2012

Improving nitrogen management in sugarcane production of the mid-South using remote sensing technology

Joshua Lofton
Louisiana State University and Agricultural and Mechanical College, jlofton@agcenter.lsu.edu

Recommended Citation

Lofton, Joshua, "Improving nitrogen management in sugarcane production of the mid-South using remote sensing technology" (2012). *LSU Doctoral Dissertations*. 1746.
https://digitalcommons.lsu.edu/gradschool_dissertations/1746

IMPROVING NITROGEN MANAGEMENT IN SUGARCANE PRODUCTION OF THE MID-SOUTH USING REMOTE SENSING TECHNOLOGY

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Plant, Environmental, & Soil Sciences

by
Joshua Lofton
B.S. Oklahoma State University, 2007
M.S. Oklahoma State University, 2009
May 2012

Acknowledgements

I would like to thank my advisor Dr. Brenda Tubana, who has helped and guided me through every step of this process. She has given me the tools to continue and be successful in my professional career. Additionally, I would like to thank my committee members Dr. Dustin Harrell, Dr. David Weindorf, Dr. Jim Wang, and Dr. Richard Johnson. They have given me advice and guidance through the entire process.

I would also like to thank Dr. Jasper Teboh for assisting me on all those hot and humid Louisiana summer days. Additionally, Yumiko Kanke and Marilyn Dalen for assisting with both field and laboratory work associated with my project. Also, this project would not have been possible without the help of the Sugar Research Station staff for all their help with trial set-up, fertilization, and harvest/processing. I would also like to thank Dr. Gary Breitenbeck and Joe Kraska for allowing me to utilize their laboratory space and equipment.

In addition I would like to give a special thanks to my family, friends, and colleagues for all the support through my educational process that helped and carry on. Also, a very special thanks to my wife Dr. Beatrix Haggard-Lofton for all the love, encouragement, help, support, and understanding throughout all of our years.

List of Tables

List of Figures

Abstract

In Louisiana, current N rate recommendations for sugarcane production are based on multiple year N response trials and refined based on soil and crop variables. Without accounting for current growing conditions, recommendations can potentially lead to over- or under-application of N. The objectives of this research were to 1) determine the ability of an in-season response index value (RI_{NDVI}) to estimate sugarcane yield response index ($RI_{Harvest}$), 2) determine if sugarcane yield potential could be determined using normalized difference vegetative index (NDVI), and 3) estimate the optimum N rate and application timing for sugarcane production in Louisiana. Experiments were established in St. Gabriel and Jeanerette, LA from 2008 through 2011. A GreenSeeker® hand-held optical active sensor was used to obtain NDVI readings for all studies. Fertilizer N was applied as urea ammonium-nitrate (UAN, 32-0-0) at the rate of 0, 45, 90, and 135 kg N ha^{-1} for most experiments with application timings ranging from early-April through late-May.

This study showed that NDVI could be used to accurately estimate both sugarcane RI and yield potential (YP). A RI value was determined using a traditional method, comparing non-limiting N to an unfertilized treatment, and modified method, comparing all N fertilized treatments to an unfertilized treatment. There was a strong relationship between RI_{NDVI} and $RI_{Harvest}$ for cane tonnage and sugar yield using both methods. Additionally, NDVI values demonstrated the ability to estimate sugarcane yield potential in-season. This relationship was improved when NDVI was adjusted using climatic variables.

An additional study was established to investigate the N rate and application timing on sugarcane production. Fertilizer rate showed a significant positive effect on sugarcane yield for two of three experiments. For these experiments, critical N rates were substantially lower than

the current N rate recommendations. The effect of application time was not as pronounced, with only the second stubble sugarcane crop in 2011 showing a significant decrease in sugarcane yield when N fertilization was delayed.

Overall, the use of remote sensing principles shows promise in Louisiana sugarcane production. However, limitations such as timing of sensing will need to be overcome prior to implementation.

Chapter 1. Introduction

1.1 Production and Economic Importance of Sugarcane

Sugarcane is the highest valued row-crop in Louisiana with economic values exceeding over $2 billion annually (Legendre et al., 2000). First recorded history of sugarcane in Louisiana is by Jesuit missionaries in 1751 (Legendre et al., 2000). This makes the production of sugarcane an important part of Louisiana history and economy and one of the most historic industries in the United States. In the early years of sugarcane production, yields ranged from 36-45 Mg ha^{-1} (Legendre et al., 2000). In the following years, the introduction of new varieties with higher yield potential and resistances to pest increased the yield across the state to an average 67-112 Mg ha^{-1} (Legendre, 2001).

Sugarcane is typically planted on a bed, usually 38 to 61 cm in width (Legendre, 2001). Sugarcane is usually planted using either whole stalks billets, which are small segments of sugarcane stalks, which are planting across the planting furrow. For planting using whole stalks, planting furrows are filled with whole stalks at the rate of three stalks side-by-side with overlapped 8 cm with a minimum of four matured internodes. Billets are shorter stalks cut into 50 cm segments with two matured internodes per segment and are typically planted six across the planting furrow. In Louisiana, sugarcane is typically planted in August with later planting dates showing significant lower yields in both the plant cane and first stubble crop (Viator et al., 2005). The crop is the harvested following December, which is considered plant cane. Sugarcane is usually harvested for two additional year; termed ratoon (stubble) crop, which is typically harvested in November and October for first stubble and second stubble, respectively.

Prior to harvest, sugarcane can be burned and then harvested or harvested without burning. After harvest, the residue, if not burned prior to harvesting, can either be burned to clean the soil surface or allowed to naturally decompose. The burning of the sugarcane before harvest has been shown to decrease leafy matter in the cane and can increase quantity and quality of sugar (Legendre et al., 2000). Due to regulations and growing interest of the general public for the environment, more acreage is being cut green, without burning the residue. The harvested cane can be "juiced" and separated into sugar and other by-products, including bagasse and molasses.

Louisiana produces approximately 40% of the overall sugar as sugarcane in the United States (Hawthorn, 2010). Since 2000, the total acreage of harvested sugarcane and overall production has decreased. However, total value for the crop has been fairly consistent due to increases in sucrose percentage (Table 1.1) (Hawthorn, 2010).

Table 1.1. Sugarcane harvest statistics for the United States in 2000 and 2008.

Year	**Harvested**	**Yield**	**Total production**	**Value**
	Ha	Mg ha^{-1}	Mg	$ (Million)
2000	188,178	66.57	12,532,667	313
2008	182,108	69.48	9,758,620	312

Sugarcane is commercially grown in four states throughout the United States: Louisiana, Texas, Florida, and Hawaii. The sugarcane industry is beneficial to the residents of these states by providing jobs throughout the industry. Louisiana's sugarcane industry can provide many jobs throughout the state due to a majority of the planting, harvesting, processing, and refining are all done within the state. In Louisiana, 27,000 to 32,000 people are employed to some extent by the sugarcane industry (Legendre et al., 2000).

With the decrease total harvested acreage, producers in Louisiana will need to increase the operation efficiency to continue maintain sustainable sugarcane production. This means decreasing excess production costs and minimizing environmental impact. One method to achieve this goal is to increase N use efficiency (NUE). By supplying the amount of N that sugarcane needs at the appropriate time, producers can decrease N losses to the environment. This research project was designed to investigate proper timing of spring N-fertilization, appropriate rate of spring N-fertilization, and use of the GreenSeeker™ hand held sensor in predicting sugarcane yield potential and response to N fertilization.

1.2 Soils in Louisiana

Soils that comprise most of Louisiana vary significantly. One reason for this high variability is the deposition process associated with many Louisiana soils. The fluvial process of soil deposition, where sediment originated from various weathered parent materials across the upper portion of the Mississippi River drainage basin, brings about highly variable soils that can be deposited in a very small area. This high variability can influence many physicochemical properties, which include texture, soil pH, and essential plant nutrients (Hodges, 1997; Stanturf and Schoenholtz, 1998).

These marked soil physicochemical changes can be observed within a single field and highly influence nutrient recommendations. Johnson and Richard (2005) found that in sugarcane fields in Louisiana many soil properties show a high degree of variability, which were not normally distributed. In addition to the within field variability present, the type of soil that sugarcane is typically grown can be quite diverse. Soil textures in which sugarcane production is common range silt loams to clays. Four benchmark soils that are well representative of the soils in which sugarcane is produced are the Commerce (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) and Cancienne (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts) for silt loam soils as well as the Sharkey (Very-fine, smectitic, thermic Chromic Epiaquerts) and Schriever (Very-fine, smectitic, hyperthermic Chromic Epiaquerts) for clay soils. They further reported that fields across the sugarcane growing region of Louisiana varied in both total cane tonnage (31 to 134 Mg ha^{-1}) and sugar yields (2.7 to 14.6 Mg ha^{-1}) within a growing cycle. They concluded that this high variability associated with sugarcane yield was influenced by the changes in soil physiochemical properties. This high documented variability creates a need for robust and diverse management plans for crop inputs that can encompass the in-field variability present in Louisiana soils.

1.3 Soil Nitrogen Introduction

A hectare of productive soil can contain as much as 3.5 Mg of N in the upper-most horizons (Brady and Weil, 2003). However, in non-legume crop production systems, N is the most limiting plant growth factor after water (Havlin et al., 2005; Ketterings et al., 2003). This is partly because the majority of N present in the soil is not plant available. Many other forms of N exist in the soil system that are not immediately plant available including N incorporated into decomposing leaf tissue, N incorporated as proteins in soil microbes, and other non-biologically available organic forms. Typically plants uptake N mainly through the inorganic forms of nitrate (NO_3^-)

and ammonium (NH_4^+) (Engels and Marschner, 1995). Once N is taken up, the assimilation pathway is dependent on the form of N. Most NH_4^+ can be directly assimilated into organic compounds in the roots, while NO_3^-, a mobile form of N, is available for long distance transport in the xylem and can be utilized by other critical growing points (Engels and Marschner, 1995). Prior to being incorporated into organic components, NO_3^- must first be reduced to NH_4^+. Ammonium/ammonia is then assimilated into amino acids and further to protein and nucleic acids (Havlin et al., 2005).

1.4 Nitrogen Cycle

1.4.1 Additions

The N-cycle is very dynamic with many additions and losses throughout the soil system. Nitrogen additions can be through both fertilizer additions and natural processes. Natural additions include biological N-fixation, atmospheric deposition, and mineralization. Biological N-fixation is a reaction that is mediated by various species of bacteria, cyanobacteria, and actinomycetes (Zuberer, 2005). Estimating the amount of N that is fixed through biological pathways is difficult; however, estimated values range from 100 to 180 million Mg N_2 year^{-1} (Havlin et al., 2005; Zuberer, 2005). Biological N-fixation can either be performed by free-living microbes or symbiotic relationships between plants and bacteria. These symbiotic relationships can range from being strict relationships between microbe and plant, such as between *Rhizobia* and legume species, or associated relationships, which have been demonstrated in sugarcane production (Boddey et al., 1995; Yoneyama et al., 1997; Boddey et al., 2003; Hoefsloot et al., 2005). While symbiotic N-fixation have been given attention in recent years in many crops, determining the contributions of such associations to the growing crops has proven difficult. However, Yoneyama et al. (1997) reported that in sugarcane the N contribution from symbiotic N-fixation can be high. They found that the average contribution of total plant N was approximately 30% but can be up to 72% depending on other agricultural inputs.

Another natural N addition is through atmospheric deposition, where N is added to the soil system from the atmosphere. Many natural and non-natural processes contribute to atmospheric N including release from denitrification, plant N losses, volatilization, animal wastes, combustion of coal and petroleum, and various pollution sources (Brady and Weil, 2003; Havlin et al., 2005). Large scale atmospheric N deposition can is difficult to accurately quantify. This is because of a lack large scale N deposition sampling system and large areas of land can be non-quantified (Whelpdale and Kaiser, 1997). However, Wedin and Tilman (1996) estimated that atmospheric N deposition has increased over the last 40 years to as high as 60 kg N ha^{-1} yr^{-1}.

In addition to N being added to the soil system naturally from the atmosphere, N can be converted from plant unavailable into plant available sources. Approximately 95-99% of soil N is in the form of an organic compound (Brady and Weil, 2003; Schulten and Schnitzer, 1998). This form of soil N limits N-losses from the soil system; however, a majority of organic N is not immediately available for plant uptake. Organic N sources must go through mineralization prior to being plant available. Nitrogen mineralization is the conversion of organic forms of N to NH_4^+. This is a two step process, aminization and ammonification in equation 1.1 and 1.2, and is carried out by various species of heterotrophic soil microorganisms.

$$\text{Proteins} \longrightarrow \text{Amino Acids} + \text{Amines} + \text{Urea} + CO_2 + \text{Energy} \qquad (1.1)$$

$$R\text{-}NH_2 + H_20 \longrightarrow NH_4^+ + R\text{-}OH + \text{Energy} \qquad (1.2)$$

The rate and efficiency of soil N mineralization is highly dependent on soil physiochemical characteristics, including NH_4^+ present in the soil system, nitrifying microorganisms, soil pH, aeration, and soil temperature. However, potentially the most important factor determining whether mineralization or immobilization will occur is the C:N ratio of the residue.

Prior to 1850, most fertilizer applied was in the form of animal manure (Havlin et al., 2005). One reason for the high use of organic manure sources was the United States produced nearly 180 million Mg of manure annually, with about 40% being produced in confined animal feeding operations (CAFO) (Araji et al., 2001; Havlin et al., 2005). The composition and quality of animal manures are highly variable and dependent on the animal feed, handling and storage of manure, quantity of miscellaneous materials, method of application, and intended crop. Usually, total N ranges from < 1% to 15% (Havlin et al., 2005; Brady and Weil, 2003; Araji et al., 2001). This low concentration of N, low initial availability, high amount of variability in application, high amounts of heavy metals, and potentially high cost of transport and application limits the use of manure in commercial production.

Synthetic fertilizer application has been increasing rapidly since the 1960s (Tilman et al., 2002). Overall, approximately 75% of fertilizers applied to land in the United States are through synthetic fertilizers. These fertilizers use the Haber-Bosch process to fix atmospheric N_2 under extreme heat and pressure into ammonia (NH_3), which can be converted, equation 1.3, to various NH_3/NH_4^+ based fertilizers (Zuberer, 2005).

$$N_2+3H_2 \xrightarrow{\text{Heat, pressure, catalyst}} 2NH_3 \qquad (1.3)$$

Advantages of these synthetic fertilizers are an increase in N applied per unit cost, fewer impurities and potentially harmful chemicals (such as organic chemicals, high levels of micronutrients and heavy metals), and homogeneity of nutrient concentration.

1.4.2 Losses

As mentioned previously, the N-cycle has many losses throughout the soil system, which include volatilization, immobilization, leaching, denitrification, and plant losses. Immobilization is not a true loss as it is only a loss of plant available N; therefore, it will be discussed in further details in the transformation section.

Volatilization is a critical loss in all ecosystems, because it is a direct loss to the soil system early in the N-cycle. Following the loss of N through volatilization, these gaseous forms of N can affect many ecosystems due to atmospheric deposition through increased surface water eutrophication, increased N-loading in soil systems, and important N-input. Ammonia volatilization is a natural process; however, the rate of N volatilization has been accelerated due to the increase use of inorganic N fertilizer (Galloway and Cowling, 2002). Volatilization is largely affected by soil pH and moisture. Several studies reported increased volatilization rate associated with high pH, warm, and drier conditions (Vjek et al., 1981; Denmead et al., 1982; Havlin et al., 2005). However, soil conditions do not solely control volatilization; volatilization is also influenced by N management practices including method of application, placement, soil cover, and residue. Bouwman et al. (1997) reported broadcast N without incorporation has a higher volatilization potential than that of either broadcast with incorporation, surface or sub-surface banding applications. Several studies showed that NH_3 volatilization increased if fertilizer is applied as urea to fields where residue is left; reportedly due to an increase in urease enzyme in the residue (Meyers et al., 1961; Khan and Rashid, 1971; McGarity and Hoult, 1971). However, Freney et al. (1992) reported volatilization was more heavily dependent on the availability of water than other influencing factors.

After soil NH_3/NH_4^+ undergoes nitrification (to be mentioned in transformation section), there is an increased potential for soil NO_3^- leaching to occur. This increased leaching potential is associated with NO_3^- solubility and the decreased interactions with permanent exchange sites for most mineral soils (Brady and Weil, 2003; Havlin et al., 2005). Many factors can influence the rate and amount of NO_3^- leaching including climate, soil properties, and management practices. One of the most important management practices for minimizing NO_3^- leaching is applying N fertilizer at the right time and at the appropriate rate (Magdoff, 1991; Karlen et al., 1998). Southwick et al. (1995) reported that approximately 3 to 8% of N applied to a sugarcane field in Louisiana would be leached within approximately 60 days. Of that amount, approximately half was leached out within 8 days of application.

In addition to leaching, N in the form of NO_3^- can be lost as a gas through denitrification. Denitrification occurs in agricultural soils that have become anaerobic or near anaerobic conditions for long periods of time (Focht and Verstraete, 1977). This is due to NO_3^- being used by anaerobic organisms as a final electron acceptor in anaerobic respiration. Soil aeration is the most important environmental factor influencing denitrification; however, other environmental factors such as soil pH, biologically available organic C, temperature, and NO_3^- levels also contribute to the extent of denitrification. In addition to denitrification occurring when the soil is completely saturated, a significant amount of N can be lost through denitrification within small anaerobic micro-zones surrounded by an otherwise aerobic soil conditions (Craswell, 1978; Kaplan et al., 1979; Skiba et al., 1993). Kaplan et al. (1979) reported that the concentration of NO_3^- in the soil was the main factor that would contribute to denitrification as opposed to anaerobic conditions. In sugarcane production in Louisiana, which can be grown on high clay content soils, denitrification in anaerobic micro-sites could be a potential major source of N loss.

1.4.3 Transformations

One of the reasons the N-cycle is so dynamic is the transformation of soil N. These transformations processes occur throughout the N-cycle and are controlled by many soil chemical processes within the soil solution. The major transformations within the soil system are mineralization/immobilization and nitrification.

Immobilization and mineralization are counter reactions, where immobilization is the conversion of inorganic N to organic N and mineralization is conversion of organic N to inorganic N. These transformations are mainly catalyzed by microbes in the soil system, which utilize these reactions as an energy and C-gaining process. However, these processes can reportedly occur through non-biological processes as well (Smith and Paul, 1990; Myrold and Bottomley, 2008). When plant/animal residues are added to the soil system, one of the main factors for determining whether the residue will be mineralized or immobilized is the C:N ratio. Several studies have reported a C:N ratio of 25:1 to be the critical point between immobilization and mineralization (Killham, 1994; Paul and Clark, 1996; Myrold, 1998). Havlin et al. (2005) indicated that a range of C:N ratios from 20:1 to 30:1 resulted in no net immobilization or mineralization. In either situation, C:N ratios wider than the critical ratio/range resulted in a net immobilization of soil N, where a C:N ratio that smaller than the critical value resulted in mineralization of soil N.

The second major transformation in the soil system is nitrification. Nitrification is a two-step microbial catalyzed oxidation of NH_4^+ to NO_3^-. The first step of nitrification is the conversion of NH_4^+ to NO_2^- catalyzed by *Nitrosomonas* bacteria based on equation 1.4 (Myrold and Bottomley, 2008).

$$2NH_4^+ + 3O_2 \xrightarrow{\textit{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+ \qquad (1.4)$$

The product of the first step of nitrification, nitrite (NO_2^-), does not typically accumulate in aerated soils (Havlin et al., 2005). This is beneficial to the soil ecosystem, due to NO_2^- being toxic to numerous organisms at high levels (Bancroft et al., 1979). The second step of nitrification is the complete oxidation of NO_2^- molecule to NO_3^- catalyzed by *Nitrobacter* through equation1.5 (Havlin et al., 2005).

$$2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacter}} 2NO_3^- \qquad (1.5)$$

Since nitrification is a microbial reaction, it is controlled by soil environmental conditions that influence soil microorganisms such as NH_4^+ supply, nitrifying bacteria, aeration, moisture, soil pH, and soil temperature (Havlin et al., 2005). The nitrification process needs CO_2, O_2, as well as NH_4^+ to proceed. In most aerated soils CO_2 and O_2 are sufficient for the process to proceed; thus NH_4^+ is the most limiting substrate (Norton, 2000). Schjonning et al. (2003) indicated that air diffusivity may be used as a good indicator of oxygen-limiting nitrification rates. Saby (1969) reported that maximum rates of net nitrification occurred at approximately -10kPa. However, when soils are drier than field capacity the rate of nitrification decreased due to a decline in physiologic metabolic activities and decreased availability of the substrate (Stark and Firestone, 1995). Since nitrification is a biological reaction, temperature can affect the rate of conversion and optimum temperature is environmentally dependent (Norton, 2000). Koops et al. (1991) reported that the optimum temperature for growth of cultured nitrifying bacteria was between 25 to 30°C; however, optimum temperatures could vary based on other soil characteristics. Soil pH also influences nitrification rates. Generally, highest rates of nitrification occur at a narrow soil pH range corresponding to optimum growth rates for the nitrifying bacteria, usually from 6.5 to 8.5 (Havlin et al., 2005; Prosser, 1989). However, many studies have indicated that nitrification can occur at more extreme pH values, both acidic and alkaline (DeBoer and Kowalchuk, 2001; Sorokin, 1998; Sorokin et al., 2001). To allow for continued nitrification in these extreme conditions, areas closer to optimum conditions can be found around nitrifying bacteria in acid soils (DeBoer and Kowalchuk, 2001).

1.5 Nitrogen Management in Sugarcane Production

Nitrogen is used by sugarcane in a fairly large amount. Golden (1981) reported that sugarcane grown in Louisiana accumulated approximately 135 kg N ha^{-1} to 168 kg N ha^{-1}, depending on N rate application, throughout the growing season. Wood (1990) found similar results on sugarcane grown under rain-fed conditions in South Africa which accumulated up to 168 kg N ha^{-1} within a 12 month growth cycle. However, due to sugarcane being a semi-perennial with two distinct growth cycles within a single planting cycle, the N demand of sugarcane varies. The worldwide application of N fertilizers for sugarcane production is highly variable, ranging from 45 to 300 kg N ha^{-1} (Srivastava and Suarez, 1992). Optimal N fertilizer application rate is dependent on many factors, such as soil type, crop age, plant and soil characteristics, climate, length of growing cycle, and length of growing season (Wiedenfeld, 1995; Wood et al., 1996; Legendre et al., 2000). One factor that is consistently important across all growing regions is crop age. Typically, stubble cane crops are applied with higher N rates than plant cane crops (de Geus, 1973; Wood, 1964). This is because stubble cane crops show a higher response to applied N compared to plant cane crops. This higher response of stubble cane crops is because sugarcane is either planted after a fallow period or within a rotation with soybeans, thus allowing the soil to build soil N reserves. While crop age is important, other factors can influence different N rates between growing regions. Curtis and Loupe (1975) reported that sugarcane production required 90-135 kg N ha^{-1} for most areas in Louisiana and 135-157 kg N ha^{-1} in the Red River Valley for plant sugarcane and 135 to 157 kg N ha^{-1} for stubble cane for all areas. The ratoon crop for sugarcane has a higher response to N fertilization, therefore, additional fertilizer compared to plant cane would be justified (Wood, 1964). Curtis and Loupe (1975) agreed reporting that ratoon sugarcane N fertilization recommendation to be higher, at 135-157 kg N ha^{-1}. Current recommendation rates for sugarcane production in Louisiana are between 67 to135 kg N ha^{-1}, depending on soil type and crop age (Legendre et al., 2001).

Many unique challenges in Louisiana sugarcane production system have altered N recommendations compared to other growing regions including shorter growing seasons, winter freezing conditions, and high yearly precipitation. Historically in Louisiana, a small amount of N fertilizers was recommended at planting to aid in early season fall growth as well as a mid-season N fertilization application in early spring (Legendre et al., 2001). However, the lack of growth during the winter months makes fall N fertilization arduous and fraught with many potential loss mechanisms (Knowles and Blackburn, 1993). Current best management practices recommend only a single N application applied prior to the grand growth stages, when growth is vigorous. Mid-season fertilization rates for Louisiana sugarcane production vary based on crop age, either plant cane or stubble cane, and soil type, generalized as either light textured or heavy textured (Legendre, 2001). The incorporation of mid-season N fertilizer applications has been shown to decrease the initial loss of N fertilization by volatilization (Prasertsak et al., 2002; Courtaillac et al., 1998).

In addition to potentially decreasing detrimental environmental impact, decreasing over-application of fertilizer N can have a positive effect on sugarcane yield as well. Studies have shown that the over-supply of N can decrease sucrose concentration in the millable stalk (Wiedenfeld, 1995; Chapman et al., 1994). Wiedenfeld (1995) reported that high N rates (168 kg N ha^{-1}) increased fresh cane yield in stubble cane crops only under high irrigation levels, but under medium or low irrigation levels, the increased N rate either had no significant effect or a negative effect on fresh cane yield. Additionally, he found that at all irrigation levels, high N rates decreased sugar content and juice purity as well as decreasing sugar yield except under high irrigation levels. However, Muchow et al. (1996) reported slightly different results. They found that while a high N rate (268 kg N ha^{-1}) slightly decreased sucrose content, it increased cane yield to a level that produced non-significantly different sugar yields when comparing the low N rate to the high N rate. While Muchow et al. (1996) found no significant differences in sugar yield between a high N rate and a low N rate, both reported a significant decrease in stalk sucrose levels when high N rates were applied.

In addition to N rate, one of the many other concerns with N management is optimizing the timing of application of N fertilizers. Wiedenfeld (1997) found that, in east Texas, the timing for a single yearly application of N should be in March or April. However, Johnson et al. (2008) suggested that sugarcane fertilization in Louisiana should be done in April. Samuels (1969) reported that sugarcane N needs are apparent early in the growth season during germination and “boomstage” or grand growth stage, which is a period of rapid growth. Current recommendations for timing of mid-season N management are similar to that suggested by Johnson et al. (2008). Timing of N fertilization can be up to two months prior to the apparent initiation of grand growth, which has been observed from late May to early June. Lack of coincidence between N fertilization and rapid sugarcane uptake of soil N could lead to high rates of N fertilizer loss from the soil system. However, very little research has been conducted to determine the effects of delaying spring fertilization into the month of May. The lack of understanding on optimum time could heavily influence crop production. If fertilizer is applied too early in the season, the plants can begin to show deficiencies in the latter part of the growing season. Fertilization too late could cause diminished yields due to lack of nutrients at the initiation of sugarcane growth (Wiedenfeld, 1997). Even though there are minor discrepancies over timing, all current recommendations suggest applying mid-season N prior to May.

1.6 Determining Crop N Status

1.6.1 Traditional Methods

Traditionally, many methods have been utilized for determining crop N status, including visual methods, tissue analysis, and chlorophyll meters (Fox and Walthall, 2008). Recently, reports have suggested that remote sensing techniques have been used to determine N status (Fox and Walthall, 2008), where remote sensing is defined as the process of obtaining data without coming in direct contact with the object (Aloisio and Cafaro, 2003). These methods either determine directly from crop N status or infer crop N status based on plant physiological characteristics (Fox et al., 1994; Piekielek and Fox, 1992; Turner and Jund, 1994).

Nitrogen deficient plants generally have stunted growth with spindly leaves. Potential explanations for these symptoms are a lowered growth rate, lowered chlorophyll synthesis, and photosynthetic rate associated with limited N supply (Havlin et al., 2005). Therefore, additional deficiencies are identified by pale or lighter green leaves, chlorotic leaves of the lower leaves, usually of grasses (Fox and Walthall, 2008; Havlin et al., 2005).

Visual methods can be a quick and inexpensive method for determining plant nutrient status; however, using solely visual symptoms can be misleading. Visual N deficiencies can be misinterpreted because of other non-nutrient stress symptoms, other nutrient deficiency symptoms, or interaction between two stresses causing similar symptoms (Fox and Walthall, 2008). Additionally, deficiency conditions that significantly decrease yield could be present without showing visual deficiency symptoms or deficiency symptoms may appear too late correction (Fox and Walthall, 2008; Havlin et al., 2005).

Another method used for determining N status of crops is tissue analysis. This method directly measures the total N present in the plant at the time of sampling. Many authors have discussed how total N concentration is dependent on sampling method, timing of sampling, and location on the plant in which the sample was obtained as well as being affected by plant variety, climate, soils, and other stress factors (Black, 1993; Munson and Nelson, 1990; Tucker, 1984). Determining the actual plant N status of the crop is based on critical nutrient concentrations. Critical concentrations determine when the crop is deficient or sufficient and are determined by 1) concentration where there is no growth or yield response, 2) concentration which yields are 95% of maximum yields, or 3) the critical point of a linear plateau model (Black, 1993). The main disadvantage of tissue testing is the time and workload needed to obtain a representative sample as well as the time associated with processing and analysis of the sample.

The potential of replacing wet chemistry methods by non-destructive plant indices began in approximately in 1975. One of the first methods that was used to non-destructively determine crop N status was the chlorophyll meter. Chlorophyll meters operate on the basis that N is the main component of chlorophyll; thus, plant N content can be determined using an estimation of chlorophyll content. Therefore, unlike tissue testing, chlorophyll meter estimates are based on an indirect measure of crop N status.

For most chlorophyll meters, radiating wavelengths are emitted at approximately 660 nm and 940 nm (Fox and Walthall, 2008). Chlorophyll absorbs at 660 nm but only transmits at the 940 nm; therefore, these meters determine percent transmittance and are related to chlorophyll concentration (Fox and Walthall, 2008). Previous research has reported that chlorophyll meters have successfully been shown to non-destructively measure chlorophyll content and thus predict plant N content for rice (Fox and Piekielek, 1998; Schepers et al., 1998). Additional N needs are determined using a chlorophyll meter based on a sufficiency index value (equation 1.6).

$$[(\text{N limited treatment})/(\text{fertilized treatment})]*100 \qquad (1.6)$$

If the sufficiency index value falls below 95%, further N applications would be needed (Peterson et al., 1993; Blackmer and Schepers, 1995; Varvel et al., 1997; Hussain et al., 2000). Zhang et al. (2008) stated that chlorophyll meters were successful at detecting severe N deficiency; however, moderate to low deficiencies could not be determined until later in the season after optimum timing for N fertilization.

The use of remote sensors for determining crop N status utilizes similar principles as the chlorophyll meters. However, instead of using percent transmittance similar to the chlorophyll meters, remote sensors measure differences in leaf reflectance. Changes in reflectance readings can be used to indirectly determine crop N status. Establishing the relationship between the canopy reflectance and green biomass is essential for remote sensing to be effective. An early study by Thomas and Oerther (1972) found that reflectance in the green and red regions of the electromagnetic spectrum were highly correlated to leaf N content determined using the Kjeldahl method. Additional efforts established the relationship between crop N content and canopy reflectance at the visible

(400-700nm) and near infrared (NIR) (700-1100nm) regions (Martin et al., 1989). The combination of spectral reflectance measurements at various regions of a crop canopy reflectance signature is called a vegetation index (VI). Spectral VI are often sensitive to changes in biophysical properties; however, they are often associated with multiple properties and need to be calibrated with destructive sampling (Fox and Walthall, 2008). Nutrient deficiencies are associated with changes in chlorophyll content as well as leaf/canopy structure, which can be determined using both visible and NIR measurements, respectively (Fox and Walthall, 2008). Canopy reflectance in the red and NIR regions have reported success at determining crop N content, due to the ability to detect changes associated with chlorophyll content and decreasing cell layers (Guyot, 1991; Thomas and Oerther, 1977).

Many VI have been reported successful in determining crop N status. Normalized difference vegetative index (NDVI) is one of the most commonly used VI and is determined per equation 1.7.

$$\text{NDVI}= (\rho\text{NIR}-\rho\text{Red})/(\rho\text{NIR}+\rho\text{Red}) \tag{1.7}$$

where:

ρNIR = reflectance at the near-infrared region electro-magnetic spectrum

ρRed = reflectance at the red region of electro-magnetic spectrum

According to Stone et al. (1996), NDVI values were found to be most effective at detecting vegetative material in winter wheat. Additionally, they reported NDVI readings and green ratios are better at predicting biomass during active vegetative growth, while red-NIR ratios are better predictors at maturation.

1.6.2 Application of Remote Sensing

Johnson and Richard (2005) found a high amount of variability in soil properties in sugarcane fields, along with the yield and quality of the sugarcane harvested. As previously discussed, N fertilizer recommendations in Louisiana are based on crop age and soil type, with current N conditions and soil N levels not influencing N recommendations. Because of high variability in Louisiana soils, this method of N recommendations can lead to potential risk of over- or under-application of N fertilizer. Raun and Johnson (1999) reported that under-application of N fertilizers can lead to crop yield loss while over-application can lead to an increased environmental impact through N loss.

Several reports have shown that plant indices based on spectral reflectance can be used to accurately predict crop physiological variables, including plant biomass (Tucker, 1979), photosynthesis (Zhao et al., 2003), chlorophyll content (Tucker, 1979), plant N status (Bronson et al., 2003), and yield (Raun et al., 2002; Zhao et al., 2003). Many researchers have substantiated the value of a decision tool which estimates the response of the crop to applied N and an estimate of crop yield potential (YP) as a practical technology to improve N management in crop production in the U.S.A., Canada, as well as other countries (Olfs et al., 2005; Bersten et al., 2006; Biermacher et al., 2006; Tremblay and Belec, 2006; Zillmann et al., 2006).

The crop response to fertilizer N has been reported to be estimated using a response index (RI) value (Johnson and Raun, 2003). According to Mullen et al. (2003)

and Hodgen et al. (2005), midseason normalized difference vegetative index (NDVI) readings can be used to determine RI in winter wheat. The RI is determined by comparing a check plot (0 N applied) with a reference plot, traditionally used as a high N rate plot where N is not the most limiting factor (Johnson and Raun, 2003). They determined RI using in-season estimates of biomass (RI_{NDVI}; equation 1.8) and yield at harvest ($RI_{Harvest}$; 1.9).

$$RI_{NDVI} = (NDVI_{Non\text{-}limiting})/(NDVI_{Check}) \tag{1.8}$$

$$RI_{Harvest} = (Yield_{Non\text{-}limiting})/(Yield_{Check}) \tag{1.9}$$

Many studies have reported a strong relationship between RI_{NDVI} and $RI_{Harvest}$ in multiple crops suggesting that an RI_{NDVI} value could be used as an estimate of $RI_{Harvest}$ (Mullen et al., 2003; Hodgen et al., 2005).

In addition to estimating crop N response, determining the crop YP is critical. The YP value is a function of the environmental conditions of the current growing season and defined as the expected achievable yield with no additional N application (Raun et al., 2002). Teal et al. (2006) reported that there was a strong relationship between NDVI and grain yield in corn using an exponential model. Lukina et al. (2000) and Raun et al. (2001) showed this relationship provided improvement when NDVI readings were adjusted using growing degree days (GDD), where NDVI was divided by GDD accumulated from planting to sensing, to create an in-season estimate of yield (INSEY). Raun et al. (2001) reported that six of nine sites over two years showed a strong relationship between INSEY and grain yield (coefficient of determination (r^2) = 0.83, $P<0.01$). However, Teal et al. (2006) found there was no significant increase or decrease in the strength of this relationship when NDVI readings were adjusted by either GDD or days from planting to sensing (DFP) when GDD was positive.

In-season remote sensing techniques have been implemented to several crops to help improve NUE (Raun et al., 2001; Raun et al., 2002). However, limited research is available for sugarcane production, particularly Louisiana sugarcane production (Johnson and Richard, 2003; Johnson and Richard, 2005). New technologies are going to be needed in the future to help increase the efficiency of sugarcane production. However, the implementation of such technology has been slow in sugarcane. Further research will help to incorporate these technologies and determine the advantages and disadvantages with using remote sensing technology in sugarcane production.

1.7 Rationale for Research

Additional research is needed that focuses on N fertility issues surrounding one of Louisiana's most important crops, sugarcane. With the highly variable conditions that are present in Louisiana, robust fertility guidelines need to be established to help producers achieve maximum production and profitability. Implementing better guidelines for N fertilization can not only increase the production but can also help to protect the environment from having excess N as a non-point source pollutant. Determining the timing in which N needs to be applied has shown to increase N-uptake, grain nutrition, and yield in many crops (Melaj et al., 2003; Fageria and Baligar, 1999). However, little research has been devoted to the effect of N fertilizer timing in sugarcane production in the US. The rate of fertilizer is also an important research focus. Numerous studies have shown high N rates decrease sugarcane productivity (Wood, 1990; Chapman et al., 1994; Muchow et al., 1996). However, little of this research has been conducted in Louisiana.

Additionally, adaptation of advanced technologies in sugarcane production has been limited, with most information being focused on aerial platforms. Many studies have shown the added benefit of using ground-based remote sensors, which differ from the more commonly perceived aerial platforms by only the distance from the measured object, such as availability of reoccurring images, limited atmospheric inference, and quickness of observed data (Havrankova et al., 2007; Bevis et al., 1992). The use of precision management, including ground-based remote sensors, can help to increase agronomic yields, increase economic profits, and protect the environment. It has been shown that in some years crops need lowered amounts of N compared to others. Therefore, applying N fertilizer on a need basis rather than pre-season N recommendations would be optimal. Due to a lack of scientific information, it is clear that there is a need to further investigate the proper timing and rate of N fertilization in sugarcane, as well as evaluating ground-based remote sensing methods for more accurate fertilizer estimations.

1.8 References

Aloisio, G., and M. Cafaro. 2003. Adynamic earth observation system. Parallel Computing 29:1357-1362.

Araji, A.A., Z.O. Abdo, and P. Joyce. 2001. Efficient use of animal maure on crop land-Economic analysis. Bioresour. Technol. 79:179-191.

Bancroft, K., I.F. Grant, and M. Alexander. 1979. Toxicity of NO_2: effect of nitrite on microbial activity in an acid soil. Appl. Environ. Microbiol. 38:940-944.

Berntsen, J., A. Thomsen, K. Schelde, O.M. Hansen, L. Knudsen, N. Broge, H. Hougaard, and R. Horfarter. 2006. Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. Prec. Agric. 7:65-83.

Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware. 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. J. Geophys. Res. 97:787-801.

Biermacher, J.T., F.M. Epplin, B.W. Brorsen, J.B. Solie, and W.R. Raun. 2006. Maximum benefit of a precise nitrogen application system for wheat. Prec. Agric. 7:193-204.

Black, C.A. 1993. Soil fertility evaluation and control. Lewis Publishers, Boca Raton, FL.

Blackmer, T.M., and J.S Schepers. 1995. Use of chlorophyll meter to monitor N status and schedule fertigation for corn. J. Prod. Agric. 8:56-60.

Boddey, R.M., J.C. Polidoro, A.S. Resende, B.J.R. Alves, and S. Urquiaga. 2003 Endophytic nitrogen fixation in sugarcane: present knowledge and future application. Plant Soil. 252:139-149.

Boddey, R.M., O. de Oliveira, S. Urquiaga, V. Reis, F. Olivares, and V. Baldani. 1995. Biological nitrogen fixation associated with sugarcane and rice: contributions and prospects for improvement. Plant Soil. 174:195-209.

Bouwman, A.F., D.S. Lee, W.A.H. Asman, F.J. Dentener, K.W. Van Der Hoek, and J.G.J. Olivier. 1997. A global high-resolution emission inventory for ammonia. Global Biogeochemical Cycles. 11:561-587.

Brady, N.C. and R.R. Weil. 2003. The nature and properties of soils. 13th ed. Pearson Education Inc. Upper Saddle River, NJ.

Bronson, K.F., T.T. Chua, J.D. Booker, J.W. Keeling, and R.J. Lascano. 2003. In-season nitrogen status sensing in irrigated cotton: II. Leaf nitrogen and biomass. Soil Sci. Soc. Am. J. 67:1439-1448.

Chapman, L.S., M.B.C. Haysom, and P.G. Saffigna. 1994. The recovery of 15N labeled urea fertilizer in crop components of sugarcane and in soil profiles. Australian Journal of Agricultural Research. 45:1577-1587.

Courtaillac, N., R. Baran, R. Oliver, H. Casabianca, and F. Ganry. 1998. Efficiency of nitrogen fertilizer in the sugarcane-vertical system in Guadeloupe according to growth and ratoon age of the cane. Nutrient Cycling Agroecosystems. 52:9-17.

Craswell, E.T. 1978. Some factors influencing denitrification and nitrogen immobilization in a clay soil. Soil Biol. Biochem. 10:241-245.

Curtis, O.D., and D.T. Loupe. 1975. Fertilizer and soil fertility practices for sugarcane production in Louisiana. Sugar Bulletin. 53:14-15.

De Boer, W., and G.A. Kowalchuk. 2001. Nitrification in acid soils: micro-organisms and mechanisms. Soil Bio. Biochem. 33:853-866.

de Geus, J.G. 1973. Sugar crops. In: J.G. de Geus et al., editors, Fertilizer guide for the tropics and subtropics. 2nd ed. Centre d'etude de l'azote, Zurich, Germany. p. 136-182.

Denmead, O.T., J.R. Simpson, and J.R. Freney. 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. Soil Sci. Soc. Am. J. 46:149-155.

Engels, C., and H. Marschner. 1995. Plant uptake and utilization of nitrogen. In: P.E. Alexander, editor, Nitrogen fertilization in the environment. Marcel Dekker, Inc. New York, NY. pg. 41-82.

Fageria, N.K., and V.C. Baligar. 1999. Yield and yield components of lowland rice as influenced by timing and nitrogen fertilization. J. Plant Nutr. 22:23-32.

Focht, D.D. and W. Verstraete. 1977. Biochemical ecology of nitrification and denitrification. In: M. Alexander, editor, Advances in microbial ecology. Plenum Press, New York. p. 135-214.

Fox, R.H., and C.L. Walthall. 2008. Crop monitoring technologies to assess nitrogen status. In: J.S. Schepers and W.R. Raun, editors, Nitrogen in Agricutlural Systems. ASA, CSSA, and SSSA, Madison, WI. p. 647-674.

Fox, R.H., W.P. Piekielek, and K.M. Macneal. 1994. Using a chlorophyll meter to predict nitrogen fertilizer needs of winter wheat. Commun. Soil Sci. Plant Anal. 25:171-181.

Freney, J.R., O.T. Denmead, A.W. Wood, P.G. Saffigna, L.S. Chapman, G.J. Ham, A.P. Hurney, and R.L. Stewart. 1992. Factors controlling ammonia loss from trash covered sugarcane fields fertilizer with urea. Fert. Res. 31:341-349.

Galloway, J.N., and E.B. Cowling. 2002. Reactive nitrogen and the world: 200 years of change. AMBIO. 32:64-71.

Golden, L.E. 1981. The effects of selected elements in fertilizers on the uptake of these elements by sugarcane. Am. S. Sugar Cane Tech. 2:22-28.

Guyot, G. 1991. Optical properties of vegetation canopies. In: M.D. Steven and J.A. Clark, editors, Application of remote sensing in agriculture. Butterworths, London.

Hawthorn, C. 2010. Agricultural statistics. USDA-NASS. http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS (date accessed August 2010).

Havlin, J.L., J.D. Beaton, S.L. Tisdal, and W.L. Nelson. 2005. Soil fertility and nutrient management. 7th ed. Prentice Hall. Upper Saddle River, NJ.

Havrankova, J., V. Rataj, R.J. Godwin, and G.A. Wood. 2007. The evaluation of ground based remote sensing systems for canopy nitrogen management in winter wheat-economic efficiency. Agricultural Engineering International, the CIGAR Ejournal Manuscript CIOSTA 07 002. Vol IX.

Hodgen, P.J., W.R. Raun, G.V. Johnson, R.K. Teal, K.W. Freeman, K.B. Brixey, K.L. Martin, J.B. Solie, and M.L. Stone. 2005. Relationship between response indices measured in-season and at harvest in winter wheat. J. Plant Nutr. 28:221-235.

Hodges, J.D. 1997. Development and evology of bottomland hardwood sites. Forest Ecology and Management. 90:117-125.

Hoefsloot, G., A.J. Termorshuizen, D.A. Watt, and M.D. Cramer. 2005. Biological nitrogen fixation is not a major contributor to the nitrogen demand of a commercially grown South African sugarcane cultivar. Plant Soil. 277:85-96.

Hussain, F., K.F. Bronson, Y. Singh, and S. Peng. 2000. Use of chlorophyll meter sufficiency indice for nitrogen management of irrigated rice in Asia. Agron. J. 92:875-879.

Johnson, R.M., and E.P. Richard Jr. 2005. Sugarcane yield, sugarcane quality, and soil variablility in Louisiana. Agron. J. 97:760-771.

Johnson, R.M., H.P. Viator, and B.L. Legendre. 2008. Sugarcane fertilizer recommendations for the 2008 crop year. Sugar Bulletin. 86:11-13.

Johnson, G.V., and W.R. Raun. 2003. Nitrogen response index as a guide to fertilizer management. J. Plant. Nutr. 26:249-262.

Kaplan, W., I. Valiela, and J.M. Teal. 1979. Denitrification in a salt marsh ecosystem. Limnol. Oceanogr. 24:728-734.

Karlen, D.L., L.A. Kramer, and S.D. Logsdon. 1998. Field-scale nitrogen balances associated with long-term continuous corn production. Agron. J. 90:644-650.

Ketterings, Q.M., S.D. Klausner, and K.J. Czymmek. 2003. Nitrogen guidelines for field crops in New York. 2nd ed. Department of crop and soil extension series E03-16. Cornell Univeristy, Ithaca, NY.

Khan, D.H., and G.H. Rashid. 1971. Losses of nitrogen from urea in soil soils of East Pakistan. Exp. Agric. 7:107-112.

Knowles, R., and T. Blackburn. 1993. Nitrogen isotope techniques. Academic Press, San Diego, USA.

Killham, K. 1994. Soil ecology. Cambridge Univ. Press, New York.

Koops, H.P., B. Bottcher, U.C. Moller, A. Pommerening-Roser, and G. Stehr. 1991. Classification of eight new species of ammonia-oxidizing bacteria: *Nitrosomonas communis* sp nov, *Nitrosomonas ureae* sp nov., *Nitrosomonas aestuarii* sp nov., *Nitrosomonas marina* sp nov., *Nitrosomonas nitrosa* sp nov., *Nitrosomonas oligotropha* sp nov., *Nitrosomonas halophila* sp nov. J. Gen. Microbiol. 137:1689-1699.

Legendre, B.L. 2001. Sugarcane production handbook. Pub. 2859. Louisiana State University AgCenter, Baton Rouge, LA.

Legendre, B.L., F.S. Sanders, and K.A. Gravois. 2000. Sugarcane production best management practices. Pub. 2833. Louisiana State University AgCenter, Baton Rouge, LA.

Lukina, E.V., W.R. Raun, M.L. Stone, J.B. Solie, G.V. Johnson, H.L. Lees, J.M. LaRuffa, and S.B. Phillips. 2000. Effect of row spacing growth stage, and nitrogen rate on spectral irradiance in winter wheat. J. Plant Nutr. 23:103-122.

Magdoff, F.R. 1991. Managing nitrogen for sustainable corn systems: Problems and possibilities. Am . J. Altern. Agric. 6:3-8.

Martin, G.C., J.S. Shenk, and F.E. Barton II. 1989. Near infrared reflectance spectroscopy (NIRS): Analysis of forage quality. USDA-ARS Agric. Handb. 643.

McGarity, J.W., and E.H. Hoult. 1971. The plant component as a factor in ammonia volatilization from pasture swards. J. Br. Grassl. Soc. 26:31-34.

Melaj, M.A. H.E. Echeverrya, S.C. Lopez, and G. Studdert. 2003. Timing of nitrogen fertilization in wheat under conventional and no-tillage system. Agron. J. 95:1525-1531.

Meyers, R.D., R.A. Olson, and H.F. Rhoades. 1961. Ammonia losses from fertilized Nebraska soils. Agron. J. 53:241-244.

Muchow, R.C., M.J. Robertson, A.W. Wood, and B.A. Keating. 1996. Effect of nitrogen on the time-course of sucrose accumulation n sugarcane. Field Crop Res. 47:143-153.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

Munson, R.D., and W.L. Nelson. 1990. Principles and practices in plant analysis. In: R.L. Westerman, editor, Soil testing and plant analysis. 3rd ed. SSSA Book Series. SSSA, Madison, WI. p. 359-387.

Myrold, D.D. 1998. Microbial nitrogen transformations. In: D.M. Sylvia et al., editors, Principles and applications of soil microbiology. Prentice Hall, Upper Saddle River, NJ. p. 259-294.

Myrold, D.D. and P.J. Bottomley. 2008. Nitrogen mineralization and immobilization. In: J.S. Schepers and W.R. Raun, editors, Nitrogen in agricultural systems. ASA, CSSA, and SSSA, Madison, WI. p.156-172.

Norton, J.M. 2000. Nitrification. In: M. Sumner, editor, Handbook of soil science. CRC Press, Inc., Boca Raton, FL. p.160-181.

Olfs, H.W., K. Blankenau, F. Brentrup, J. Jasper, A. Link, and J. Lammel. 2005. Soil- and plant-based nitrogen-fertilizer recommendations in arable farming. J. Plant Nutri. Soil Sci. 168:414-431.

Paul, E.A., and F.E. Clark. 1996. Soil microbiology and biochemistry. 2nd ed. Academic Press, San Diego, CA.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. NebGuide. Coop. Ext., Institute of Agric. and Natural Res., Univ. Nebraska, Lincoln.

Piekielek, W.P., and R.H. Fox. 1992. Use of a chlorophyll meter to predict sidedress N requirement for maize. Agron. J. 84:59-65.

Prasertsak, P., J.R. Freney, O.T. Denmead, P.G. Saffigna, B.G. Prove, and J.R. Reghenzani. 2002. Effect of fertilizer placement on nitrogen loss from sugarcane in tropical Queensland. Nutrient Cycling Agroecosystems. 62:229-239.

Prosser, J.I. 1989. Autotrophic nitrification in bacteria. Adv. Microb. Physiol. 30:125-181.

Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Tomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131-138.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with sensing and variable rate application. Agron. J. 94:815-820.

Saby, B.R. 1969. Influence of moisture tension on nitrate accumulation in soils. Soil Sci. Soc. Am. Proc. 33:263-266.

Samuels, G. 1969. Major element nutrition with respect to foliar diagnosis. In: G. Samuels, editor, Foliar diagnosis of sugarcane. Adams Press, Chicago. p.217-243.

Schepers, J.S., T.M. Blackmer, and D.D. Francis. 1998. Chlorophyll meter method for estimating nitrogen content in plant tissue. In: Y.P. Kalra, editor, Handbook of reference method for plant analysis. CRC Press, Boca Raton, FL. p.129-135.

Schjonning, P., I.K. Tomsen, P. Moldrup, and B.T. Christensen. 2003. Linking soil microbial activity to water- and air-phase contents and diffusivities. Soil Sci. Soc. Am. J. 65:156-165.

Schulten, H.R., and M. Schnitzer. 1998. The chemistry of soil organic nitrogen: a review. Biol. Fert. Soils. 26:1-15.

Skiba, U., K.A. Smith, and D. Fowler. 1993. Nitrification and denitrification as sources of nitric oxide and nitrous oxide in a sandy loam soil. Soil Biol. Biochem. 25:1527-1536.

Smith, J.L., and E.A. Paul. 1990. The significance of soil microbial biomass estimations. In: J. Bollag and G. Stotzky, editors, Soil biochemistry. Vol. 6. Marcel Dekker, New York. p.357-396.

Sorokin, D.Y. 1998. On the possibility of nitrification inextremely alkaline soda biotopes. Microbiol. 67:335-339.

Sorokin, D.Y., G.A. Kowalchuk, D. DeJong, E. Kline, J.R. Stephen, and H.J. Laanbroek. 2001. Microvariation artifacts introduced by PCR and cloning of closely related 16S rRNA gene sequences. Appl. Environ. Microbiol. 67:469-472.

Srivastava, S.C., and N.R. Suarez. 1992. Sugarcane. In: W. Wichmann, editor, World Fertilizer use manual. BASF AG, Germany. p. 257-266.

Southwick, L.M., G.H. Willis, D.C. Johnson, and H.M. Selim. 1995. Leaching of nitrate, atrazine, and metribuzin from sugarcane in Southern Louisiana. J. Envir. Qual. 24:684-690.

Stanturf, J.A., and S.H. Schoenholtz. 1998. Soils and landforms. In: M.G. Messina and W.H. Conner, editors, Southern forested wetlands: ecology and management. Boca Raton, FL. Lewis Publishers/CRC Press. p.123-147.

Stark, J.M., and M.K. Firestone. 1995. Mechanisms for soil moisture effects on activity of nitrifying bacteria. Appl. Environ. Microbiol. 62:218-221.

Stone, M.L., J.B. Solie, R.W. Whitney, and W.R. Raun. 1996. Sensor for detection of nitrogen in winter wheat. Trans. ASAE. 39:1623-1631.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488-1494.

Thomas, J.R., and G.F. Oerther. 1972. Estimating nitrogen content of sweet pepper leaves by reflectance measurements. Agron. J. 64:11-13.

Thomas, J.R., and G.F. Oerther, Jr. 1977. Estimation of crop conditions and sugar cane yields using aerial photography. Proc. Am. Soc. Sugar Cane Technol. 6:93-99.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature. 418:671-677.

Tremblay, N., and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal condition with the least impact on-the environment. Horticulture technology. 16:408-412.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Tucker, T.C. 1984. Diagnosis of nitrogen deficiency in plants. In: R.D. Hauck, editor, Nitrogen in crop production. ASA, CSSA, SSSA, Madison, WI. p. 249-262.

Turner, F.T., and M.F. Jund. 1994. Assessing N requirements of rice crop with a chlorophyll meter. Aust. J. Exp. Agric. 34:1001-1005.

Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997. Chlorophyll meter and stalk nitrate techniques as complementary indices for residual nitrogen. J. Prod. Agric. 10:147-151.

Viator, R.P., D.D. Garrison, E.O. Dufrene, T.L. Tew, and E.P. Richard. 2005. Planting method and timing effects on sugarcane yield. Crop Management. Online.

Vjek, P.J.G., I.R.P. Fillery, and J.R. Burford. 1981. Accession, transformation, and loss of nitrogen in soils of the arid region. Plant and Soil. 58:133-175.

Wedin, D.A., and D. Tilman. 1996. Influence of nitrogen loading and species composition on the carbon balance of grasslands. Science. 274:1720-1723.

Whelpdale, M.L., and M.S. Kaiser. 1997. Global acid deposition assessment. Report number 106. World Meterological Organization, Geneva, Switzerland.

Wiedenfeld, R.P. 1995. Effects of irrigation and N fertilizer application on sugarcane yield and quality. Field Crop Res. 43:101-108.

Wiedenfeld, R.P. 1997. Sugarcane responses to nitrogen fertilizer application on clay soils. J. Amer. Soc. Sugar Cane Technol. 17:14-27.

Wood, A.W., R.C. Muchow, and M.J. Robertson. 1996. Growth of sugarcane under high input conditions in tropical Australia. III. Accumulation, partitioning and use of nitrogen. Field Crop Res. 48:223-233.

Wood, R.A. 1964. Analogous nitrogen mineralization effects produced by soils undergrass leys and sugar cane. Int. Congr. Soil Sci. 8:255-260.

Wood, R.A. 1990. The roles of nitrogen, phosphorus and potassium in the production of sugarcane in South Africa. Fert. Res. 26:89-98.

Yoneyama, T., T. Muraoka, T.H. Kim, E.V. Dacanay, and Y. Nakanishi. 1997. The natural 15N abundance of sugarcane and neighbouring plants in Brazil, the Philippines and Miyako. Plant Soil. 189:239-244.

Zhang, J., A.M. Blackmer, J.W. Ellsworth, and K.J. Koehler. 2008. Sensitivity of chlorophyll meters for diagnosing nitrogen deficiencies of corn in production agriculture. Agron. J. 100:543-550.

Zhao, D., K.R. Reddy, V.G. Kakani, J.J. Read, and G.A. Carter. 2003. Corn growth, leaf pigment concentration, photosynthesis and leaf hyperspectral reflectance properties as affected by nitrogen supply. Plant Soil. 257:205-217.

Zillmann, E., S. Graeff, J. Link, W.D. Batchelor, and W. Claupein. 2006. Assessment of cereal nitrogen requirements derived by optical on-the-go sensors on heterogeneous soils. Agron. J. 98:682-690.

Zuberer, D.A. 2005 Biological dinirogen fixation: introduction and nonsymbiotic. In: D.M. Sylvia et al., editors, Principles and applications of soil microbiology. Prentice Hall. Upper Saddle River, NJ.

Chapter 2. Predicting Sugarcane Response to Nitrogen Using a Canopy Reflectance-Based Response Index Value*

2.1 Introduction

Sugarcane (*Saccharum officinarum*) is one of the most important row-crops in Louisiana with economic values exceeding over $2 billon (Legendre et al., 2000). Sugarcane is an integral part of Louisiana's economy thus it is essential to employ production technologies which will help decrease cost of production and environmental risk while maximizing yields. Applying N only when the crops are responsive will not only improve production, but also decrease the potential of over-application (Lukina et al., 2000; Flowers et al., 2004). Over-application of N fertilizers can lead to excess NO_3-N accumulation in the soil, potentially leading to pollution of ground and surface waters (Embelton et al., 1986; Vyn et al., 1999; Chen et al., 2004). Goolsby et al. (2001) reported that mean annual discharge of all forms of N down the Mississippi Tiverwas approximately 1,568,000 MT yr^{-1}.

Sugarcane is a semi-perennial crop and is harvested for at least two additional years after the first harvest, which are termed plant cane for the first crop after planting and stubble cane for the subsequent crops after the first harvest. Plant cane is generally not responsive to N fertilization; however, this does not apply to the following stubble cane crops. In Louisiana, N fertilizer recommendations are established based on multi-site and multi-year response trials using the most prevalent cane varieties in the state. The recommendations are further refined for specific crop age i.e. plant and stubble cane, and soil type, generalized as either light textured soil or heavy textured soil (Legendre et al., 2000). Unlike most other cropping systems, current growing conditions and soil N levels

*Permission to reprint from Agronomy Journal are not accounted for when determining N recommendations. Therefore, there is a potential risk of over- or under-application of N fertilizers. Shanahan et al. (2008) reported that implementation of in-season monitoring approach to guide N management decision in cereal production can improve the precision of N recommendation. Similarly in sugarcane, a more robust approach to guide N fertilizer recommendation that can be adjusted based on current growing conditions is needed to minimize this risk.

One way to derive N recommendation, specifically in grain crop production, is based on pre-plant established yield goal and soil NO_3-N level (Meisinger et al., 2008). To determine N recommendation rate, the soil NO_3-N level is subtracted from the crop's total N requirement associated with a specified yield goal (Meisinger et al., 2008). The soil sample can be obtained either prior to planting, pre-plant soil testing (PPST), or prior to sidedress application, pre-sidedress soil test (PSST). Meisinger et al. (2008) noted that while PSST may achieve a higher degree of accuracy over PPST in determining crop N demand, these soil tests generally will have limited application in humid regions where there is high leaching potential. Evanylo and Alley (1997) reported that only 13 out of 47 sites over two years showed a significant response to sidedress application of N in corn (*Zea mays).* This lack of response was attributed to high plant available N from mineralization of organic sources.

Due to the reported limitations of soil-test based N recommendation, research has been centered to develop in-season monitoring approach as a guide to N management decisions. Several studies reported that hand-held chlorophyll meters can accurately predict N requirement based on a sufficiency index (Wood et al., 1992; Blackmer and Schepers, 1995; Waskom et al., 1996) computed in equation 2.1.

$$\text{Sufficiency index (\%)} = [(\text{fertilizer needed plot})/(\text{well fertilized plot})] \qquad (2.1)$$

According to Varvel et al. (1997), additional N is recommended when sufficiency index values fall below 95%. One major limitation of using chlorophyll meters to determine N fertilizer recommendations is obtaining a representative sample across a highly variable field (Blackmer and Schepers, 1995). In addition to field scale variability, chlorophyll meters can produce highly variable values within a single plant (Peterson et al., 1993). Therefore, obtaining accurate values in highly variable environments can be costly and time consuming.

Several reports have shown that plant indices based on spectral reflectance can be used to accurately predict crop physiological variables, including plant biomass (Tucker, 1979), photosynthesis (Zhao et al., 2003), chlorophyll content (Tucker, 1979), plant N status (Bronson et al., 2003), and yield (Raun et al., 2002; Zhao et al., 2003). One of the most widely used plant indices is normalized difference vegetative index (NDVI). According to Rouse et al. (1973), NDVI is calculated by comparing reflectance at the red and near infrared regions of the electromagnetic spectrum based equation 2.2.

$$\text{NDVI} = (\rho_{\text{NIR}}-\rho_{\text{Red}})/(\rho_{\text{NIR}}+\rho_{\text{Red}}) \qquad (2.2)$$

where:

ρ_{NIR}= reflectance at the near infrared (NIR) region

ρ_{Red}= reflectance at the red region

Ma et al. (1996) reported that NDVI showed a stronger relationship to different N treatments compared to other indices. Also, NDVI values were well correlated with both leaf chlorophyll and leaf area.

Johnson and Raun (2003) introduced response index (RI) as a measure of the plant's response to additional N fertilizer. According to Mullen et al. (2003) and Hodgen et al. (2005), midseason NDVI readings can be used to determine RI. The RI is determined by comparing a check plot (0 N applied) with a reference plot, traditionally used as a high N rate plot where N is not the most limiting factor (Johnson and Raun, 2003). They determined RI using in-season estimates of biomass (RI_{NDVI}) and yield at harvest ($RI_{Harvest}$) based on equations 2.3 and 2.4.

$$RI_{NDVI} = (NDVI_{Non\text{-}limiting})/(NDVI_{Check}) \tag{2.3}$$

$$RI_{Harvest} = (Yield_{Non\text{-}limiting})/(Yield_{Check}) \tag{2.4}$$

Mullen et al. (2003) reported a strong correlation between RI_{NDVI} and the $RI_{Harvest}$ in winter wheat (*Triticum aestivum* L.). Hodgen et al. (2005) reported similar results, in winter wheat, showing that RI_{NDVI} and $RI_{Harvest}$ were well correlated. The relationship between RI_{NDVI} and $RI_{Harvest}$ as a function of time was also evaluated by several researchers. Chung et al. (2010) found that the relationship between RI_{NDVI} and $RI_{HARVEST}$ in winter wheat was not constant throughout the growing season. They found that the linear relationship between RI_{NDVI} and $RI_{Harvest}$ became stronger until Feekes growth stage 7, at which point the relationship stabilized. Hodgen et al. (2005) reported a decrease in the strength of the relationship between RI_{NDVI} and $RI_{Harvest}$ at later growth stages, specifically Feekes stage 11, due to early maturation of the check plots.

The RI_{NDVI} is a component of an in-season N decision tool developed by Raun et al. (2002), in which an area that has received either a small amount or no N applications (check) is compared to a reference plot. The reference plots are areas which have received a high rate of N to represent an area which is not limited by N. Many researchers have substantiated the value of this decision tool as a practical technology to improve N management in crop production in the U.S.A., Canada, and other countries (Olfs et al., 2005; Berntsen et al., 2006; Biermacher et al., 2006; Tremblay and Belec, 2006; Zillmann et al., 2006). Based on these recent reports, the concept of RI_{NDVI} offers a considerable promise to improve N management in sugarcane production. However, there is no existing information on the use of canopy reflectance to estimate RI in sugarcane. The objectives of this study were to: 1) determine if sugarcane yield response to N fertilizer ($RI_{Harvest}$) can be predicted using in-season canopy reflectance readings (RI_{NDVI}), and 2) determine the minimum number of weeks from the time of N fertilization when RI_{NDVI} could be used to estimate $RI_{Harvest}$.

2.2 Materials and Methods

Field data was collected from different N fertility field research trials in St. Gabriel (30°15′13″N 91°06′05″W) and Jeanerette (29°54′59″N 91°40′21″W), Louisiana from 2008-2010 (Table 2.1). Soils for each trial are as follows: Commerce silt loam (Fine-silty, mixed, superactive, non-acid, thermic Flucaquentic Endoaquept) for Experiments 1, 2, 3, 4 and 9; Canciene silty clay loam (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquept) for Experiments 5, 6, 7, and 8; and Baldwin silty clay loam (Fine, smectitic, hyperthermic, Chromic Vertic Epiaqualf) for Experiments 10

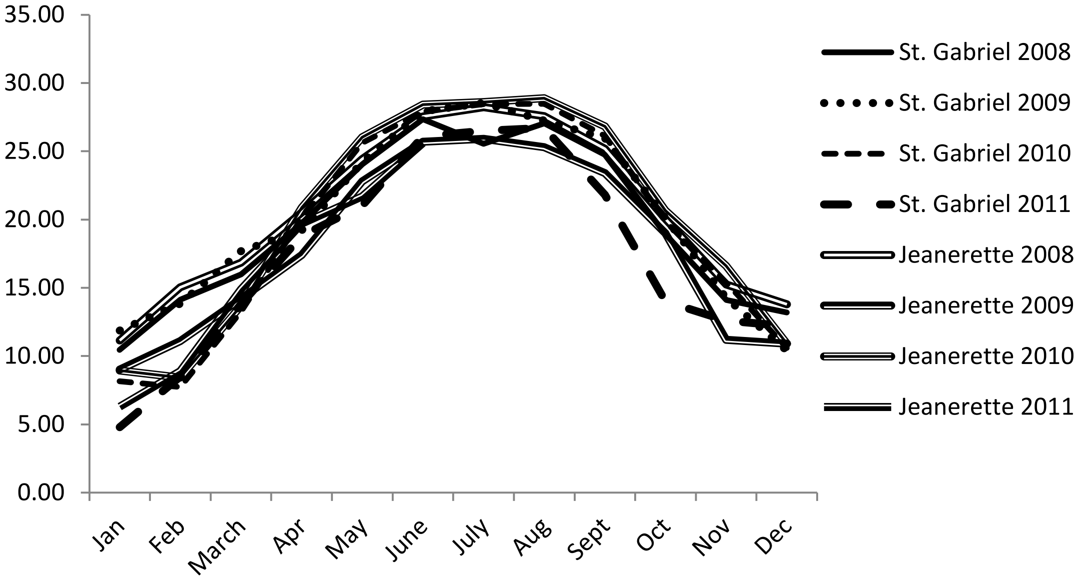


Figure 2.1. Average monthly temperatures from the beginning of the season until harvest observed in 2008 to 2010 at St. Gabriel and Jeanerette, LA (LSU AgWeather, 2011).

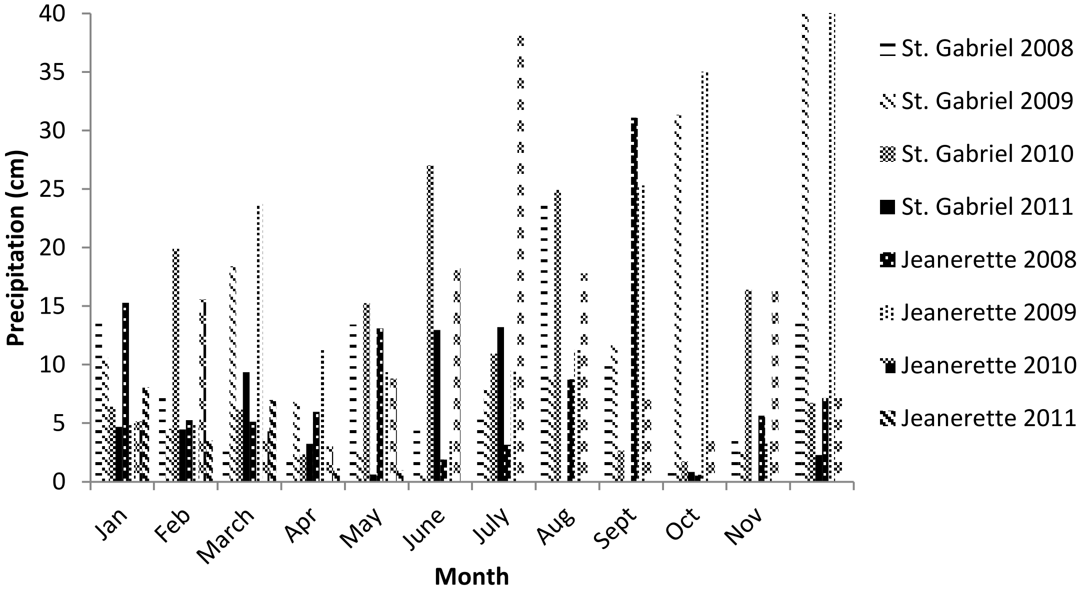


Figure 2.2. Average monthly precipitation from the beginning of the season until harvest observed in 2008 to 2010 at St. Gabriel and Jeanerette, LA (LSU AgWeather, 2011).

and 11. Average monthly temperatures and rainfall for each site are provided in Figures 2.1 and 2.2.

All experiments were independent trials with different purpose and treatment structure. Descriptions of the experiments, planting date, harvest date, and time of fertilization are detailed in Table 2.1. Additionally, varieties used for all experiments are presented in Table 2.2. Trials were planted on 3-bed plots, measuring 2 m wide with length ranging from 8-15 m long. The specific lengths for each plot are as follows: Plot length for Experiments 1, 2, 3, 4, 5 and 8 was 15 m; Experiment 7, 13.3 m; Experiment 6, 11.6 m; and Experiment 9, 8 m. Except for Experiment 6, all trials were planted by hand using whole stalks. Each opened planting furrow was filled with whole stalks at the rate of three stalks side-by-side across planting furrow i.e. three-whole stalks were placed with an overlapped of 8 cm or minimum of two mature internodes on the next three-whole stalks. Experiment 6 was planted using billets, sugarcane stalk cut into approximately 50 cm-segments, at the rate of six billets across the planting furrow. These billets are then planted in 50 cm sections down the planning furrow. The sugarcane in each row was covered with approximately 6 cm of soil and pressed firmly using a custom roller packer.

Trials received the same N fertilization rates (0, 45, 90, and 135 kg N ha^{-1}) applied as urea-ammonium nitrate (UAN; 32-0-0) with the exception of Experiments 2, 3, 5 (2008), and 8 (Table 2.3), which received the following N rates: Experiment 2, received 0 and 135 kg N ha^{-1}; Experiment 3, received 0, 45, and 90 kg N ha^{-1}; Experiment 5, received 0, 17, 67, 135, and 201 kg N ha^{-1}; Experiment 8, received 0, 45, 90, 135, and 180 kg N ha^{-1}. Weeds in plots were controlled according to LSU AgCenter's current

Table 2.1. Field activity information of all the experiments established in St. Gabriel and Jeanerette, LA 2008-2011.

Experiment No.	Year	Crop	Description	Location	Planting date	Spring fertilization date	Harvest date
1	2008	2nd Stubble‡	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2006	15 Apr.	27 Oct.
2	2008	2nd Stubble	N Response Study	St. Gabriel, LA	Aug. 2006	15 Apr.	27 Oct.
3	2008	1st Stubble	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2007	15 Apr.	4 Nov.
	2009	2nd Stubble	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2007	15 Apr.	4 Nov.
4	2008	1st Stubble	Variety x N rate	St. Gabriel, LA	Aug. 2006	17 Apr.	5 Nov.
	2009	2nd Stubble	Variety x N rate	St. Gabriel, LA	Aug. 2006	29 Apr.	4 Nov.
5	2008	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2007	14 Apr.	17 Nov.
	2009	1st Stubble	Variety x N rate	St. Gabriel, LA	Sept. 2007	6 Apr.	18 Nov.
6†	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	15 Apr.	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	29 Apr.	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	13 May	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	27 May	8 Dec.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	13 Apr.	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	23 Apr.	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	11 May	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	25 May	8 Nov.
7	2010	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2009	22 Apr.	22 Nov.
	2011	1st Stubble	Variety x N rate	St. Gabriel, LA	Sept. 2009	13 Apr.	3 Nov.
8	2011	2nd Stubble	Variety x N rate	St. Gabriel, LA	Sept. 2007	12 Apr.	13 Oct.
9	2011	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2010	13 Apr.	1 Dec.
10	2008	2nd Stubble	Variety x N rate	Jeanerette, LA	Aug. 2006	25 Apr.	13Nov.
11	2010	Plant Cane	Variety x N rate	Jeanerette, LA	Nov. 2009	23 Apr.	17 Nov.
	2011	1st Stubble	Variety x N rate	Jeanerette, LA	Nov. 2009	11 Apr.	18 Oct.

†Four values are for the different spring N fertilization times, which yield was calculated separately for each timing.

‡Stubble crop indicates the crop grown after the first year's harvest.

Table 2.2. Varieties used in all experiments from 2008 to 2011 in St. Gabriel and Jeanerette, Louisiana.

Experiment No.	Variety
1	Ho 95-988
2	L 97-128
3	L 97-128
4	L 99-226
	L 99-233
5	L 99-226
	LCP 85-384
	HoCP 96-540
6	L 01-283
7	L 99-226
	L 01-283
	HoCP 96-540
8	L 97-128
9	L 99-226
	L 01-283
	HoCP 96-540
10	HoCP 00-950
11	L 99-226
	L 01-283
	HoCP 96-540

herbicide recommendations where metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methyltio-1,2,4-triazin-5-one) was applied in early spring prior to emergence of the current sugarcane crop and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) was applied when beds were rebuilt in late spring (lay-by), approximately middle of May.

GreenSeeker® hand held optical active sensor (Trimble Navigation, Ltd., Sunnyvale, California) was used to collect NDVI readings at all locations. The sensor measured within red (670±10 nm) and NIR (780±10 nm) regions and calculated NDVI based on equation 2.2. Sensor readings were taken weekly for three weeks beginning in May, approximately three weeks after fertilization. The RI_{NDVI} were calculated by taking average values of NDVI readings from the non-limiting N rate plots, between 90 to 201 kg N ha^{-1}, and dividing by the check plot, 0 kg N ha^{-1} (Johnson and Raun, 2003). The $RI_{Harvest}$ was calculated for both cane tonnage and sugar yield. Both were calculated similar to RI_{NDVI} i.e. by dividing the yield from the non-limiting N plots by the yield of the check plot.

Plots were mechanically harvested using a Cameco C2500 chopper harvester (Cameco Industries, Thibodaux, LA). Total plot yield was determined by obtaining the millable stalks from each of the three rows in each plot using a weigh wagon fitted with load cells. Ten stalks were randomly selected from the middle row; leaves were stripped from the stalks that were cut approximately 10 to 12 cm below the apical meristem. After mean 10-stalk weight determination, these samples were shredded and analyzed for sugar quality measurements using a Spectracane Near Infrared System (Bruker Coporation, Billerica, Massachusetts). Statistical analysis was performed using the SAS program for Windows (SAS, 2009). For each individual experiment, ANOVA was performed for cane tonnage and sugar yield using PROC MIXED with a Satterthwaite approximation, where fixed effect was N rate and random effect was replication. Differences between N fertilized plots and the check plots were analyzed using a Dunnett's test. The variety by N rate interaction effect for Experiments 4, 5, 7, 8 and 9 was not significant therefore values were reported across variety. For Experiments 1 and 3, the result of ANOVA showed no significant effect of either the foliar treatment or foliar by N rate interaction;

therefore, values were reported across foliar treatment. Regression analysis was performed using PROC REG to determine the relationship between RI_{NDVI} and $RI_{Harvest}$.

2.3 Results and Discussion

2.3.1 Sugarcane Response to N Fertilization

Cane tonnage and sugar yields were highly variable across the experiments (Table 2.3). Sugarcane yields ranged from 31 Mg ha^{-1} to 100 Mg ha^{-1} for cane tonnage and 4.19 Mg ha^{-1} to 12.45 Mg ha^{-1} for sugar yields. Experiment 11 in 2011 yielded the greatest (135 kg N ha^{-1}) while Experiment 8 in 2008 yielded the least (0 kg N ha^{-1}) (Table 2.3). Johnson and Richard (2005) reported similar variability between sugarcane yields. This variability in cane tonnage and sugar yield can be partially explained by the differences in the amount of precipitation (Figure 2.2). St. Gabriel in 2010 received the highest rainfall in the month of June during the initiation of grand growth, at which time water consumption is highest (Gascho, 1985). In addition to low moisture, the lower yields for Experiment 8 for 2008 can be attributed to the age of the sugarcane, being second stubble. Johnson and Richard (2005) reported that sugarcane yield tended to decrease with crop age.

Sugarcane yields did not consistently respond to applied N with highest significant yield differing between years (Table 2.3). All plant cane experiments did not significantly respond to applied N (P<0.05), which is consistent with earlier reports by Carnauba (1990) and Wiedenfeld (1995). This lack of yield response, which is commonly observed in Louisiana sugarcane, is due to planting normally occurring after a fallow period, which allows for natural increase soil N reserves (Thorburn et al., 2005). Conversely, stubble crops in Experiment 3 (2009), Experiment 4 (2008), and

Table 2.3. Average cane tonnage and sugar yield at different nitrogen fertilizer rates for all experiments in St. Gabriel and Jeanerette, LA 2008-2010.

		Cane tonnage				Sugar yield			
Experiment No.	Crop age	0N†	45	90	135	0	45	90	135
						Mg ha^{-1}			
1	2nd stubble	68	71	**73‡**	71	8.53	8.76	**9.06**	8.68
2§	2nd stubble	39	-	-	**68**	5.21	-	-	**7.54**
3§	1st stubble	71	74	**77**	-	8.72	8.94	**9.20**	-
	2nd stubble	54	53	55	-	6.15	6.07	6.36	-
4	1st stubble	56	62	63	61	6.87	7.34	7.35	7.17
	2nd stubble	51	69	**76**	75	5.13	7.13	**7.65**	7.49
5¶	Plant cane	83	75	85	83	10.53	9.46	10.49	10.25
	1st stubble	49	**54**	48	53	2.25	2.52	2.82	**3.16**
6#	Plant cane	97	88	89	91	12.45	11.43	11.40	11.66
	1st stubble	58	66	**70**	68	**10.09**	8.69	9.04	8.82
7	Plant cane	83	90	85	91	10.20	11.95	12.87	13.27
	1st stubble	46	62	**79**	77	5.64	7.82	**10.00**	9.68
8	2nd stubble	39	43	41	41	4.41	4.62	4.40	4.34
9	Plant cane	81	83	86	90	10.20	10.50	10.80	11.40
10††	2nd stubble	31	51	**53**	44	4.19	6.79	**7.35**	6.00
11	Plant cane	66	68	70	65	8.26	8.38	8.98	7.86
	1st stubble	83	92	85	**100**	10.88	11.22	10.61	**11.37**

†Indicate applied N rates in kg N ha^{-1}.

‡ Bolded values indicate the highest significant yield in response to applied N within an experiment ($P<0.05$).

§Data points were not available due to particular plots did not receive designated N rates.

¶ N rates used were 0, 17, 67, 135, and 201 kg N ha^{-1}. Yield values for the 45 and 90 kg N ha^{-1} columns were plots which received 17 and 67 kg N ha^{-1}, respectively. Aditionally 201 kg N ha^{-1} yielded 83 MT ha^{-1} and 10463 kg ha^{-1} for cane tonnage and sugar yield, respectively.

Indicate a significant response ($P<0.05$); however, the highest significant yield was the check plot.

†† Additionally 180 kg N ha^{-1} yielded 64 Mg ha^{-1} and 8.8 Mg ha^{-1} for cane tonnage and sugar yield, respectively.

Experiment 9 (2011) did not significantly (*P*<0.05) respond to applied N which can be attributed to either high natural N additions or a more limiting growth factor such as temperatures and precipitation, or essential plant nutrients. For N responsive site-years, it can be observed that increases in cane tonnage and sugar yields due to applied N were highly variable. For example, increases in sugarcane yield, when comparing between the highest N rate plot and the check plot, ranged from 5 to 25 Mg ha^{-1} for cane tonnage while for sugar yield, ranged between 0.48 to 3.16 Mg ha^{-1}. These results demonstrate the variability of N response between growing season and within growing season. Johnson and Raun (2003) found similar variability in winter wheat yield response to applied N. They attributed this variability to differences in both moisture and temperature, as well as other environmental conditions that influence supply of non-fertilizer N including natural deposition and organic mineralization. The high amount of variability of sugarcane yield response, as shown in Table 2.3, suggests that a more dynamic means of determining in-season N fertilization is needed to account for spatio-temporal variability across the Louisiana sugarcane growing region. The concept of utilizing canopy reflectance to evaluate RI during the vegetative growth (Mullen et al., 2003) holds considerable promise. This approach has the ability to obtain spatial differences in crop biomass while accounting for climatic conditions which affect crop growth from planting to the time of N application (Raun et al., 2002; Shanahan et al., 2008).

2.3.2 RI Determination Using NDVI

In essence, RI_{NDVI} is an estimate of $RI_{Harvest}$, which is the actual response of sugarcane to applied N. The $RI_{Harvest}$ is the ratio between the highest yielding N fertilized plots to the check plot. It is important to note that for this study, the actual response of sugarcane to applied N is expressed as increases in cane tonnage and sugar yield. Thus there were two sets of $RI_{Harvest}$ values that were regressed with RI_{NDVI}. Table 2.4 shows the relationship of $RI_{Harvest}$ to RI_{NDVI} which were computed from NDVI readings collected at three, four and five weeks after N fertilization. Based on the r^2 and P-values, the earliest time where RI_{NDVI} can accurately predict $RI_{Harvest}$ was at four weeks after N fertilization. The implications of timing for RI estimation will be discussed further in the next section.

The results of the regression analysis show that RI_{NDVI}, four weeks after N fertilization, had a significant linear relationship with cane tonnage $RI_{Harvest}$ with r^2 of 0.92 (Fig. 3). Similarly, the linear relationship between RI_{NDVI} and sugar yield $RI_{Harvest}$ was significant with r^2 of 0.81 (Fig. 4). These findings suggest that RI_{NDVI} can be used to estimate the actual response of sugarcane to applied N in-season using the equations in Fig. 3 for cane tonnage and Fig. 4 for sugar yield.

Sugarcane, as with crops in general, does not positively respond to applied N rates above optimum level, showing either small, non-significant increases in yield or yield reduction. Several reports suggest that sugarcane yield was reduced when supplied with high, non-limiting rates of N fertilizer (Wiedenfeld, 1995; Muchow et al., 1996; Kwong et al., 1996; Keating et al., 1997). Das (1936) reported that excess N fertilization can lead to increased lodging, which can decrease cane tonnage and sugar yield due to problems associated with harvesting the sugarcane. Numerous studies have also reported a decrease in sugar content per harvested unit of sugarcane if excess N was applied (Wiedenfeld, 1995; Muchow et al., 1996; Kwong et al., 1996). Thorburn et al. (2003) also found that cane yield, crop biomass N, and juice amino acid N decreased with higher N rates (>100 kg N ha^{-1}). In this study, the increase in cane tonnage and sugar yield did not proportionately

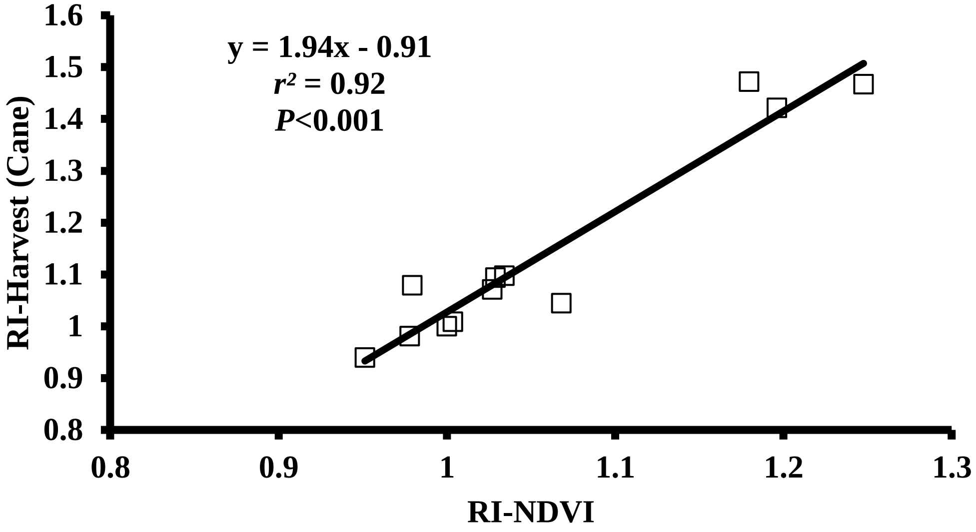


Figure 2.3. Relationship between response index calculated using normalized difference vegetative index and response index calculated at harvest for cane yield four weeks after fertilization in Louisiana, USA.

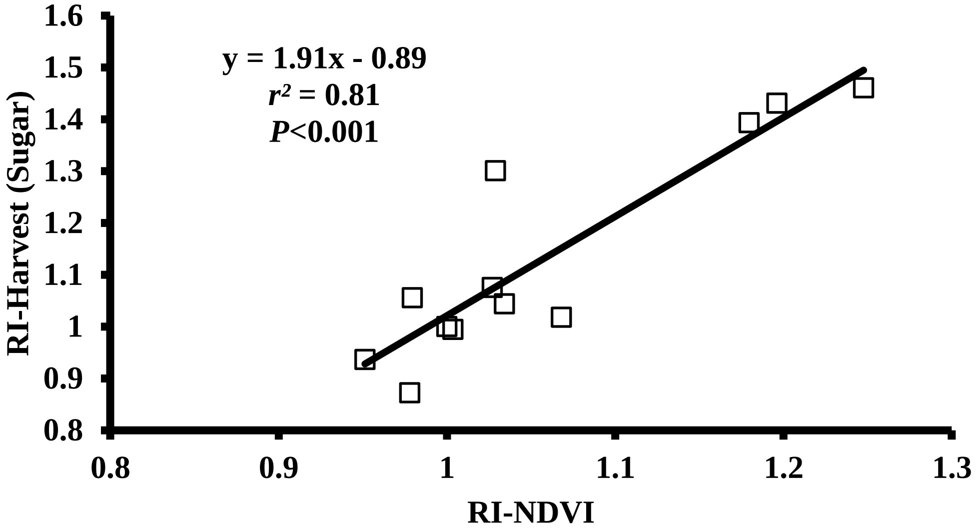


Figure 2.4. Relationship between a response index calculated using normalized difference vegetative index and response index calculated at harvest for sugar yield four weeks after fertilization in Louisiana, USA.

increase with increasing N rates (Table 2.3). For example, in a few of the experiments, the 135 kg N ha^{-1} rate plots yielded less cane tonnage and sugar yield than plots which received lower N rates. With the aforementioned observations, further analysis and processing of data were conducted to determine the relationship between RI_{NDVI} and $RI_{Harvest}$, where RIs were computed for all individual applied N rates to the check plot. By performing this modification, the relationship between RI_{NDVI} and $RI_{Harvest}$ included sugarcane response across N rates (Figs. 5 and 6). The modified RI compared all applied N rates to the check plot for both RI_{NDVI} and $RI_{Harvest}$ via equations 2.5, 2.6 and 2.7.

$$RI_{45} = 45 \text{ kg N ha}^{-1} \text{ plot/check plot} \quad (2.5)$$

$$RI_{90} = 90 \text{ kg N ha}^{-1} \text{ plot/check plot} \quad (2.6)$$

$$RI_{135} = 135 \text{ kg N ha}^{-1} \text{ plot/check plot} \quad (2.7)$$

There was a strong relationship between the RI_{NDVI} and the $RI_{Harvest}$ when the modified method of calculating RI was implemented (r^2= 0.85 for cane tonnage and 0.81 for sugar yield) (Figs. 5 and 6). While there was a slight reduction in the linear relationship between RI_{NDVI} and cane tonnage $RI_{Harvest}$, when compared to using only non-limiting N rate (r^2 values, 0.92 vs. 0.85), the accuracy (slope) and precision (r^2) of predictive model was not compromised. This also applies for sugar yield $RI_{Harvest}$. The slight difference between RI_{NDVI} and $RI_{Harvest}$ was expected for this study as sugarcane may have encountered growing conditions that can potentially alter yield post sensing. This is similar to the report provided by Mullen et al. (2003) for corn. The outcome of this procedure suggests that both methods of computing RI (traditional and modified) were able to establish models that can be used to predict cane tonnage and sugar yield response to applied N using NDVI readings. The benefits of determining RI for multiple

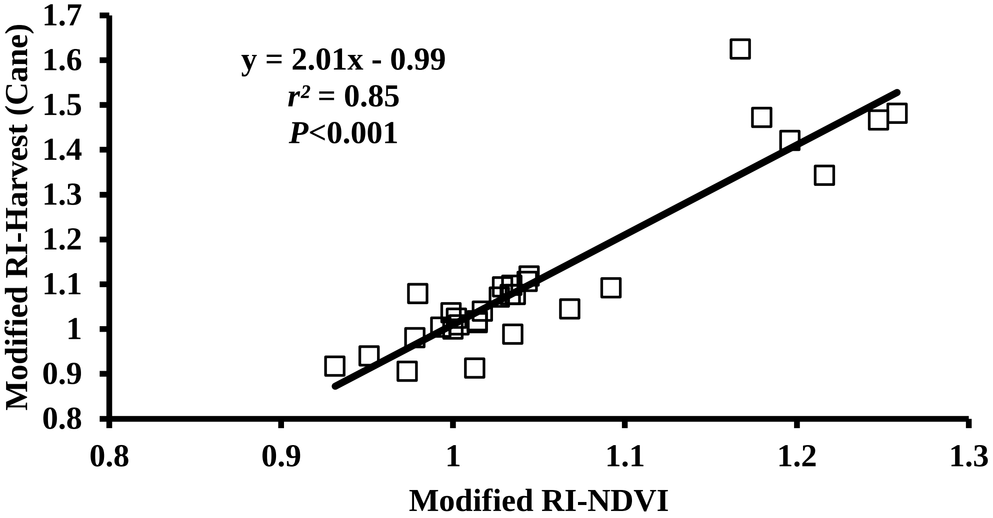


Figure 2.5. Relationship between a response index calculated using normalized difference vegetative index using all N rates and a response index calculated at harvest using all N rates for cane tonnage four weeks after fertilization in Louisiana, USA.

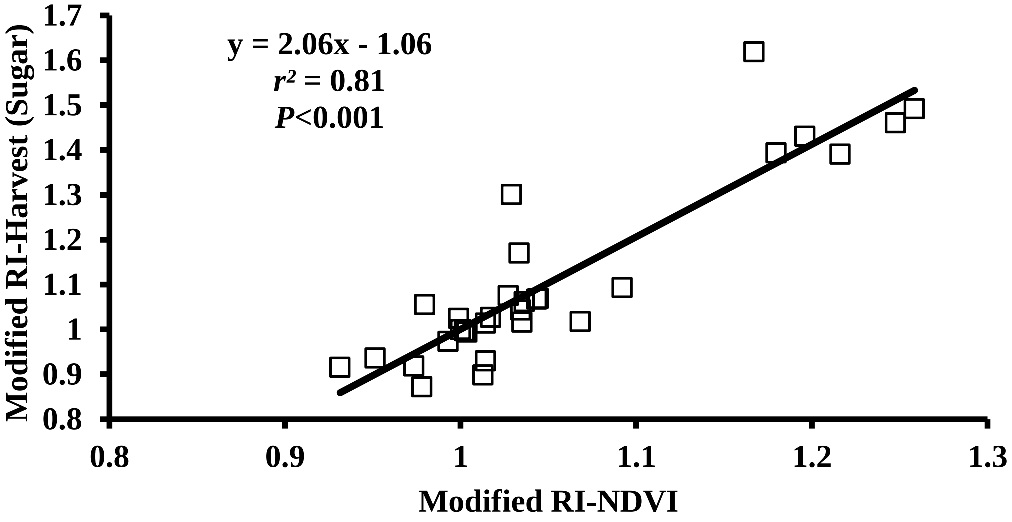


Figure 2.6. Relationship between a response index calculated using normalized difference vegetative index using all N rates and a response index calculated at harvest using all N rates for sugar yields four weeks after fertilization in Louisiana, USA.

N rates (modified RI procedure) are evident when the application of high N rates does not achieve the greatest cane tonnage and sugar yield response. While the establishment of N reference plots with multiple rates may be more time consuming, it provides a better understanding of both cane tonnage and sugar yield response to N compared to using a single high N rate.

2.3.3 Optimum Timing for RI Estimation

Identifying the optimum timing for RI estimation with NDVI has an implication in terms of the feasibility of using an in-season N monitoring via remote sensor in producers' fields. The NDVI readings were collected at three, four and five weeks after N fertilization. Later sampling dates were not pursued since the existing time frame of spring N fertilization for sugarcane production in Louisiana is narrow. This means that the usefulness of in-season N monitoring is confined within the time period closest to current spring N fertilization schedule. According to Legendre et al. (2000), current spring N fertilization is commonly scheduled by sugarcane growers between April 1st to 30th. While there is no documentation on the negative impacts of delaying N fertilization into May on sugarcane growth, the feasibility of May N fertilization is limited by the ability of equipment to cross the field without incurring physical damage to the sugarcane plants.

Table 2.4 summarizes the relationships between RI_{NDVI} and $RI_{Harvest}$ for both methods as a function of time. At three weeks after N fertilization, RI_{NDVI} was not able to establish a good relationship with $RI_{Harvest}$ for both cane tonnage and sugar yield. At this period, it is possible that the effects of N which was applied three weeks prior have not affected the canopy and leaf variables for the sensor to discriminate. Using the modified method, the RI_{NDVI} at four and five weeks after N fertilization obtained significant ($P<0.05$)

Table 2.4. Equation, coefficient of determination (r^2), and *P*-value for relationships of response index normalized difference vegetative index (RI_{NDVI}) and modified RI_{NDVI} with response index at harvest ($RI_{Harvest}$) at different weeks after fertilization.

	Cane tonnage			Sugar yield		
Week after fertilization	Equation	r^2	*P*-Value†	Equation	r^2	*P*-Value†
			RI_{NDVI} and $RI_{Harvest}$			
3	0.09x+0.87	0.02	0.56	0.09x+0.796	0.47	0.62
4	1.94x-0.91	0.92	<0.001	1.91x-0.89	0.81	<0.001
5	1.67x-0.63	0.81	0.012	1.57x-0.532	0.70	<0.001
			Modified RI_{NDVI} and $RI_{Harvest}$			
3	0.57x+0.52	0.21	0.025	0.16x+0.904	0.02	0.59
4	2.01x-0.99	0.85	<0.001	2.06x-1.06	0.81	<0.001
5	1.7x-0.68	0.83	<0.001	1.69x-0.66	0.77	<0.001

† Designated P-values are for overall model components

linear relationships with $RI_{Harvest}$ (Figs. 5 and 6). The r^2 values four weeks after fertilization were 0.85 and 0.81 for cane tonnage and sugar yield, respectively. Even with the traditional method of calculating RI, both RI_{NVDI} at four and five weeks were able to establish strong relationships with $RI_{Harvest}$ (with r^2 values, four weeks after fertilization, of 0.92 and 0.81 for cane tonnage and sugar yield, respectively). Results obtained by Chung et al. (2010) in winter wheat showed a similar trend. They reported the relationship between RI_{NDVI} and $RI_{Harvest}$ became stronger throughout the growing season until Feekes 7, at which point the relationship stabilized.

An N management program that utilizes an in-season RI will allow producers to determine the possibility of achieving an N response at harvest. A RI value is an estimation of the percent increase in yield that can be expected in conjunction with a particular N rate. Therefore, RI cannot exclusively be used to determine N rate recommendations. However, it is a vital component of an in-season N decision tool that has shown to be successful in many crops (Mullen et al., 2003; Hodgen et al., 2005; Teal et al., 2006; Tubana et al., 2008; Raun et al., 2011). Therefore, RI estimate for sugarcane can be established and calculated separately, and in combination with estimate of yield potential, can be used to determine an accurate in-season N fertilization recommendation. The implementation of in-season N decision tool requires establishment of an N reference strip within each management zone. Based on the findings of this study, to achieve full potential, an N reference strip of either a single high N rate (traditional RI) or multiple increasing N rates (modified RI) should be established at least four weeks prior to proposed N fertilization. By using the latter method, producers can take advantage of years in which optimum yield can be achieved with minimal or no N fertilizer.

2.4 Conclusions

This study demonstrated that sugarcane yield response to applied N can be estimated using NDVI readings. Both traditional and modified methods of determining RI_{NDVI} provided a good estimation of $RI_{Harvest}$. The benefit of the modified RI is it allows for estimation of the highest sugarcane yield response, which may not coincide with the highest N rate. The ability to utilize an N management scheme which incorporates an in-season estimation of sugarcane yield response would allow producers to take into account variability of the current growing conditions associated with different weather patterns and growth limiting factors. While the use of an in-season estimation of sugarcane yield response appears beneficial, it is imperative that yield response estimation can be utilized within the narrow time frame of spring N fertilization. The strongest relationship between RI_{NDVI} and $RI_{Harvest}$ occurred four weeks after N fertilization. Therefore, N reference strips would need to be implemented approximately one month prior to proposed spring N fertilization. Further research is needed to determine the effects of a wider array of fertilization timings, including early March to as late as the end of May, on the relationship between RI_{NDVI} and $RI_{Harvest}$ in anticipation to any future research on the potential of split and delayed N spring fertilization in Louisiana sugarcane production.

2.5 References

Berntsen, J., A. Thomsen, K. Schelde, O.M. Hansen, L. Knudsen, N. Broge, H. Hougaard, and R. Horfarter. 2006. Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. Prec. Agric. 7:65-83.

Biermacher, J.T., F.M. Epplin, B.W. Brorsen, J.B. Solie, and W.R. Raun. 2006. Maximum benefit of a precise nitrogen application system for wheat. Prec. Agric. 7:193-204.

Blackmer, T.M., and J.S. Schepers. 1995. Use of chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. J. Prod. Agric. 8:56-60.

Bronson, K.F., T.T. Chua, J.D. Booker, J.W. Keeling, and R.J. Lascano. 2003. In-season nitrogen status sensing in irrigated cotton: II. Leaf nitrogen and biomass. Soil Sci. Soc. Am. J. 67:1439-1448.

Carnauba, B.A.A. 1990. The nitrogen and the sugarcane (Translated from Portuguese). Stab,Açúcar, Álcool e Subprodutos. 8:24-42.

Chen, Q., X. Li, D. Horlacher, and H. P. Liebig. 2004. Effect of different nitrogen rates on open-field vegetable growth and nitrogen utilization in the north China plain. Commun. Soil Sci. Plant Anal. 35:1725–1740.

Chung, B., K. Girma, W.R. Raun, and J.B. Solie. 2010. Changes in response indices as a function of time in winter wheat. J. Plant Nutr. 33:796-808.

Das, U.K. 1936. Nitrogen nutrition of sugar cane. Plant Physiol. 11:251-317.

Embelton, T.W., M. Matsumura, L.H. Stolzy, D.A. Devitt, W.W. Jones, R. El Motaium, and L.L. Summers. 1986. Citrus nitrogen fertilizer management, groundwater pollution, soil salinity, and nitrogen balance. Appli. Agric. Res. 1:57–64.

Evanylo, G.K., and M.M. Alley. 1997. Presidedress soil nitrogen test for corn in Virginia. Commun. Soil Sci. Plant Anal. 28:1285-1301.

Flowers, M., R. Weisz, R. Heiniger, D. Osmond, and C. Crozier. 2004. In-season optimization and site-specific nitrogen management for soft red winter wheat. Agron. J. 96:124-134.

Gascho, G.J. 1985. Water-sugarcane relationship. Sugar Journal. 48:11-17.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen input to the Gulf of Mexico. J. Environ. Qual. 30: 329-336.

Hodgen, P.J., W.R. Raun, G.V. Johnson, R.K. Teal, K.W. Freeman, K.B. Brixey, K.L. Martin, J.B. Solie, and M.L. Stone. 2005. Relationship between response indices measured in-season and at harvest in winter wheat. J. Plant Nutr. 28:221-235.

Keating, B.A., K. Vertburg, N.I. Huth, and M.J. Robertson. 1997. Nitrogen management in intensive agriculture: sugarcane in Australia. In: B.A. Keating and J.R. Wilson, editors, Intensive sugarcane production: meeting the challenge beyond 2000. CAB International, Wallingford, UK, p 221-242.

Kwong, K.F.N., G. Umrit, and J. Deville. 1996. Nitrogen fertilization of sugarcane in intercropping system with maize and potato in the humid tropical climate of Mauritius. Exp. Agric. 32:213-218.

Johnson, G.V., and W.R. Raun. 2003. Nitrogen response index as a guide to fertilizer management. J. Plant. Nutr. 26:249-262.

Johnson, R.M., and E.P. Richard. 2005. Sugarcane yield, sugarcane quality, and soil variability in Louisiana. Agron. J. 97:760-771.

Legendre, B.L., F.S. Sanders, and K.A. Gravois. 2000. Sugarcane production best management practices. Pub. 2833. Louisiana State University AgCenter, Baton Rouge, LA.

LSU AgWeather. 2011. Louisiana agriclimatic information system. http://weather.lsuagcenter.com/ (Accessed date Nov. 2011).

Lukina, E.V., W.R. Raun, M.L. Stone, J.B. Solie, G.V. Johnson, H.L. Lees, J.M. LaRuffa, and S.B. Phillips. 2000. Effect of row spacing growth stage, and nitrogen rate on spectral irradiance in winter wheat. J. Plant Nutr. 23:103-122.

Meisinger J.J., J.S. Schepers, and W.R. Raun. 2008. Crop nitrogen requirement and fertilization. In: W.R. Raun and J.S. Schepers, editors, Nitrogen in agricultural systems, Agronomy Monography 49. ASA Madison, p 563-612.

Ma, B.L., J.M. Morrison, and D.M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. 88:915-920.

Muchow, R.C., M.J. Robertson, A.W. Wood, and B.A. Keating. 1996. Effects of nitrogen of the time-course of sucrose accumulation in sugarcane. Field Crops Res. 47:143-153.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

Olfs, H.W., K. Blankenau, F. Brentrup, J. Jasper, A. Link, and J. Lammel. 2005. Soil- and plant-based nitrogen-fertilizer recommendations in arable farming. J. Plant Nutri. Soil Sci. 168:414-431.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. Coop. Exten. Service, NebGuide G93-1171A. Univ. Nebraska, Lincoln.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with sensing and variable rate application. Agron. J. 94:815-820.

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop response. Precision Agric. 12:508-518.

Rouse, J.W., R.H. Haas, J.A. Schell, D.W. Deering, and J.C. Harlan. 1973. Monitoring the vernal advancement and retrogradation of natural vegetation, NASA/GSFC Type III Final Report, Greenbelt, MD.

SAS. 2009. The SAS system for Windows. Version 9.0. Cary, NC: SAS Institute.

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cereals. Comp. and Elect. Agri. 61:51-62.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488-1494.

Thorburn, P.J., E.A. Meier, and M.E. Probert. 2005. Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. Field Crop Res. 92:337-351.

Thorburn, P.J., I.K. Dart, I.M. Biggs, C.P. Baillie, M.A. Smith, and B.A. Keating. 2003. The fate of nitrogen applied to sugarcane by trickle irrigation. Irrig. Sci. 22:201-209.

Tremblay, N., and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal condition with the least impact on-the environment. Horttechnology 16:408-412.

Tubana, B.S., D.B. Arnall, O. Walsh, B. Chung, J.B. Solie, K. Girma, and W.R. Raun. 2008. Adjusting midseason nitrogen rate using a sensor-based optimization algorithm to increase use efficiency in corn. J. Plant Nut. 31:1393-1419.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Varvel, G.E., D.D. Francis, and J.S. Schepers. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meter. Soil Sci. Soc. A. J. 61:1233-1239.

Vyn, T.J., K.J. Janovicek, M. H. Miller, and E. G. Beauchamp. 1999. Spring soil nitrate accumulation and corn yield response to preceding small grain N fertilization and cover crops. Agron. J. 91:17–24.

Waskom, R.M., D.G. Westfall, D.E. Spellman, and P.N. Soltanpur. 1996. Monitoring nitrogen status of corn with a portable chlorophyll meter. Commun. Soil Sci. Plant Anal. 27:545-560.

Wiedenfeld R.P. 1995. Effects of irrigation and N fertilizer application on sugarcane yield and quality. Field Crops Res. 43:101-108.

Wood, C.W., D.W., Reeves, R.R. Duffield, and K.L. Edmisten. 1992. Field chlorophyll measurements for evaluation of corn nitrogen status. J. Plant Nutr. 15:487-500.

Zhao, D., K.R. Reddy, V.G. Kakani, J.J. Read, and G.A. Carter. 2003. Corn growth, leaf pigment concentration, photosynthesis and leaf hyperspectral reflectance properties as affected by nitrogen supply. Plant Soil. 257:205-217.

Zillmann, E., S. Graeff, J. Link, W.D. Batchelor, and W. Claupein. 2006. Assessment of cereal nitrogen requirements derived by optical on-the-go sensors on heterogeneous soils. Agron. J. 98:682-690.

Chapter 3. Estimating Sugarcane Yield Potential Using an In-Season Determination of Normalized Difference Vegetative Index

3.1 Introduction

Sugarcane (*Saccharum officinarum*) is an integral part of Louisiana economy and culture, with an economic value exceeding $2 billion annually (Legendre et al., 2000). In recent decades significant yield increases have been attributed to the addition of fertilizer N beyond any other agricultural input (Johnson, 2000). Nitrogen (N) is one of the most important crop growth factors, influencing both productivity and crop quality. Therefore, utilizing methods that can more accurately determine N rate recommendations is essential to maintain agronomic productivity (Wiedenfeld, 1995).

Sugarcane is a semi-perennial crop, which can be harvested annually up to five years without replanting; the first harvested crop is termed plant cane and stubble cane for each successive harvest. These long growth cycles combined with a short growing season in Louisiana, nine months compared to >12 for other growing regions, make accurate N rate recommendations that optimize yields and minimize environmental impacts difficult. Worldwide N recommendations for sugarcane production are dependent on climate, crop age, length of growth cycle, plant characteristics, and soil characteristics (Wiedenfeld, 1995). However, currently for Louisiana sugarcane production N rate recommendations are dependent on crop age, either plant cane or stubble cane, and soil type, generalized as light or heavy textured soils, while not accounting for other crop and environmental characteristics such as crop growth conditions or crop N demand (Legendre et al., 2000). These N rate recommendations are applied in a single application from the beginning of April to the beginning of May. This N application timing provides sugarcane producers the flexibility to utilize further management techniques to accurately estimate N rate recommendations in-season, which can account for the spatio-temporal variability of sugarcane production system.

Historically, soil sampling has been a technique utilized for determining N rate recommendations. However, the reliability of soil N tests is often questionable due to the challenges associated with the dynamic nature of N in the soil, particularly in the humid alluvial soils of Louisiana (Ma et al., 2005). Therefore, crop yield monitoring has become an important aspect of many N management schemes. A common method of incorporating crop yield into N rate recommendations is through the use of yield goals, specifically in cereal crop production (Johnson, 1991). A yield goal is defined as yield per unit area expected to achieve given adequate growing conditions and determined by taking a recent five year average plus 30% to account for potentially above average growing conditions. Johnson et al. (1997) and Schmitt (1998) reported the importance of yield goal for N recommendations in winter wheat (*Triticum aestivum*) and corn (*Zea mays*), respectively. They indicated that 33 kg N ha^{-1} for every 1 Mg of wheat and 20 kg N ha^{-1} for every 1 Mg of corn would be required. However, setting yield goals at unrealistic levels can lead to under- or over-estimation of N rate recommendations. This is envisaged especially when N recommendations based on yield goals across large scale spatial variability do not take into account temporal variability, due to environmental growing conditions, nor within field spatial variability.

Due to limitations associated with utilizing yield goals, research in other crops such as wheat and corn has focused on in-season crop monitoring as an approach to N management. However, limited research is available for sugarcane production, particularly Louisiana sugarcane production. Additionally, research that is available has produced negative or inconclusive results (Rudorff and Batista, 1990; Wiedenfeld, 1997). Wiedenfeld (1997) reported that chlorophyll meters were not a viable tool for predicting N recommendations for sugarcane grown in the Lower Rio Grande Valley. This lack of viability is partially due to the chlorophyll meter relying solely on plant tissue N concentrations and N accumulation in sugarcane occurred later in the season compared to when measurements were taken.

Many plant indices based on canopy spectral reflectance have shown the ability to accurately estimate crop physiological properties, including plant biomass and crop yield (Tucker 1979; Raun et al., 2002; Zhao et al., 2003). The NDVI value, which is a vegetative index that compares reflectance at the red and near infrared region, has also shown the ability to determine yield potential (YP) (Raun et al., 2001; Teal et al., 2006; Harrell et al., 2011). Yield potential differs from yield goal because it is a function of the environmental conditions of the current growing season and is defined as achievable yield with no additional N fertilizer (Raun et al., 2002). Teal et al. (2006) reported that there was a strong relationship between NDVI and grain yield in corn using an exponential model. Lukina et al. (2000) and Raun et al. (2001) showed this relationship was improved when NDVI readings were adjusted using growing degree days (GDD), where NDVI was divided by GDD accumulated from planting to sensing, to create an in-season estimate of yield (INSEY). Raun et al. (2001) reported that six of nine sites over two years showed a strong relationship between INSEY and grain yield at harvest (coefficient of determination (r^2 = 0.83, P<0.01). However, Teal et al. (2006) found there was no significant increase or decrease in the strength of this relationship when NDVI readings were adjusted by either GDD or days from planting to sensing (DFP) when GDD was positive.

Several studies have suggested that growth stage, or time of sensing, were important in the ability to predict yield (Lukina et al., 2000; Raun et al., 2001; Teal et al., 2006). Raun et al. (2001) and Lukina et al. (2001) reported that the strongest relationship between NDVI and winter wheat grain yield was between Feekes 4 to 6. While Teal et al. (2006) found that the optimum growth stage for predicting corn yield was at the eight leaf vegetative phase, or between 800-1000 GDD. They found a weak relationship during early growth stages, which was attributed to the yield potential not fully developed. Additionally, they explained the disappearance of this weaker relationship later in the season was due to canopy closure, which resulted in the inability to detect variability associated with differing N-rates.

Several reports have shown that an estimate of yield alone is poorly correlated with optimum N rate (Kachansoki et al., 1996). However, Raun et al. (2002) showed the potential of utilizing a predicted YP as a component of N management scheme. This technology has shown the ability to improve N management decisions in many cropping systems across U.S.A., Canada, Mexico, and other countries (Olfs et al., 2005; Tremblay and Belec, 2006; Zillman et al., 2006). These reports suggest the potential of using yield prediction as an integral part of an N management decision tool to improve recommendations in sugarcane production. However, there are few existing reports on the use and ability of ground-based remote sensors to accurately predict sugarcane yield in-season. The objectives of this study were to: 1) determine the ability of an in-season estimation of NDVI to predict sugarcane yield potential and 2) determine optimum timing for predicting sugarcane in-season yield potential.

3.2 Materials and Methods

Research was conducted in St. Gabriel (30°15’13”N 91°06’05”W) and Jeanerette (29°54’59”N 91°40’21”W), Louisiana on several N-rate field trials. Soils utilized for each experiment are as follows: Commerce silt loam (Fine-silty, mixed, superactive, non-acid, thermic Fluvaquentic Endoaquept) for Experiments 1, 2, 3, 4, and 9; Canciene silty clay loam (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquept) for Experiments 5, 6, 7, and 8; and Baldwin silty clay loam (Fine, smectitic, hyperthermic, Chromic Vertic Epiaqualf) for Experiments 10 and 11. Average monthly temperature and precipitation for each location and year are provided in Tables 3.1 and 3.2, respectively. Detailed descriptions for all experiments are provided in Table 3.3, as well as varieties used presented in 3.4. Experiments were planted on beds in a three-row plot, measuring approximately 2 m wide. The row length of most experiments was 15 m long with the exception of Experiment 7 (13.3 m long), 6 (11.6 m long), and 9 (8 m long). Excluding Experiment 6, all experiments were planted by hand using whole stalks where open furrows where filled with stalks that were placed with an overlap of 8 cm or two matured internodes of the adjacent stalk. Experiment 6 was billet planted, using 50 cm segments of sugarcane (billets), planted at the rate of 6 billets wide within an open furrow. These billets are then planted in 50 cm sections down the planning furrow. Following planting, all rows were covered with approximately 6 cm of soil and packed firmly using a custom roller packer. Nitrogen fertilizer was knifed in the shoulder of the bed as urea-ammonium nitrate (UAN; 32-0-0) to all trials at the rate of 0, 45, 90, and 135 kg N ha^{-1}, with the exception of Trial 2, 3, 5 (2008), and 8 which received the following N-rate: Experiment 2, received

Table 3.1. Average monthly temperature (°C) observed in 2008-2011 for St. Gabriel and Jeanerette, LA.

	St. Gabriel, LA				Jeanerette, LA			
Month	2008	2009	2010	2011	2008	2009	2010	2011
January	10.4	11.9	8.2	4.8	11.2	9.0	8.9	6.3
February	14.1	13.9	7.7	8.5	15.0	11.1	8.4	8.9
March	16.0	17.7	13.3	13.8	16.8	14.2	13.7	14.9
April	19.7	19.2	20.1	18.8	20.5	17.4	20.9	19.7
May	24.1	24.2	25.6	21.0	24.4	22.8	26.0	21.7
June	27.4	27.9	27.9	26.1	27.6	25.7	28.4	25.6
July	24.5	28.5	28.4	26.5	28.2	25.9	28.6	N/A†
August	27.2	27.2	28.5	26.7	27.6	25.3	28.9	N/A
September	24.7	26.0	26.1	21.8	25.2	23.4	26.8	N/A
October	18.9	20.1	19.9	14.0	20.0	19.0	20.7	N/A
November	14.1	14.3	15.4	12.6	15.3	11.2	16.6	N/A
December	13.2	10.4	10.6	12.2	13.8	10.9	10.9	N/A

†Indicates the information is not available for this month due to malfunctioning weather sensors.

Table 3.2. Average monthly precipitation (cm) observed in 2008-2011 for St. Gabriel and Jeanerette, LA.

	St. Gabriel, LA				Jeanerette, LA			
Month	2008	2009	2010	2011	2008	2009	2010	2011
January	14.1	10.6	6.4	4.7	15.3	5.0	5.2	8.1
Febuary	7.6	4.5	19.9	4.5	5.3	4.9	15.6	3.5
March	2.6	18.4	6.2	9.4	5.1	23.7	4.3	7.0
April	2.2	6.8	2.3	3.2	6.0	11.4	3.0	1.2
May	13.5	2.4	15.3	0.6	13.1	9.4	8.8	1.0
June	4.4	0.7	27.1	13.0	1.9	3.5	18.2	N/A†
July	5.7	7.9	10.9	13.2	3.2	9.5	38.1	N/A
August	23.7	9.0	24.9	N/A	8.8	11.3	17.8	N/A
September	9.9	11.7	2.7	N/A	31.1	25.3	7.0	N/A
October	0.9	31.4	1.7	0.8	0.6	35.1	4.3	N/A
November	3.5	2.6	16.4	N/A	5.6	3.4	16.8	N/A
December	13.8	41.2	6.7	2.3	7.1	46.9	7.2	N/A

†Indicates the information is not available for this month due to malfunctioning weather sensors.

Table 3.3. Agronomic practices for all experiments established at St. Gabriel and Jeanerette, LA from 2008 through 2011.

Experiment No.	Year	Crop	Description	Location	Planting date	Spring fertilization date	Harvest date
1	2008	2nd Stubble‡	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2006	15 Apr.	27 Oct.
2	2008	2nd Stubble	N Response Study	St. Gabriel, LA	Aug. 2006	15 Apr.	27 Oct.
3	2008	1st Stubble	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2007	15 Apr.	4 Nov.
	2009	2nd Stubble	Foliar fertilization x N rate	St. Gabriel, LA	Aug. 2007	15 Apr.	4 Nov.
4	2008	1st Stubble	Variety x N rate	St. Gabriel, LA	Aug. 2006	17 Apr.	5 Nov.
	2009	2nd Stubble	Variety x N rate	St. Gabriel, LA	Aug. 2006	29 Apr.	4 Nov.
5	2008	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2007	14 Apr.	17 Nov.
	2009	1st Stubble	Variety x N rate	St. Gabriel, LA	Sept. 2007	6 Apr.	18 Nov.
6†	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	15 Apr.	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	29 Apr.	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	13 May	8 Dec.
	2010	Plant Cane	N rate x N timing	St. Gabriel, LA	Sept. 2009	27 May	8 Dec.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	13 Apr.	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	23 Apr.	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	11 May	8 Nov.
	2011	1st Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2009	25 May	8 Nov.
7	2010	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2009	22 Apr.	22 Nov.
	2011	1st Stubble	Variety x N rate	St. Gabriel, LA	Sept. 2009	13 Apr.	3 Nov.
8†	2011	2nd Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2007	13 Apr.	13 Oct.
	2011	2nd Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2007	23 Apr.	13 Oct.
	2011	2nd Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2007	11 May	13 Oct.
	2011	2nd Stubble	N rate x N timing	St. Gabriel, LA	Sept. 2007	25 May	13 Oct.
9	2011	Plant Cane	Variety x N rate	St. Gabriel, LA	Sept. 2010	13 Apr.	1 Dec.
10	2008	2nd Stubble	Variety x N rate	Jeanerette, LA	Aug. 2006	25 Apr.	13Nov.
11	2010	Plant Cane	Variety x N rate	Jeanerette, LA	Nov. 2009	23 Apr.	17 Nov.
	2011	1st Stubble	Variety x N rate	Jeanerette, LA	Nov. 2009	11 Apr.	18 Oct.

†Four values are for the different spring N fertilization times, which yield was calculated separately for each timing.
‡Stubble crop indicates the crop grown after the first year's harvest

Table 3.4. Varieties used in all experiments from 2008 to 2011 in St. Gabriel and Jeanerette, Louisiana.

Experiment No.	Variety
1	Ho 95-988
2	L 97-128
3	L 97-128
4	L 99-226
	L 99-233
5	L 99-226
	LCP 85-384
	HoCP 96-540
6	L 01-283
7	L 99-226
	L 01-283
	HoCP 96-540
8	L 97-128
9	L 99-226
	L 01-283
	HoCP 96-540
10	HoCP 00-950
11	L 99-226
	L 01-283
	HoCP 96-540

0 and 135 kg N ha^{-1}; Experiment 3, received 0, 45, 90 kg N ha^{-1}; Experiment 5; received 0, 17, 67, 135, and 201 kg N ha^{-1}; Experiment 8, received 0, 45, 90, 135, and 180 kg N ha^{-1}. Following application of fertilizer, knife furrows were covered. Weed management was carried out according to current Louisiana State University AgCenter herbicide recommendations which included application of metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methyltio-1,2,4-triazin-5-one) in early spring prior to emergence of the sugarcane crop and atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) was applied when beds were rebuilt in-season (lay-by), approximately in the middle of May.

Sensor readings were taken weekly for eight weeks beginning approximately in the middle of April (115 DFY) until early June (163 DFY), where DFY means days from start of the year with GDD > 0. For Experiment 6 and 8, sensor readings were taken for five consecutive weeks starting one week after fertilization, with fertilizers being applied from the middle of April until the end of May. Sensor readings were taken with the GreenSeeker® ground-based handheld sensor (Trimble Navigation, Ltd., Sunnyvale, CA). Sensor readings were measured at the red region (670±10 nm) and the NIR region (780±10 nm) and NDVI was determined based on equation (3.1).

$$\text{NDVI}= [(\rho_{\text{NIR}}-\rho_{\text{Red}})/(\rho_{\text{NIR}}+\rho_{\text{Red}})] \tag{3.1}$$

where:

ρ_{NIR}= reflectance at the near infrared (NIR)

ρ_{Red}= reflectance at the red

Plots were harvested with a Cameco C2500 chopper harvester (Cameco Industries, Thibodaux, LA) and total harvested cane tonnage was determined using a weigh wagon fit with load cells. Ten randomly selected sub-sample stalks were collected from the middle row, leaves were removed from the stalk, and each stalk was cut approximately 10 to 12 cm below the apical meristem. After weight determination, the sub-samples were analyzed for sugarcane quality parameters using a Spectracane Near Infrared System (Bruker Coporation, Billerica, Massachusetts).

Prior to analysis, data were grouped by sensing date and cumulative growing degree days (CGDD) at time of sensing. Normalized difference vegetative index values were adjusted by two different methods to create an INSEY. The first normalization (INSEY-

DFY) was calculated similar to Raun et al. (2002), based on equation (3.2).

$$\text{In-season estimate of yield- day of year} = \text{NDVI/DFY} \tag{3.2}$$

where:

DFY= all days from the beginning of the year where GDD>0

Teal et al. (2006) implemented a similar index in corn by dividing NDVI values by the number of days from planting to sensing. However, since sugarcane is a semi-perennial crop and senesces during the winter, the beginning of the calendar year was used. In the second method, the plant index was determined by comparing NDVI values to the CGDD from the beginning of the year (INSEY-GDD), based on equation (3.3):

$$\text{In-season estimate of yield- cumulative growing degree days} = \text{NDVI/CGDD} \tag{3.3}$$

where:

CGDD = the cumulative growing degree days from the beginning of the calendar year.

Growing degree days were determined by the optimum day method (Barger, 1969), based on equation (3.4):

$$\text{Cumulative growing degree days} = ((\text{Temp.}_{max}-\text{Temp.}_{min})/2)\text{-base temperature} \tag{3.4}$$

Where:

Temp_{max}= maximum daily temperature

Temp_{min}= minimum daily temperature

Base temperature= 18°C for sugarcane production

Statistical analysis was performed using SAS software (SAS, 2009). For Experiments 1 and 3, no significant effect of foliar fertilization was found; therefore, further analysis was carried out across foliar treatments. In addition, for Experiments 4, 5, 7, 8, and 9 the variety by N-rate effect was not significant and analysis was carried out across varieties. Linear and non-linear regression analysis was performed to determine the relationship between NDVI, INSEY-DFY, INSEY-CGDD, and sugarcane yield components using Proc Reg and NLIN, respectively. Coefficient of determination values obtained from Proc Reg and NLIN were used to evaluate the models.

3.3 Results and Discussion

3.3.1 Sugarcane Yield Summary

Cane tonnage and sugar yield varied across sites and years (Table 3.5). Sugarcane yields in Louisiana, as well as soil properties, have been previously found to show similar variability based on crop age and growth conditions (Johnson and Richard, 2005). The average yield across all 12 site years was 65 Mg ha^{-1} for cane tonnage and ranged from 31 Mg ha^{-1} to 100 Mg ha^{-1}; additionally sugar yield averaged 7.8 Mg ha^{-1} and ranged from 2.2 to 12.1 Mg ha^{-1}. Yield achieved by Experiment 11 in 2011 achieved the highest cane tonnage with 100 Mg ha^{-1} and Experiment 7 in 2010 achieved the highest sugar yield with 12.1 Mg ha^{-1}. The higher yields were potentially associated initiation of rapid biomass accumulation, at which time water consumption is highest (Gascho, 1985). Experiment 8 in 2011 yielded the lowest cane tonnage with 31 Mg ha^{-1} and Experiment 5 in 2009 with 2.2 Mg ha^{-1} for sugar yield. The lowered production for both cane tonnage and sugar yields can be attributed to the increased crop age, both being 2nd stubble sugarcane crops. Johnson and Richard (2005) reported that sugarcane yield typically decreased with

Table 3.5. Average sugarcane yield at different nitrogen fertilization rates achieved from 2008-2011 from St. Gabriel and Jeanerette, LA.

		Cane tonnage				Sugar yield			
Experiment No.	Year	0N†	45	90	135	0	45	90	135
		Mg ha^{-1}							
1	2nd stubble	68	71	73	71	8.53	8.76	9.06	8.68
2‡	2nd stubble	39	-	-	68	5.21	-	-	7.54
3‡	1st stubble	71	74	77	-	8.72	8.94	9.20	-
	2nd stubble	54	53	55	-	6.15	6.07	6.36	-
4	1st stubble	56	62	63	61	6.87	7.34	7.35	7.17
	2nd stubble	51	69	76	75	5.13	7.13	7.65	7.49
5§	Plant cane	83	75	85	83	10.53	9.46	10.49	10.25
	1st stubble	49	54	48	53	2.25	2.52	2.82	3.16
6¶	Plant cane	97	88	89	91	12.45	11.43	11.40	11.66
	1st stubble	58	66	70	68	10.09	8.69	9.04	8.82
7	Plant cane	83	90	85	91	10.20	11.95	12.87	13.27
	1st stubble	46	62	79	77	5.64	7.82	10.00	9.68
8	2nd stubble	39	43	41	41	4.41	4.62	4.40	4.34
9	Plant cane	81	83	86	90	10.20	10.50	10.80	11.40
10#	2nd stubble	31	51	53	44	4.19	6.79	7.35	6.00
11	Plant cane	66	68	70	65	8.26	8.38	8.98	7.86
	2nd stubble	83	92	85	100	10.83	11.22	10.61	11.37

†Indicate applied N rates in kg N ha^{-1}.

‡Data points were not available due to particular plots did not receive designated N rates.

§N rates used were 0, 17, 67, 135, and 201 kg N ha^{-1}. Yield values for the 45 and 90 kg N ha^{-1} columns were plots which received 17 and 67 kg N ha^{-1}, respectively. Additionally 201 kg N ha^{-1} yielded 83 MT ha^{-1} and 10463 kg ha^{-1} for cane tonnage and sugar yield, respectively.

¶Indicate a significant response ($P<0.05$); however, the highest significant yield was the check plot.

#Additionally 180 kg N ha^{-1} yielded 64 Mg ha^{-1} and 8.8 Mg ha^{-1} for cane tonnage and sugar yield, respectively.

increasing age. In addition, the lowered cane tonnage for 2011 could be attributed to a high lodging rate due to winds associated with tropical storm Lee, which made landfall during maturation on September 9th, 2011. This high lodging rate can attribute to low harvest efficiency.

3.3.2 Optimum Timing for Prediction of Sugarcane Yield Potential Using NDVI

Timing of sensing is an important factor in determining the feasibility of integrating predicted YP into N management schemes. GreenSeeker® sensor readings were obtained from early April until the first of June; further sensing dates were not investigated due to the potential of physically damaging the sugarcane crop by equipment crossing the field. Sensing dates that do not fully coincide with the existing narrow timeframe associated with in-season fertilization of sugarcane in Louisiana (April 1st through April 30th) were investigated due to limited research currently available for the effects of later fertilization timings.

Sugarcane grown in Louisiana goes through four growth stages: emergence, tillering, grand growth, and maturation, each lasting from one to three months. Therefore, identifying sensing ranges based on growth stage, as proposed by several other studies, may not be feasible (Lukina et al., 2000; Raun et al., 2002; Teal et al., 2006). Overall, using DFY in which the CGDD >0 as a measure of time of sensing resulted in weak exponential or non-significant relationships (Table 3.6). These weak relationships can be attributed to rapid accumulation of days in the beginning of the season, even when the weather is cooler and growth is minimal. For example, if the average daily temperature was 19 °C there would be no difference in the number of days accumulated compared to the average daily temperature of 32 °C, the latter being within optimum temperature range for sugarcane growth.

However, when CGDD was used as a measure of time, stronger exponential relationships were achieved (Table 3.6). All spectral reflectance measurements showed a no significant or a weak relationship for both cane tonnage and sugar yield from 150 to 600 CGDD (Table 3.6). This weak relationship was potentially due to lowered N uptake and YP not being fully developed at early growth. Kwong and Deville (1994) reported that fertilizer N accumulation in sugarcane was low prior to a period of rapid N uptake, approximately 140 to 150 days after previous harvest. Thus differentiation in N uptake between high N rate plots and lower N rate plots would not be evident until later in the growing season. The strongest relationship occurred between 601 to 751 CGDD (Table 3.6). This timeframe corresponded to the last week in May to

Table 3.6. Exponential relationship between spectral reflectance measurements and sugarcane crop yield component as a function of time in St. Gabriel and Jeanerette, Louisiana from 2008 through 2011, using cumulative growing degree days (CGDD) and day of year (DOY) when growing degree days >0.

Coefficient of determination (r^2)						
	Cane tonnage			Sugar yield		
Growth Stage	NDVI	INSEY-DFY†	INSEY-CGDD‡	NDVI	INSEY-DFY	INSEY-CGDD
CGDD						
150-300	NS§	NS	NS	NS	NS	NS
301-450	NS	NS	NS	0.30	NS	0.25
451-600	0.24	NS	0.24	0.22	NS	NS
601-750	0.20	0.23	0.46	0.21	0.33	0.42
>751	NS	0.19	0.31	0.15	0.19	0.22
DOY						
116-123	NS	NS	NS	NS	NS	0.10
124-131	NS	NS	NS	NS	NS	NS
132-139	0.07	NS	NS	0.11	NS	NS
140-147	NS	NS	0.21	0.11	0.15	0.34
148-155	NS	0.05	0.21	NS	NS	0.15
156-163	NS	0.25	0.31	NS	0.28	0.34

†NDVI measurement adjusted for days from beginning of year (DFY) where the growing degree days are >0.
‡NDVI measurement adjusted for cumulative growing degree days (CGDD).
§Indicates the relationship was not significant at a 0.05 level.

the first week in June for all years. The relationship between spectral reflectance values and sugarcane yield after 751 CGDD substantially decreased. Teal et al. (2006) reported also a critical timeframe for determination of the relationship between NDVI and yield. Additionally, they found that both prior to and following this critical timeframe, the relationship between NDVI and yield substantially decreased. Aparicio et al. (2000) found that the relationship between NDVI and Durum wheat (*Triticum turgidum*) yield decreased in later stages, specifically when biomass and leaf area accumulation was high. For this study, the grand growth phenological stage resulted from the accumulation of 751 CGDD. During this stage of growth the sugarcane crop began to rapidly accumulate biomass. This increased biomass production resulted in canopy closure, decreasing the ability of NDVI to distinguish variation (Teal et al., 2006).

Flowers et al. (2004) reported that the application of N fertilizer when the crop is responsive, i.e. during rapid accumulation, can increase crop yield and decrease loss. According to Teboh et al. (unpublished data, 2011) the initiation of rapid N uptake was approximately June 5th for sugarcane production in Louisiana. However, N fertilization for sugarcane production in Louisiana is between April 1st and April 30th, which is approximately 100 to 275 CGDD during a normal site year (Figure 3.1) (Legendre et al., 2000). However, limited research has been conducted to determine the effects of delaying fertilization later into May (approximately 250 to 650 CGDD, 2. 1). Even though the effects of delaying N fertilization are unknown, these effects are influenced by environmental conditions that control natural N additions and crop response. This research indicates that delaying N fertilization is essential to integrate an in-season yield potential into sugarcane N management schemes. However, the benefits of delaying sugarcane N fertilization to coincide with optimum time for sugarcane yield prediction may not outweigh the risks involved with delayed fertilization in late May, such as yield losses from physical damage to the sugarcane by the fertilizer applicator.

3.3.3 Adjusting NDVI Readings Using DFY and CGDD

Overall, the exponential relationship measured from 601 through 750 CGDD between NDVI and sugarcane yield was low (Table 3.6) compared to similar models for both corn and winter wheat (Lukina et al., 2001; Teal et al., 2006). One potential factor for weaker relationship between NDVI readings and sugarcane yield was the variability of NDVI readings associated with different growing conditions between locations and years. Normalization methods have been implemented previously in an attempt to standardize the variability associated with

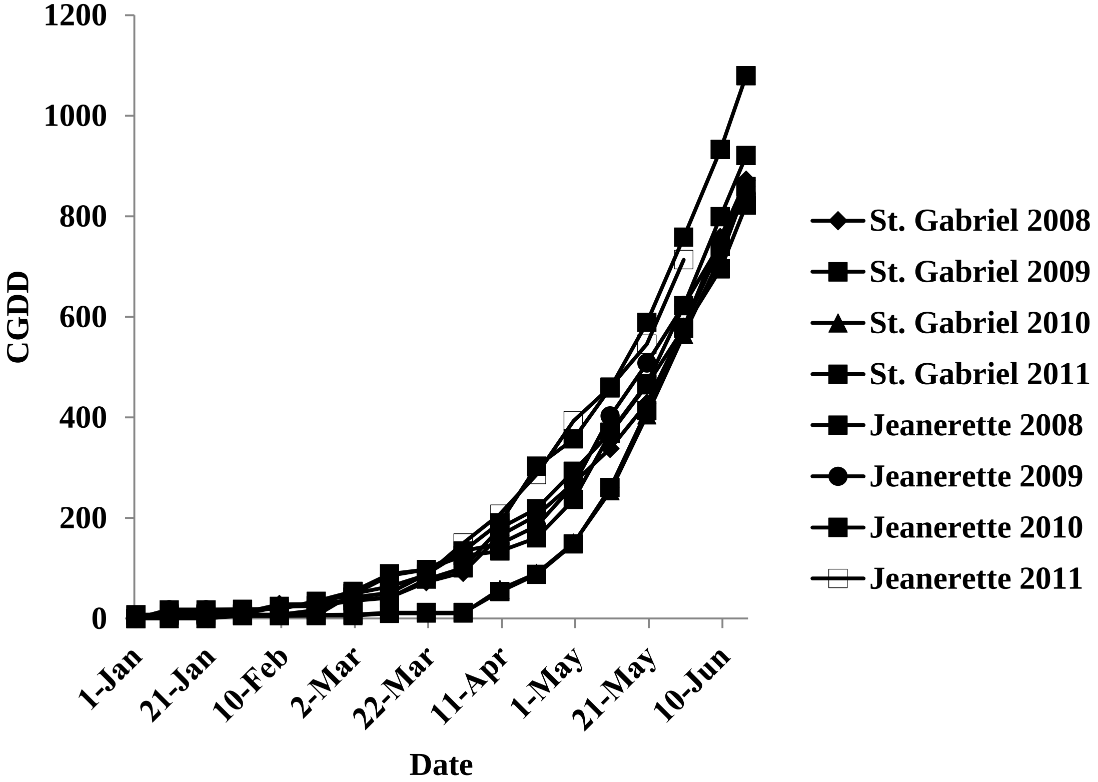


Figure 3.1. Total accumulation of growing degree days (CGDD) as a function of day of the year from the beginning of January until mid-June.

different growing conditions (Teal et al., 2006). Two adjustment methods were evaluated in this study, both the INSEY-DFY and INSEY-CGDD.

Both adjusted methods responded similarly to NDVI as a function of time in which CGDD of 601 through 750 being the optimum time for both methods (Table 3.6). Table 3.7 reports the relationship between sugarcane yield and both adjustment methods, as well as NDVI, at the 601 to 750 CGDD stage across all varieties. The INSEY-DFY only slightly improved YP estimation compared to the unadjusted NDVI for cane tonnage (r^2= 0.23 compared to 0.2 for unadjusted NDVI); however, INSEY-DFY substantially strengthened the relationship with sugar yield compared to the unadjusted NDVI value (r^2= 0.33 compared to 0.21 for unadjusted NDVI). The INSEY-CGDD adjustment substantially improved the relationship between cane tonnage and sugar yield compared to both unadjusted and INSEY-DFY (r^2= 0.48 and 0.42 for cane tonnage and sugar yield, respectively).

Table 3.7. Coefficient of determination (r^2), equation, and *P*-value for relationship between NDVI, INSEY-DFY, and INSEY-CGDD with sugarcane yield component fit with an exponential relationship at 650 through 750 CGDD.

	Cane tonnage			Sugar yield		
Plant index	r^2	Equation	*P*-value†	r^2	Equation	*P*-value
NDVI	0.20	$y = 25.2e^{1.5x}$	0.014	0.21	$y = 2.9e^{1.5x}$	0.025
INSEY-DFY	0.23	$y = 39.5e^{59.2x}$	<0.001	0.33	$y = 3.6e^{87.3x}$	<0.001
INSEY-CGDD	0.46	$y = 18.9e^{1303x}$	<0.001	0.42	$y = 2.1e^{1390x}$	<0.001

†*P*-values are for overall models.

It has been documented that temperature significantly affects canopy development in sugarcane production (Inman-Bamber, 1994; Robertson et al., 1998; Sinclair et al., 2004). Inman-Bamber (1994) reported that moisture did not significantly impact early canopy development and only influenced the number of green leaves per stalk and final leaf area under water stressed conditions. Although INSEY-DFY was found to improve the YP estimation, especially for sugar yield, INSEY-CGDD obtained more consistent improvement across different growing conditions for both cane tonnage and sugar yield. This is because CGDD is a measure of cumulative temperature across the growing season and NDVI is a measure of crop greenness and biomass. Therefore, in highly variable conditions associated with sugarcane production in the mid-South, INSEY-CGDD adjustment would increase the stability of sugarcane yield prediction models utilized across different locations and years.

3.3.4 Separating Prediction Models Based on Canopy Structure

The canopy structure of sugarcane has been shown to be highly variable, particularly between the different varieties (Galvao et al., 2005; Tejera et al., 2007; Marchiori et al., 2010). Galvao et al. (2005) further reported that spectral reflectance can be used as a tool for distinguishing different sugarcane varieties, due to difference in canopy architecture. Therefore, the accuracy of a yield prediction model based on canopy reflectance created across varieties could be lowered due to the variability associated with differing canopy structures. While having a separate YP equation for each variety would provide the most accuracy, the feasibility of creating multiple models for in-season management decision for sugarcane production would be challenging. However, a model which grouped varieties based on canopy structure would decrease the variability associated with different architectures.

For this study, varieties were grouped as either erectophile (erect) or planophile (droopy) based on varietal registration reports (Table 3.8). Figures 3.2 through 3.5 illustrate the relationship between INSEY-CGDD and sugarcane yield when varieties were separated as either droppy (Figures 3.2 and 3.3) or erect (Figures 3.4 and 3.5) when measurements were taken

Table 3.8. Varieties utilized in the study, designated canopy type, and source of canopy designation.

Variety	Canopy structure	Source†
L 97-128	Droopy	Gravois et al., 2008
L 99-226	Droopy	Bischoff et al., 2009
L 99-233	Droopy	Gravois et al., 2009
L 01-283	Erect	Gravois et al., 2010
LCP 85-384	Erect	Milligan et al., 1994
HoCP 96-540	Erect	Tew et al., 2005b
Ho 95-988	Erect	Tew et al., 2005a

†Citation for given variety registration report.

between 601 to 750 CGDD. The model that contained solely the erect varieties improved the YP model, with r^2 values of 0.53 for cane tonnage and 0.47 for sugar yield compared to 0.46 and 0.42 for cane tonnage and sugar yield, respectively of all varieties. Conversely, there was a slight reduction in the exponential relationship with models that contained only the droopy varieties, with r^2 values of 0.45 and 0.40 for cane tonnage and sugar yield, respectively. This decreased exponential relationship can be attributed to droopy varieties canopy spreading wider than erect leaf canopy structure leading to canopy closure earlier in the season. Therefore, the sensor's field of view tends to be occupied more with green biomass and only limited soil background (Tubana et al., 2011). In such conditions the sensor loses its sensitivity. This situation is not the case for erect leaf-canopy structure. Separating YP models based on canopy structure increased the accuracy at which the erect varieties could be predicted; however, it decreased the YP estimation of the droopy varieties.

An N management scheme that utilizes predicted YP would allow sugarcane producers to adjust in-season N recommendations based on expected yield. Since YP is the yield expected to be achieved with no additional N fertilizer, it cannot be used independently to determine N rate recommendations. However, YP has been successfully integrated into an N management scheme which incorporates YP and a response index value to successfully estimate in-season N rate

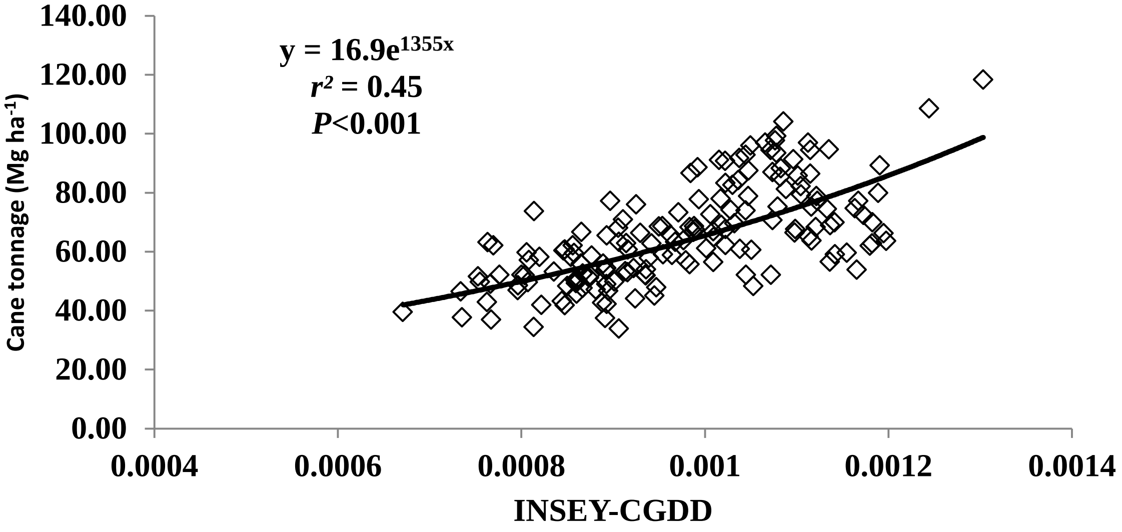


Figure 3.2. Relationship between cumulative growing degree days adjusted NDVI (INSEY-CGDD) and cane tonnage for droopy varieties for all locations between 601 through 750 CGDD in Louisiana, U.S.A.

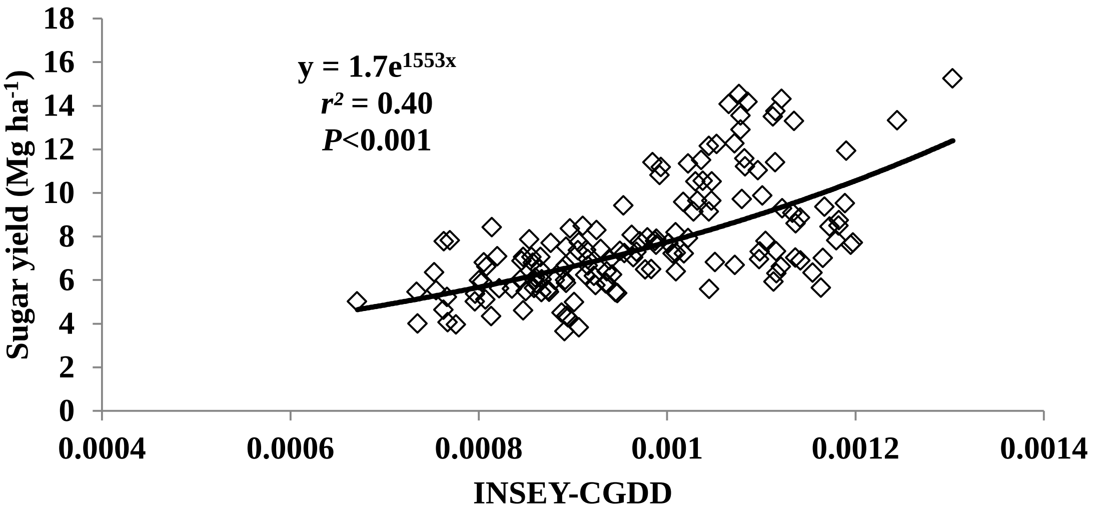


Figure 3.3. Relationship between cumulative growing degree days adjusted NDVI (INSEY-CGDD) and sugar yield for droopy varieties for all location between 601 and 750 CGDD in Louisiana, USA.

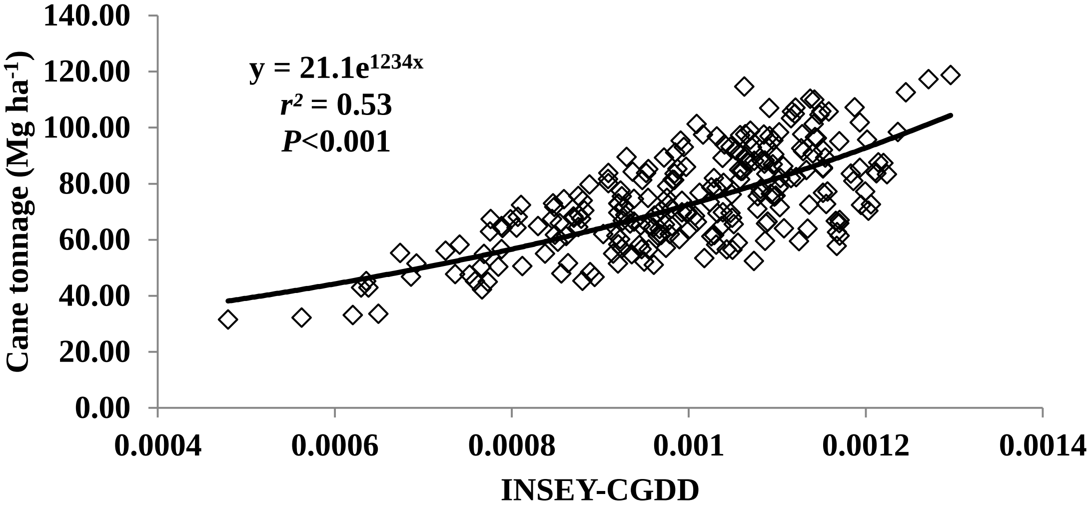


Figure 3.4. Relationship between cumulative growing degree days adjusted NDVI (INSEY-CGDD) and cane tonnage for erect varies for all locations between 601 through 750 CGDD in Louisiana, USA.

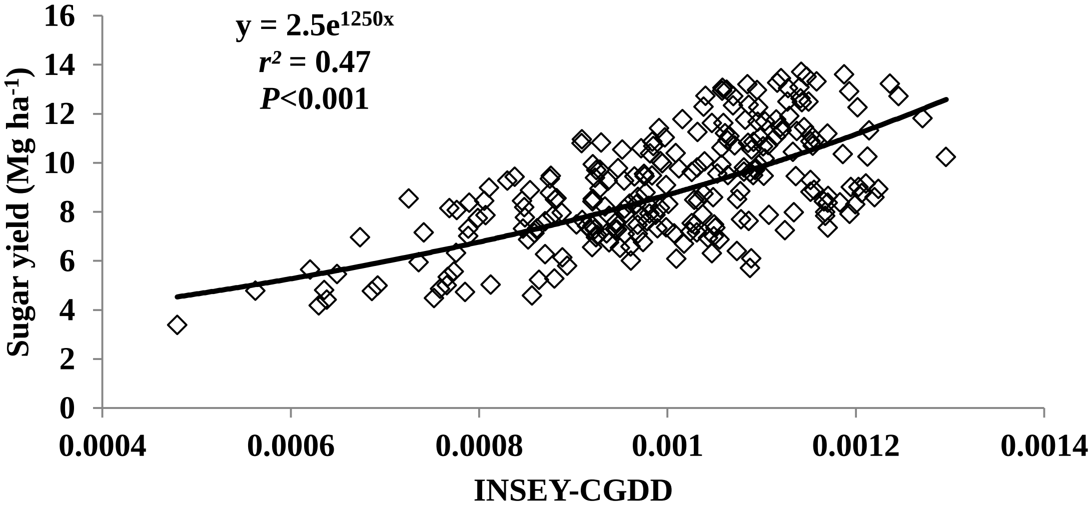


Figure 3.5. Relationship between cumulative growing degree days adjusted NDVI (INSEY-CGDD) and sugar yield for erect varies for all locations between 601 through 750 CGDD in Louisiana, USA.

recommendations in other crops (Hodgen et al., 2005; Teal et al., 2006; Raun et al., 2011). Lofton et al. (2012) reported that an in-season response index value could be successfully used to predict sugarcane yield response to applied N. To incorporate an N management decision tool that utilizes in-season estimation of YP, N fertilization would need to be delayed to coincide with the optimum timeframe for estimating YP, 601 to 750 CGDD, based on the findings of this study. The decision to delay N fertilization to coincide with in-season estimate of YP would need to be carefully evaluated on a field by field basis due to risks associated with N fertilization later in the season, including physical damage to the sugarcane by mechanically passing through the field. Additionally, due to chemical and physical factors that could influence the accuracy of YP estimations, YP should be determined separately for each management zone across the field. By using an N management scheme which takes into account YP, sugarcane producers can take advantage of years in which N demand may be higher or lower due to other yield limiting or enhancing factors.

3.4 Conclusions

This study demonstrated that NDVI readings can be used to estimate in-season sugarcane YP. The use of DFY did not provide positive results as a measure of time because of rapid accumulation of days early in the growing season when growth is minimal. The optimum timeframe for estimating sugarcane YP was determined to be from 601 through 750 CGDD. Because this timeframe is outside the current recommendations for N fertilization, sugarcane producers would need to delay in-season N fertilization by one month in order to integrate yield potential into an N management scheme. The risks and benefits of adopting this N management scheme would need to be evaluated on a producer basis.

Adjusting NDVI readings using CGDD and DFY increased the accuracy of YP estimation models but only CGDD adjustment increased the relationship between NDVI and cane tonnage. The CGDD adjustment provided a better prediction of sugarcane YP because it provided a better estimation of temperature throughout the growing season compared to DFY. Additionally, separating varieties based on canopy structure increased the r^2 value of the YP model with the varieties that were classified as erect; however, it had a slightly negative effect on the relationship between canopy reflectance and sugarcane yield for the droopy varieties. This was due to increased canopy closure early in the growing season of the droopy varieties. This increased green vegetation and decreased soil background diminished the sensitivity of the sensor to detect canopy variability associated with different N treatments. Therefore, when an N management system which integrates in-season predicted yield potential is implemented, sugarcane producers need to be aware of both the CGDD throughout the growing season, because this is utilized as a time-frame for when to collect NDVI readings and an adjustment method for NDVI values, and sugarcane variety, due to differences between varieties associated with different canopy structures.

Further research is needed to develop specific guidelines for distinguishing different canopy structures. In this study, the authors utilized variety reports to determine differences in canopy structure; however, numerical guidelines that take into account physiological characteristics of each variety, such as leaf angle or length of leaf to the first bend, would provide a more precise method of separating sugarcane varieties. Additionally, continued updates will be essential to increase the robustness of this sugarcane YP model. These updates will need to incorporate new commercially available varieties as they become available and additional diverse growing conditions.

3.5 References

Aparicio, N., D. Villegas, J. Casadesus, J.L. Araus, and C. Royo. 2000. Spectral vegetation indices as nondestructive tools for determining durum wheat yield. Agron. J. 92:83-91.

Barger, G.L. 1969. Total growing degree days. Weekly Weather Crop Bull. 56:10.

Bischoff, K.P., K.A. Gravois, T.E. Reagan, J.W. Hoy, C.M. Laborde, C.A. Kimbeng, G.L. Hawkins, and M.J. Pontif. 2009. Registration of 'L-99-226' sugarcane. J. Plant Regis. 3:21-247.

Flowers, M., R. Weisz, R. Heiniger, D. Osmond, and C. Crozie. 2004. In-season optimization and site- specific nitrogen management for soft red winter wheat. Agron. J. 96:124-134.

Gascho, G.J. 1985. Water-sugarcane relationship. Sugar J. 48:11-17.

Galvao, L.S., A.R. Formaggio, and D.A. Tisot. 2005. Discrimination of sugarcane varieties of southeastern Brazil with EO-1 hyperion data. Remote Sens. Environ. 94:523-534.

Gravois, K.A.,, K.P. Bischoff, C.M. Laborde, J.W. Hoy, T.E. Reagan, M.J. Pontif, C.A. Kimbeng, G.L. Hawkins, D.R. Sexton, and D.P. Fontenot. 2010. Registration of 'L 01-283' sugarcane. J. Plant Regis. 4:183-188.

Gravois, K.A., K.P. Bischoff, J.W. Hoy, T.E. Reagan, C.M. Laborde, C.A. Kimbeng, G.L. Hawkins, and M.J. Pontif. 2009. Registration of 'L99-233' sugarcane. J. Plant Regis. 3:248-252.

Gravois, K.A., K.P. Bischoff, S.B. Milligan, F.A. Martin, J.W. Hoy, T.E. Reagan, C.A. Kimbeng, C.M. Laborde, and G.L. Hawkins. 2008. Registration of 'L97-128' sugarcane. J. Plant Regis. 2:24-28.

Harrell, D.L., B.S. Tubana, T.W. Walker, and S.B. Phillips. 2011. Estimating rice grain yield potential using normalized difference vegetation index. Agron. J. 103:1717-1723.

Hodgen, P.J., W.R. Raun, G.V. Johnson, R.K. Teal, K.W. Freeman, K.B. Brixey, K.L. Marin, J.B. Solie, and M.L. Stone. 2005. Relationship between response indices measure in-season and at harvest in winter wheat. J. Plant Nutr. 28:221-235.

Inman-Banber, N.G. 1994. Temperature and seasonal effect on canopy development and light interception of sugarcane. Field Crop Res. 36:41-51.

Johnson, A.E. 1991. Soil fertility and soil organic matter. In: W.S. Wilson, editor, Advances in soil organic matter research: the impact of agriculture and the environment. Royal Society of Chemistry, Cambridge.

Johnson, A.E. 2000. Efficient use of nutrient in agriculture production systems. Comm. Soil Sci. Plant Anal. 31:1599-1620.

Johnson, G.V., W.R. Raun, H. Zhang, and J.A. Hattey. 1997. Soil fertility handbook. Oklahoma Agriculture Experiment Station, Stillwater, OK.

Johnson, R.M., and R.P. Richard. 2005. Sugarcane yield, sugarcane quality, and soil variability in Louisiana. Agron. J. 97:760-771.

Kachansoki, R.G., I.P. O'Halloran, D. Aspinall, and P. Von Bertoldi. 1996. Delta yield: Mapping fertilizer nitrogen requirement for crops. Better Crops. 80:20-23.

Kwong, K.F.N., and J. Deville. 1994. The course of fertilizer nitrogen uptake by rain-fed sugarcane in Mauritius. J. Agric. Sci. 122:385-391.

Legendre, B.L., F.S. Sanders, and K.A. Gravois. 2000. Sugarcane production best management practices. Pub. 2833, Louisiana State University Agricultural Center, Baton Rouge, LA.

Lofton, J., B.S. Tubana, Y. Kanke, J. Teboh, and H. Viator. 2012. Predicting sugarcane response to nitrogen using a canopy reflectance-based response index value. Agron. J. 104:106-113.

Lukina E.V., W.R. Raun, M.L. Stong, J.B. Solie, G.V. Johnson, H.L. Lees, J.M. Laruffa, and S.B. Phillips. 2000. Effect of row spacing, growth stages, and nitrogen rate on spectral irradiance in winter wheat. J. Plant Nutr. 23:103-122.

Ma, B.L., K.D. Subedi, and C. Costa. 2005. Comparison of crop-based indicators with soil nitrate test for corn nitrogen management. Agron. J. 97:462-471.

Marchiori, P.E.R., R.V. Ribeiro, L. Da Silva, R.S. Machado, E.C. Machado, and M.S. Scarpari. 2010. Plant growth, canopy photosynthesis, and light availability in three sugarcan varieties. Sugar Technologist. 12:160-166.

Milligan, S.B., F.A. Martin, K.P. Bishoff, K.P. Quebedeaux, E.O. Defrene, K.L. Quebedeaux, J.W. Hoy, T.E. Reagan, and B.L. Legendre. 1994. Registration of 'LCP 85-384' sugarcane. Crop Sci. 34:819-820.

Olfs, H.W., K. Blankenau, F. Brentrupm, J. Jasper, A. Link, and J. Lammel. 2005. Soil- and plant-based nitrogen fertilizer recommendations in arable farming. J. Plant Nutr. And Soil Sci. 168:414-431.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Ston, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131-138.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullens, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in ceral grain production with seaing and variable rate application. Agron. J. 94:815-820.

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop nitrogen response. Precision Agriculture. 12:508-518.

Robertson, M.J., G.D. Bonnett, R.M. Hughes, R.C. Muschow, and J.A. Campbell. 1998. Temperature and leaf are expansion of sugarcane: Integration of controlled-environments, field, and model studies. Australian Journal of Plant Physiology. 25:819-828.

Rudorff, B.F.T., and G.T. Batista. 1990. Yield estimation of sugarcane based on agrometeorolgical-spectral models. Remote Sens. Envir. 33:183-192.

SAS. 2009. The SAS system for Windows. Version 9.0. Cary, NC: SAS Institute.

Schmitt, M.A., G.W. Randall, and G.W. Rehm. 1998. A soil nitrogen test option for nitrogen recommendations with corn. FO-06514-GO, University of Minnesota Extension Service, St. Paul, MN.

Sinclair, T.R., R.A. Gilbert, R.E. Perdomo, J.M. Shine, G. Powell, and G. Montes. 2004. Sugarcane leaf area development under field conditions in Florida, USA. Field Crop Res. 88:171-178.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488-1494.

Tejera, N.A., R. Rodes, E. Ortega, R. Campos, and C. Lluch. 2007. Comparative analysis of physiological characteristics and yield components in sugarcane cultivars. Field Crop Res. 102:64-72.

Tew, T.L. D.M. Burner, B.L. Legendre, W.H. White, M.P. Grisham, E.O. Dufrence, D.D. garrison, J.C. Veremis, Y.B. Pan, and E.P. Richard. 2005a. Registration of ‘Ho95-988’ sugarcane. Crop Sci. 45:1660.

Tew, T.L. W.H. White, B.L. Legendre, M.P. Grisham, E.O. Dufrene, D.D. Garrison, J.C. Veremis, Y.B. Pan, E.P. Richard, and J.D. Miller. 2005b. Registration of ‘HoCP 96-540’ sugarcane. Crop Sci. 45:785-786.

Tremblay, N., and C. Belec. 2006. Adopting nitrogen fertilization to unpredictable season conditions with the least impact on the environment. Hort. Tech. 16:408-412.

Tubana, B., D. Harrell, T. Walker, J. Teboh, J. Lofton, Y. Kanke, and S. Phillips. 2011. Relationships of spectral vegetation indices with rice biomass and grain yield at different sensor view angles. Agron. J. 103:1405-1413.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Wiedenfeld, B. 1995. Effects of irrigation and N fertilizer application on sugarcane yield and quality. Field Crop Res. 43:101-108.

Wiedenfeld, B. 1997. Evaluation of new tools for determining crop nitrogen status and availability. Subtropical Plant Sci. 49:46-49.

Zhao, D., K.R. Reddy, K.G. Kakani, J.J. Read, and G.A. Carter. 2003. Corn growth, leaf pigment concentration, photosynthesis, and leaf hyper-spectral reflectance properties as affected by nitrogen supply. Plant and Soil. 257:205-217.

Zillman, E., S. Graefe, J. Link, W.D., Batchelor, and W. Claupein. 2006. Assessment of cereal nitrogen requirement derived by optical on-the go sensors on heterogeneous soils. Agron. J. 98:682-690.

Chapter 4. Effect of Nitrogen Rate and Application Time on Sugarcane (*Saccharum officinarum* L.) Yield and Quality

4.1 Introduction

Nitrogen (N) is one of the most important agricultural crop inputs. One reason is that many metabolic processes are reliant on N; especially those associated with crop growth including tillering and stalk elongation (Koochekzadeh et al., 2009). Deficiency of N results in with decreased light interception and photosynthesis due to the overall reduction of leaf area, chlorophyll synthesis, and biomass production. Many intensive agricultural production systems, such as sugarcane which accumulate a high amount of biomass typically require higher rates of N (Thorburn et al., 2005; van Heerden et al., 2010). However, N recommendations should utilize an application rate which minimizes environmental impact while maintaining productive agronomic yields. This is achieved by applying the optimum rate of N at the appropriate timeframe.

Worldwide application rates of N fertilizers for sugarcane production are highly variable, ranging from 45 to 300 kg N ha^{-1} (Srivastava and Suarez, 1992). Several reports have shown the recommended N application rate to be dependent on many factors, include soil type, crop age, plant and soil characteristics, climate, length of growing cycle, and length of growing season (Wiedenfeld, 1995; Wood et al., 1996; Legendre et al., 2000). However, many unique challenges associated with Louisiana sugarcane production, such as shorter growing season due to freezing conditions at the end of harvest season, have altered the N fertilization recommendation compared with other growing regions. Currently N recommendations for Louisiana sugarcane production vary from 67 to 135 kg N ha^{-1} and are dependent on crop age and soil type, generalized as either light or heavy textured (Legendre, 2001). Sugarcane is a semi-perennial crop and has two distinct growth phases within a planting cycle; the first growth season following planting is named plant cane with the successive growing seasons following the first harvest being termed as stubble cane. As mentioned previously, N recommendations vary based on crop age with higher N rates typically applied to stubble cane as compared with plant can (de Geus, 1973).

Over-application of fertilizer N can have a negative effect on sugarcane yieldand can potentially be detrimental to the environmental impact. Studies have shown that the over-supply of N can decrease sucrose concentration in the millable stalk (Wiedenfeld, 1995; Chapman et al., 1994; Borden, 1942). Wiedenfeld (1995) reported that high N rates (168 kg N ha^{-1}) increased fresh cane yield in stubble cane crops only under high irrigation levels, while under medium or low irrigation levels the increased N either had no significant benefit or negatively affected fresh cane yield. Additionally, he found that at all irrigation levels high N rates decreased sugar content and juice purity as well as sugar yield except under optimum water conditions associated with high irrigation levels. However, Muchow et al. (1996) reported slightly different results. They found that while a high N rate (268 kg N ha^{-1}) slightly decreased sucrose content, these higher N rates increased cane yield to a level that produced similar sugar yields compared to the low N rate. This would indicate that lower N fertilization rates could produce similar sugar yields with decreased cane tonnage. This would reduce production and transport cost.

In addition to N rate, another concern with N management is optimizing the timing of fertilizer application. Wiedenfeld (1997) reported that the application of N fertilizer outside the optimum timeframe can result in an overall reduction in cane tonnage and sugar yield. This was as a result of decrease in cane tonnage from early fertilization and loss of juice quality through later fertilization. They theorized that early fertilization resulted in a decrease of plant available

N due to leaching or immobilization prior to full growth potential had been achieved. Additionally, late fertilization resulted in decreased early growth which could only be partially compensated for later in the growing season. Wiedenfeld (1997) also suggested that the timing for a single yearly application of N should be in March or April in east Texas. However, differences in growing season have resulted in altering recommended N application time in Louisiana. Johnson et al. (2008) suggested that fertilization of sugarcane in Louisiana should be done from April 1st to April 30th. Samuels (1969) reported that sugarcane N needs are highest early in the growing season during germination and “boomstage”, or grand growth stage, which is a period of rapid growth. Current recommendations for mid-season N fertilization in Louisiana are similar to that suggested by Johnson et al. (2008). This timing of N fertilization can be up to two months prior to the apparent initiation of the period of rapid N uptake, which has been observed from late May to early June (Teboh et al., unpublished data). This lack of coincidence between N fertilization and rapid sugarcane uptake of soil N could lead to high rates of N fertilizer loss from the soil system. However, very little research has been conducted to determine the effects of delaying spring fertilization into the month of May. The lack of understanding on optimum time could heavily influence crop production. If fertilizer is applied too early in the season, the plants can begin to show deficiencies in the latter part of the growing season; however, if fertilization is too late then the sugarcane crop could already have diminished yields due to lack of nutrients at the initiation of sugarcane growth (Wiedenfeld, 1997).

Proper N management is essential to maintain sustainable sugarcane production in Louisiana. Additionally, determining the optimum N rate and critical application timing, as well as the changes of optimum N rate with respect to different N timings, would allow for potential use of technologies that can more precisely manage N applications in sugarcane production. One technology that has shown potential usage is remote sensing technology. However, there is no existing information on the effect of various N rates on fertilization dates as late as May on sugarcane production in Louisiana, which has been demonstrated as the optimum timeframe for utilizing this technology (Lofton et al., 2012; Lofton et al., unpublished data). The objectives of this study were to 1) determine the effect of various N rates and application timing on sugarcane yield, and 2) determine the effect of delayed application timing and high N rates on sugarcane quality.

4.2 Materials and Methods

Experiments were established in 2010 and 2011 at Sugar Research Station in St. Gabriel, LA (30°15’13”N 91°06’05”W). The dominant soil type for both experiments was a Commerce soil series (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquept). Each experiment, however, had varying surface textures with Experiment 1 being a Commerce silt loam and Experiment 2 being a Commerce silty clay loam.

A detailed description of all agronomic management practices are given in Table 4.1. Experiment 1 was planted with variety L01-283 and Experiment 2 was planted with L97-128. All experimental plots were mechanically planted with sugarcane billets, 50 cm segments of sugarcane containing at least one matured internode, at the rate of 6 billets across the planting furrow. These billets are then planted in 50 cm sections down the planning furrow. After planting, beds were covered with 15-20 cm of soil and pressed firmly using a custom roller packer. Plots were maintained weed-free according to the current LSU AgCenter’s weed management guidelines, where atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine) was applied at the middle of May when the beds were rebuilt and metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methyltio-1,2,4-triazin-5-one) prior to sugarcane emergence in the early spring.

Table 4.1. Agronomic practices for all experiments at St. Gabriel, Louisiana during the 2010 and 2011 growing seasons.

Experiment	Year	Crop	N Application time	Planting date	Harvest date
1	2010	Plant cane	15-Apr	Sept. 2009	8-Dec
		Plant cane	29-Apr	Sept. 2009	8-Dec
		Plant cane	13-May	Sept. 2009	8-Dec
		Plant cane	26-May	Sept. 2009	8-Dec
1	2011	1st stubble†	13-Apr	Sept. 2009	8-Nov
		1st stubble	23-Apr	Sept. 2009	8-Nov
		1st stubble	11-May	Sept. 2009	8-Nov
		1st stubble	25-May	Sept. 2009	8-Nov
2	2011	2nd stubble	13-Apr	Aug. 2008	14-Oct
		2nd stubble	23-Apr	Aug. 2008	14-Oct
		2nd stubble	11-May	Aug. 2008	14-Oct
		2nd stubble	25-May	Aug. 2008	14-Oct

† Stubble crop indicates crop grown following the plant cane crop

Treatments consisted of four different N fertilization rates and four different application timings which were arranged in a split plot design. The field was divided into six-row plots measuring 4 m wide and 92 m long. Each plot was divided into three row sub-plots measuring 2 m wide and 10.6 m long with 0.9 m alley between sub-plots. Fertilizer application timing was assigned as the main plot and fertilizer rate the sub-plot. Each treatment was replicated four times in a randomized complete block design.

Four application timings were investigated which represented fertilizer applications during the middle and end of the months of April and May (Table 4.1). Two of the fertilizer application timings, mid-April and late-April, coincide with the current N fertilizer management recommendations for sugarcane production in Louisiana. Whereby, the two subsequent application timings, mid-May and late-May, represent delaying N fertilizer later in the growing season past current N recommendations. Similar fertilization rates were applied across all four application timings. The rates investigated in this study were 0, 45, 90, and 135 kg N ha^{-1}. All fertilizer rates were applied by knifing urea ammonium-nitrate (UAN, 32-0-0) into the shoulder of the bed and knifed furrows were closed immediately following application.

At harvest, total cane tonnage, sugar yield, and quality parameters were determined. A Cameco C2500 chopper harvester (Cameco Industries, Thibodaux, LA) was used to harvest all experiments and a weigh wagon fitted with load cells were used to determine total plot weight. Prior to harvesting 10 whole stalk sub-samples were taken for determination of sugar yield, plant populations, and quality parameters. These 10 sub-samples were randomly selected across the middle row, leaves were removed from the stalk, and each stalk was cut approximately 10 to 12 cm below the apical meristem. The stalk sub-samples were weighed and added to the total plot harvest weights. Stalk sub-sample weights were used to determine average stalk weight. Total plot weights were then divided by the average stalk weight to determine a rough estimation of hectare plant population. While these determination methods resulted in underestimation of total stalk counts previously found, it followed trends evident in field. Following weight determination sugarcane stalks were analyzed using a Spectracane Near Infrared System (Bruker Corporation, Billerica, Massachusetts) to determine quality parameters such as theoretical recoverable sugars (TRS), total soluble solids (BRIX), purity, and percent fibers.

All data collected were analyzed using SAS 9.2 (SAS, 2009). Analysis of variance was utilized to determine difference in treatment using Proc MIXED because it allowed for both continuous and discrete variables that are both fixed and random within the same model. Within these models the variables N rate, application timing, and their interactions were designated as fixed variables while year, block, and their interactions were designated random variables. Differences between treatment levels were determined using Tukey's post-hoc analysis with an alpha value of 0.05. For experiments where N rate was found to be significant, the agronomically optimum N rate was determined using a linear-plateau model. The optimum N rate was determined as the minimum N rate that corresponds to agronomically maximum yields (Waugh et al., 1973). A linear-plateau model is comprised of three components which includes the linear region, the critical point, and the plateau region, with the model defined as:

$Y= b_1+b_0N, \qquad N<C$

$Y = P, \qquad N\geq C$

Where :

Y = sugarcane yield component

N = the rate of N application

B_1 = linear plateau intercept, sugarcane yield at zero applied N

B_0 = linear slope coefficient

C = is critical rate of fertilizer that corresponds to plateau point

P = is plateau yield

The linear region corresponds to the region where increases in N rate result in increased yield. Yields within the plateau region are considered statistically similar and the critical point, which represents the critical N rate, is the junction between these two regions. All parameters were determined by fitting the model to the collected data.

4.3 Results

Monthly average temperature and precipitation for both years along with monthly 5-year average are presented in Figures 4.1 and 4.2, respectively. While the average monthly temperatures for both 2010 and 2011 were fairly similar to the 5-year averages, the average monthly precipitation for both 2010 and 2011 were substantially different from the 5-year average and also varied greatly between years. In 2010, the higher than average precipitation occurred from May until August as well as during maturity in November. This high rainfall could potentially lead to higher biomass production. In 2011 below average precipitation occurred for 10 of the 12 months which led to low sugarcane yields for both Experiment 1 and 2.

Overall, sugarcane yield and quality was found to be significantly different between both years and experiments. Therefore, analysis was carried out separately for both year and experiments. A non-significant (*P* = 0.56) interaction between N rate and application timing was

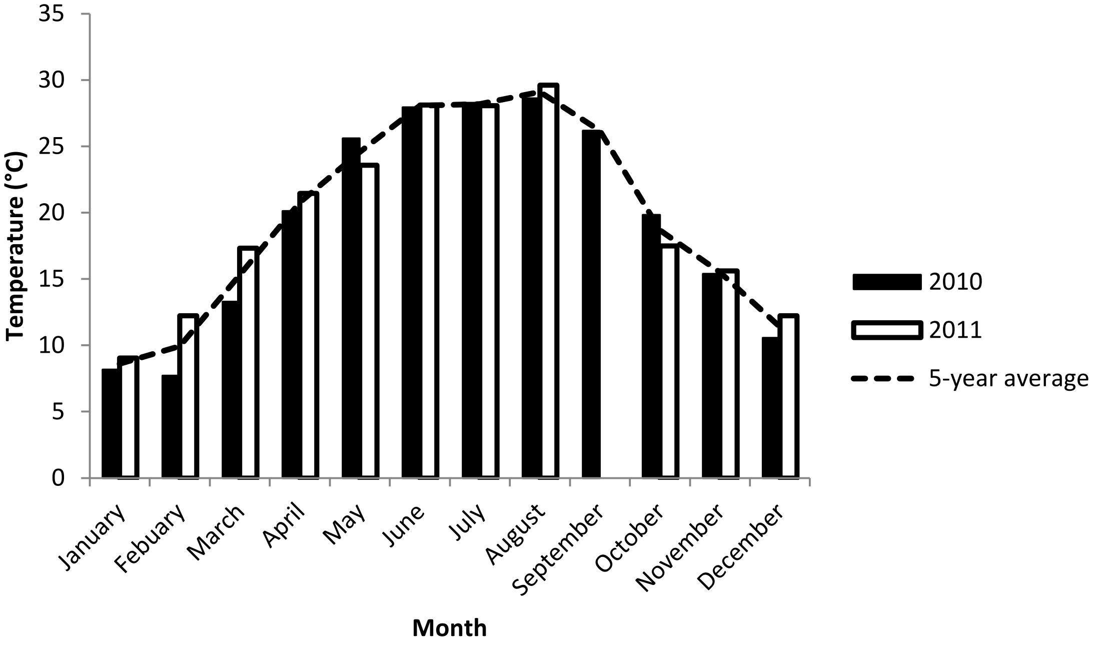


Figure 4.1. Average monthly temperatures along with 5-year average in St. Gabriel, Louisiana from beginning of season until harvest for 2010 and 2011.

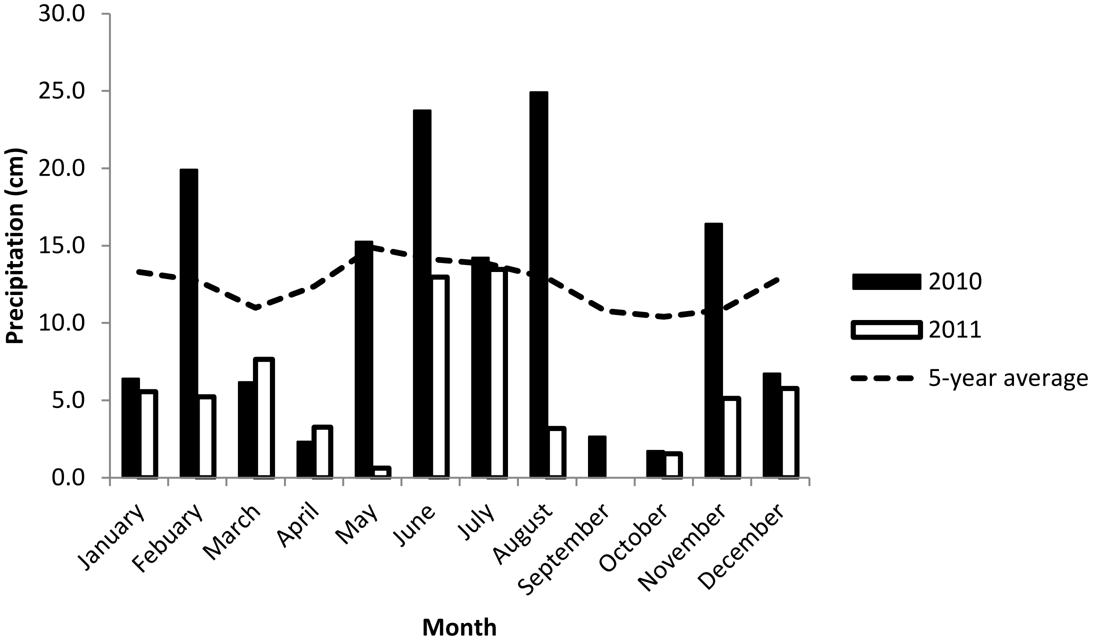


Figure 4.2. Average monthly precipitation along with 5-year average in St. Gabriel, Louisiana from the beginning of season until harvest for 2010 and 2011.

not observed. This lack of significant interaction indicated that the effect of N rate was not changed based on timing of application. Furthermore, this lack of interaction allowed for the determination of a single recommended N rate to be simplified to a single critical value across application timings for each response variable.

4.3.1 Effect of N Rate on Sugarcane Yield

The effect of N rate on cane tonnage and sugarcane yield varied as shown in Table 4.2. For cane tonnage, N rate had a significant effect for all experiments across both years; however, the rate of application only significantly affected sugar yield for Experiment 1 in 2011. The significant increase of cane tonnage for both experiments in 2011 follows the trends demonstrated in the current literature where stubble cane crops significantly respond to applied N (Wiedenfeld, 1997). This trend is expected in stubble crops due to continued depletion of soil

Table 4.2. Effect of N rate on sugarcane yield and quality parameters for all experiments pooled over application timings in 2010 and 2011.

Nitrogen rate	Cane tonnage	Sugar yield	BRIX	TRS	Fiber	Purity	Stalk weight	Plant population
	——— Mg ha^{-1}	———	%	kg Mg^{-1}	——— %	———	g	stalks ha^{-1}
Experiment 1 2010								
0	98.1 A†	12.7	20.5	122.2 B	11.0	87.4	998	15412 A
45	88.8 B	11.3	20.3	129.0 A	10.9	86.7	1094	14026 B
90	89.3 B	11.5	20.3	128.1 A	11.1	86.4	1044	14136 B
135	89.7 B	11.4	20.2	127.9 A	10.9	86.3	1053	13608 B
Significance	**	NS‡	NS	*	NS	NS	NS	*
Experiment 1 2011								
0	62.8 B	8.4 B	22.3	132.1	10.2	82.6	690 B	19432 A
45	68.5 A	11.1 A	22.4	130.4	9.9	81.8	778 A	13879 B
90	66.2 A	9.7 A	22.2	130.6	10.7	82.2	790 A	14552 B
135	65.8 A	9.5 A	22.4	129.1	10.5	81.2	763 A	14696 B
Significance	***	***	NS	NS	NS	NS	**	***
Experiment 2 2011								
0	36.6 B	4.4	19.6 A	114.3 A	11.8	81.9	687	9158
45	42.6 A	4.6	19.1 AB	108.5 B	11.8	80.4	667	10347
90	40.6 A	4.4	19.2 AB	108.0 B	11.7	80.1	688	9573
135	41.4 A	4.3	18.8 B	105.0 B	11.4	79.4	678	9994
Significance	**	NS	*	**	NS	NS	NS	NS

* 0.05, ** 0.01, and *** <0.01 level of significance according to a Tukey's post-hoc analysis.

† Mean levels within the same column for each experiment followed by the same letter indicate no significant differences between the treatment means according to the Tukey's post-hoc analysis.

‡ Indicates no significant differences were found for the given sugarcane yield or quality parameter and experiment.

N that may have been deposited during a fallow period prior to sugarcane planting. In this study, the 0 kg N ha^{-1} plot yield significantly less than the N fertilizerd plots, additionally there were no significant effects of applied N between other fertilized treatments.

Since N rate showed a significant positive response on cane yield, a linear-plateau model was utilized to determine agronomically optimum N rate for Experiment 1 and 2 for 2011 in Fig. 4.3. Based on the linear-plateau model the optimum yield, as well as, the N rate needed to achieve this optimum yield varied for each experiment. The N rate of 60 kg N ha^{-1} was needed to achieve an optimum yield of 69.1 Mg ha^{-1} for experiment 1, while the critical N rate of 42 kg N ha^{-1} was needed to produce an optimum yield of 41.5 Mg ha^{-1} cane tonnage for Experiment 2. As mentioned previously the N rate effect trends were similar, however, the critical N rate needed to achieve maximum yields varied. While these critical N rates are nearly 20 kg N ha^{-1} different, both are substantially lower than the current recommended N rates for stubble sugarcane which ranges from 90 to 135 kg N ha^{-1}. This could indicate that an N rate recommendation that does not take into account current sugarcane growth or environmental conditions could be over-estimating sugarcane N needs.

As opposed to cane tonnage only one experiment showed a significant sugar yield response to applied N was observed in sugar yield. For Experiment 1 in 2011 sugar yield increased from the 0 kg N ha^{-1} plot yielded significantly lower than the N fertilized plots with no additional significant differences. A linear-plateau analysis was carried out to determine the optimum N rate on sugar yield (Figure 4.4). According to the linear-plateau model, the N rate of 55 kg ha^{-1} was needed to achieve the optimum yield of 8,894 Mg ha^{-1}. This indicates that the critical N rate needed to achieve optimum yield for both cane tonnage and sugar yield were within 5 kg ha^{-1} of each other in Exp. 1 2011. Similar to cane tonnage, this critical N rate is substantially lower than the N rates currently being recommended

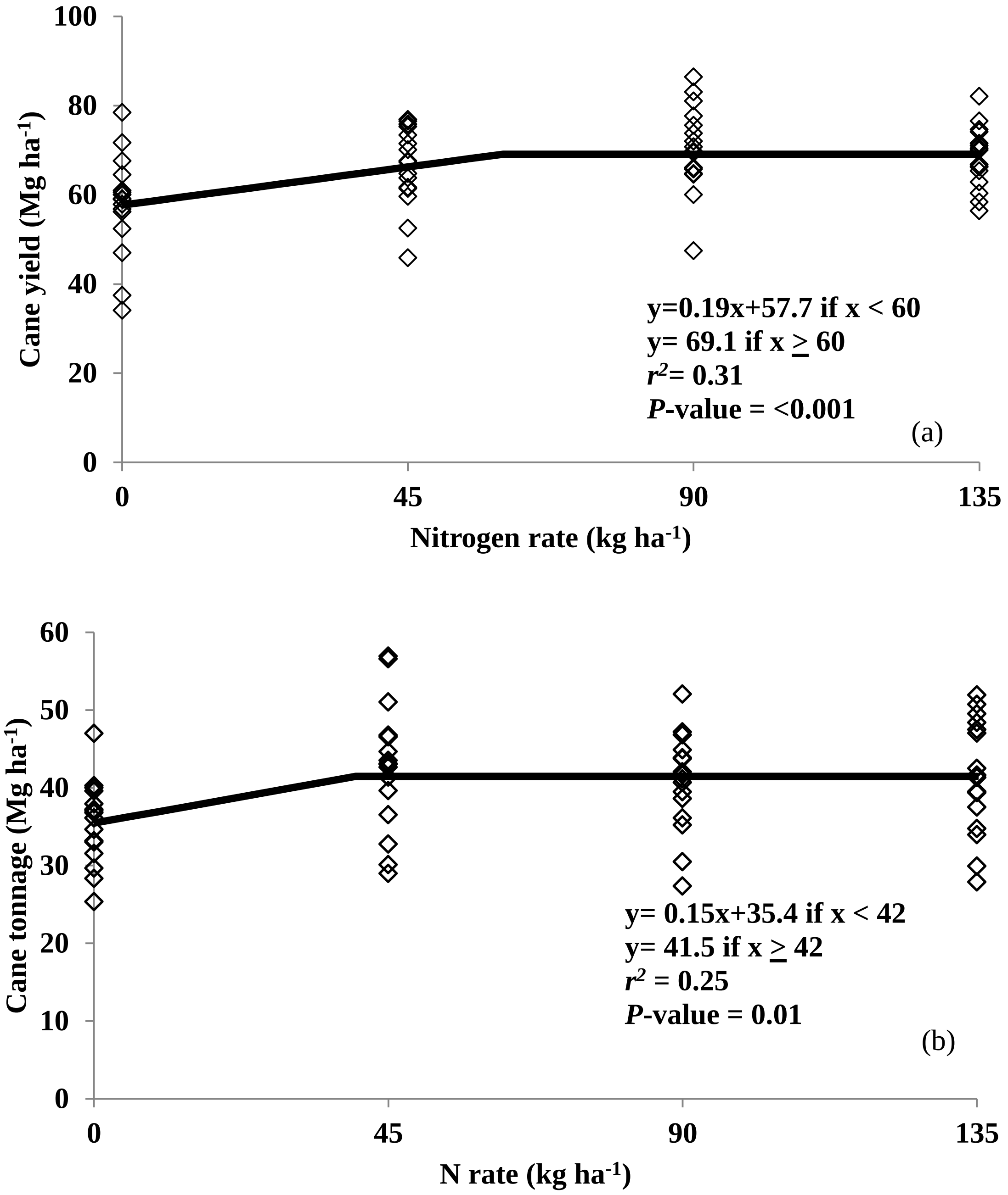


Figure 4.3. Linear-plateau analysis for the relationship between N rate and average cane tonnage for experiment 1 (a) and 2 (b) in 2011.

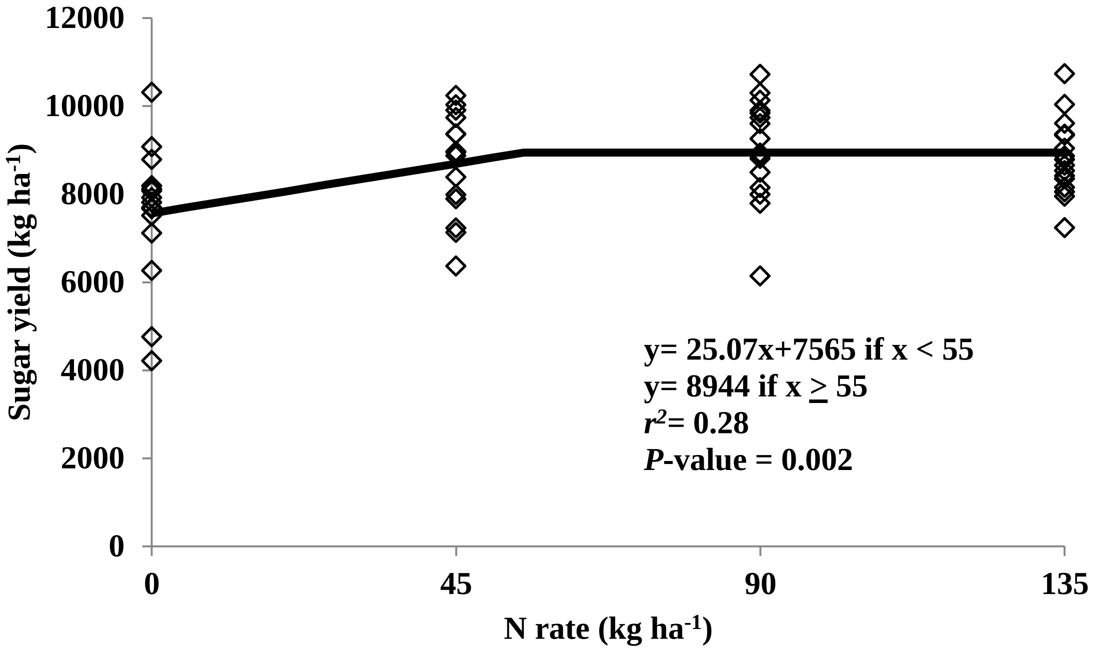


Figure 4.4. Linear-plateau analysis for the relationship between N rate and average sugar yield for experiment 1 in 2011.

for sugarcane production in Louisiana. There was, however, no significant effect of N rate on sugar yield for Experiment 2 in 2011. This lack of effect on sugar yield with a significant increase in cane tonnage can be attributed to decreased sugarcane quality for the high N rate plots (Muchow et al., 1996).

Contrary to the results of 2011, the check plot for Experiment 1 in 2010 yielded significantly higher than all N fertilized plots, with no significant difference between the N fertilized plots. This response of cane tonnage to fertilizer N is not typical and can potentially be attributed to increased lodging of the higher N rate plots (Das, 1936; Berding and Hurney, 2005). Additionally for Experiment 1 in 2010, sugar yield showed no significant effect to N rate. Similar results were obtained in Experiment 2 in 2011. This lack of effect for sugar yield can be attributed to decreased sugarcane quality, which will be further discussed within the next section.

According to our results the current N rate recommendations may be higher than needed for optimum cane and sugar yield. Current N recommendations for plant cane production range from 67 kg N ha^{-1} to 112 kg N ha^{-1} for plant cane and from 90 kg N ha^{-1} to 135 kg N ha^{-1} for the stubble cane crop, which are substantially higher than that found as the critical level for both plant and stubble cane crop in this study. Additionally, the effect of N rate changed based on crop characteristics as well as environmental conditions, including precipitation. Therefore, other techniques and technologies may be needed to more precisely estimate optimum N rate recommendations on a year-by-year basis as well as on a field-by-field basis, which take into account both temporal and spatial variability.

4.3.2 N Rate Effect on Sugarcane Quality

High N rates have been reported to increase cane tonnage (Wiedenfeld, 1997). Muschow et al. (1996) found that high N rates can also result in decreased sugar yields due to decreased sugarcane quality. They indicated that the reason for this decline was because of the decrease in sucrose concentration on a fresh weight basis. Decreased sugar quality was potentially the reason for the lack of sugar yield response to N rate in Experiment 1 in 2010 and Experiment 2 in 2011, even though both experiments showed a significant increase in cane tonnage associated with high N applications.

Experiment 1 in 2011 was the only trial that did not demonstrate a significant influence of N rate on any sugarcane quality component (Table 4.2). Sugarcane quality parameters were significantly affected by N rate in Experiment 1 in 2010 and Experiment 2 in 2011 (Table 4.2). Only TRS was significantly for Experiment 1 in 2010, at the 0 kg N ha^{-1} as compared with higher N rates. This decrease in TRS with lowered N rate contributed to the non-significant effect of N rate on sugar yield even though there was a significantly higher cane tonnage. Conversely, Muchow et al. (1996) reported that there was a significant decrease in recoverable sucrose with increasing N rate above 0 kg N ha^{-1}. Another potential explanation for the opposing results maybe increased sucker, or later forming tillers of a mature sugarcane crop, development under the 0 kg N ha^{-1} treatment which was observed by Berding et al., 2005. In our study, this is validated by the significantly higher plant populations in the zero N rate plots as compared with the N fertilized plots and agronomically decline in stalk weights (Table 4.2). Berding et al. (2005) reported that sucker development could significantly reduce recoverable sugars by a significant amount with only 10% sucker production.

In addition to TRS, BRIX significantly responded to N rate for Experiment 2 in 2011 (Table 4.2). In contrary to Experiment 1 in 2010 TRS significantly decreased when N was applied with no significant differences with additional N. Similarly, BRIX values of the 0 kg N ha^{-1} treatment were significantly higher than that of the 135 kg N ha^{-1} treatment, with no other significant differences. Several studies have demonstrated a decrease in TRS and BRIX values with increasing N (Muschow et al., 1996; Wiedenfeld, 2000). Muschow et al. (1996) reported that the decrease in recoverable sugars and BRIX was associated with a decrease in sugar content in stalk dry matter. This paired response of these two quality components could be expected because BRIX is used to calculate TRS, however, this is not always the case.

4.3.3 Effect of Fertilization Timing on Sugarcane Yield

In addition to the effects of N rate, timing of application of N fertilizers can significantly influence yield production. Delaying N application to coincide with a period of rapid growth and N uptake can decrease residual N as well as fertilizer N loss (Kwong and Deville, 1987). However, delaying N applications can decrease yield by delaying crop growth and maturation (Thomas et al., 1985). Application timings were investigated which encompassed current recommendations for application, from April 1st through April 30th, as well as later application times of mid-May and late-May. Later application dates were not pursued due to the risk of physically damaging the sugarcane crop by passing the application equipment over the field.

Sugarcane yield did not consistently respond to timing of application (Table 4.3). Cane tonnage and sugar yield of Experiment 2 in 2011 significantly responded to application timing. In Experiment 2 in 2011 both cane tonnage and sugar yield for the late-May fertilization date yielded significantly lower than the mid-April fertilization date; however, no other significant differences were observed. This indicated that while there was a benefit of early fertilization compared to the latest fertilization date, delaying N fertilization into mid-May did not significantly hinder sugarcane yield. Additionally, delaying N fertilization to mid- and late-May did not significantly decrease sugarcane yield compared to later fertilization within the current recommended timeframe (late-April). Wiedenfeld (1997) explained that this decrease in yield from late fertilization could be due to loss of early growth when N levels could be limited. Wiedenfeld (1997) further discussed that this decreased early season growth could partially be compensated by later season growth. However, due to increased environmental stress as well as the inherent decreased yield associated with second stubble sugarcane, the later fertilization date could not compensate for potential decreased early season growth similar to the findings by Johnson and Richard, 2005.

Experiment 1 in 2010 and 2011 showed no significant detrimental effect of delaying N fertilization later than the current recommendation (Table 4.3); however, both years demonstrating a minimal agronomic differences in cane tonnage and sugar yield. This trend was similar to that discussed by Wiedenfeld (1997), which theorized that when N fertilization was delayed sugarcane crop is unable to compensate for decreased early season growth which results in decreased cane tonnage. Our results differ from those studies discussed above for experiment

Table 4.3. Effect of timing of application of N fertilizer on sugarcane yield and quality parameters for all experiments in 2010 and 2011.

Fertilization timing	Cane tonnage	Sugar yield	BRIX	TRS	Fiber	Purity	Stalk weight	Plant population
	Mg ha^{-1}		%	kg Mg^{-1}	%		g	stalks ha^{-1}
Experiment 1 2010								
Mid-April	97.1	11.3	20.4	129.1	11.3	86.3	1035	14699
Late-April	98.3	11.6	20.5	130.3	11.1	86.5	1044	13766
Mid-May	98.6	11.4	20.1	127.9	10.9	86.7	1053	14382
Late-May	94.7	10.9	20.4	129.8	10.8	87.1	1053	13705
Significance	NS‡	NS	NS	NS	NS	NS	NS	NS
Experiment 1 2011								
Mid-April	67.9	8.9	22.3	132.1	10.2	82.3	750	14673
Late-April	66.9	8.7	22.4	130.3	10.0	81.7	719	15301
Mid-May	66.0	8.6	22.2	130.6	10.7	82.2	777	14253
Late-May	62.3	7.9	22.4	129.1	10.5	81.2	783	18120
Significance	NS	NS	NS	NS	NS	NS	NS	NS
Experiment 2 2011								
Mid-April	46.9 A†	5.3 A	19.1	112.9 A	11.6	79.6	713	10794 A
Late-April	41.5 AB	4.4 AB	19.2	106.7 B	11.8	80.4	695	9709 AB
Mid-May	40.1 AB	4.4 AB	18.9	106.1 B	11.6	80.1	663	9812 AB
Late-May	34.9 B	3.7 B	19.4	105.9 B	11.7	81.7	654	8756 B
Significance	**	***	NS	*	NS	NS	NS	**

* 0.05, ** 0.01, and *** <0.01 level of significance according to a Tukey's post-hoc analysis

† Mean levels within the same column for each experiment followed by the same letter indicate no significant differences between the treatment means according to the Tukey's post-hoc analysis.

‡ Indicates no significant differences were found for the given sugarcane yield or quality parameter and experiment.

2 in 2011. One potential explanation for these results was the distribution of precipitation during 2010. Experiment 1 in 2010 received higher than average rainfall toward the end of May through August compared to April which gave early fertilization dates little added benefit. Conversely, Experiment 1 in 2011 received similar precipitation, however, Experiment 2 in 2011 was an older sugarcane crop (2nd stubble) compared with Experiment 1 (1st stubble). The importance of crop age on sugarcane growth was reported by Park et al. (2005) which found older sugarcane crops had a lower growth rates compared with younger crops. This is emphasized by the significant decrease in plant population and the decrease in stalk weight of experiment 2 in 2011 compared with experiment 1 in 2011 (Table 4.3).

Our results indicate that delaying N fertilization later than the current recommendation was possible without sacrificing sugarcane yield. The ability to delay N fertilization later would allow for the application of N fertilizer to coincide with a period of rapid N uptake, which according to Teboh et al. (unpublished data, 2011) initiated in early June. In addition, delaying N fertilization would allow for the utilization of remote sensing systems to more precisely management N recommendations (Lofton et al., 2012; Lofton et al.,unpublished data).

4.3.4 Effect of N Application Timing on Sugarcane Quality

Timing of application did not have a major impact on sugarcane quality (Table 4.3). Similar to sugarcane yield, there was no significant effect of application time on sugarcane quality parameters from Experiment 1 in 2010 or 2011. Only TRS for experiment 2 in 2011 was significantly affected by N application time, wherein the mid-April application time produced the most TRS as compared with all other application times. Moreover, this decrease in TRS could potentially be due to delayed maturity associated with the delayed N fertilization in a low precipitation environment on 2nd stubble sugarcane.

Overall, these results indicate a need for agronomic management practices or techniques which can more accurately estimate N rate recommendations for sugarcane production. Reports have indicated that sugarcane yield response to applied N as well as yield potential could be estimated using a ground based hand-held remote sensor (Lofton et al., 2012; Lofton et al., unpublished). These two components have been shown successful as part of an in-season N recommendations system in other crops (Mullen et al., 2003; Teal et al., 2006; Raun et al., 2011). Lofton et al. (unpublished) further discussed that the sole drawback was this system would require N fertilization to be delayed into May to more accurate estimate of yield potential, outside the recommended N fertilization timeframe from April 1st to April 30th. However, according to this study sugarcane yield did not significantly decreased when N fertilization was delayed into May. This would indicate that for most years N fertilization could be delayed to allow for the incorporation of a similar remote sensing system.

4.4 Conclusions

Sugarcane yield as well as sugarcane quality were significantly affected by N rate in two out of three experiment years in this study. The effects of N rate had a positive effect on two of three experimental years. However, agronomically critical N rates based on the linear-plateau model were found to be much lower than the current recommendations for N fertilization in sugarcane production in Louisiana. This could potentially indicate that natural deposition events or residual soil N levels are contributing to current sugarcane growth. Additionally, the experiment which showed a negative response to higher N rates could be attributed to environmental factors in which decreased yield could be associated with potentially higher growth rates.

The effect of application time was not as pronounced as N rate across all experiments. Experiment 2 in 2011 was the only experiment that was found to be significantly affected by timing of application. The later fertilization dates were theorized to delayed maturity, which these affects were increased because of lower than average precipitation and the lowered growth of older sugarcane crops. However, in the other experimental years delaying N fertilization did not significantly decrease sugarcane yield nor have a detrimental effect on sugarcane quality.

Because the effect of N rate was highly variable other means of determining N recommendations could be needed to account for the spatial and temporal variability associated with sugarcane production in Louisiana may be beneficial. The lack of detrimental effect associated with delaying N fertilization would allow for wider timeframe for utilizing these non-traditional methods of N rate determination such as remote sensing techniques.

While these results indicated that N fertilization rate was lower than the current N rate recommendation and the application of N could be delayed without significantly decreasing yield or quality. Further investigations of these effects are needed. One potential study is to investigate the effects of splitting N applications between two timings within the late-spring. This would allow for documentation of the effects of single application compared with the effects of splitting N applications with one application in early to mid-April and a second closer to the period of rapid N uptake in May. Split applications which include early spring and May applications would allow the sugarcane crop to take advantage of timely rains in early spring and attempting to increase N uptake efficiency with later N applications. Also, additional varieties will need to be investigated. This will assure that the effects are consistent across varieties as well as to allow for continued updating of N rate affect and application timing under varied weather conditions.

4.5 References

Berding, N., and A.P. Hurney. 2005. Flowering and lodging, physiological-based traits affecting cane and sugar yield. What do we know of their control mechanisms and how do we manage them? Field Crop Res. 92:261-275.

Berding, N., A.P. Hurney, B. Salter, and G.D. Bonnett. 2005. Agronomic impact of sucker development in sugarcane under different environmental conditions. Field Crop Res. 92:203-217.

Borden, R.J. 1942. A search for guidance in the nitrogen fertilization of the sugar cane crop. Part 1. The plant crop. Hawaii Plant Research. 191-238.

Chapman, L.S., M.B.C. Haysom, and P.G. Saffigna. 1994. The recovery of 15N labeled urea fertilizer in crop component of sugarcane and in soil profiles. Australian Journal of Agricultural Research. 45:1577-1587.

Das, U.K. 1936. Nitrogen nutrition of sugar cane. Plant Physiol. 11:251-317.

de Geus, J.G. 1973. Sugar crops. In: J.G. de Geus et al., editors, Fertilizer guide for the tropics and subtropics. 2nd ed. Centre d’etude de l’azote, Zurich, Germany. p. 136-182.

Johnson, R.M., and E.P. Richard. 2005. Sugarcane yield, sugarcane quality, and soil variability in Louisiana. Agron. J. 97:760-771.

Johnson, R.M., H.P. Viator, and B.L. Legendre. 2008. Sugarcane fertilizer recommendations for the 2008 crop year. Sugar Bulletin. 86:11-13.

Koochekzadeh, A., G. Fathi, M.H. Gharineh, S.A. Siadat, S. Jafari, and K. Alami-Saeid. 2009. Impacts of rate and split application of N fertilizer on sugarcane quality. International Journal of Agricultural Research. 4:116-123.

Kwong, K.F.N.G., and J. Deville. 1987. Residual fertilizer nitrogen as influenced by timing and nitrogen forms in a silty clay soil under sugarcane in Mauritius. Fertilizer Res. 14:219-226.

Legendre, B.L., F.S. Sanders, and K.A. Gravois. 2000. Sugarcane production best management practices. Pub. 2833. Louisiana State University AgCenter, Baton Rouge, LA.

Legendre, B.L. 2001. Sugarcane production handbook. Pub. 2859. Louisiana State University AgCenter, Baton Rouge, LA.

Lofton J., B.S. Tubana, Y. Kanke, J. Teboh, and H. Viator. 2012. Predicting sugarcane response to nitrogen using a canopy reflectance-based response index value. Agron. J. 104:106-113.

Muchow, R.C., M.J. Robertson, A.W. Wood, B.A. Keating. 1996. Effect of nitrogen on the time-course of sucrose accumulation n sugarcane. Field Crop Res. 47:143-153.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

Park, S.E., M. Robertson, and N.G. Inman-Bamber. 2005. Decline in the growth of a sugarcane crop with age under high input conditions. Field Crop Res. 92:305-320.

Phillips, S.B., J.G. Warren, and G.L. Mullins. 2005. Nitrogen rate and application timing affect 'Beauregard' sweetpotato yield and quality. Hort. Sci. 40:214-217.

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop response. Precision Agric. 12:508-518.

Samuels, G. 1969. Foliar diagnosis of sugarcane. Adams Press, Chicago, IL.

SAS. 2009. The SAS system for Windows. Version 9.0. Cary, NC: SAS Institute.

Srivastava, S.C., and N.R. Suarez. 1992. Sugarcane. In: W. Wichmann, editor, World Fertilizer Use Manual BASF AG, Germany. p. 257-266.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488-1494.

Thomas, J.R., A.W. Scott Jr., and R.P. Wiedenfeld. 1985. Fertilizer requirement of sugarcane in Texas. J. Am. Soc. Sugar Cane Technol. 4:62-72.

Thorburn, P.J., E.A. Meier, and M.E. Probert. 2005. Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. Field Crop Res. 92:337-351.

van Heerden, P.D.R., R.A. Donaldson, D.A. Watt, and A. Singels. 2010. Biomass accumulation in sugarcane: unraveling the factors underpinning reduced growth phenomena. J. Exper. Botany. 61:2877-2887.

Waugh, D.L., R.B. Cate, and L.A. Nelson. 1973. Discontinuous models for rapid correlation, interpretation, and utilization of soil analysis and fertilizer response data. Tech. Bull. 7. International Soil Fertility Evaluation and Improvement Program. North Carolina State Univ., Raleigh, North Carolina.

Wiedenfeld, R.P. 1995. Effects of irrigation and N fertilizer application on sugarcane yield and quality. Field Crop Res. 43:101-108.

Wiedenfeld, R.P. 1997. Sugarcane responses to N fertilizer application on clay soils. J. Amer. Soc. Sugar Cane Technol. 17:14-27.

Wiedenfeld, R.P. 2000. Water stress during different sugarcane growth periods on yield and response to N fertilization. Agricultural Water Management. 43:173-182.

Wood, A.W., R.C. Muchow, and M.J. Robertson. 1996. Growth of sugarcane under high input conditions in tropical Australia. III. Accumulation, partitioning and use of nitrogen. Field Crop Res. 48:223-233.

Chapter 5. Conclusions

Based on the results of this study, a ground based hand-held remote sensing system which utilized NDVI can be used to determine sugarcane yield response to applied N and sugarcane YP. When using an NDVI value to determine the response of cane tonnage and sugar yield to applied N, both traditional and modified methods of RI determination demonstrated similar accuracy and precision. However, utilizing the modified RI value would allow for users to document the full response of sugarcane to applied N. This is accomplished by having RI values compared to the check plot for all N rates; this is in contrast to solely using the highest N rate with the traditional method of RI determination. Additionally, using this technology four weeks after fertilization provided the optimum relationship between RI_{NDVI} and $RI_{Harvest}$, for either method. This optimum timeframe was true for all applied N timings, which ranged from mid-April through late-May. Therefore, implementation of an N reference strip, or the part of the field meant to represent an area of non-limiting N supply, four weeks prior to the intended fertilization date would allow adequate time for the sugarcane crop to respond.

In addition, NDVI was successful at being incorporated into YP estimation. However, unadjusted NDVI alone did not provide a strong relationship with cane tonnage or sugar yield. Adjusting the NDVI reading to create an INSEY value using either DFY or CGDD strengthened the relationship with sugarcane yield. While DFY did strengthen the relationship between NDVI and sugarcane yield, CGDD provided a better relationship across sites and years. In addition to adjusting NDVI readings, using CGDD as an estimate of time for YP estimation provided the best results. When using CGDD, the optimum timeframe for YP determination was found between 601 through 750 CGDD which was typically the last week of May through the first week of June. Although the overall model between INSEY-CGDD and sugarcane yield components within the optimum timeframe provided a good estimation of sugarcane YP, this relationship was strengthened when the varieties were separated based on canopy structure. This technology has the potential to provide important insight which could be beneficial in accurately determining sugarcane N requirement. A major drawback to integrating YP into an N management system is the potential physical damage of the sugarcane crop outside the optimum timeframe for N applications.

Another study was conducted that investigated the effects of N rate and application timing on sugarcane yield and quality. This study found that N rate significantly affected sugarcane yield and quality. Two of the three experiments showed a positive response of sugarcane yield to N rate. However, it was found that for both of these experiments critical N rates for both cane tonnage and sugar yield were substantially lower than the current N rate recommendations and variable between years. The effects of timing of application were not as critical as N rate with only one experiment found to be significantly affected by application time. Within this one experiment only the latest time of application showed a significant decrease in sugarcane yield compared to the earliest fertilization time. This would indicate that producers could delay N fertilization later than the current N recommendations without significantly decreasing sugarcane yield. Additionally, the variable response of sugarcane yield to applied N indicated that other means of determining N recommendations needed to be incorporated that take into account the current growth and environmental conditions.

The ability to delay N fertilization without significantly affecting sugarcane yield could be advantageous. This is due to one of the major limitations for the implementation of remote sensing techniques previously discussed for sugarcane production was as having to delay fertilization until May to coincide with the optimum timeframe for determination of YP.

Therefore, if fertilization can be delayed without significantly decreasing sugarcane yield remote sensing techniques have the potential to be implemented as an N management system.

Additionally, it was found that NDVI readings followed the same trend indifferent of fertilization timing (A.1, A.2, and A.3); however, the trend was not similar between years. As can be seen from figure A.1, NDVI readings showed a gradual increasing trend until shortly after the first of June at which point the NDVI readings sharply flattened. This was not the general trend observed for A.2 and A.3. These two experiments found a relatively minimal change in NDVI readings until late May or early June with an increase throughout the remaining readings. This trend was potentially due to the lack of precipitation in late spring with a flush of growth associated with grand growth and timely rains in June. This indicates that timing of application of N may not alter NDVI compared to the altered trend associated with environmental conditions. In addition, the relationship between NDVI and YP as well as RI_{NDVI} and $RI_{Harvest}$ was consistent throughout all application timings and years.

While these results indicate a promising future for the implementation of remote sensing techniques in sugarcane production, further investigation will be needed. One of these studies would need to develop/validate an in-season N recommendation tool which incorporates these two components. Additionally, a continued evaluation of timing of N application will be needed. One such season that will need to be incorporated before an N application system described in this research can be implemented would be an above-average growing condition. This would investigate if the flush of sugarcane growth associated with optimum conditions was conducive for the application of N fertilizers in late spring.

In summary, the ability of NDVI to quickly and accurately estimate sugarcane yield characteristics is promising. It allows for the incorporation of this or other ground based remote sensors that take into account current growing conditions and crop growth into N management systems.

Appendix A: NDVI Collected Throughout the Growing Season

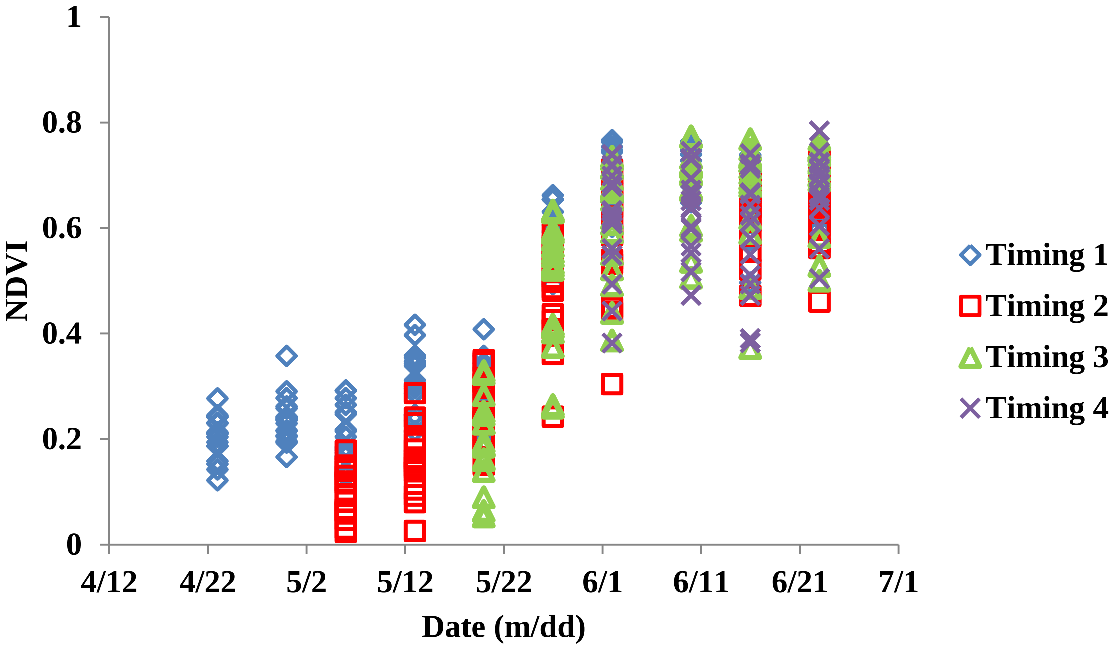


Figure A.1. NDVI readings collected throughout the growing season for the four N fertilization timings for Experiment 1 in 2010 in St. Gabriel, LA.

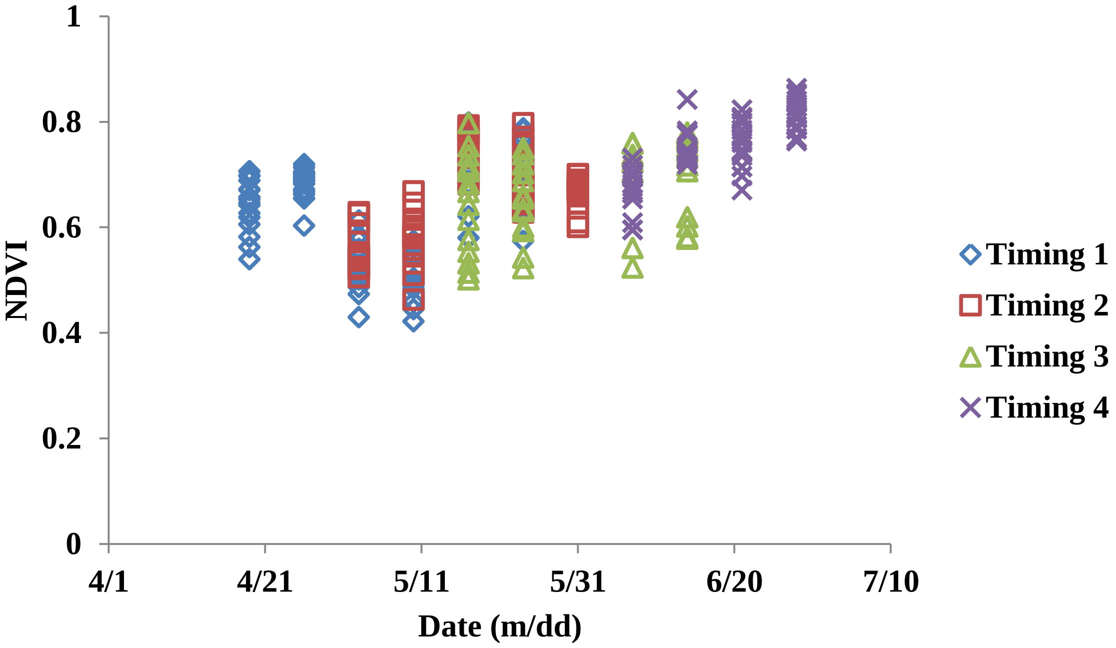


Figure A.2. NDVI readings collected throughout the growing season for the four N fertilization timings for Experiment 1 in 2011 in St. Gabriel, LA.

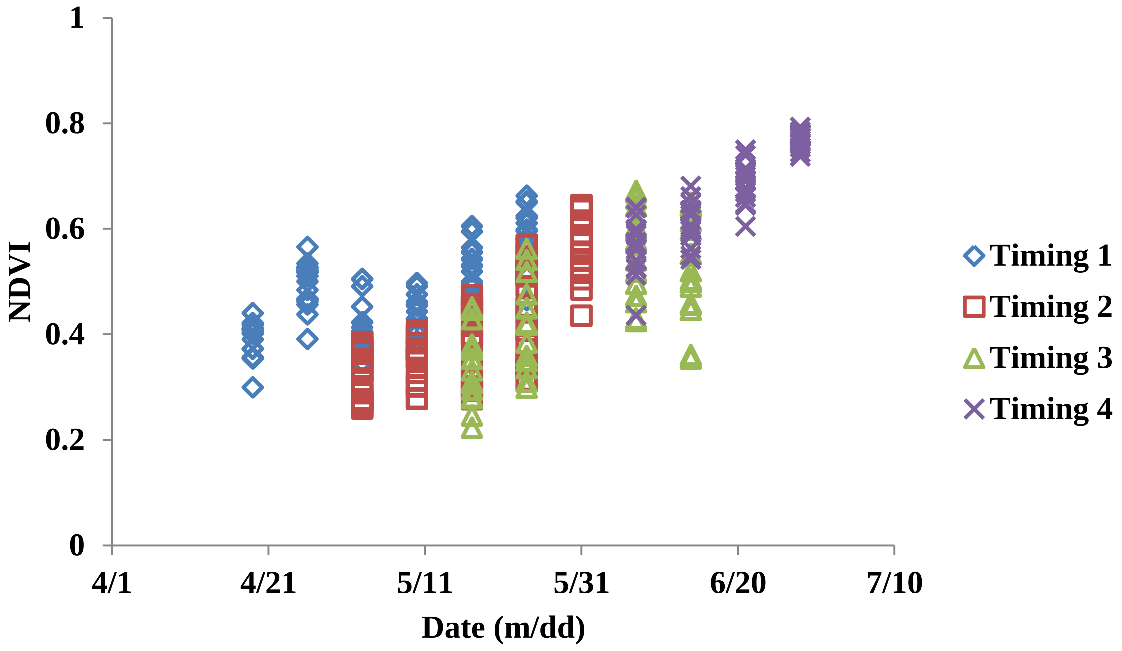
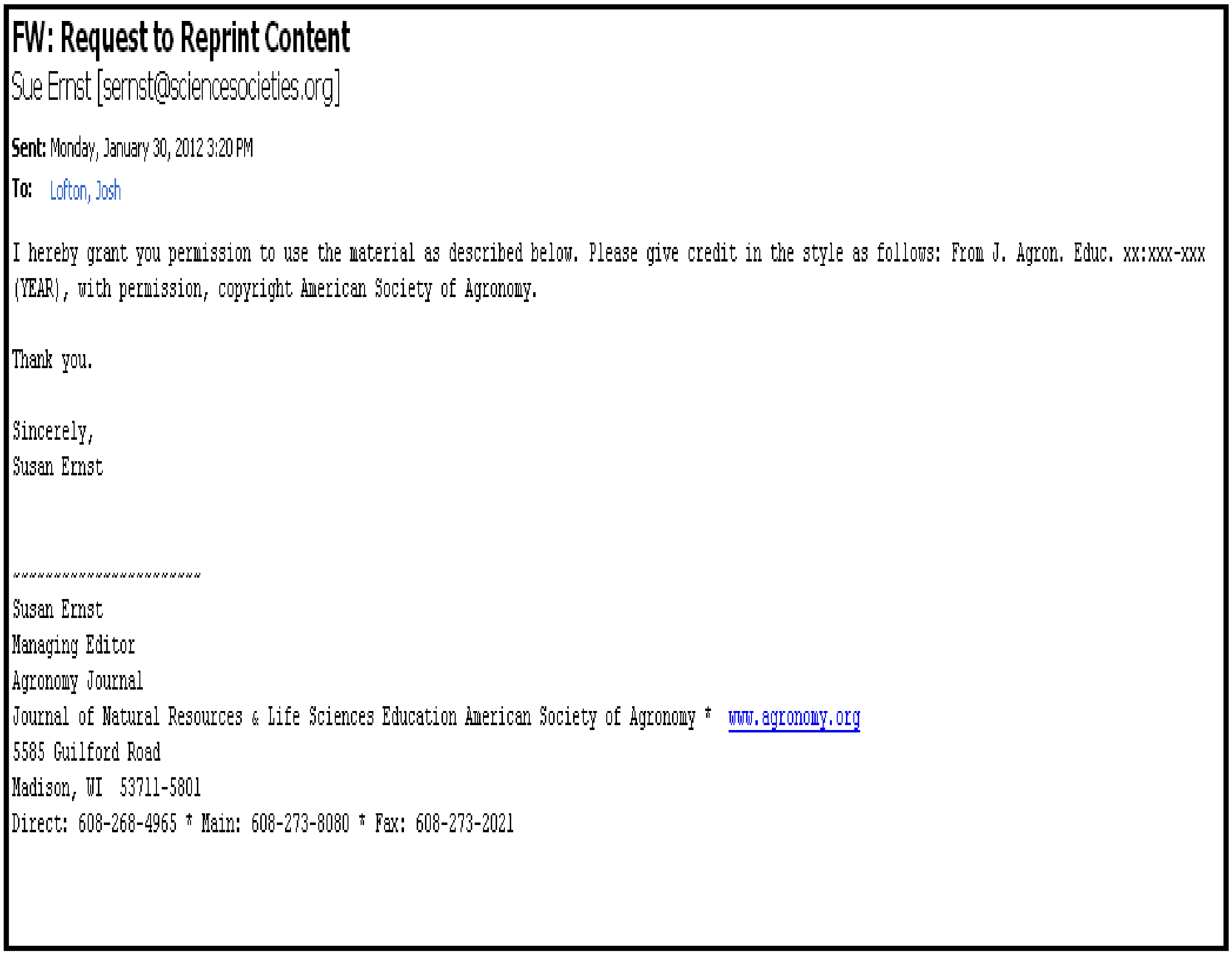


Figure A.3. NDVI readings collected throughout the growing season for the four N fertilization timings for Experiment 2 in 2011 in St. Gabriel, LA.

Appendix B: Permission to Reprint



FW: Request to Reprint Content

Sue Ernst [sernst@sciencesocieties.org]

Sent: Monday, January 30, 2012 3:20 PM

To: Lofton, Josh

I hereby grant you permission to use the material as described below. Please give credit in the style as follows: From J. Agron. Educ. xx:xxx-xxx (YEAR), with permission, copyright American Society of Agronomy.

Thank you.

Sincerely,
Susan Ernst

"""""""""""""""""""""""

Susan Ernst
Managing Editor
Agronomy Journal
Journal of Natural Resources & Life Sciences Education American Society of Agronomy * www.agronomy.org
5585 Guilford Road
Madison, WI 53711-5801
Direct: 608-268-4965 * Main: 608-273-8080 * Fax: 608-273-2021

Vita

Joshua Jon Lofton was born in May 1985, in Tulsa, Oklahoma. He attended Oklahoma State University at Stillwater, Oklahoma, where he received his Bachelor of Science degree in Plant and Soil Science in 2003. Upon completion, he continued at Oklahoma State University and graduated in 2009 with a Master of Science in Plant and Soil Science under the guidance of Dr. Chad Godsey. In June of 2009 he was admitted into the doctoral program in the School of Plant, Environmental, and Soil Science at Louisiana State University Agricultural and Mechanical College. He has since been under the guidance of Dr. Brenda Tubana working in N management in sugarcane production in Louisiana. The title of his dissertation is “Improving nitrogen management of sugarcane production in the mid-South using remote sensing technologies.”