consistently significant ($p<0.05$) effect on cane tonnage from 2014 to 2016. Across the cropping years, sugar yields were higher in N treated plots than the untreated check plots, but only in the 2015 ratoon crop were significant ($p<0.001$) differences in yield due to N rate detected. The N source and interaction (rate x source) had no effect on both cane tonnage and sugar yield. There were yield differences between years (or crop age) and the two sites. Overall, the first and second ratoon's cane tonnage at site 1 were 10 and 20% lower than plant cane, respectively (Table 3.4). Table 3.5 shows that both N source and rate in site 2 had no effect on cane tonnage and sugar yield. Figures 3.4 and 3.5 show the average NDVI readings collected at 21 and 60 DANF for each N rate treatment for the different site-years. Increasing NDVI readings were observed with increasing N application rates at 21 DANF for site 1 (2015) and site 2 (2016). Increases in NDVI readings for each step increase in N rate were more evident at 60 DANF for site 1 in 2015 and 2016. Remarkably, these years also showed a strong linear trend between cane tonnage and N rate in addition to the large increases in cane tonnage due to N application (17 and 9 Mg ha^{-1} for 2015 and 2016, respectively).

For site 2 (2016), the NDVI readings taken 60 DANF were virtually the same across N rates. This was confirmed when N rate showed no effect on both cane tonnage and sugar yield at harvest (Table 3.5). The changes in NDVI readings with N rate indicate that the sensor picked up the effect of N rate on early-season biophysical attributes of sugarcane canopy, i.e., leaf elements including the chlorophyll content and canopy coverage.

Table 3.4 Means and analysis of variance for the effect of N source and rate on cane tonnage and sugar yield from 2014 to 2016, site 1, in St. Gabriel, LA.

Effect	2014 Plant Cane		2015 First Ratoon		2016 Second Ratoon	
	Cane tonnage	Sugar yield	Cane tonnage	Sugar yield	Cane tonnage	Sugar yield
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
Source						
UAN Knife	90	9617	84	10232	69	7417
UAN Dribble	86	9322	79	9612	68	7131
Urea	89	9174	79	9603	69	7240
AN	88	9041	78	9447	72	7584
p-value	NS	NS	NS	NS	NS	NS
Rate						
0	84	8929	64	7839	67	6413
45	86	9374	79	9639	69	7444
90	90	9339	84	10236	71	7602
135	93	9511	91	11181	76	7954
p-value	0.05	NS$^{\Psi}$	**<0.001**	**<0.001**	**<0.001**	NS
Linear	0.04	-$^{\Phi}$	**<0.001**	**<0.001**	**<0.001**	**-**
Quadratic	NS	-	NS	NS	NS	-
Cubic	NS	-	NS	NS	NS	-
Source*N Rate	NS	NS	NS	**NS**	NS	NS
Mean	88	9288	80	9724	70	7348
Standard Deviation	3	230	8	949	3	452

UAN: urea-ammonium nitrate

AN: Ammonium nitrate

Ψ NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis.

Φ Not applicable due to non-significance of the main effect.

Table 3.5 Means and analysis of variance for the effect of N source and rate on cane tonnage and sugar yield in 2016 plant cane, site 2, St. Gabriel, LA.

Effect	Cane tonnage	Sugar yield
	Mg ha^{-1}	kg ha^{-1}
Source		
UAN Knife	85	10328
CRF 1	88	10463
CRF 2	90	10681
p-value	NS	NS
Rate		
0	83	10083
45	88	10600
90	92	10695
135	90	10583
p-value	NS^{Ψ}	NS
Linear	-	-
Quadratic	$-^{\Phi}$	-
Cubic	-	-
Source*N Rate	NS	NS
Mean	89	1049
Standard Deviation	3	221

UAN: urea-ammonium nitrate
CRF 1: controlled release N and K fertilizer
CRF 2: controlled release K fertilizer
Ψ NS indicates no significant differences at the α=0.05 level of significance based on the Tukey`s post-hoc analysis.
Φ Not applicable due to non-significance of the main effect.

3.3.3 Validation of Predicted Models for Sugarcane Yield Potential Using NDVI, INSEY-DFY, and INSEY-CGDD Measured at 21 and 60 Days After N Fertilization.

Table 3.6 provides the slopes and r^2 of the linear regression line obtained from the relationship between predicted and measured cane tonnage and sugar yield using the 2012 and 2015 models with NDVI as a predictive variable. The predicted yields were based on NDVI readings taken at 21 and 60 DANF.

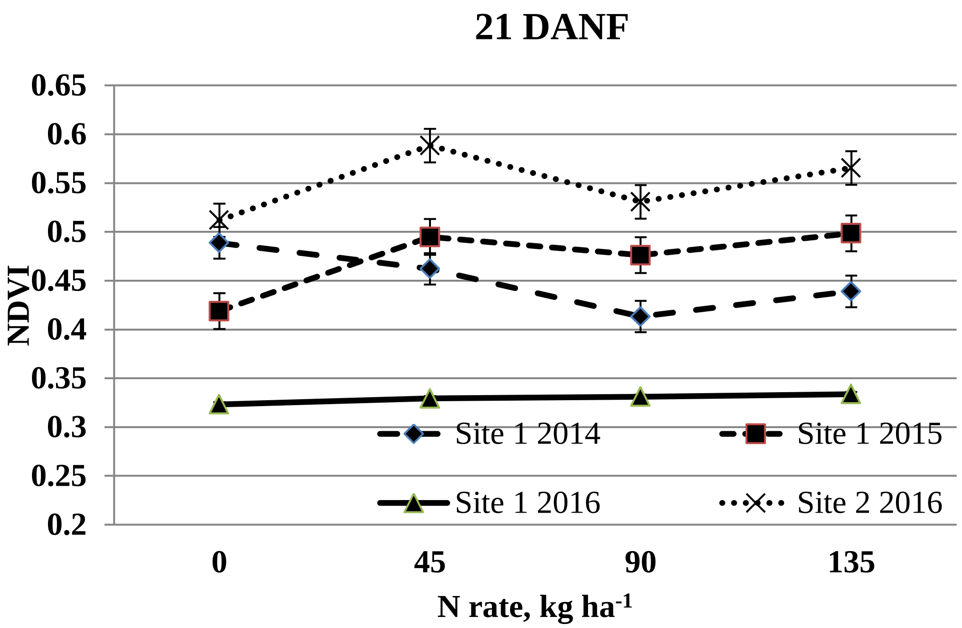

Figure 3.4. Normalized difference vegetation index readings as a function of N rate collected at 21 DANF across the different sites and years at the Sugar Research Station in St. Gabriel, LA.

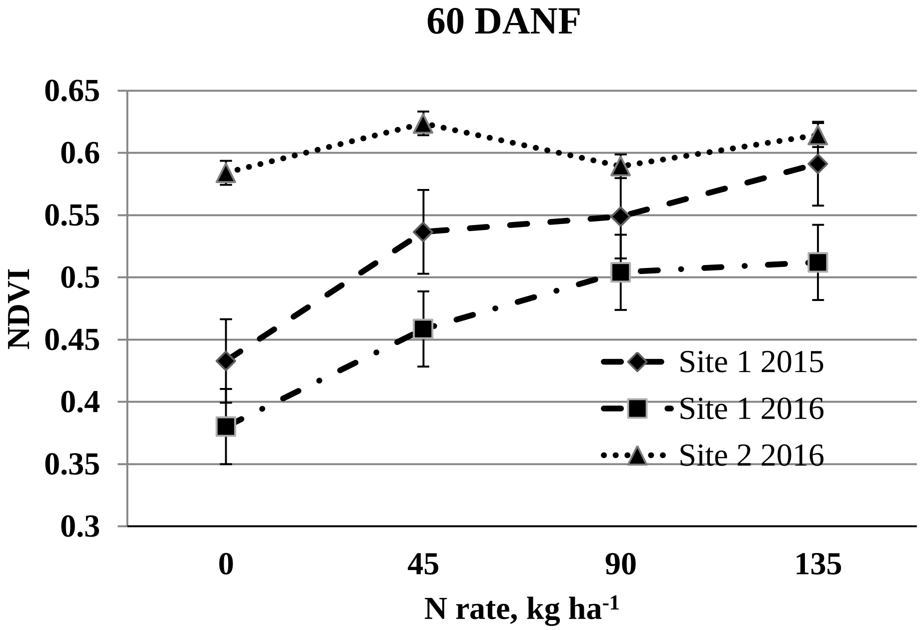

Figure 3.5. Normalized difference vegetation index readings as a function of N rate collected at 60 DANF across the different sites and years at the Sugar Research Station in St. Gabriel, LA.

The NDVI taken at 60 DANF predicted cane tonnage and sugar yield level better than NDVI collected at 21 DANF. This was more evident for cane tonnage with the predicted and measured values having a ratio of almost 1 (slope = 1) indicative of the accuracy of prediction. The precision of the models turned out to be better also for NDVI collected 60 DANF. The r^2 values ranged from 0.41 to 0.52 for NDVI collected 60 DANF and was lower (0.30–0.51) for NDVI collected 21 DANF. Between these two sampling dates, the 21 DANF has more value regarding managing N fertilizer whereas yield prediction made from NDVI readings taken at later sampling date (e.g. 60 DANF) can be used to improve scheduling of harvest and processing logistics of millable stalks. The unique aspect of sensor-based N management in sugarcane is having this option of adjusting N fertilizer recommendation on the basis of cane tonnage (millable stalks) or sugar yield. It is notable that the prediction made for sugar yield at 21 DANF using both models attained a good level of accuracy as well with slope values of 1.04 and 0.82 and r^2 values of 0.51 and 0.50 for 2012 and 2015 models, respectively. This means that predicted sugar yield can be used as a basis for modifying N recommendation. Overall, both models exhibited great potential in predicting sugarcane yield that is comparable to a yield goal approach, yet with an advantage regarding the speed of acquisition of georeferenced-information. Lofton et al. (2012a) indicated that the high variability due to different crop year, growth stage, locations, and variety could affect sensor reading values. Also, a recognized limitation of sensing technique is its inability to account for the differences in biophysical attributes of crop canopies that may take place post-sensing. Thus, if growth conditions drastically change and depart from average growth environment post-sensing, a sensor-based parameter such as NDVI can lose power as a predictive variable. This explains why most of the sensor-based crop yield potential predictive models are not linear (Raun et al., 2001; Teal et al., 2006; Harrell et al., 2011; Lofton et al., 2012a).

Table 3.6 Validation of cane tonnage and sugar yield potential models established from normalized difference vegetation index (predictor) in 2012 and 2015 at the Sugar Research Station in St. Gabriel, LA.

Days‡	2012 Model				2015 Model			
	Cane tonnage		Sugar yield		Cane tonnage		Sugar yield	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
21	0.68Ψ	0.30	1.04	0.51	0.66	0.30	0.82	0.50
60	1.02	0.41	1.43	0.52	1.01	0.41	1.11	0.52

‡ Numbers of days after N fertilization.
Ψ Data points = 504.

Refinement of predictive models can be done through the building of a stronger (large) sensor and yield database and standardization of sensor data. Sensor-based vegetation indices such as NDVI respond significantly with changing canopy structure and leaf elements. This was also demonstrated in this study where the changes in biophysical attributes of sugarcane due to N application were reflected in the NDVI readings taken by the sensor (Figure 3.5). These properties vary with growth stage and variety, and for sugarcane, crop age is an additional factor. Adjusting NDVI readings using CGDD and DFY have been used to overcome these factors that affect NDVI reflectance readings (Raun et al., 2001). Standardization of NDVI readings using CGDD and DFY were reported in several studies (Raun et al., 2001; Teal et al., 2006; Lofton et al., 2012a; Tubaña et al., 2015). According to Raun et al. (2001), standardizing NDVI readings with CGDD in wheat improved the r^2 of the potential predictive model. Lukina et al. (2000) and Raun et al. (2002) showed the improved relationship between NDVI and grain yield in winter wheat when the NDVI readings collected between Feekes 4 to 6 were adjusted using GDD (r^2 = 0.83, p<0.01). Lofton et al. (2012a) also evaluated the use of INSEY-DFY and INSEY-CGDD as predictive models for sugarcane. It was found that the optimal sensing time should be around the growth period where the CGDD sits between 650 and 750; this is typically past the early spring, and when cane has reached the active tillering stage. However, unlike in wheat, the use of DFY (r^2=0.23 for cane and r^2=0.33) to adjust NDVI readings slightly improved the YP_0 model whereas CGDD improved the predictive model with r^2=0.46 for cane and r^2=0.42 for sugar.

Table 3.7 shows the slope and r^2 of the linear regression between predicted cane and sugar yield using INSEY-DFY and INSEY-CGDD as predictive variables for 21 and 60 DANF sensing dates. At 21 DANF, the YP_0 model utilizing INSEY-DFY as a predictor had a better estimate of actual cane tonnage and sugar yield compared with the YP_0 model based on INSEY-CGDD. The slope of the linear regression between INSEY-DFY predicted yield and actual yields was 1.15 for cane tonnage and 1.11 for sugar yield whereas the yields predicted by INSEY-CGDD had slopes <0.15. The precision of the model using INSEY-DFY was better as well than INSEY-CGDD (0.33-0.48 vs. 0.17 vs. 0.30). At 60 DANF, the predictions of both models had higher precision, i.e., r^2 values ranged from 0.40-0.48 for INSEY-DFY as a predictor and from 0.35-0.40 INSEY-CGDD as a predictor. However, the accuracy significantly dropped with a slope value of 3.01 for both cane tonnage and sugar yield. This means that INSEY-DFY model yield prediction was 3 times lower than the actual yield. Similarly, the prediction made by INSEY-CGDD model was about 2 times lower than the actual yield.

Based on these results, the models using NDVI and INSEY-DFY as predictors performed better and are likely suitable for predictions of yield potential that will be used for deriving N fertilizer recommendations. At the later sampling date, the only model which maintained a good level of accuracy and precision were the 2012 and 2015 models using NDVI as predictors.

Table 3.7 Validation of cane tonnage and sugar yield potential models established from INSEY-DFY and INSEY-CGDD (predictors) using 2012 models at the Sugar Research Station in St. Gabriel, LA.

Days‡	INSEY-DFY				INSEY-CGDD			
	Cane tonnage		Sugar yield		Cane tonnage		Sugar yield	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
21	1.15Ψ	0.33	1.11	0.48	0.09	0.17	0.13	0.30
60	3.01	0.40	3.01	0.48	1.59	0.35	1.92	0.40

‡ Numbers of days after N fertilization.
Ψ Data points = 504.

It seems that standardizing NDVI with the use of ambient temperature did not present any advantage. This was also observed in corn (Teal et al., 2006) and rice (Harrell et al., 2011) which are summer crops.

3.3.4 Validation of Sugarcane Predicted Response Index Models Based on Normalized Difference Vegetation Index (RI_{NDVI}) and Modified RI_{NDVI} Collected at 21 and 60 Days after N Fertilization.

Response index is used as an indicator of the crop's need for N fertilizer (Raun et al., 2003). The predictive models for estimating increases in cane tonnage and sugar yield due to N fertilization using early-season NDVI readings were established by Lofton et al. (2012a) (Table 3.4). For the validation of these models, the NDVI readings collected at 21 and 60 DANF from all site years were used to compute predicted RI. At harvest, actual RI was measured using both cane tonnage and sugar yield.

The slope and r^2 of the linear relationships between the predicted RI and measured RI (cane tonnage and sugar yield) are shown in Table 3.8. At 21 DANF, both models prediction of RI was relatively poor in terms of accuracy. The slope values ranged from 0.32 to 0.37. The accuracy did not improve even when the prediction was made using NDVI collected at 60 DANF. With these slope values, the yield increases due to N fertilization were overestimated by almost 3 times by both models. The precision of the models was better when the prediction was made using NDVI readings at 60 DANF; r^2 was improved from 0.15 to 0.31.

Table 3.8 Validation of response index models based on normalized difference vegetation index (RI_{NDVI}) and modified RI_{NDVI} collected at different days after N fertilization at the Sugar Research Station in St. Gabriel, LA.

Days	RI-NDVI[‡]				RI-NDVI Modified[†]			
	Cane tonnage		Sugar yield		Cane tonnage		Sugar yield	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
21	0.32[Ψ]	0.15	0.34	0.17	0.33	0.15	0.37	0.15
60	0.33	0.30	0.37	0.30	0.32	0.30	0.37	0.31

‡ Response index computed considering the highest N rate (135 kg N ha^{-1})
† Response index computed considering all N rates (45, 90, 135 kg N ha^{-1})
Ψ Data points = 504.

While Lofton et al. (2012b) showed that the established relationship between RI_{NDVI} and $RI_{HARVEST}$ for both cane and sugar yield was strong as shown by the high r^2 values (0.92 and 0.8) of the models, the validation done in this study revealed their limitations. A recognized limitation of using in-season sensor data to predict agronomic variables at harvest (e.g. yield) is the inability of this technology to account for changes post sensing. The prediction is essentially not useful in years where extreme changes in growing environments take place after sensing. Raun et al. (2011) reported that RI and yield potential are two independent components of the N fertilization algorithm. This means that a crop with high yielding potential is not necessarily responsive to N fertilization and vice versa. Unlike RI, yield potential is not exclusively relying on one growth factor. Therefore, the high amount of available N in the soil does not guarantee high yields. Thus, if extreme changes in growth condition take place after sensing, the impact on RI prediction is higher than on yield prediction. This is due to the fact that projected cane yield increases due to N fertilization can be easily disrupted by simply altering one factor in the environment i.e. the amount of plant-available N in the soil. Johnson and Raun et al. (2003)

noted that on warm and moist soils during the early season, slow crop development may reduce RI values whereas on hot, dry soils it may lead to high RI values. Kanke et al. (2016) also pointed out that sugarcane response to N fertilization was highly diverse across sugarcane variety, location, and crop age.

3.4 Conclusions

This study showed that overall both 2012 and 2015 models using NDVI as a predictor performed better than the model which used INSEY-CGDD as a predictor. Accurate and precise yield predictions were made at 21 and 60 DANF using NDVI. However, the NDVI readings collected at 60 DANF had predicted cane tonnage and sugar yield better than the NDVI collected at 21 DANF. However, this particular growth stage is considered outside the current timeframe of N application in Louisiana. This study also demonstrated the good level of accuracy and precision on the prediction made by both models at 21 DANF for sugar yield. The standardization of NDVI readings by DFY and CGDD generates two predictors, INSEY-DFY and INSEY-CGDD, respectively. The model using INSEY-DFY predicted yield with higher precision and accuracy than the INSEY-CGDD at 21 DANF; predictions made by both models at 60 DANF were far from actual yield. Based on these results, models which use NDVI and INSEY-DFY are suitable for yield prediction that will be used for adjusting N fertilizer rate, but for yield prediction that will be made later in the sugarcane growth stage, only the model using NDVI will be suitable.

Our study also showed that the two RI models use for predictions of yield increases due to N at 21 and 60 DANF had low accuracy and precision. The NDVI readings taken by the sensor picked up the difference in biomass production early in the growth stage of sugarcane in response to varying N rate. However, this response was not carried over to harvest possibly due to a significant change in growing environment conditions posts sensing. This is a recognized limitation of remote sensing technique; the changes in the factors affecting the growth of crops post sensing will not be taken into account.

The validation conducted in this study revealed both the potentials and limitations of the YP_0 and RI models. It turned out that the accuracy and precision of RI models are easily compromised by extreme changes in growth factors especially after sensing than in the YP_0 models. The refinement process should focus on strengthening the sensor and yield database system along with identification of wavebands that are more sensitive to biophysical attributes of sugarcane canopies.

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Chapter 4. Conclusions

Effective nitrogen (N) management practices are essential to optimize crop productivity. In Louisiana sugarcane production systems, urea-ammonium nitrate (UAN, 28-32% N) solution is the most common source of N fertilizer and little is know about the performance of other N sources. The major goal of this research was to improve N fertilizer use efficiency in Louisiana sugarcane production through the use of remote sensing technology to develop efficient N management strategies using the optimun source and application rate of N.

The outcome of this study showed that crop-year had a significant effect on yield, quality parameters, N uptake and fertilizer N recovery. While plant cane had better N status which led to higher cane tonnage over the first ratoon crop, the lower TRS of plant cane offset the increase in cane tonnage, subsequently reducing sugar yield. The significant effect of N rate on cane tonnage and sugar yield was not consistent across crop-years. For all crop-years, N application rate significantly increased cane tonnage. However, N rate effect on sugar yield was only significant in 2015. Overall, a reduction in cane tonnage was observed in ratoon crops compared to plant cane. Nitrogen sources did not affect cane and sugar yields across cropping years. However, the highest cane tonnage and sugar yield were attained with the application of UAN knife-in followed by urea and ammonium nitrate using 90 and 135 kg N ha^{-1}. In plant cane and second ratoon, sugar yield tended to lower in plots applied with urea and ammonium nitrate partly due to low TRS and sucrose content. However, in 2016 second ratoon, a significant interaction effect of N source and rate was observed on TRS, sucrose, brix, and polarity. Across cropping years, a reduction in N fertilizer recovery and N uptake was observed with increasing N rate application. Nitrogen fertilizer recovery was not affected by N source, however; cane applied with granular fertilizers (urea and ammonium nitrate) had numerically higher N fertilizer recovery than those which received UAN. Soil NH_4^+ was the predominant form of inorganic N (over NO_3^-) across cropping years regardless of N source and the rate at 21 days after N fertilization (DANF) for plots treated with urea and ammonium nitrate in both depth (0-15 and 15-30 cm). Overall, the outcome of this study showed that N rate had a greater impact on sugarcane yield and N fertilizer recovery than N source. There was no compelling evidence collected from this study that suggest UAN is better than granular N fertilizer and vice versa. Urea-ammonium nitrate solution is, therefore, a better choice because fertilizer implements and applicators of sugarcane producers are designed for UAN solution. Flying urea over sugarcane is an option in years where weather interferes with the timely application of N fertilizer. Other findings in this study show a significant linear relationship between N rate, cane tonnage (across cropping year) and sugar yield (2016 second ratoon) suggesting that higher N rate application can further maximize yield. However, more studies are needed to evaluate the response of sugarcane yield and quality parameters to application of higher N rates.

The validation process conducted in this study revealed the potentials and limitations of yield potential and response index models developed in 2012 and 2015 based on normalized difference vegetation index (NDVI). Previous research showed that NDVI could be used to estimate sugarcane yield potential and relative response to applied N, the two components that sensor-based N decision tools use for deriving N recommendation in sugarcane production. Models that utilize NDVI and a standardized NDVI by days from planting to sensing (INSEY-DFY) as predictors made more accurate and precise cane tonnage and sugar yield prediction at 21 and 60 DANF. Between the sensing dates, higher accuracy and precision of yield prediction was made by NDVI models at 60 DANF compared to the prediction at 21 DANF. Yield prediction made at 60 DANF can be used as a basis to improve scheduling of harvest while the yield prediction at 21 DANF can be used for adjusting N recommendation. The model which uses NDVI that was standardized by cumulative growing degree days CGDD (INSEY-CGDD) as a predictor had yield predictions that were not accurate; the low r^2 values also suggest poor precision of the model.

Response index (RI) models were established to predict an increase in cane tonnage and sugar yield due to N application using NDVI readings collected at the early growth stage of cane or within the timeframe of N fertilization. Both RI and modified RI models showed low accuracy and precision in predicting measured RI at 21 and 60 DANF for both cane and sugar yield. The RI models had higher precision when prediction was made at 60 DANF (r^2=0.30) compared to the prediction made at 21 DANF (r^2=0.15). This highlighted the limitation of remote sensing technique on its inability to account for changes in growth factors post sensing, which cause the discrepancy between the N response observed early in the season and at harvest.

The current N recommendation for sugarcane production remains valid but there were indications that application of higher N rate may further maximize yield. The choice between UAN and urea (or other granular fertilizer) will be made on the basis of application logistics of sugarcane producers and circumstances that may compromise timely application of N fertilizer. The validation conducted in this study revealed both the potentials and limitations of the YP_0 and RI models. It turned out that the accuracy and precision of RI models are easily compromised by extreme changes in growth factors, especially after sensing, compared to the YP_0 models. Future research should focus on refining the models, especially the RI models. The refinement process should include strengthening the sensor and yield database system, establishment of a threshold value for RI to avoid over or underestimation of N impact on sugarcane yield, and identification of wavebands that are more sensitive to biophysical attributes of sugarcane canopies.

Vita

Daniel E. Forestieri was born in Guayaquil, Ecuador in September of 1988. He attended the Panamerican Agriculture University, Zamorano in Honduras and received his Bachelor of Science in Agricultural Sciences and Production in December of 2013. After graduating, he came to Louisiana State University as a Student Visiting Scholar and was later accepted in August of 2014 into the Master program in the School of Plant, Environmental, and Soil Science under the guidance of Dr. Brenda Tubaña working on improving nitrogen management in sugarcane production in Louisiana specifically on establishing the optimum rate of the right source and application method of nitrogen fertilizer. He is also validating the use of remote sensing technology in predicting the in-season response of sugarcane to nitrogen fertilization.