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Integrated Nutrient Management and Cover Cropping Practices in Louisiana Sugarcane Production Systems

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INTEGRATED NUTRIENT MANAGEMENT AND COVER CROPPING PRACTICES IN LOUISIANA SUGARCANE PRODUCTION SYSTEMS

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, and Soil Sciences

by
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December 2021
This dissertation work is dedicated with love and affection to the memory of my loving father, Giovanni Forestieri. He has been my constant source of inspiration, for earning an honest living for us and for supporting and encouraging me always to be a better human being.

To my loving mother, Nancy Muñoz, who instilled in me the virtue of perseverance and commitment, relentlessly encouraged me to strive for excellence.
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ABSTRACT

Integrating effective fertilizer management with conservation practices is essential to improve farm income and promote environment friendly sugarcane production systems. A study was conducted in multiple to document the impact of nitrogen (N) source and cover cropping on sugarcane yield and quality components. The treatment consisted of different N sources: urea, knife-in urea ammonium nitrate (UAN) solution, calcium nitrate-CaNO₃, ammonium sulfate-NH₄SO₄, and knife-in UAN. + foliar N, applied at 90 kg ha⁻¹ and control (0 N). The cover crops included: crimson clover (*Trifolium incarnatum*), hairy vetch (*Vicia villosa*), and oilseed radish (*Raphanus sativus* L.) planted at 13, 17, and 1 kg ha⁻¹, respectively. A split-plot design was used having cover crops treatments (with and without) as main plots, and N sources as subplots with four replications. This study was also used for the acquisition of sugarcane normalized difference vegetation index (NDVI) 4 weeks after N fertilization using two platforms, a GreenSeeker® handheld sensor and a DJI Phantom 4 drone equipped with MicaSense RedEdge-M™ sensor to establish and validate NDVI conversion model and sugarcane prediction models. Cane and sugar yield, juice quality components, and stalk N content and uptake were determined at harvest. Soil and leaf tissue samples were collected for soil NH₄⁺-N and NO₃⁻-N and leaf-N monitoring. Across sites, sugarcane was very responsive to N application; the highest cane and sugar yield recorded was 118 Mg ha⁻¹ and 12,600 Kg ha⁻¹, respectively. Across sites, both UAN. and NH₄SO₄ treated plots achieved the highest increase in cane (115 and 117 Mg ha⁻¹, respectively) and sugar yield (13,283 and 12,236 Kg ha⁻¹, respectively). Ammonium was the predominant form of N in the soil compared to NO₃⁻. This highest concentration of NH₄⁺-N was in knife-in UAN, and NH₄SO₄ treated plots. The cover crops biomass removed a higher amount of nutrients from the soil than the no-cover crop. The converted aerial-NDVI can predict sugarcane yield potential using models
established from a ground-based sensor. The use of cover crops and remote sensing technology can be used as a decision tool to improve fertilizer recommendations and management practices for sustainable sugarcane production in Louisiana.
CHAPTER 1. GENERAL INTRODUCTION

1.1 INTRODUCTION

1.1.1 Sugarcane: Crop and Growing Conditions

Sugarcane (Saccharum spp. hybrids) is a tropical and subtropical perennial grass that accumulates sucrose in its juice. Once extracted and processed, it will crystalize into what we know as sugar (Verheye, 2010). The worldwide sugarcane production was estimated at 1980 million Mg from 22 million hectares (Salassi, 2015). Sugarcane is cultivated worldwide, wherein the largest production areas are in Brazil and India (Fortes, 2013). Sucrose is synthesized by sugarcane using the energy generated during the photosynthesis process. Sugarcane is the most important crop in terms of sugar production. Still, it is also used to produce energy from the combustion of the bagasse and alcohol of different grades for fuel and pharmaceutic purposes (Alexander, 1985).

The productivity of sugarcane is influenced by many factors such as weather, topography, and soil type. It grows well in regions with warm temperatures, high atmospheric humidity, and high annual rainfall, especially during the grand growth stage. While sugarcane can tolerate and survive extreme weather conditions, the optimal temperature is critical, especially during the growth and the ripening stage. Its growth and development are impaired by cold or too high and dry temperatures; likewise, excess water during a long period of rain could be harmful in the ripening stage (Hunsigi, 1993).

The optimal temperature for germination and root development is between 26 to 33°C; if the temperature goes below 20°C, germination and root systems development could be compromised (Hunsigi, 1993). Sugarcane will stop growing if the temperature drops below 15°C
or above 38°C, having the optimal growth temperature on average between 30 to 34°C (Bakker, 1999).

Light, intensity, and day duration highly influence root development, growth, and length of the ripening process (Bakker, 1999). Mineral nutrients are assimilated during the day, and the absorption of water for sugarcane on a sunny day is almost double compared to a cloudy day (Bakker, 1999). The photosynthesis process, which produces sucrose, depends directly on solar radiation. Sugarcane is grown in regions with rainfall periods of 50-250 cm per year (Hunsigi, 1993). A very wet cropping season influences planting and harvesting and could negatively affect sugar recovery at harvest (Hunsigi, 1993).

1.1.2 Sugarcane Production

Sugarcane is propagated vegetatively by stalks or billets (stem cuttings) with three or more buds. In general, there are two planting methods, known as manual and mechanical planting. After the material is planted and covered with soil, the germination process takes place from the living buds to produce a primary stalk. The setts can be planted end to end or in an overlapping pattern (Hunsigi, 1993). Setts have three to four nodes; each node will develop a root system. Sugarcane has four main growth stages: germination and root system development, grand growth, and tillering, ripening and maturation, and ratooning (Hunsigi, 1993). Ratooning crops like sugarcane can be harvested several times from the regrowth of the original setts planted in the first year (Humbert, 1963). Sugarcane can be repeatedly ratooned from three to six years; however, this will depend on each region and cultural practices (Bakker, 1999). The soil properties, climate conditions, sugarcane cultivars, and cultivar management are keys to secure a stable and productive sugarcane cropping system (Bakker, 1999). To ensure a successful crop establishment and optimal performance, the planting materials must meet some quality
standards, i.e., the planting materials must be free from any disease and pest, with good nutritional status, taken from tall and erect plants, no mechanical or physical damage, and most importantly collected from varieties suitable to the soil type and weather of the field location where the cane will be grown.

Sugarcane is commonly planted on raised beds to reduce problems of inundation or flooding. Row distance adopted worldwide ranged from 1.2 to 1.9 cm, grown as a single- or double-row (Bakker, 1991). Planting machinery is designed for two groups of planting methods: billets and whole stalk planting. For many years the whole stalk planting was the primary planting method. Here, seeds are cut from the base, transported with wagons, and mainly hand-planted (Hoy, 2001). However, weather and lodging, especially in high-yielding cane variety, have posed limitations on whole-stalk planting. More efficient harvester machinery and more efficient harvester machinery and billets planting have become the predominant planting method in several countries (Hoy, 2001). One main disadvantage of planting with billets is the higher requirement of planting material than the whole stalk plant. Without proper care and growing conditions, establishing a good stand and good ratooning cane crop can reduce productivity. Planting depth varies with soil texture, drainage system, and cultural practices such as fertilizer and disease control, soil to cover the seed to preserve the moisture, and harvesting operation (Yadava, 1991).

Harvesting of cane occurs after the cane has ripened, determined by the amount and accumulation of sugar in the plant (Hunsigi, 1993). Blackburn (1984) described the ripening and maturation process as the culmination of physiological growth processes (growth is ceased and minimal stalk elongation) and the beginning of sugar accumulation in the expanded internodes. Similarly, chemical ripening suppresses the level of nitrogen (N) biomass content and water in
the millable stalk (Blackburn, 1984). Hunsigi (1993) considers ripening a function of age, N, and moisture status; however, light, temperature, humidity, and rainfall also play an essential role. Currently, the use of ripeners or sucrose enhancers is being tested in sugarcane production (Orgeron et al., 2020). Lastly, sugarcane is harvested 13 to 18 months after the cane was first planted. After the planting and crop establishment and before the first harvest, the crop is called plant cane, and the regrowth after the first harvest is termed the ratoon crop(s). Worldwide harvesting operation is made by hand or with a combine harvester.

1.1.3. Sugarcane Nutrition and Fertilization

Sugarcane is grown on different soil textures, from light (sandy) to heavy textured soils (clayey) (Husingi, 1993). Studies conducted in several countries have confirmed that sugarcane is more productive when grown on clay, clay loam and sand, and sandy loam soils (Tabayoyong, 1959). The nutritional status of sugarcane per se does not limit its productivity since nutritional deficiency can be corrected by good nutrient management liming program. There are soils that can impose many problems to cane other than nutrient deficiency or toxicity.

In many countries, sugarcane production is limited when grown on problem soils. There are different types of problem soils, such as those with extreme pHs (acidic and alkaline) and high salt content (saline). These problematic soils will cause restrictions on average growth and negatively affect sugar and cane yields (Hunsigi, 1993). Overall, sugarcane performs well in soil pH values between 5.5 to 8. Sugarcane takes up significant amounts of N and potassium (K) (Glynn, 2004). The uptake of mineral nutrients varies by crop age, soil type, and variety (Legendre, 2000). Understanding the importance of sugarcane nutrition is the key to improve production and an adequate supply of nutrients required by sugarcane (Meyer, 2013).
Improved sugarcane nutrient management includes balancing the crop nutrient requirement, soil properties, fertilizer management using the right amount, source, and application timing (Meyer, 2013).

Sugarcane is considered a nutrient-demanding crop. Thus, meeting its nutrient requirement is essential for optimal and sustainable production (Titshall, 2020). For this reason, and with many pathways from which nutrients can be lost from the soil, implementing effective nutrient management and fertilization guidelines becomes more important. Most nutrients in the soil are transported to the rhizosphere by mass flow and diffusion. Nitrogen is transported to the sugarcane root rhizosphere through mass flow, whereas phosphorus (P) and K are transported to the roots by diffusion process (Huber and Graham, 1999).

Nitrogen is one of the nutrients that is commonly, if not always, applied to sugarcane. Generally, sugarcane requires 1.4 to 1.8 kg N per ton of cane (Chapman et al., 1992). Nitrogen has many essential physiological functions and can significantly impact cane quality. (Thorburn et al., 2003). Both P and K play a critical role in energy transfer and healthy root development (Fageria and Baligar, 2001). Sugarcane suffering from P deficiency produces thin stalks, a low number of tiller, and has poor and weak root systems (Burkitt et al., 2000). On average, P cane leaf critical levels range between 0.18 and 0.20 % (Burkitt et al., 2000). Potassium is present in the soil in inorganic form $K^+$, either in soil solution and exchange sites and associated with minerals such as feldspars and micas (Mclaren and Cameron, 1996). Potassium plays an essential role in plant growth and photosynthesis (Meyer, 2013).

Depending on the crop age, soil type, and soil K concentration, K is taken up by sugarcane in higher amounts than N. Normally, sugarcane takes up 8 kg K per ton of cane (Santo et al., 2018). Most of the K is used during photosynthesis and sugar translocation in the phloem
(Lee and Martin, 1999). Potassium reaches the maximum absorption level during the grand growth stage, where the internodes' intense development takes place to store sugar (Botha and Meyer, 2004).

Calcium (Ca) absorbs rapidly during the early growth stages and plays a vital role in root development, and also it is required for cell division (Legg et al., 1992). In contrast, sulfur (S) and magnesium (Mg) are absorbed more slowly, and in later stages of growth, both are essentials for the quality of sugar juice (Kington, 2000). A high soil Mg level relative to soil Ca interfere with K uptake (Santo et al., 2000). The deficiency of Mg could lead to slow growth and poor tillering (Kington, 2000). Under normal conditions, sugarcane can uptake 30 to 40 kg of S per ha, and Mg supplies must be maintained for the crop to produce a high sugar yield (Santo et al., 2000). The most crucial role of S is to catalyze the nitrate reductase enzyme, which converts nitrate to ammonium (Santo et al., 2000).

Other nutrients essential to sugarcane include boron (B), zinc (Zn), copper (Cu), iron (Fe), molybdenum (Mo), and manganese (Mn). Iron, and Mn are the micronutrients that sugarcane absorbs in higher quantities compared to B, Cu, and Zn, which have an essential function with chlorophyll formation and cell wall formation in the case of B (Gasho, 2001). Silicon (Si) and cobalt (Co) are beneficial nutrients to sugarcane. Some findings demonstrated the vital role of these nutrients in the physiological function of sugarcane. For example, Si is responsible for increasing sugarcane resistance to insects and diseases (Meyer and Keeping, 2005). There is also documentation supporting that Si can alleviate Mn and aluminum (Al) toxicity (Potingo et al., 2017). Several insect pest management practices (I.P.M.) consider using Si fertilizer as a strategy to reduce chemical fungicide and pesticide use (Kanamugire et al., 2006).
1.1.4 Louisiana Sugarcane Production

Sugarcane is one of Louisiana's most essential commodities. Louisiana is the second-largest producer of cane in the United States after Florida. Sugarcane has been cultivated for more than 200 years in south Louisiana since the Jesuit priest first brought it in 1751 (Gravois, 2001). Nowadays, the sugar industry represents Louisiana with an annual income of more than $3.5 billion in value to the economy. It is cultivated in 24 parishes across the states and processed to raw sugar molasses in 11 sugar mills (Gravois, 2001).

In Louisiana, sugarcane is cultivated in ~ 200,000 hectares; the production in 2019 reached 13 million Mg of harvested cane and 1556 million Mg of sugar (Deliberto et al., 2020). The average cane yield was 79 Mg per hectare, and the average sugar recovery was 104 kg of sugar per Mg of cane (Gravois, 2020). The most prevalent variety is L 01-299 planted to more than 56% of the production area, followed by HoCP 96-540, L 01-283, HoCP 09-804, and finally HoCP-838 with 15, 14, 5, and 4 %, respectively (Gravois, 2020).

The growing conditions in Louisiana vary every year and have been outside the normal range in recent years. For example, in 2019, the total annual precipitation was 163 millimeters with the minimum and maximum average temperature values of 14.4 to 26.1 °C, respectively, compared to the 40-year average, where rainfall reported a mean average of 159 millimeters but with 13 and 20°C for average minimum and maximum temperatures, respectively (U.S Climate Data, 2021). Sugarcane is a resilient crop; thus, while it is commonly planted in countries with tropical and sub-tropical climates, it is not unusual to grow sugarcane in a temperate environment and attain a high yield. The mission of the ongoing sugarcane breeding programs between LSU AgCenter, USDA-ARS facilities in Canal Point in Florida, and Houma in Louisiana, and the American Sugarcane League is to develop cane varieties that hold good yield,
longevity in the field, cold tolerance, and resistance to the most common pest and diseases in Louisiana (Gravois, 2012). In the history of Louisiana's sugarcane industry, approximately 75 sugarcane varieties have been released (Gravois, 2001).

The availability of high-yielding and robust variety has positively impacted this industry. Incorporating more advanced harvesting methods and machinery combined with yield monitors can strengthen this effort to understand sugarcane's yield potential better.

Disease-free seed cane is planted early summer to early fall in raised planting beds, usually 38 to 61 cm width, and will be harvested for the next three to four cropping seasons (Legendre, 2001). Cane germinates three to four weeks after planting, and the first harvest, called plant cane crop, is done 12 to 14 months after planting. The subsequent harvest seasons, called stubble or ratoon crops, are done 11 months from the previous harvest (Gravois, 2001). Typically, in Louisiana, sugarcane is grown three to four years. The planting system adopted by growers is primarily a single row configuration using the whole stalk; here, a set of three to four whole stalks is laid by hand, overlapping with another set by three to four internodes. Finally, in less proportion, seed cane is also planted using billets. Billets are considered small stalks in size, with an average of 60 cm with two to three mature internodes. (Hoy, 2001). Billets planting rates are recommended to plant six to eight across the planting furrow (Hoy, 2001).

Louisiana's soils are diverse and possess a large variability of soil types, mainly due to the alluvial soils formed by sediments deposited from the Mississippi River basin (Weindorf, 2013). The texture, organic matter content, pH, salinity, and cation exchange capacity (CEC) of these soils highly vary, and so with the amounts of essential plant nutrients (Johnson and Richard, 2005). Across Louisiana, sugarcane is cultivated in different soil texture types, from silt loam to clays.
A good fertilization scheme is essential to maximize the return from the fertilizer cost, reduce environmental impact to the ecosystem and ensure a good yield every cropping season. Typically, sugarcane production in Louisiana manages their fertilizer and lime applications based on soil test recommendations. Soil test recommendations are valuable for identifying critical areas in the field that need to be fertilized and adjust the soil pH.

Nitrogen fertilizer is applied once every cropping season with the common source as urea ammonium nitrate (UAN) solution by injecting it below the soil surface. Others surface bands applied (dribble) the solution followed by incorporation with tillage to reduce N losses (Legendre et al., 2000). Nitrogen fertilizer recommendation in sugarcane production can attain a certain level of precision when several factors such as soil type, crop age, climate, and growing cycles are considered (Wiedenfeld, 1995; Wood et al., 1996; Legendre et al., 2000). The window for N fertilizer application is between April to May (Legendre et al., 2001). Currently, N fertilizer recommendations are based on crop year/age (plant cane or stubble) and soil type (light or heavy texture soils) (Gravois, 2014). The most common N source of fertilizer is UAN, with 32% N at the rates of 112 to 135 kg of N per ha to meet sugarcane nutrient requirements (Gravois, 2014). Based on the sugarcane N removal rate at 1 kg per hectare, the estimated N application rate to meet this requirement is between 67 to 135 kg N per hectare (Tubana et al., 2018).

Other essential nutrients like P, K, S, and Zn are included in the fertilization guidelines for sugarcane production in Louisiana (Gravois, 2014). Phosphorus at the early stage of development is critical for root growth and energy formation; approximately sugarcane removes close to 1.9 kg P₂O₅ per ton cane (Gravois, 2014). Potassium is essential to regulate water and gas exchange during biochemical and physiological processes such as respiration and
photosynthesis (Knowles and Blackburn, 1993). Potassium is broadcast-applied as muriate of potash (KCl, 60% K) at rates based on soil testing. Sugarcane removes 3.4 kg K₂O per ha ton of cane (Gravois, 2014). Sulfur is another essential mineral nutrient for the plant, especially during chlorophyll formation, photosynthesis, and enzyme synthesis. Sulfur fertilizers recommendation in Louisiana suggests if soil S level is below 10 mg kg⁻¹ based on Mehlich-3 extraction procedure, S fertilizer application between 25 to 28 kg S per ha can avoid deficiency (Gravois, 2014). Micronutrient fertilization for sugarcane does not have a routine application; however, any deficiency is suggested to be correct according to the soil and tissue analysis provided. Louisiana's current fertilizer recommendation guidelines indicate two threshold levels on Zn soil levels, deficient (less than 1 mg kg⁻¹) and low (less than 2.25 mg kg⁻¹). Based on these two categories, the application rates recommend 6.72 and 3.36 lbs Zn ha⁻¹. (Gravois, 2021).

1.1.5 Nitrogen in Soil and Assimilation by Plants

Nitrogen is an essential and the most limiting nutrient for plant growth. It is necessary for chlorophyll formation, critical during the photosynthesis process (Havlin et al., 2005; Kettrings et al., 2003). Nitrogen is also required to produce enzymes, proteins, and hormones (Engels and Marschner, 1995). When N is deficient, the plant shows the older leaves' chlorotic and with a yellow appearance. Stunting growth is another symptom, and for sugarcane, N deficiency can cause reduced tillering and sucrose accumulation (Havlin et al., 2005).

Generally, soil fraction has both inorganic and organic forms of N. The inorganic form is available but present in smaller quantities than the organic form (Engels and Marschner, 1995). Plants absorb N as nitrate (NO₃⁻) and ammonium (NH₄⁺). These are transported from the soil to the root rhizosphere by mass flow and diffusion (Engels and Marschner, 1995). While most plants uptake both N forms, the absorption rate is higher for NO₃ than NH₄ mainly because of
higher concentration of NO$_3$ is readily available in the soil (Havlin et al., 2014). Inside the roots, NH$_4$ is converted into organic forms and transported to the shoots to complete its assimilations into organic N. In contrast, NO$_3$, whether in the roots or the shoot, must be reduced to NH$_4^+$ before being assimilated into organic N forms. Excess NO$_3$ is stored in the vacuole (Engels and Marschner, 1995).

Nitrogen is very dynamic in the soil. There are many pathways by which N is lost from the soil: immobilization, leaching, denitrification, and volatilization (soil and plant) (Galloway and Cowling, 2002). Nitrate-N is very mobile in the soil hence prone to be lost via the leaching process (Havlin et al., 2005; Zuberer, 2005). On the other hand, NH$_4$-N is held onto the soil exchange sites that prevent its loss by leaching until they are transformed to NO$_3$ by microorganisms (Havlin et al., 2005). However, NH$_4$ can also be lost from the soil via volatilization under certain conditions, i.e., high pH, high temperature, and dry conditions (Brady and Weil, 2003; Havlin et al., 2005). Nitrate can also be lost via the denitrification process. The pathway involves reducing NO$_3$ to nitrite (NO$_2$), nitric oxide, nitrous oxide, and finally losing the N in the form of a gas (N$_2$) (Galloway and Cowling, 2002). Usually, denitrification occurs under saturated conditions (soil with standing water for a long time), high temperatures, and increased soil organic matter. Generally speaking, conditions like soil pH, soil moisture, temperature, plant residues, and aeration influence the nitrification and denitrification process (Galloway and Cowling, 2002).

Plants acquire available N from organic matter mineralization and applied N fertilizer (Robinson, 1963). The mineralization of N starts with ammonification which is the conversion of amine to NH$_4^+$+. Ammonium, under favorable conditions, is transformed further to NO$_3^-$ via a series of oxidation processes facilitate by *Nitrosomonas* (conversion NH$_4^+$ to NO$_2^-$) and
Nitrobacter (conversion of NO₂⁻ to NO₃⁻) (Thorburn et al., 2003). Mineral N can become unavailable to plants via the immobilization process. Immobilization converts inorganic N to organic N, especially by microorganisms that need N to build up the protein for their cellular tissues (Bramley et al., 1996). Immobilization rates depend on the C: N ratios of the decomposing organic materials (Brady and Weil, 2003; Havlin et al., 2005). The N fixation process can add N to the soil. The general process involves converting atmospheric N (N₂) to NH₄⁺ (Havlin et al., 2005). Biological fixation of N can occur with (symbiotic) and without (non-symbiotic) association with host plants; symbiotic N fixation by certain bacteria occurs in legume roots inside the formed nodules (Bramley et al., 1996).

Usually, N represents 3 to 5 % of the total crop biomass (Havlin et al., 2005). Plant biomass at harvesting also removes most of the soil N available. Generally, sugarcane removes up to 2 kg of N per ha per ton of cane harvested (Tubana et al., 2019). For sugarcane, crop stage (plant or stubble cane) and growing cycle, sugarcane varieties, climate, and soil mineralization potential significantly affect the amount of N required by the cane, affecting the N and fertilizers efficiency (Weigel et al., 2008).

1.1.6 Nitrogen Fertilizers

Mineral N fertilizers were developed to supply and meet the crop N requirements. The right choice of fertilizer should be based on several factors such as the crops, soil type, and climate as this influence N removal, transformation processes, and loss pathways. Currently, most of the fertilizers are salt-based, except for organic fertilizers. Nitrogen fertilizers can be divided into several groups: amide, NH₄, NO₃, NH₄-NO₃, and finally, slow-release fertilizers (Jones et al., 2007).
Urea (CO\(_2\)(NH\(_2\))\(_2\)) is an amide-type of fertilizers containing 46 % N. In the presence of urease enzymes, urea converts rapidly to produce NH\(_4\) and bicarbonate ions; however, with the warm temperature and on dry soil, N in urea can be lost by volatilization (Batchelor and Shipley, 1991). Ammonium fertilizers, such as anhydrous ammonia (82 % N), and ammonium sulfate [(NH\(_4\))\(_2\)SO\(_4\), 21 % N, 24% S], are gas and granular fertilizer types. Anhydrous ammonia has the highest N concentration than any other N fertilizers and is applied to the soil by injection (Batchelor and Shipley, 1991). Ammonium sulfate is an acidifying fertilizer and an S source; (NH\(_4\))\(_2\)SO\(_4\) can be considered an option to raise the pH of alkaline soil (Batchelor and Shipley, 1991). Urea-ammonium nitrate is a solution N fertilizer that contains 28-32 % N. Nitrate fertilizers, such as calcium nitrate (CaNO\(_3\), 14 % N), is very soluble, quick-acting but can rapidly increase the soil pH (Whitehead and Raistric, 1990; Jones et al., 2007). Selecting N fertilizers is driven by the price of N in the market, amount, logistics, and cultural practices (Meyer, 1995).

The best N fertilizer management is implemented to ensure that most applied fertilizer is utilized to achieve optimum yields and minimize N losses. Nitrogen management practices involve applying the right amount using the right source in the right place. Generally, N should be applied during the rapid vegetative growth stage to minimize N fertilizer loss potential and maximize crop yield and nitrogen use efficiency (NUE) (Bock and Hergret, 1991; Johnston and Fowler, 1991). The optimum N rate varies by crop, soil type, yield goal, and economic return (Mesinger et al., 2008). Nitrogen rate recommendations are typically estimated based on yield and soil testing (Johnson, 1991).

Determining the right amount of N fertilizer has always been a challenge. Soil testing remains an effective tool in estimating plant-available N in the soil, at least in some regions in the U.S. (Stanford and Hanway, 1955; Bundy and Andraski, 1995). However, monitoring plant
N content to determine in-season N fertilizer recommendations has been widely used in agronomic crop production (Fox and Walthall, 2008).

1.1.7 Remote Sensing Technology

Monitoring of crop N status has been accomplished through soil testing, tissue analysis, and chlorophyll meters (Fox and Walthall, 2008). Soil testing and plant tissue analysis are practical tools to diagnose crop nutrient status; however, the cost and turn-around time are their main limitations. These highlighted the need to develop a quick and easy-to-use tool to monitor crop health and N status (Schöder et al., 2000). Before adopting precision ag tools in farming, N fertilizer recommendations were made based on yield goal, yield records, soil type, crop age, and cultivars (Stanford, 1973). Determining crop nutrient requirements accurately could be challenging if growers rely on yield goals and soil characteristics, and so many other factors. These factors change every year and vary within fields and from field to field. Therefore, it is imperative to accurately assess and consider the spatial and temporal variation on factors used to derive N rate recommendation.

Since the 1970s, remote sensing has been used to monitor N status in crop production (Fox et al., 2008). These diagnostic tools utilize non-destructive monitoring of plant N status, such as taking canopy reflectance readings. A vast amount of work has been done using this approach that subsequently paved the way to generating in-season, variable N rate recommendation (Raun et al., 2002; Singh et al., 2006; Shanahan et al., 2008; Tubaña et al., 2015). The chlorophyll meter is another instrument that can be used for non-destructive monitoring of plant N status. Plant N status is determined based on chlorophyll content estimated from multiple sampling areas in each leaf (Fox and Walthall, 2008). Chlorophyll meters emit light at red (660 nm) and infrared (940 nm) band spectrum (SPAD 502 chlorophyll meter,
Minolta Camera Co. Osaka, Japan). This instrument estimates chlorophyll content based on the percentage of transmitted light at these wavebands (Fox and Piekielek, 1998; Schepers et al., 1998). Researchers have used chlorophyll readings and sufficiency index (SI) approach to estimate N fertilizer recommendations for corn (Zea mays), cotton (Gossypium hirsutum), rice (Oryza sativa), and wheat (Triticum aestivum) (Blackmer and Schepers, 1995). If the SI values were below 95%, farmers would need additional N (Schepers et al., 1992). The SI values are determined by collecting reading from fertilized or non-N limiting reference strip and from a non-fertilized area, SI= (Average farmers practice reading/Average reference reading) *100 (Shapiro et al., 2006).

Active crop canopy sensor commonly uses the amount of reflected visible (red) and near-infrared (NIR) light from crop canopies to determine plant N health status (Arnold et al., 2002). Near-infrared reflectance light ranges from 750 to 1350 nm, and it is associated to plant cell structures and pigments (Sims and Gamon, 2002). In most plants that carry out photosynthesis, the primary pigments absorbing light energy are chlorophylls (a and b) and carotenoids. Chlorophylls a and b absorb light primarily in the visible spectrum's blue and red wavelengths (Schwinn and Davies, 2004). Visible light reflectance values range between 400 to 750 nm, and it is related to plant photosynthetic pigments such as chlorophylls, carotenoids, and anthocyanins (Sims and Gamon, 2002). The reflection of green light, which is weakly absorbed by chlorophyll pigments, accounts for plants' photosynthetic tissues (Richardson et al., 2002). Depending on the conditions, typically, bare ground soil and plant canopy reflect 15 to 30 % and 70 to 90 % of the NIR light, respectively (Arnold et al., 2002).

Vegetation index or indices (VI) is described as the relationship between spectral reflectance measurements at different wavelengths collected from the crop canopy (Fox and
Walthall, 2008). Other vegetation indices like simple ratio (SR), normalized difference vegetation index (NDVI), NDVI red-edge, SR red-edge, and modified red-edge S.R. are commonly used to predict biomass yield (Blackburn, 1998; Gitelson et al., 2002). The NDVI is one of the most widely used VIs and is known for its successful use in monitoring plant health status, estimating plant biomass yield, and generating variable N recommendations (Raun et al., 2002; Scharf et al., 2009; Tubana et al., 2011). One of the most common crop canopy sensors used to predict plant yield biomass and N fertilizer recommendation is the GreenSeeker® handheld sensor. This active sensor uses mainly two wavelength bands, the red (670 ± 10 nm) and NIR (780 ± 10 nm). Crop active sensors can be used to estimate plant N status at any time because they have their source of light (Singh et al., 2006; Shanahan et al., 2008). The NDVI is generated by the GreenSeeker using the following equation:

\[
\text{NDVI}= \frac{(\rho_{\text{NIR}}-\rho_{\text{Red}})}{(\rho_{\text{NIR}}+\rho_{\text{Red}})}
\]  

(1.1)

Where:

\(\rho_{\text{NIR}}\) = reflectance at the near-infrared region of the electromagnetic spectrum

\(\rho_{\text{Red}}\) = reflectance at the red region of the electromagnetic spectrum

The GreenSeeker handheld sensor is the primary sensor used to determine N fertilizer recommendation in Louisiana sugarcane production systems. The current N working algorithm for sugarcane N fertilizer recommendations is composed of predicted sugarcane yield potential and N response index (RI), an estimate of available N in the soil (Lofton et al., 2012a and 2012b; Tubaña et al., 2015). Crop response to N fertilization is the actual response to applied N fertilizer (Johnson and Raun, 2003). It is calculated using an RI equation that divides the average NDVI value collected from the non-limiting reference strip area by the NDVI obtained from the check
or non-applied N fertilizer (Johnson and Raun, 2003). Several studies have used the R.I. concept to estimate crop N response using NDVI readings (Raun et al., 2010; Harrell et al., 2011; Tubaña et al., 2012). This was based on the study by Mullen et al. (2003) demonstrating that $RI_{NDVI}$ could be used to predict crop yield response to N measured at harvest or $RI_{HARVEST}$. Yield potential with no N fertilizer application (YP0) and yield potential with N fertilizer application (YPN) are also critical components of the working algorithm (Raun et al., 2002). Normalized difference vegetation index collected from crop canopy and crop biomass yield is an essential component used to predict YP0.

These components, YP0, YPN, and RI, are used for an N fertilizer optimization to develop a sensor-based N rate calculator to variably apply N for sugarcane in Louisiana.

Unmanned aerial vehicle (UAV) equipped with digital cameras/sensors have many uses in agriculture, such as providing fertilizer recommendations, yield prediction and mapping, or identifying crop pests and diseases. Unmanned aerial vehicle systems are used to survey land and capture high-resolution images to decide fertilizer application, replanting, crop yield estimation, and crop nutrients requirements for growers (Zhu et al., 2009). Massive, accurate, and faster data collection are the main advantages of UAV systems.

Hyperspectral and multispectral sensors cameras mounted in UAV can also collect VIs and reflectance readings at different wavebands like the ground (proximal) crop canopy sensors. Remote sensors cameras mounted in drones are considered passive sensors. Passive sensors measure reflected light emitted by the sun. Therefore, the intensity of light and environmental conditions could affect the imagery’s quality (Lelong et al., 2008). There are few strategies to overcome this variability source: reducing the angle of sunlight incidence by flying at certain hours of the day, for example, between 10 am to 2 pm, and using light normalizing sensors
(Lelong et al., 2008; Swain et al., 2010). A UAV mounted with multispectral or hyperspectral sensors shows potential for monitoring crop N status. Initial validation work showed a strong relationship between the outputs (VIs/reflectance) from ground crop canopies and the UAV-sensor system (Quemada et al., 2014). The similarities of output from these two platforms have opened many opportunities to study their correlations and assess the possibility of using UAV-derived NDVI to generate midseason N fertilizer recommendations.

1.1.8 Cover Cropping and Soil Nutrient Cycling

As farming intensifies, there is an urgent need to use conservation practices to preserve and enhance soil health using cover crops after, during, or before the main crop is planted to reduce soil losses, increase fertility status and microbial activity, and control weeds (Blanco-Canqui et al., 2013). Continuous farming could deplete soil mineral nutrients, minimize yield potential, and decrease organic matter content (Causarano et al., 2006). Part of an effective nutrient management plan is to reduce soil and nutrients losses.

Minimum and no-tillage practices are considered conservation practices in which residues from the previously harvested crop are used as mulch to protect soil surface, increase soil nutrient, and promote soil aggregation (Busari et al., 2015). Cover cropping provides a similar set of benefits and more. Cover crops protect bare ground and act as scavengers of nutrients released from organic matter decomposition and applied fertilizers (Heggenstaller et al., 2008). Without cover crops, the available soil pool of nutrients would be lost by runoff or leaching (Justes et al., 2012). With years in practice, cover cropping may decrease fertilizer use, improve soil health, and increase crop yield.

Overall, there is a vast amount of literature and studies that support the use and benefits of cover crops. Cover crops can produce a lot of biomass thus, the cover crops' benefits depend
on choosing the suitable species, seeding rate, planting method, and termination time (Tonitto et al., 2006). The benefits of cover crops are many: pest suppression, improving soil biological, chemical, and physical properties (Tillman et al., 2004; Hooks et al., 2013). After cover crops are terminated, decomposition of the biomass will take place releasing the nutrients, all these with time result in increased soil organic matter and, improved nutrient cycling and soil structure. (Dabney et al., 2001; Mazzoncini et al., 2011). Another benefit of cover crops is that they can minimize nutrient losses from runoff and erosion during heavy rainfall, especially after the soil has been disturbed (Ashworth et al., 2017). Some cover crop species like the Crimson clover (*Trifolium incarnatum*) and Hairy vetch (*Vicia villosa*) can fix N to the soil, suppress weeds establishment, and provide a habitat for beneficial insects.

The use of cover cropping after harvest, when the soil is vulnerable, would protect the soil and minimize soil erosion, leaching, and runoff of nutrients during rainfall (Tubana et al., 2020). Research conducted in Louisiana using different cover crops showed that cool-season cover crops could improve soil microbial community and enhance soil health. In the same study, soil enzyme activity was correlated to soil organic matter decompositions and the release of soil mineral nutrients (Fultz et al., 2020). Another study on cover crops showed the effect of planting date on cover crop biomass yield. Three cover corps species [(tillage radish (*Raphanus sativus* L.), crimson clover, and hairy vetch)] were planted at three different times, September, October, and November. They found that cover crops planted in September produced the highest biomass, resulting in increased nutrients in the soil (Tubana et al., 2020).

Studies were conducted to evaluate the nutrient contributions of cover crops and document their subsequent impact on cane and sugar yield, stalks population, and juice quality traits. Typically, in Louisiana sugarcane is grown for three to five consecutive years. After the
last harvesting season, growers combine deep plowing and light disking to terminate the previous sugarcane crop and then rebuild and pack the rows. All these tillage operations disturb the soils and expose them to erosion by rain or wind. There are two scenarios where cover cropping can be implemented in this production system. One is during the fallow period, and the second is after planting a new cane crop in summer. There are sugarcane growers using soybeans both as a cash crop and cover crop. However, with grains being harvested, there is minimal nutrient turnover to the soil (Orgeron et al., 2020). On the other hand, other warm-season cover crops like sunn hemp (Crotalaria juncea L.) and cowpea (Vigna unguiculata (L.) Walp.) can produce an average of 12.8 ton ha\(^{-1}\) biomass. They can return N to the soil by as much as 250 kg ha\(^{-1}\) without affecting neither cane nor sugar yields (White et al., 2020).

1.1.9 Rationale

Nitrogen fertilizer is one of the most costly inputs in sugarcane production. Nitrogen is very dynamic in the soil. With many pathways from which N can be lost from the soil profile, the need to have an adequate N fertilizer management practice becomes more evident to improve nutrient use efficiency and productivity.

Agriculture has evolved to become sustainable and profitable at the same time. This has been attributed to the implementation of best management practices such as choosing the right N fertilizer source and sensor-based N recommendation using UAV to variably apply N fertilizer. The use of cover crops to improve nutrient cycling, soil health, and microbial community in the soil is considered a novel approach in Louisiana sugarcane production system (Tubana et al., 2020; Orgeron et al., 2020; Fultz et al., 2020; White et al., 2020). There is a limited information on how precision nutrient management and cover crops can increase economic profits, protect the environment, and improve current N fertilizer recommendations in sugarcane
production. Thus, this study was designed to document the impact of integrated nutrient management and cover cropping practices in Louisiana sugarcane production systems. To address this goal, studies at different locations were conducted to:

1) Evaluate the effect of different N sources on soil NH$_4$ and NO$_3$ content, and yield, quality components, and N uptake of sugarcane,

2) Evaluate the impact of cover cropping on nutrient content in the soil and sugarcane productivity, and

3) Evaluate the feasibility of using aerial image-based NDVI on yield prediction and N health monitoring in sugarcane production
CHAPTER 2. EVALUATE THE EFFECT OF N SOURCE ON SOIL AMMONIUM AND NITRATE, N UPTAKE, AND SUGARCANE PRODUCTIVITY

2.1 INTRODUCTION

Sugarcane (*Saccharum spp.*.) is a tropical and subtropical perennial grass (Verheye, 2010). In 2014, worldwide sugarcane production was close to 1980 million Mg from a total of 22 million hectares production areas (Salassi, 2015). Sugarcane is mainly cultivated in tropical and subtropical regions worldwide, with Brazil and India as among the top producers (Fortes, 2013). Louisiana is the second-largest producer of cane in the United States after Florida. Sugarcane has been cultivated for more than 200 years in south Louisiana since the Jesuit priest first brought it in 1751 (Gravois, 2001) and has brought, on average, an annual income of more than $3.5 billion in value to the state’s economy. Currently, sugarcane is cultivated in 24 parishes across the states and processed into raw sugar molasses in 11 sugar mills (Gravois, 2001).

Nitrogen fertilizer is applied once every cropping season with the common source as urea ammonium nitrate (UAN) solution used by injecting it below the soil surface. Others surface bands applied (dribble) the solution followed by incorporation with tillage to reduce N losses (Legendre et al., 2000). Nitrogen fertilizer recommendation in sugarcane production can attain a certain level of precision when several factors such as soil type, crop age, climate, and growing cycles are considered (Wiedenfeld, 1995; Wood et al., 1996; Legendre et al., 2000). The window for N fertilizer application is between April to May (Legendre et al., 2001). Currently, N fertilizer recommendations are based on crop year/age (plant cane or stubble) and soil type (light or heavy textured soils) (Gravois, 2014). The most common N source of fertilizer is UAN, with 32 % N at the rates of 112 to 135 kg of N per ha to meet sugarcane nutrient requirements.
(Gravois, 2014). Based on the sugarcane N removal rate at 1 kg per hectare, the estimated N application rate to meet this requirement is between 67 to 135 kg N per hectare (Tubana et al., 2018).

Nitrogen is an essential and the most limiting nutrient for plant growth. It is necessary for chlorophyll formation, critical during the photosynthesis process (Kettrings et al., 2003; Havlin et al., 2005). Nitrogen is also required to produce enzymes, proteins, and hormones (Engels and Marschner, 1995). When N is deficient, the plant is pale green in color and with chlorotic leaves. Stunting growth is another symptom, and for sugarcane, N deficiency can cause reduced tillering and sucrose accumulation (Havlin et al., 2005). Naturally, plants absorb N as nitrate (NO$_3^-$) and ammonium (NH$_4^+$). These are transported from the soil to the root rhizosphere by mass flow and diffusion (Engels and Marschner, 1995). While most plants uptake both N forms, the absorption rate is higher for NO$_3^-$-N than NH$_4^+$-N mainly because of the higher concentration of NO$_3^-$-N is readily available in the soil (Havlin et al., 2014). Nitrogen is very dynamic in the soil. There are many pathways by which N is lost from the soil: immobilization, leaching, denitrification, and volatilization (soil and plant) (Galloway and Cowling, 2002). Nitrate-N is very mobile in the soil hence prone to be lost via the leaching process (Havlin et al., 2005; Zuberer, 2005). On the other hand, NH$_4^+$-N is held onto the soil exchange sites that prevent its loss by leaching until they are transformed to NO$_3^-$-N by microorganisms (Havlin et al., 2005). However, NH$_4^+$-N can also be lost from the soil via volatilization under certain conditions, i.e., high pH, high temperature, and dry conditions (Brady and Weil, 2003; Havlin et al., 2005). Nitrate can also be lost via the denitrification process. The pathway involves reducing NO$_3^-$ to nitrite (NO$_2^-$), nitric oxide, nitrous oxide, and finally losing the N in the form of a gas (N$_2$).
(Galloway and Cowling, 2002). Another process from which N can be lost from the soil is also through plant removal.

Most plants uptake both N forms; however, since NO$_3^-$ is already available, the absorption rate is higher for nitrate than NH$_4^+$ (Havlin et al., 2014). However, this will change according to the soil pH, soil moisture, weather, and plant species, while both NO$_3^-$ and NH$_4^+$ are absorbed and assimilated by sugarcane. Robinson et al. (2011) reported that N-repleted sugarcane prefers NH$_4^+$ over NO$_3^-$. So, the main question is which N form is selected by plants to maximize crop productivity. Because NH$_3$ is rapidly converted to NO$_3^-$ by microorganisms in moist soil when aeration and temperature are optimal for plant growth, NO$_3^-$ is considered the primary form of N available. There are many reasons why it has been challenging to resolve the effects of NO$_3^-$ or NH$_4^+$ on plant assimilation and growth. First, the two ions' inherent characteristic and properties are different, NH$_4^+$ is a cation, and NO$_3^-$ is an anion. The soil is mostly negatively charged, so NO$_3^-$ remains mobile while the NH$_4^+$-N form is held on the soil exchange site. Hence, NO$_3^-$ can move with the soil solution to the root or be more readily leached from the soil. Second, in fertilizer salts, the two forms of N are associated with different companion ions. It can affect plant growth and can make soil more acidic or more alkaline, etc.

A previous study on sugarcane in solution culture treated with various N sources showed that NH$_4^+$ fertilizer had a toxic effect on root growth (Weigel et al., 2008). They also reported that unlike most higher plants, sugarcane absorbs N primarily as NH$_4^+$ and not as NO$_3^-$. Many studies showed that plant cane absorbs N, either as NO$_3^-$ or NH$_4^+$, but NO$_3^-$ is then converted rapidly to NH$_4^+$ form at the tip of the roots (Havlin et al., 2005). The ammonia is then converted immediately to amides and amino acids and later to proteins. Outside its system, sugarcane response to inorganic N form will depend on factors that can alter the soil NH$_4^+$ and NO$_3^-$ content.
and N transformation processes, including N fertilizer source, organic matter content, pH, moisture, etc. The impact of cover crops on nutrient recovery and turnover to the soil to decrease fertilizer use, improve soil health and increase yield are benefits that cover crops could provide to ensure crop productivity and sustainability (Fultz et al., 2020; Orgeron et al., 2020; Tubana et al., 2020; White et al., 2020). For sugarcane, the use of cover crops has put a critical interest, especially on N cycling and N release from cover crop residues. This study evaluated the effect of different N sources, covered cropping on soil NO$_3^-$ and NH$_4^+$ content, and documented their subsequent impact on sugarcane productivity, N uptake, and leaf inorganic N concentration under Louisiana production systems.

2.2 MATERIALS AND METHODS

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

The study was conducted at four sites (site 1-4) at the Louisiana Agricultural Center Sugar Research Station in St. Gabriel, LA, USA (Latitude 30°, 15', 13" N; Longitude 91°, 06', 05" W). These four sites were on two soil types: Commerce silt loam and Commerce silty clay loam (Fine-silty, mixed, superactive, non-acid, thermic Fluvaquentic Endoaquept). In addition to these sites, a similar study (fewer treatments) was conducted on on-farm demonstration plots (site 5) in Paincourtville, LA, USA (Latitude 29°, 59', 34" N: Longitude 91°, 03', 38" W). The predominant soil texture was Cancienne silt loam (Fine-silty, mixed, superactive, non-acid, hyperthermic Fluvaquentic Epiaquepts). Table 2.1 shows the initial chemical properties of soil for all sites. All sites were planted with sugarcane variety L01-299 between 2016 to 2018 using whole stalk and billets (Table 2.2). All sites were planted at the Sugar Research Station using billets on beds in a three-row plot configuration. Each plot contained three (3) 1.83 m-wide by 15-m long beds. The opened beds were filled with stalks cut into 40 to 50 cm-long billets at the
rate of 6-8 billets for every 50 cm section down the planting furrow. At site 5, sets of three to four whole stalks were laid onto opened (15-cm depth) beds by hand, keeping about 8 cm (3 to 4 internodes)- overlap with the next set of stalks. At this site, each strip or plot consisted of two or three beds measuring 1.7 m wide by 170 m long. Following planting, beds were covered with 8 cm of soil and packed to keep enough moisture to have good germination. Table 2.2 provides details of planting materials and dates of major field operations for all the sites. After beds were packed, herbicide application was carried out to seal the soil using a pre-emergence mix of herbicides using metribuzin [4-amino-6-tert-butyl-3-methylthio-1,2,4-triazin-5(4H)-one] at 3.4 kg a.i. ha\(^{-1}\) and pendimethalin [N-(1-ethyl propyl)-2,6-dinitro-3,4-xylidine] at 2.2 kg a.i. ha\(^{-1}\).

Table 2.1. Chemical properties of the initial soil samples collected from all the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>(\hat{p})H</th>
<th>(\hat{\psi})Organic matter (g\ kg^{-1})</th>
<th>(\hat{\psi})Extractable Nutrients, mg kg(^{-1})</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Ca</th>
<th>Mg</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1</td>
<td>17</td>
<td></td>
<td>22</td>
<td>93</td>
<td>14</td>
<td>1633</td>
<td>346</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>18</td>
<td></td>
<td>21</td>
<td>184</td>
<td>12</td>
<td>2896</td>
<td>468</td>
<td>4.1</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>19</td>
<td></td>
<td>64</td>
<td>194</td>
<td>13</td>
<td>2500</td>
<td>524</td>
<td>4.2</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>21</td>
<td></td>
<td>23</td>
<td>196</td>
<td>9.3</td>
<td>2900</td>
<td>553</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>16</td>
<td></td>
<td>22</td>
<td>183</td>
<td>11</td>
<td>2045</td>
<td>343</td>
<td>3.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

\(\hat{\psi}\) Based on Mehlich 3 (Mehlich, 1984) procedure.
\(\hat{\psi}\) 1:1 w/v soil: deionized water ratio (McLean, 1982)
\(\hat{\psi}\) Acid-dichromate oxidation (Nelson and Sommer, 1982)

Treatments for sites 1-4 consisted of six different N sources (including a control, no N) arranged in a randomized complete block design considering the different N sources as a main effect. Each N source treatment was replicated eight times. Site 5 consisted of three different N sources arranged in a completed randomized block design with six replications. Table 2.3 describes the treatment structure implemented in these studies.
Table 2.2. Agronomic practices for all the sites established at the LSU AgCenter Sugar Research Station and the grower’s field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Site</th>
<th>Planting date</th>
<th>Planting Material</th>
<th>Crop age</th>
<th>Year</th>
<th>Location</th>
<th>Fertilization date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August 2016</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2017</td>
<td>St. Gabriel</td>
<td>April 28</td>
<td>December 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>Second stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 25</td>
<td>October 20</td>
</tr>
<tr>
<td>2</td>
<td>August 2016</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2017</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>Second stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 25</td>
<td>October 20</td>
</tr>
<tr>
<td>3</td>
<td>August 2017</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 15</td>
<td>December 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 18</td>
</tr>
<tr>
<td>4</td>
<td>August 2018</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 15</td>
<td>December 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2020</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 18</td>
</tr>
<tr>
<td>5</td>
<td>August 2017</td>
<td>Whole stalk</td>
<td>Plant cane</td>
<td>2018</td>
<td>Paincourtville</td>
<td>April 19</td>
<td>December 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole stalk</td>
<td>First stubble</td>
<td>2019</td>
<td>Paincourtville</td>
<td>April 17</td>
<td>November 18</td>
</tr>
</tbody>
</table>
Table 2.3. Description of the different N sources used as treatments at the LSU AgCenter Sugar Research Station and the grower’s field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatments</th>
<th>N rate (kg ha(^{-1}))</th>
<th>N source</th>
<th>Composition</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Gabriel</td>
<td>1</td>
<td>0</td>
<td>Control</td>
<td>Granular</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>90</td>
<td>Urea</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>90</td>
<td>UAN</td>
<td>Liquid</td>
<td>Injected</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90</td>
<td>(\text{NH}_4^+) sulfate</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>90</td>
<td>CaNO(_3)</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>67 + 23</td>
<td>UAN + (\text{NH}_4^+) sulfate</td>
<td>Liquid</td>
<td>Injected + Foliar</td>
</tr>
<tr>
<td>Paincourtville</td>
<td>1</td>
<td>90</td>
<td>CaNO(_3)</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>90</td>
<td>UAN</td>
<td>Liquid</td>
<td>Injected</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>90</td>
<td>(\text{NH}_4^+) sulfate</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

Fertilizer analysis: CO(NH\(_2\))\(_2\)- urea – 46% N; UAN – urea ammonium nitrate solution, 32% N; (NH\(_4^+\))\(_2\)SO\(_4\) -ammonium sulfate, 21 %N; calcium nitrate – (NO\(_3\))\(_2\)Ca, 15.5 %N [1% Ammoniacal N and 14.5 % nitrate N] and 19 %C
Before fertilization in April, the planted row sides were off-barred using a three-row disk cultivator. Granular N fertilizers were broadcast to the trench created by the disk cultivator, whereas UAN solution was either injected or dribbled on both shoulders of the planted row. Rows were closed or wrapped up with soil to prevent any N loss. Treatment 6 (UAN knife-in + NH₄⁺ sulfate foliar) at the Sugar Research Station was a combination of liquid UAN knife-in at 67 kg N ha⁻¹ and a foliar application of solution N three weeks after at a rate of 23 kg N ha⁻¹. For foliar application, NH₄⁺ sulfate was diluted by mixing 11.4 liters water with 1 kg of NH₄⁺ sulfate fertilizer.

2.2.2 Soil Sampling

Soil samples were collected at 0-15 and 15-30 cm depth with a soil probe (JMC; Model No. 641-792-8285) at two, four, and six weeks after N fertilization (WANF) and after harvest every year for all sites. A total of sixteen (16) 30-cm soil cores were pulled out from each plot and separated into 0-15 and 15-30 cm depth. Samples were dried at 60°C for four days in an oven (Despatch LBB series; model number LBB2-18-1). Later, they were processed with a Humboldt electric flail grinder and sieved through a built-in 2 mm sieve.

2.2.3 Soil Analysis

Soil NH₄⁺ and NO₃⁻ concentrations were determined using a spectrophotometric measurement with an automated flow injection system (Lachat QuickChem 8500 series 2). One molar (M) potassium chloride (KCl) was added to a 125 ml plastic bottle containing five (5) grams dried soil sample. The samples were shaken for one hour on a reciprocal shaker (Eberbach; model number-E6010.00) at high speed. The soil suspension was filtered using No. 42 Whatman filter paper.
2.2.4 Leaf Sampling

Sugarcane leaf tissue sampling was done by collecting the 2\textsuperscript{nd} leaf from the top visible dewlap (TVD). The TVD refers to the uppermost leaf with a visible dewlap or joint triangle. A total of sixteen (16) leaves were collected in each plot at two, four, and six-week WANF and at harvest. The leaf samples were dried for four days at 60°C using an oven (Despatch LBB series; model number LBB2-18-1). Dried samples were ground using a Wiley mill (Model No. 3, Arthur H. Thomas CO. Philadelphia, USA), thoroughly mixed, passed through a 1 mm sieve, and stored in labeled coin envelopes.

2.2.5 Plant Nitrogen Analysis

The N content (%) analysis was done on both leaf (leaf blade with the midrib) and shredded stalk samples. Each sample was weighed (20 mg) using an analytical balance and analyzed using a CN dry combustion analyzer (Elementar Americas Inc, Vario EL Cube). Stalk N content was used to determine stalk N uptake in kg ha\textsuperscript{-1} using the following formula:

\[
N \text{ Uptake (kg ha}^{-1}\text{)} = [(\text{cane yield}) - (\text{cane yield x (% moisture/100))] x [\% N/100] \quad (2.1)
\]

2.2.6 Cane and Sugar Yield and Quality Components

The plots from all sites were harvested using a single-row chopper harvester (John Deere 350 model). A modified single axle high dump weigh wagon equipped with load cell sensors (Cameco Industries, Thibodaux, LA) was used to determine stalk weight for every row of each plot. At the grower’s field, yield data was collected from a yield harvest monitor georeferenced to a precise location point using global positioning system (GPS). Ten stalks were cut from the middle row by hand, leaves were stripped off from the stalk, and the top was cut between the first 10 cm below the apical meristem.
Total plot weight was calculated by adding the weight from the ten stalks to the plot yield. Sugarcane stalks were shredded using a Dedini laboratory disintegrator (Dedini S/A Industrias de Base, Piracicaba, Brazil) and analyzed using a Spectracane Near Infrared System (Bruker Corporation, Billerica, Massachusetts) to determine juice quality components (theoretically recoverable sugars -TRS, total soluble solids -BRIX, and sucrose content). Grab samples of the shredded stalk were collected to determine stalk N uptake following the procedure detailed in the previous (leaf analysis) section. The weight of the 10 sampled stalks was then used to determine average stalk weight and to estimate sugarcane stalk population using the following formula:

\[
\text{Stalks per ha}^{-1} = \left( \frac{\text{Total plot weight}}{\text{average stalk weight}} \right) \times \left( \frac{10,000 \text{ m}^2}{\text{plot area in m}^2} \right) \quad (2.2)
\]

2.2.7 Data Analysis

Agronomic variables such as cane and sugar yield, quality parameters, soil, and plant variables were subjected to analysis of variance (ANOVA) using PROC MIXED in SAS version 9.4 (SAS Institute, Cary, NC, USA. 2012). Site, crop age and N source were the fixed effects whereas replication was set as random effect. The least square means (LS means) were determined, and the means of significant effects were separated using the PDIF option \( (p \leq 0.05) \). Letters grouping was converted using the PDMIX800 (Saxton 1998).

2.3 RESULTS AND DISCUSSION

The average monthly temperature and precipitation at the Sugar Research Station in St. Gabriel across the different crop years are reported in Figures 2.1 and 2.2, respectively. Generally, the pattern of monthly average temperature was similar from 2017 to 2020 (Figure 2.1). The temperature registered in January 2018 was the lowest average monthly value across years. This is important because a low-temperature trend at the early stage will affect sugarcane
growth vigor later, adding more stress making cane susceptible to insect and disease. Also, temperature has an essential impact on sugarcane growth; on average, the optimal temperature for sugarcane to grow is between 30-33ºC; at temperatures below 16ºC, sugarcane development is compromised (Bakker, 1999). Low temperature can enhance the ripening process and accumulate more sugar (Bakker, 1999). Dry matter accumulation and stalk elongation have been reported in a range of temperature close to 17.2 to 22.2 ºC (Hunsigi, 1993).

From June to September for all years, the temperature recorded the highest average values of 26, 28, 29, and 27ºC, respectively (Figure 2.1). November 2018 and 2019 reported the lowest temperature (approximately 4 ºC) compared to the other years. L01-299 has been registered as a medium cold tolerant variety (Gravois, 2014). April and May 2019 reported the highest precipitation than the rest of the years (Figure 2.2). The rainfall reported from 2017 to 2020 at the Sugar Research Station on average was remarkably higher than the 40 years average precipitation. After N fertilization, the highest rainfall in April and May was reported in 2019, with an average of 20 and 26 cm, respectively. Heavy rainfall events, especially after N fertilization, could lead to N losses by runoff and NO₃⁻ leaching throughout the soil profile.

The average monthly temperature and precipitation at the grower’s field in Paincourtville across the crop years are reported in Figures 2.3 and 2.4, respectively. Overall, the monthly average temperature reported in 2017 was lower than in 2018 and 2019. The average monthly temperature reported in August to September across years was 26 and 28ºC, respectively. Precipitation in May, June, July, and August was higher in 2017 than in the other years (Figure 2.4). Precipitation reported in 2018 was relatively low at early and midseason; however, the month of September, November, and December reported the highest rainfall event than the other years.
Figure 2.1. Average monthly temperature from January to December 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA.

Figure 2.2. Average monthly precipitation from January to December in 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.3. Average monthly temperature from January to December in 2017, 2018, 2019, and 2020 at the grower’s field in Paincourtville, LA.

Figure 2.4. Average monthly precipitation from January to December in 2017, 2018, 2019, and 2020 at the grower’s field in Paincourtville, LA.
2.3.1 Effect of Nitrogen Sources on all Measured Plant Variables

Table 2.4 shows the effect of site, crop age, N source, and their interactions on cane and sugar yield, quality parameters, stalk population, and N uptake. There was an evident cane and sugar yield response to applied N sources across sites and crop ages ($p \leq 0.05$, Table 2.4). Significant 2-way (crop age x N sources) and 3-way (site x crop age x N sources) interaction effects were observed for cane and sugar yield. There was a significant interaction effect between the N sources and crop age on plant population whereas site x crop age interaction was significant on quality components and N uptake.

The 3-way significant interaction effect of site, crop age, and N source was the main reason to analyze N sources effect by site and crop age. For Site 1, Tables 2.5, 2.6, and 2.7 show the results on mean separation for the effect of N source on cane and sugar yield, TRS, Brix, sucrose, stalk population, and N uptake for 2017 plant cane, 2018 first stubble, and 2019 second stubble, respectively. Soil type for site 1 is dominated by silt loam (77 %) and less silty clay loam (23 %) Commerce soil type. There was a clear and significant effect of N sources on cane yield across crop ages (Tables 2.5, 2.6, and 2.7). Based on the differences among treatment means, the control (0 N) plots showed lower sugarcane yield than the N fertilized plots across crop ages.

The mean separation results showed no significant differences in cane yield among N sources for 2017 plant cane (Table 2.5) and 2019 second stubble (Table 2.7). However, in the 2018 first stubble, a significant difference was observed between N sources wherein significantly higher cane yield was observed in UAN knife-in, CaNO$_3$, NH$_4$ sulfate, UAN knife-in + foliar-treated plots than urea and the control plots. However, there was no significant difference among UAN knife-in CaNO$_3$, NH$_4$ sulfate, or UAN knife in + foliar treated plots (Table 2.6). On
average, for site 1 (Commerce silt loam soil), cane achieved higher yields at the first stubble than plant cane and second stubble crop from the N fertilized plots than the control (Tables 2.5, 2.6, and 2.7). For example, on average cane yield on the first stubble was higher (106 Mg ha$^{-1}$) in the N fertilized plots than in the control plots (63 Mg ha$^{-1}$) compared to the N fertilized 98 and 81 Mg ha$^{-1}$ vs. 73 and 55 Mg ha$^{-1}$ in plant cane and second stubble, respectively.

The yield increases due to N application were 25 (35%), 43 (64%), and 26 (48%) Mg ha$^{-1}$ for the plant cane, first stubble, and second stubble, respectively. As mentioned before, N played an essential role in affecting cane yield, but crop age was also important.

Cane yield typically declines with crop age. Stubble cropping is technically defined as the cultivation of the subsequent crop growth after sugarcane is harvested (Hunsigi, 1993). In general, stubble crop yields and juice quality tend to be lower than the plant cane. Blackburn (1984) did several N responsive studies to show that sugarcane does not have any preference for N source except under specific conditions. Urea (46 % N), NH$_4$ sulfate (21 % N), UAN (28-32 %N), and NH$_4$NO$_3$ (34 % N) are the most common sources of N fertilizers applied in sugarcane production systems around the world (Vallis et al., 2009).

Similar results were found by Basantha et al. (2003) using five different N sources conducted in the red soils of Brazil with no significant difference in cane yield or commercial recovery sugar among N treatments. Nitrogen sources can affect soil inorganic N; for example, loss through NO$_3^-$ leaching is lower using slow-release N fertilizer. The application of urea in saline soils can reduce plant dry matter due to slow N uptake (Isa et al., 2006).
Table 2.4. Probability values associated with the analysis of variance of fixed effects and their interactions for all the plant measured variables, Sugar Research Station, St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$-value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Crop age</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.1483</td>
</tr>
<tr>
<td>N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Site*crop age</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>0.0471</td>
</tr>
<tr>
<td>Site*N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0466</td>
<td>NS</td>
</tr>
<tr>
<td>Crop age*N sources</td>
<td>0.0023</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Site<em>crop age</em>N sources</td>
<td>0.0101</td>
<td>0.0147</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0461</td>
<td>NS</td>
</tr>
</tbody>
</table>

*NS indicates no significant difference at the $\alpha=0.05$ level of significance.
Table 2.5. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2017 plant cane for site 1 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Sources of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS*</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td><strong>N Source</strong>(^{\dagger})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>73 b(^{\psi})</td>
<td>9,566 b</td>
<td>130</td>
<td>19.69</td>
<td>17.77</td>
<td>88,297</td>
<td>64 b</td>
</tr>
<tr>
<td>Urea</td>
<td>97 a</td>
<td>12,790 a</td>
<td>131</td>
<td>20.06</td>
<td>18.02</td>
<td>102,220</td>
<td>104 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>98 a</td>
<td>12,901 a</td>
<td>131</td>
<td>20.14</td>
<td>17.99</td>
<td>94,580</td>
<td>94 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>101 a</td>
<td>12,903 a</td>
<td>128</td>
<td>19.58</td>
<td>17.56</td>
<td>98,524</td>
<td>99 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>96 a</td>
<td>12,525 a</td>
<td>129</td>
<td>19.91</td>
<td>17.82</td>
<td>96,430</td>
<td>98 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>97 a</td>
<td>12,821 a</td>
<td>132</td>
<td>20.04</td>
<td>18.13</td>
<td>94,766</td>
<td>100 a</td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS(^{\dagger})</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

\(^{\dagger}\) TRS Theoretical recoverable sugar

\(^{\dagger}\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife-in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.

\(\dagger\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.

\(\psi\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.6. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2018 first stubble for site 1 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Sources of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS*</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>kg ha⁻¹</td>
<td>kg Mg⁻¹</td>
<td>%</td>
<td>%</td>
<td>kg N ha⁻¹</td>
<td>kg N ha⁻¹</td>
</tr>
<tr>
<td><strong>N Source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>63 c</td>
<td>6,567 c</td>
<td>109</td>
<td>17.67 b</td>
<td>15.26</td>
<td>78,976 b</td>
<td>46 b</td>
</tr>
<tr>
<td>Urea</td>
<td>96 b</td>
<td>10,456 b</td>
<td>111</td>
<td>18.00 ab</td>
<td>15.48</td>
<td>92,208 b</td>
<td>89 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>111 a</td>
<td>12,568 a</td>
<td>115</td>
<td>18.42 a</td>
<td>15.98</td>
<td>117,463 a</td>
<td>94 a</td>
</tr>
<tr>
<td>NH₅ Sulfate</td>
<td>104 ab</td>
<td>11,721 a</td>
<td>114</td>
<td>18.31 a</td>
<td>15.85</td>
<td>113,124 a</td>
<td>94 a</td>
</tr>
<tr>
<td>CaNO₃</td>
<td>109 a</td>
<td>12,019 a</td>
<td>111</td>
<td>18.26 a</td>
<td>15.62</td>
<td>114,868 a</td>
<td>91 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>110 a</td>
<td>12,121 a</td>
<td>112</td>
<td>18.15 a</td>
<td>15.63</td>
<td>113,934 a</td>
<td>96 a</td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>0.0134</td>
<td>NS</td>
<td>0.0002</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

≠ TRS Theoretical recoverable sugar
¥ All N sources were applied at 90 kg N ha⁻¹ to the soil except for UAN Knife-in + Foliar, which was knife-in applied at 67 kg N ha⁻¹ to the soil and 23 kg N ha⁻¹ as foliar.
£ NS indicates no significant difference at the α=0.05 level of significance.
ψ Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at p<0.05.
Table 2.7. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2019 second stubble for site 1 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS¥</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td></td>
<td></td>
<td>kg N ha(^{-1})</td>
</tr>
<tr>
<td><strong>N Source(^\ddagger)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>55 b(^\psi)</td>
<td>5,313 b</td>
<td>98</td>
<td>18.41</td>
<td>14.42</td>
<td>78,861 b</td>
<td>55 b</td>
</tr>
<tr>
<td>Urea</td>
<td>80 a</td>
<td>7,677 a</td>
<td>99</td>
<td>18.54</td>
<td>14.56</td>
<td>105,846 a</td>
<td>78 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>82 a</td>
<td>7,659 a</td>
<td>96</td>
<td>18.41</td>
<td>14.24</td>
<td>112,098 a</td>
<td>74 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>83 a</td>
<td>7,760 a</td>
<td>96</td>
<td>18.43</td>
<td>14.33</td>
<td>107,140 a</td>
<td>80 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>78 a</td>
<td>7,522 a</td>
<td>99</td>
<td>18.76</td>
<td>14.61</td>
<td>106,068 a</td>
<td>78 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>81 a</td>
<td>7,399 a</td>
<td>95</td>
<td>18.34</td>
<td>14.12</td>
<td>99,893 a</td>
<td>75 a</td>
</tr>
</tbody>
</table>

\(\neq\) TRS Theoretical recoverable sugar
\(\ddagger\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.
\(\psi\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
\(\psi\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Tables 2.8, 2.9, and 2.10 show the means and ANOVA for the effect of N sources on all the plant measured variables for site 2 for plant cane (2017), first (2018), and second (2019) stubble crops, respectively. The soil at site 2 is composed of Commerce silty clay loam (74%) and Commerce silt loam (24%). The effect of N source on cane yield was significant in plant cane, first, and second stubble crops ($p<0.0001$). All N source treatments across crop ages performed significantly better than the control (0 N). On average for plant cane (2017), cane yield from N fertilized plots was higher (103 Mg ha$^{-1}$) compared to the control plots (72 Mg ha$^{-1}$) (Table 2.8). Similarly, cane yield in the first and stubble crops was higher in N-fertilized plots (106 and 90 Mg ha$^{-1}$) than the control plots (70 and 62 Mg ha$^{-1}$) (Tables 2.9 and 2.10).

In plant cane and first stubble crops for site 2 (Tables 2.8 and 2.9), cane yield responded to N fertilization, but no significant statistical differences were observed among N sources (Tables 2.8 and 2.9). Conversely, in the second stubble crop cane yield was statistically different among N sources (Table 2.10). Significantly higher cane yield was recorded for NH$_4$SO$_4$ treatment (98 Mg ha$^{-1}$) followed by CaNO$_3$ (92 Mg ha$^{-1}$), urea (89 Mg ha$^{-1}$), UAN knife-in + foliar (87 Mg ha$^{-1}$), and UAN knife-in (84 Mg ha$^{-1}$); all these treatments performed significantly better than the control. There is no question that sugarcane has been extensively studied, particularly on its mineral nutrition. In general, few studies pursued fertilizer choice reporting that sugarcane does not show any marked preference to different N fertilizer sources (Blackburn, 1984). However, several studies reported that NH$_4^+$ is the N form preferred by sugarcane (Singh and Yadav, 1996; Basantha et al., 2003; Franco et al., 2015; Boschiero et al., 2020). However, the intensity of sugarcane in up taking one form of N source to another does not mean an actual preference for other N form.
Nitrogen fertilizer recovery usually provides detailed information about this fact; however, the N cycle is very dynamic. In certain conditions, N fertilizers sources such as urea or NH$_4$ sulfate are prone to ammonia volatilization, causing low fertilizer recovery by sugarcane. Thus, to achieve more efficient fertilizer recovery, the N demand at a given sugarcane yield potential as determined by weather conditions, cultural practices, crop ages, variety, and soil type should be closely matched by the N application rate.
Table 2.8. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2017 plant cane for site 2 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS#</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td>N Source(^{\psi})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>72 b(^{\psi})</td>
<td>8,595 b</td>
<td>119</td>
<td>19.18</td>
<td>16.66</td>
<td>99,944 b</td>
<td>59 c</td>
</tr>
<tr>
<td>Urea</td>
<td>102 a</td>
<td>11,911 a</td>
<td>116</td>
<td>18.98</td>
<td>16.32</td>
<td>106,059 ab</td>
<td>85 ab</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>103 a</td>
<td>11,999 a</td>
<td>117</td>
<td>19.01</td>
<td>16.35</td>
<td>104,418 ab</td>
<td>80 b</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>108 a</td>
<td>12,573 a</td>
<td>115</td>
<td>18.91</td>
<td>16.31</td>
<td>116,286 a</td>
<td>101 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>103 a</td>
<td>11,944 a</td>
<td>116</td>
<td>19.26</td>
<td>16.23</td>
<td>112,719 ab</td>
<td>83 ab</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>100 a</td>
<td>12,009 a</td>
<td>120</td>
<td>19.03</td>
<td>16.73</td>
<td>109,422 ab</td>
<td>77 b</td>
</tr>
</tbody>
</table>

\(p\)-value <0.0001 <0.0001 NS\(^{\£}\) NS NS NS 0.0006

\(#\) TRS Theoretical recoverable sugar

\(^{\psi}\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.

\(^{\£}\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.

\(^{\psi}\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.9. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2018 first stubble for site 2 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS(\neq)</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td>N Source(^\psi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>70 b(^\psi)</td>
<td>8,162 b</td>
<td>119</td>
<td>19.12</td>
<td>16.55</td>
<td>101,887 b</td>
<td>63 b</td>
</tr>
<tr>
<td>Urea</td>
<td>103 a</td>
<td>11,934 a</td>
<td>118</td>
<td>18.94</td>
<td>16.40</td>
<td>134,243 a</td>
<td>113 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>106 a</td>
<td>11,919 a</td>
<td>115</td>
<td>18.86</td>
<td>16.11</td>
<td>135,706 a</td>
<td>102 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>106 a</td>
<td>11,927 a</td>
<td>114</td>
<td>18.68</td>
<td>16.03</td>
<td>131,100 a</td>
<td>106 a</td>
</tr>
<tr>
<td>CaNO</td>
<td>107 a</td>
<td>11,792 a</td>
<td>113</td>
<td>18.64</td>
<td>15.87</td>
<td>132,743 a</td>
<td>108 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>105 a</td>
<td>11,703 a</td>
<td>114</td>
<td>18.75</td>
<td>16.05</td>
<td>132,921 a</td>
<td>107 a</td>
</tr>
<tr>
<td>(p)-value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS(^\£)</td>
<td>NS</td>
<td>NS</td>
<td>0.003</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

\(\neq\) TRS Theoretical recoverable sugar
\(^\$\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.
\(\£\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
\(^\psi\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.10. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2019 second stubble for site 2 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS#</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>kg ha⁻¹</td>
<td>kg Mg⁻¹</td>
<td>%</td>
<td>%</td>
<td>stalk ha⁻¹</td>
<td>kg N ha⁻¹</td>
</tr>
<tr>
<td>N Source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>62 c</td>
<td>5,833 c</td>
<td>95</td>
<td>17.39</td>
<td>13.85</td>
<td>86,235 c</td>
<td>58 b</td>
</tr>
<tr>
<td>Urea</td>
<td>89 ab</td>
<td>8,167 ab</td>
<td>92</td>
<td>17.26</td>
<td>13.55</td>
<td>111,110 ab</td>
<td>98 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>84 b</td>
<td>7,767 b</td>
<td>93</td>
<td>17.14</td>
<td>13.61</td>
<td>98,753 bc</td>
<td>83 a</td>
</tr>
<tr>
<td>NH₄ Sulfate</td>
<td>98 a</td>
<td>8,729 a</td>
<td>90</td>
<td>16.86</td>
<td>13.18</td>
<td>117,328 a</td>
<td>99 a</td>
</tr>
<tr>
<td>Ca(NO₃)₃</td>
<td>92 ab</td>
<td>8,397 ab</td>
<td>93</td>
<td>17.18</td>
<td>13.59</td>
<td>111,794 ab</td>
<td>96 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>87 b</td>
<td>8,331 ab</td>
<td>96</td>
<td>17.49</td>
<td>14.01</td>
<td>113,934 a</td>
<td>95 a</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.0001</td>
<td>0.0036</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0005</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

≠ TRS Theoretical recoverable sugar
¥ All N sources were applied at 90 kg N ha⁻¹ to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha⁻¹ to the soil and 23 kg N ha⁻¹ as foliar.
£ NS indicates no significant difference at the α=0.05 level of significance.
ψ Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at p<0.05.
Tables 2.11 and 2.12 provide the means and ANOVA for the effect of N sources and cover crops on all the plant variables measured at site 3 for plant cane (2018) and first (2019) stubble crop. Like site 2, site 3 was established on mixed Commerce silty clay loam (83%) and Commerce silt loam (17%) soil. The effect of the different N sources on cane yield was significant in plant cane ($p<0.0001$) and first stubble crops ($p<0.0001$). In general, N sources across crop ages performed significantly better than the control (0 N). On average, for plant cane (2018) cane yield from N fertilized plots was higher (128 Mg ha$^{-1}$) compared to the control plot (116 Mg ha$^{-1}$) (Table 2.11). Similarly, cane yield in the N-fertilized first stubble crop was higher (105 Mg ha$^{-1}$) than the control plots (88 Mg ha$^{-1}$).

In plant cane and first stubble crop for site 3 (Tables 2.11 and 2.12), cane yield did respond to the N fertilization. Cane yield was significantly higher in plots fertilized with urea (131 Mg ha$^{-1}$), UAN knife-in (130 Mg ha$^{-1}$), and UAN knife-in + foliar (129 Mg ha$^{-1}$) compared to the control (116 Mg ha$^{-1}$). Cane yield from NH$_4$ sulfate (125 Mg ha$^{-1}$) and CaNO$_3$ (124 Mg ha$^{-1}$) treatments were not significantly different from the yield achieved by the control or other N sources. In the first stubble crop, a more evident response of cane yield to N sources was observed (Table 2.11). Significantly higher cane yield was observed with NH$_4$ sulfate treatment (115 Mg ha$^{-1}$), followed by urea (108 Mg ha$^{-1}$), and lastly, UAN knife-in (97 Mg ha$^{-1}$). All these treatments performed significantly better than the control (88 Mg ha$^{-1}$) (Table 2.12). On the other hand, cane yield was also significantly increased using CaNO$_3$ (103 Mg ha$^{-1}$) followed by UAN knife in + foliar (100 Mg ha$^{-1}$) compared to the yield observed with the control (88 Mg ha$^{-1}$). However, these N sources were not statistically different from urea and UAN knife-in + foliar (Table 2.12).
Tables 2.13 and 2.14 provide the means and ANOVA for the effect of N sources on all the plant variables measured for site 4 for plant cane (2019) and first (2020) stubble crop. Site 4 was established on soil with Commerce silty clay loam (98 %) and Commerce silt loam (2%) soil types. While the effect of N source on cane yield was not significant in plant cane (Table 2.13), there was an evident effect observed on cane yield of the first stubble crop ($p<0.0001$) (Table 2.14). Data in Table 2.13 shows numerically higher sugarcane yield utilizing CaNO$_3$ (76 Mg ha$^{-1}$) followed by urea and UAN knife-in + foliar, both recorded a 73 Mg ha$^{-1}$, compared to other sources. Moreover, the application of NH$_4$ sulfate and UAN knife-in did not result in significant cane yield increases in reference to the control plots (Table 2.13).
Table 2.11. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2018 plant cane for site 3 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS#</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Source(\text{\textsuperscript{(\gamma)}})</td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>116 b(\text{\textsuperscript{(\upsilon)}})</td>
<td>12,307 b</td>
<td>108</td>
<td>17.56</td>
<td>15.09</td>
<td>111,564</td>
<td>89 b</td>
</tr>
<tr>
<td>Urea</td>
<td>131 a</td>
<td>13,744 a</td>
<td>106</td>
<td>17.65</td>
<td>14.92</td>
<td>131,251</td>
<td>132 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>130 a</td>
<td>13,247 ab</td>
<td>103</td>
<td>17.37</td>
<td>14.58</td>
<td>135,245</td>
<td>122 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>125 ab</td>
<td>12,959 ab</td>
<td>105</td>
<td>17.71</td>
<td>14.89</td>
<td>120,188</td>
<td>119 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>124 ab</td>
<td>12,675 ab</td>
<td>104</td>
<td>17.67</td>
<td>14.75</td>
<td>119,404</td>
<td>131 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>129 a</td>
<td>13,188 ab</td>
<td>104</td>
<td>17.57</td>
<td>14.74</td>
<td>120,662</td>
<td>125 a</td>
</tr>
</tbody>
</table>

\(p\)-value | 0.036 | \(<0.0001\) | NS\(\text{\textsuperscript{\(\varepsilon\)}}\) | NS | NS | NS | \(<0.0001\) |

\(\neq\) TRS Theoretical recoverable sugar
\(\text{\textsuperscript{\(\gamma\)}}\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.
\(\varepsilon\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
\(\upsilon\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.12. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2019 first stubble for site 3 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS*</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td></td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
</tr>
<tr>
<td>N Source(^{\psi})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>88 d(^{\psi})</td>
<td>7,158 d</td>
<td>83</td>
<td>16.22</td>
<td>12.37</td>
<td>119,117 c</td>
<td>69 b</td>
</tr>
<tr>
<td>Urea</td>
<td>108 b</td>
<td>8,961 ab</td>
<td>84</td>
<td>16.52</td>
<td>12.58</td>
<td>144,436 ab</td>
<td>109 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>97 c</td>
<td>8,081 bc</td>
<td>85</td>
<td>16.63</td>
<td>12.66</td>
<td>132,032 abc</td>
<td>104 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>115 a</td>
<td>9,711 a</td>
<td>86</td>
<td>16.61</td>
<td>12.73</td>
<td>152,768 a</td>
<td>114 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>103 bc</td>
<td>8,321 bc</td>
<td>83</td>
<td>16.46</td>
<td>12.42</td>
<td>121,603 c</td>
<td>101 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>100 bc</td>
<td>8,041 cd</td>
<td>82</td>
<td>16.23</td>
<td>12.27</td>
<td>127,069 bc</td>
<td>104 a</td>
</tr>
<tr>
<td>(p)-value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS(^{\psi})</td>
<td>NS</td>
<td>NS</td>
<td>0.0306</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

\(^{*}\) TRS Theoretical recoverable sugar
\(^{\psi}\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.
\(^{\psi}\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
\(\psi\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Several studies have demonstrated that plant cane crop is less responsive to N fertilizers than stubble crops (Wiedenfeld, 1995; Viator et al., 2013). Typically, the N requirement of plant cane crop is 30 to 40 kg N ha\(^{-1}\) lower than stubble crop (Meyer, 2013). The main reason for this is plant cane benefits from the mineral N release to the soil N pool during the fallow period. Overall, fertilizer N requirement of sugarcane has been based on climate conditions (i.e., temperature, sunshine, and radiation), soil type, soil conditions (i.e., soil moisture), crop age (plant cane or stubble crops), growth stage, cultivars, and soil mineralization potential (Meyer, 2013).
Table 2.13. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2019 plant cane for site 4 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS#</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>kg ha⁻¹</td>
<td>kg Mg⁻¹</td>
<td>%</td>
<td></td>
<td>Stalk ha⁻¹</td>
<td>kg N ha⁻¹</td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>69</td>
<td>6,469 a</td>
<td>96 a</td>
<td>18.08</td>
<td>14.13</td>
<td>78,532</td>
<td>48 b</td>
</tr>
<tr>
<td>Urea</td>
<td>72</td>
<td>6,089 ab</td>
<td>86 ab</td>
<td>17.68</td>
<td>13.11</td>
<td>81,228</td>
<td>70 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>68</td>
<td>5,738 ab</td>
<td>84 ab</td>
<td>17.77</td>
<td>13.05</td>
<td>82,627</td>
<td>67 a</td>
</tr>
<tr>
<td>NH₄ Sulfate</td>
<td>69</td>
<td>5,054 b</td>
<td>74 b</td>
<td>17.54</td>
<td>12.01</td>
<td>81,579</td>
<td>66 a</td>
</tr>
<tr>
<td>CaNO₃</td>
<td>76</td>
<td>6,187 ab</td>
<td>84 ab</td>
<td>17.73</td>
<td>12.87</td>
<td>87,901</td>
<td>73 a</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>73</td>
<td>5,921 ab</td>
<td>83 ab</td>
<td>17.31</td>
<td>12.67</td>
<td>84,464</td>
<td>67 a</td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>NS£</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

≠ TRS Theoretical recoverable sugar
¥ All N sources were applied at 90 kg N ha⁻¹ to the soil except for UAN Knife in + Foliar, which was knife-in applied at 67 kg N ha⁻¹ to the soil and 23 kg N ha⁻¹ as foliar.
£ NS indicates no significant difference at the α=0.05 level of significance.
Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at p<0.05.
Table 2.14. Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2020 first stubble for site 4 at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td><strong>N Source</strong>(^¥)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>84 d(^\psi)</td>
<td>9,789 d</td>
<td>116</td>
<td>19.68</td>
<td>16.43</td>
<td>87,047</td>
<td>53 c</td>
</tr>
<tr>
<td>Urea</td>
<td>97 b</td>
<td>11,483 ab</td>
<td>116</td>
<td>19.75</td>
<td>16.47</td>
<td>92,213</td>
<td>82 a</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>91 c</td>
<td>10,621 c</td>
<td>115</td>
<td>19.63</td>
<td>16.37</td>
<td>91,200</td>
<td>64 bc</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>102 a</td>
<td>12,088 a</td>
<td>117</td>
<td>19.71</td>
<td>16.55</td>
<td>91,054</td>
<td>76 ab</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>95 bc</td>
<td>10,963 bc</td>
<td>113</td>
<td>19.41</td>
<td>16.14</td>
<td>84,829</td>
<td>74 ab</td>
</tr>
<tr>
<td>UAN Knife-in + Foliar</td>
<td>91 c</td>
<td>10,583 c</td>
<td>115</td>
<td>19.65</td>
<td>16.36</td>
<td>84,907</td>
<td>71 ab</td>
</tr>
</tbody>
</table>

\(!\) TRS Theoretical recoverable sugar

\(¥\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil except for UAN Knife-in + Foliar, which was knife-in applied at 67 kg N ha\(^{-1}\) to the soil and 23 kg N ha\(^{-1}\) as foliar.

£ NS indicates no significant difference at the \(\alpha=0.05\) level of significance.

\(\psi\) Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.15 shows the effect of crop age, N sources and their interactions on cane and sugar yield, quality parameters, stalk population, and N uptake at site 5. There was a significant impact of N sources for all these parameters. Similarly, a significant N source and crop age interaction effect was observed on yield, quality parameters, and other measured variables. Tables 2.16 and 2.17 report results on the mean separation procedure for the effect of N sources at site 5 in 2018 (plant cane) and 2019 (first stubble crop), respectively. Site 5 was established on a Cancienne silt loam soil. The effect of N sources on cane yield was significant in plant cane ($p<0.0001$) and first stubble crops ($p<0.0001$). All N source treatments across crop ages performed significantly better than the control (0 N).

On average for plant cane 2018, cane yield from N fertilized plots was higher (103 Mg ha$^{-1}$) compared to the cane yield from the control plots (72 Mg ha$^{-1}$) (Table 2.16). Similarly, cane yield in the first stubble crop was higher (87 Mg ha$^{-1}$) than the control plots (57 Mg ha$^{-1}$) (Table 2.17). The mean separation revealed that while there was a significane effect of N sources detected on cane yield, there was no significant differences among N sources for plant cane crop (Table 2.16). On the other hand, the first stubble crop fertilized with UAN knife-in obtained the highest cane yield at 96 Mg ha$^{-1}$. This yield level was significantly higher than the plots treated with CaNO$_3$ and NH$_4$ Sulfate (Table 2.17).

This study revealed that the choice of N source could make a difference in cane yield. However in the present study, none of the sources was consistent in terms of performance, especially when the evaluation was done across crop age, and sites suggesting that soil type and cropping systems affect crop N recovery.

A study conducted in the South Africa sugar industry demonstrated the importance of choosing the right N source based on soil-specific conditions (Calcino and Burgess, 1995).
According to the result of this study, banded urea had more N loss via volatilization than broadcasted urea on light-textured soil, especially in the sand and sandy loam soils. Several studies conducted in the Australian sugar industry revealed that N source choice is commonly influenced by soil type and sugarcane cultivar (Prammanee 1989; Wood et al. 1990). Other studies were conducted to evaluate the rating of potential N losses through the soil and plant across different soil types, environments, irrigation practices, and sugarcane varieties showing that the application of \(\text{NO}_3^-\)-N fertilizers sources such as ammonium nitrate (34% N) and potassium nitrate (13% N) resulted in lower levels of \(\text{NH}_4^+\)-N in the surface soil (0 to 30 cm) and an increase in \(\text{NO}_3^-\)-N levels in the first 15 cm (du Toit 1957; Wood 1968, Prammanee 1989; Wood et al. 1990).

This study also demonstrated the potentials that were shown by N sources other than UAN. For example, \(\text{NH}_4\) sulfate which can be recommended for soils where S is tested low or where soil acidification is desirable. After all, the results from the mean separation procedure showed that there was a significant effect of N fertilization on sugar yield \((p<0.0001)\) but practically nothing between N sources (Tables 2.5 to 2.17). At site 1, N application regardless of N source resulted in significantly higher sugar yield than the control across crop age (Tables 2.5, 2.6, and 2.7). However, there were no significant differences in sugar yield across the N source for plant cane (Table 2.5) and second stubble (Table 2.7). For the first stubble where a significant difference was observed on sugar yield, urea recorded a lower sugar yield than the rest of the N sources but higher than the control (Table 2.6). Plots treated with urea attained 10,456 kg ha\(^{-1}\) sugar yield, which was significantly higher than the 6,567 kg ha\(^{-1}\) of the control; however, this level was 1,265 – 2,112 kg ha\(^{-1}\) lower than the yields obtained from plots which received the other N sources.
Table 2.15. Analysis of variance for the effect of crop age, and N source on cane and sugar yield, quality parameters, stalk population, and N uptake at site 5, Paincourtville, LA.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop age</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>&lt;0.0001</td>
<td>0.0001</td>
<td>&lt;0.0001</td>
<td>0.0056</td>
<td>0.0011</td>
</tr>
<tr>
<td>N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0005</td>
<td>0.0277</td>
<td>0.0008</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Crop age*N sources</td>
<td>0.0004</td>
<td>0.0436</td>
<td>0.0259</td>
<td>0.0027</td>
<td>0.0314</td>
<td>0.0015</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
Table 2.16 Means and analysis of variance for the effect of N source on cane and sugar yield, quality parameters, N uptake, and stalk population in 2018 plant cane for site 5, Paincourtville, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS*</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td>N Source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>72 b</td>
<td>7,327 c(^v)</td>
<td>102 a</td>
<td>17.14</td>
<td>14.57 a</td>
<td>75,647 b</td>
<td>35 b</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>105 a</td>
<td>10,500 a</td>
<td>100 b</td>
<td>17.19</td>
<td>14.26 ab</td>
<td>100,386 a</td>
<td>53 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>103 a</td>
<td>10,032 ab</td>
<td>97 b</td>
<td>16.87</td>
<td>13.94 b</td>
<td>100,420 a</td>
<td>52 a</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>102 a</td>
<td>9,892 b</td>
<td>96 b</td>
<td>17.02</td>
<td>13.89 b</td>
<td>102,979 a</td>
<td>51 a</td>
</tr>
<tr>
<td>(p)-value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0047</td>
<td>NS(^{\ell})</td>
<td>0.0112</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

\(^\ne\) TRS Theoretical recoverable sugar
\(^\gamma\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil.
\(\ell\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.

Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
Table 2.17. Means and analysis of variance for the effect of N source and cover crops on cane and sugar yield, quality parameters, N uptake, and stalk population in 2019 first stubble for site 5, Paincourtville, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS#</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk population</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td></td>
<td>Stalk ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
</tr>
<tr>
<td><strong>N Source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (0 N)</td>
<td>57 c</td>
<td>6,591 c(^v)</td>
<td>115 a</td>
<td>18.34 a</td>
<td>16.04 a</td>
<td>94,572 b</td>
<td>29 c</td>
</tr>
<tr>
<td>UAN Knife-in</td>
<td>96 a</td>
<td>10,457 a</td>
<td>110 c</td>
<td>17.93 b</td>
<td>15.43 c</td>
<td>109,405 a</td>
<td>48 a</td>
</tr>
<tr>
<td>NH(_4) Sulfate</td>
<td>81 b</td>
<td>8,955 b</td>
<td>111 bc</td>
<td>17.97 bc</td>
<td>15.54 bc</td>
<td>86,539 b</td>
<td>41 b</td>
</tr>
<tr>
<td>CaNO(_3)</td>
<td>83 b</td>
<td>9,388 d</td>
<td>114 ab</td>
<td>18.20 ab</td>
<td>16.05 a</td>
<td>107,770 a</td>
<td>42 b</td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0078</td>
<td>0.0047</td>
<td>0.0057</td>
<td>0.0031</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

\(^{\#}\) TRS Theoretical recoverable sugar
\(^{v}\) All N sources were applied at 90 kg N ha\(^{-1}\) to the soil.
\(^{£}\) NS indicates no significant difference at the \(\alpha=0.05\) level of significance.

Means followed by the same lowercase letter are not significantly different using Fisher's protected LSD at \(p<0.05\).
At site 2 for the first and second stubble (Tables 2.10), NH\textsubscript{4} sulfate and UAN knife-in fertilizer application resulted in significantly higher sugar yield compared to the control. However, UAN knife-in fertilizer was numerically lower compared to CaNO\textsubscript{3}, UAN Knife-in + foliar and urea treatments (Table 2.10). In plant cane and first stubble crop, sugar yield significantly responded to the N sources; however, the means of sugar yield were statistically the same among N sources (Tables 2.8 and 2.9).

At site 3, sugar yield in both plant cane and first stubble crop significantly responded to N fertilization (\(p<0.0001\)) (Tables 2.11 and 2.12). In plant cane, the urea-treated cane had a significantly higher sugar yield (13,744 kg ha\textsuperscript{-1}) compared to the control (12,307 kg ha\textsuperscript{-1}) but not with the rest of the N sources (Table 2.11). However, in the first stubble crop the application of NH\textsubscript{4} sulfate significantly increased sugar yield to 9,711 kg ha\textsuperscript{-1} compared to the control (7,158 kg ha\textsuperscript{-1}) (Table 2.12).

At site 4, sugar yield was significantly different between N-fertilized cane and the control for both plant cane (2019) and first stubble crop (2020) (Tables 2.13 and 2.14). Here, the control had a statistically higher sugar yield (6,469 kg ha\textsuperscript{-1}) than the average of all N-fertilized cane (5,798 kg ha\textsuperscript{-1}). The application of NH\textsubscript{4} sulfate (5,054 kg ha\textsuperscript{-1}) fertilizer resulted in the lowest sugar yield among N sources, while no statistical difference was found among N sources (Table 2.13). From the first stubble crop, sugar yield was significantly higher in N-fertilized plots compared to the control (\(p<0.0001\)) (Table 2.14). On average, sugar yields responded substantially to N fertilizer application bringing in sugar yield at level of 11,148 kg ha\textsuperscript{-1} vs. 9,789 kg ha\textsuperscript{-1} of the control. Among the N sources, both urea and NH\textsubscript{4} sulfate applications resulted in the highest production of sugar yield at 11,483 kg ha\textsuperscript{-1} and 12,088 kg ha\textsuperscript{-1}, respectively. Both UAN knife-in and UAN knife-in + foliar have the lowest sugar yield at 10,621 kg ha\textsuperscript{-1} and
10,583 kg ha\(^{-1}\), respectively (Table 2.14). At site 5, sugar yield significantly responded as well to N source but with UAN knife-in treatment consistently producing the highest sugar yield compared to CaNO\(_3\) and NH\(_4\) sulfate \((p<0.0001)\) (Tables 2.16 and 2.17). Generally, across the sites, the sugar yield of plant cane was higher than the stubble crops. A declining sugar yield was observed in the successive stubble crops.

The factors evaluated in this study had varying effects on sugar yield and quality parameters. Sugar yield is determined based on stalk yield (cane tonnage) and TRS; therefore, the effect of N fertilization is essential and accomplished to improve both quality components and number of millable stalks. Sugarcane yield and quality parameters response to varying N rates have been extensively studied worldwide. Most of these studies reported that increasing N fertilizer application rates had no impact on sugarcane yield; however, for stubble crops, juice quality and sugar yield declined as N application rate increased (Gopalasundaram et al., 1994; Wiedenfeld, 1995; Srinivasan, 1995; Singh and Yadav, 1996). In the present study, N source had a greater impact on cane yield than sugar yield due to the lack of TRS response to N sources. However, the results observed at site 5 in Paincourtville showed that UAN knife-in fertilizer application significantly increased sugar yield compared to the control and the rest of the N sources even if TRS mean values across crop ages were significantly lower than the control (Tables 2.16 and 2.17). Singh and Yadav (1996) reported that sugar yield N fertilizer sources had the same effect on sugar yield under field conditions. Similarly, Forestieri (2017) reported that N source did not influence sugar yield and quality parameters (TRS, sucrose, and polarity) across crop age. Borden (1948) documented that sugarcane and sugar yield were positively affected by N fertilizer rate and application time, but not N source.
The effect of N sources on sugar quality parameters was specific and unique for each site due to soil type and crop age. The results on ANOVA at site 1 demonstrated that except for Brix and sucrose in the first stubble crop, there was no significant N source effect observed on plant cane and second stubble crop (Tables 2.5, 2.6, and 2.7). UAN knife-in treatment attained the highest Brix at 18.42 % and sucrose content at 15.98 % among the N source. (Table 2.6). For all other sites at the Sugar Research Station, the effect of N source on quality parameters was not observed, except for the plant cane at site 4 (TRS only). At site 5 in Poaincourtville, quality parameters were generally lower in N-treated cane. The largest reduction occurred in UAN knife-in-treated cane for plant cane and first stubble crops (Tables 2.16 and 2.17).

Studies had shown the negative effect of N rate on sugarcane quality parameters. Muschow et al. (1998) also observed a reduction in sugarcane quality parameters due to N application when higher N fertilizer doses were applied compared to the lower N rates. Wiedenfeld (1995) reported that the quality parameters could be negatively affected by higher N rate application due to the activation of a specific enzyme that will degrade sucrose and transform it into glucose and fructose.

In the present study, stalk population response to N source was not consistent across sites and crop age. The effect of N was mainly observed between the control and all N-fertilized plots and not between N sources with a few exceptions. For example, at site 2 on the second stubble crop where NH₄ sulfate treatment attained a significantly higher population than UAN knife-in treatment (Table 2.10), and CaNO₃ and UAN knife-in + foliar at site 3 on the first stubble cane (Table 12). Many studies were conducted to evaluate the stalk yield component in response to N application. Kolage et al. (2001) and Sinha et al. (2005) evaluated the effect of N rate, source, and application timing on stalk diameter and height and population of millable stalks per unit of
area. This study showed that with certain N sources and optimal timing, increased in plant height, cane, and sugar yield was observed. On the other hand, Patel et al. (2004) did not observe significant differences in stalk height and population in response to different rates and sources of N fertilizer application.

Stalk N uptake significantly responded to N application across all the sites and crop ages ($p<0.0001$) (Tables 2.5 to 2.17). However, stalk N uptake was statistically the same among N source across sites and crop age, except on plant cane at site 2. Here NH$_4$ sulfate treatment recorded the highest stalk N uptake at 101 kg ha$^{-1}$, which was significantly higher than UAN knife-in and UAN knife-in + foliar treatments (Table 2.8). Overall, a lower stalk N uptake was reported in the second stubble crop than the first stubble and plant cane crops (Tables 2.5, 2.6, and 2.7). This may be partly due to the lower stalk N concentration, stalk dry matter content and low stalk population. Muchow and Robertson (1994) explained that sugarcane N demand and yield potential is determined by weather condition, crop management, variety, and crop age as main factors.

Basant et al. (2003) evaluated the N fertilizer recovered by sugarcane in Brazil from three crop seasons. They reported that the crop N uptake was only 42% with 29% remained in the soil and 29% was lost from the soil system. Several studies have reported that about 80% of the N needed for sugarcane to produce quality yield comes from the soil pool N, and only 20% from mineral fertilizers (Chang and Weng, 1983; Weng and Li, 1992). Thus, the low N fertilizer recovery for sugarcane could be explained probably due to N's mineralization in the soil releasing plant-available N from the previous stubble crops (Basant et al., 2003). Studies have shown that N recovered by crop residues, once incorporated back to the soil, can range from 2 to 15% of the total N content (Basant et al., 2003). Nitrogen losses through volatilization could
cause low N recovery, which is enhanced during residue decomposition. Studies proved that residues' enzymatic activity considerably increased N's volatilization from applied urea (Denmead et al., 1990; Wood 1991; Cantarella, 1998).

2.3.2 Effect of Nitrogen Source on Soil Inorganic N Monitoring

The levels of NH$_4^+$ and NO$_3^-$ (kg ha$^{-1}$) content in the soil treated with different N sources for each site are shown in Figures 2.5 to 2.14. Table 2.18 shows the results on ANOVA indicating significant effects of site, crop age (hereafter will be termed as crop year or year), and N source on soil N content ($p<0.0001$). When the ANOVA was done by site, a significant interaction was observed between crop year and N sources ($p<0.05$); this effect was only observed for the soil NH$_4^+$ content (Table 2.19). The soil NH$_4^+$ and NO$_3^-$ during the growing season, on average, were 26 and 15 kg N ha$^{-1}$ at 0-15 cm, respectively, with lower levels recorded, as expected, within the 15-30 cm depth at 18 and 6 kg N ha$^{-1}$, respectively. Overall, across sites, the total inorganic N (NH$_4^+$ + NO$_3^-$) in the soil averaged 31 kg N ha$^{-1}$ and 24 kg N ha$^{-1}$, at 0-15 and 15-30 cm, respectively. However, site 1 and site 3 reported inorganic N values numerically higher than the observed N mean values. For example, for site 1 in plant cane, inorganic N averaged 34 and 26 kg N ha$^{-1}$, at 0-15 and 15-30 cm depth, respectively. Similarly, in the first stubble crop, values averaged 40 and 27 kg N ha$^{-1}$, at 0-15 and 15-30 cm depth, respectively. The inorganic N content values ranged 42 and 30 at 0-15 and 15-30 cm depth in the second stubble crop, respectively.

Due to differences in soil texture and temporal variation in rainfall and distribution, a wide range of soil NH$_4^+$ + NO$_3^-$ values were recorded in this study. Several studies conducted by Takahashi (1969), Chang and Weng (1983), and Sampaio et al. (1984), and Vallis et al.
(1994), showed that, on average, sugarcane N fertilizer recovery ratios are 21 to 40% of the applied N fertilizer.

Table 2.18. Analysis of variance on soil NH$_4^+$ and NO$_3^-$ content at 0-15 and 15-30 cm depth.

<table>
<thead>
<tr>
<th>Effects</th>
<th>NO$_3^-$ 0-15 cm</th>
<th>NH$_4^+$ 0-15 cm</th>
<th>NO$_3^-$ 15-30 cm</th>
<th>NH$_4^+$ 15-30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Crop year</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Site*crop year</td>
<td>&lt;0.0001</td>
<td>0.0021</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Site*N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Crop year*N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Site<em>crop year</em>N sources</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0011</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

On average, across sites at the Sugar Research Station, soil NH$_4^+$ was 35, 47, and 57% higher than the soil NO$_3^-$ content for 2017, 2018, and 2019 crop year, respectively. Similar results were observed at site 5. The higher levels of soil NO$_3^-$ and NH$_4^+$ content within the 0-30 cm depth during the 2018 and 2019 crop year compared to what was obtained during the 2017 crop year could be due to the soil N build-up from the N fertilizer applied in the previous year. The presence of adequate rainfall events could also stimulate N mineralization, increasing the concentration of soil inorganic N (Wiedenfeld, 1995).

Overall, the N source significantly affected soil NO$_3^-$ and NH$_4^+$ content at 0-15 and 15-30 cm depth. At site 1, the average soil NO$_3^-$ content across N source and sampling time were relatively lower compared to NH$_4^+$ during the 2017, 2018, and 2019 crop years with values of 14 vs. 17 kg N ha$^{-1}$, 9 vs. 24 kg N ha$^{-1}$, and 10 vs. 26 kg N ha$^{-1}$, respectively (Figures 2.5 A-B, 2.6 A-B, and 2.7 A-B).
Table 2.19. Analysis of variance for the effect of N source and cover crops on soil NH$_4^+$ and NO$_3^-$ content at 0-15 and 15-30 cm depth across sites at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Effects</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
</tr>
</thead>
<tbody>
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In most cases, the highest soil NO$_3^-$ content was observed in CaNO$_3$-treated soil, followed by UAN-treated soils across the 3 years (Figure 2.5 A). The NO$_3^-$ level of CaNO$_3$-treated soil at 4 WANF were 23, 18, and 14 kg N ha$^{-1}$ higher than levels recorded from the UAN knife-in-treated soil for 2017, 2018, and 2019 crop year, respectively. At the 15-30 cm depth, CaNO$_3$-treated soils had the highest NO$_3^-$ content (34 kg N ha$^{-1}$) at 4 WANF, followed by UAN knife-in (17 kg N ha$^{-1}$) and UAN knife-in + foliar (16 kg N ha$^{-1}$). However, the highest soil NO$_3$ content was observed with UAN knife-in + foliar followed by UAN knife-in for 2018 and UAN knife-in followed by UAN knife-in + foliar in 2019 crop (Figure 2.5 B).
A significant N source effect on soil NH$_4^+$ content was observed for site 1 (Table 2.19). The control plots had a higher NH$_4^+$ level within the 0-30 cm with cover crop than measured in control plots across crop years; levels obtained were 16 vs. 12 kg N ha$^{-1}$, 22 vs. 19 kg N ha$^{-1}$, and 21 vs. 22 kg N ha$^{-1}$, for 2017, 2018, and 2019, respectively (Figure 2.6 A and B). The NH$_4^+$ sulfate-treated plots consistently maintained elevated levels of soil NH$_4^+$ across crop years (Figure 2.6 A and B).

At site 1 in 2017, the soil NH$_4^+$ content at 0-15 cm was the highest compared to soils treated with UAN knife-in, urea, and UAN knife-in + foliar at 4 WANF (Figure 2.6 A). For both 2018 and 2019, soil NH$_4^+$ level was higher in urea treatment, followed by NH$_4$ sulfate and UAN knife-in treatments (Figure 2.6 A). At 15-30 cm, NH$_4^+$ level in the soil across the N sources averaged between 14 to 18 kg N ha$^{-1}$, 16 to 21 kg N ha$^{-1}$, and 18 to 23 kg N ha$^{-1}$, in 2017, 2018, and 2019 crop year, respectively (Figure 2.6 B). For soils treated with NH$_4$ sulfate, higher NH$_4^+$ content was observed at 6 WANF for the 2018 (35 kg N ha$^{-1}$) and 2019 crop year (40 kg N ha$^{-1}$) (Figure 2.6 B).

For site 2 in 2017 at 4 WANF, both soil NO$_3^-$ and NH$_4^+$ at the 0-15 cm depth-averaged at 17 and 25 kg N ha$^{-1}$, respectively (Figure 2.7 A). Lower soil NO$_3^-$ and NH$_4^+$ levels at 15-30 cm were reported at 9 and 17 kg N ha$^{-1}$. A drastic reduction in soil NO$_3^-$ and NH$_4^+$ levels was observed at 6 WANF and harvest (Figure 2.7 B). In 2017 at 2 and 4 WANF, soil treated with CaNO$_3$ had the highest soil NO$_3^-$ content at the 0-15 cm depth at values of 47 and 28 kg N ha$^{-1}$, respectively.
Figure 2.5. Soil NO$_3^-$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatment, site 1 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.6. Soil NH₄⁺ content at 0-15 and 15-30 cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatment, site 1 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.7. Soil NO$_3^-$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 2 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.8. Soil NH$_4^+$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 2 at the Sugar Research Station in St. Gabriel, LA.
A similar pattern was observed on soil NO$_3^-$ content at 15-30 cm with 19 kg ha$^{-1}$ at 2 WANF and 17 kg N ha$^{-1}$ at 6 WANF (Figure 2.7 B). At 4 WANF, soil NO$_3^-$ at 0-15 cm of CaNO$_3$-treated soil was the highest, followed by UAN knife-in and urea treatments with values at 28, 23, and 22 kg N ha$^{-1}$, respectively (Figure 2.7 A). On the other hand, the NH$_4$ sulfate treatment had the highest soil NH$_4^+$ content at 0-15 cm measured at 2 and 4 WANF with values of 37 and 31 kg N ha$^{-1}$, respectively (Figure 2.8 A). At 2 and 4 WANF within the 0-15 cm depth, urea and UAN knife-in treatments recorded soil NH$_4^+$ content at 33 and 23 kg N ha$^{-1}$, and 24 and 27 kg N ha$^{-1}$, respectively (Figure 2.8 A). With CaNO$_3$ as N source, the highest soil NO$_3^-$ content at 0-15 cm was recorded at 11 and 7 kg N ha$^{-1}$ in 2018 and 12 and 7 kg N ha$^{-1}$ in 2019, respectively.

At site 3, the highest soil NO$_3^-$ content at 0-15 cm depth was attained under CaNO$_3$ treatment, followed by urea and UAN knife-in treatments across sampling time (Figure 2.9 A). A similar pattern was observed at 15-30 cm depth (Figure 2.9 B). Soils treated with NH$_4$ sulfate and urea had the highest soil NH$_4^+$ content at 0-15 and 15-30 cm depth for both the 2018 and 2019 crop years across sampling dates (Figure 2.10 A and B). On average, at 0-15 cm across sampling time in 2018, the soil NH$_4^+$ content was recorded at 55 and 49 kg N ha$^{-1}$ for NH$_4$ sulfate and urea treatments, respectively. In 2019, NH$_4$ sulfate and urea treatments also had the highest soil NH$_4^+$ content at 71 and 67 kg N ha$^{-1}$, respectively (Figure 2.10 A). On average, soil NH$_4^+$ content had a similar pattern across N sources (Figure 2.10 B). However, in the 2019 crop year, the soil NH$_4^+$ content was higher than in 2018.
Figure 2.9. Soil NO$_3^-$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 3 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.10. Soil NH$_4^+$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 3 at the Sugar Research Station in St. Gabriel, LA.
At site 4, there were higher levels of soil NO₃⁻ measured at both 0-15 and 15-30 cm depth with Ca(NO₃)₂ and UAN knife-in as N sources at 4 WANF, but by 6 WANF, urea and Ca(NO₃)₂ treated soils substantially declined in NO₃⁻ content (Figure 2.11 A and B). Soil NO₃⁻ content at 15-30 cm was, on average, lower than the level reported at 0-15 cm depth, 6.15 vs. 18.4 kg N ha⁻¹, respectively (Figure 2.11 B). This difference in NO₃⁻ content was more pronounced at 6 WANF, with 40% more in Ca(NO₃)₂ and urea treatment than liquid fertilizer forms i.e., UAN knife-in and UAN knife-in + foliar (Figure 2.11 B). Increases in soil NO₃⁻ content at 15-30 cm were recorded at 4 WANF with Ca(NO₃)₂ and UAN knife-in treatments at values of 27 and 20 kg N ha⁻¹, respectively (Figure 2.11 B). Most of the NO₃⁻ recovered at 0-15 cm had decreased 14 days later (6 WANF), suggesting that NO₃⁻ movement had taken place from the surface to the deeper soil layers via leaching. Soil NH₄⁺ content at 0-15 cm was, on average, higher than the 15-30 cm depth (36 and 23 kg N ha⁻¹, respectively) (Figure 2.12 A).

The soil NH₄⁺ content being higher at 0-15 cm depth than at 15-30 cm before and 2 WANF of NH₄ sulfate and urea sources demonstrated the occurrence of soil NH₄⁺ movement within the soil profile (Figure 2.12 A and B). The soil NH₄⁺ content at 0-15 and 15-30 cm was 43 and 21 kg N ha⁻¹, respectively. One possible explanation is that such an effect occurred in response to the faster release of soil NH₄⁺ from urea and NH₄ sulfate to the soil pool N. However, most of the NH₄⁺ recovered at 0-15 cm had disappeared at 4 WANF (Figure 2.12 A).
Figure 2.11. Soil NO$_3^-$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 4 at the Sugar Research Station in St. Gabriel, LA.
Figure 2.12. Soil NH₄⁺ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatment, site 4 at the Sugar Research Station in St. Gabriel, LA.
The application of UAN knife-in and UAN knife-in + foliar increased soil NH$_4^+$ content at 4WANF, but after 6 WANF, most of the NH$_4^+$ released by these two N sources had disappeared (Figure 2.12 A and B). At 6 WANF, NH$_4$ sulfate-treated soil had the highest NH$_4^+$ content at 43 kg N ha$^{-1}$ compared to the rest of the N sources (Figure 2.12 A). A corresponding lower NH$_4^+$ content was reported at 15-30 cm soil depth (Figure 2.12 B). However, NH$_4^+$ content significantly increased perhaps from what was released from urea and NH$_4$ sulfate at 6 WANF with 32 and 29 kg N ha$^{-1}$ values, respectively (Figure 2.12 B).

At site 5, the average NH$_4^+$ and NO$_3^-$ content observed in 2018 was lower (24 and 16 kg N ha$^{-1}$, respectively) than in 2019 (36 and 20 kg N ha$^{-1}$, respectively). For 2018, the soil N content values of NH$_4^+$ and NO$_3^-$ at 0-15 and 15-30 cm depths were 29 and 23 kg N ha$^{-1}$, and 19 and 8 kg N ha$^{-1}$, respectively, whereas the 2019 crop year averaged 43 and 30 kg N ha$^{-1}$, and 28 and 10 kg N ha$^{-1}$, respectively. The total inorganic N in the soil in the 2018 crop year were 51 and 28 kg N ha$^{-1}$ at 0-15 and 15-30 cm depth, respectively. For the 2019 crop year, the total inorganic N content in the soil was 73 and 38 kg N ha$^{-1}$, at 0-15 and 15-30 cm, respectively (Figures 2.13 and 2.14).

A clear impact of year and N source was observed on soil NH$_4^+$ and NO$_3^-$ distribution pattern at this particular site. Soil treated with CaNO$_3$ and UAN knife-in had the highest NH$_4^+$ content for crop years (Figure 2.14 A). At 0-15 cm depth at 4 and 6 WANF, CaNO$_3$ and UAN knife-in treatments had significantly increased the soil NO$_3^-$ content (Figure 2.13 A).
Figure 2.13. Soil NO$_3^-$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatments, site 5 in Paincourtville, LA.
Figure 2.14. Soil NH$_4^+$ content at 0-15 (A) and 15-30 (B) cm depth at 2, 4, 6 weeks after N fertilization and harvest across crop year under different N source treatment, site 5 in Paincourtville, LA.
This increase in soil \(\text{NO}_3^-\) content on the sub-surface soil layer may have originated from the surface via the leaching process, especially during the early sampling times. This is very common for N sources like \(\text{CaNO}_3\) (Figures 2.13 A and B). Soil \(\text{NO}_3^-\) content at 0-15 was, on average, higher than at 15-30 cm depth (18 and 6.15 kg N ha\(^{-1}\), respectively) (Figure 2.13 A). Similarly, soil \(\text{NH}_4^+\) content at 0-15 was, on average, was higher than at 15-30 cm depth (36 and 23 kg N ha\(^{-1}\), respectively) (Figure 2.14 B). In most cases, \(\text{NH}_4^+\) was the predominant form of inorganic N during the first two weeks of sampling after N was applied. The soil \(\text{NH}_4^+\) content with UAN and \(\text{NH}_4\) sulfate as N source peaked at 6 WANF for both crop years but with a higher level (+20 kg ha\(^{-1}\)) in 2019 than in 2018 (Figure 2.14 A). The rainfall occurrence can explain such difference after N fertilization in 2018 that subsequently resulted in the \(\text{NH}_4^+\) movement to 15-30 cm depth and possibly beyond the 30 cm depth. At 15-30 cm depth at 6 WANF, the UAN knife-in-treated soil had the highest \(\text{NH}_4^+\) content at 33 kg N ha\(^{-1}\) among the soils treated with the rest of the N sources (Figure 2.14 B).

The increased \(\text{NO}_3^-\) levels in the soil were accompanied by reducing \(\text{NH}_4^+\) content at 15-30 cm. Overall, increases in soil \(\text{NO}_3^-\) concentration levels were observed within the first 30 days after N application in the second (first stubble) and third (second stubble) crop year. Nitrate from organic matter mineralization was assumed to contribute to cases where soil \(\text{NO}_3^-\) levels were high even before N fertilization. The increasing soil \(\text{NO}_3^-\) level observed at the subsoil layer with time in some sites such as site 3 and site 4 can be attributed to leaching. Overall, across sites, soil depths, and crop years, downward movement of \(\text{NH}_4^+\) was detected along with \(\text{NO}_3^-\). All these are evidence showing the transformation and activity of N, specifically \(\text{NO}_3^-\) and \(\text{NH}_4^+\) within the soil, afterall N only needed the proper moisture and temperature to take place. While this facilitates the plant N uptake, a condition such as having excessive moisture could lead to N
losses. Yin et al. (2007) reported that the plant could take up 54-72 % of mineral N fertilizer while 8-21 % N can be lost throughout denitrification and 2-18% via leaching.

2.3.3 Effect of Nitrogen Source on Leaf N Monitoring

The leaf N concentration (%) in the present study ranged from ~0.25 % to 3% across sites, sampling time, and crop ages (Figures 2.15 to 2.19). Tables 2.20 and 2.21 show the ANOVA for the different factors affecting leaf N concentration. Overall, sites and N sources were the only sources of variation that significantly impacted leaf N. On average, the leaf N concentration were 1.43, 1.52, 1.43, 1.35, and 1.49 % N for sites 1, 2, 3, 5, and 5, respectively (Figures 2.15 to 2.19). Overall, the leaf N recorded in this study was above the critical values (1.4-1.6 %) established by Anderson and Bowen (1990) and Samuels (1969a). The leaf N concentration at 4 WANF was 1.71, 1.89, 1.94, 1.90, and 1.89 % N for sites 1 to 5. Higher leaf N concentration was measured in sugarcane treated with N (than untreated cane) regardless of N source. In general, leaf N decreased with sampling time across sites. Leaf N concentration increased at 2 WANF, which averaged at 2.14% N. This was the highest leaf N across sampling times for all sites; at 4 and 6, WANF leaf N concentration ranged only between 1.6 to 1.7 % (Figures 2.15 to 2.19). The right temperature and moisture allowed sugarcane growth and accumulated more dry matter, triggering N dilution in the leaves. Overall, leaf N concentrations were not different across crop ages. The significant effect detected from the N source was mainly from the control (no N) vs. all N-fertilized plots. There were virtually no differences among N sources except site 2, where a peak in leaf N at 6 WANF separated CaNO$_3$-treated cane from the rest. This lack of significant N sources was also observed on sugarcane cane yield, quality components, population, and stalk N uptake. Leaf N monitoring did not shed much information on N source impact on N acquisition by a cane.
Table 2.20. Analysis of variance of fixed effects on leaf N concentration across sites (1-4) and sampling time at the Sugar Research Station in St. Gabriel, LA.

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<td>Site<em>Crop age</em>N sources</td>
<td>NS</td>
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</tbody>
</table>

*NS indicates no significant difference at the α=0.05 level of significance.

Table 2.21. Analysis of variance of fixed effects on leaf N concentration across sampling time at site 5, Paincourtville, LA.

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<tr>
<td>Crop age*N sources</td>
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</table>

*NS indicates no significant difference at the α=0.05 level of significance.
Figure 2.15. Leaf N concentration of sugarcane at 2, 4, 6 weeks after fertilization of different N sources, and at harvest for site 1 pooled across crop year (2017-2019), Sugar Research Station in St. Gabriel, LA.

Figure 2.16. Leaf N concentration of sugarcane at 2, 4, 6 weeks after fertilization of different N sources, and at harvest for site 2 pooled across crop year (2017-2019), Sugar Research Station in St. Gabriel, LA.
Figure 2.17. Leaf N concentration of sugarcane at 2, 4, 6 weeks after fertilization of different N sources, and at harvest for site 3 pooled across crop year (2018-2019), Sugar Research Station in St. Gabriel, LA.

Figure 2.18. Leaf N concentration of sugarcane at 2, 4, 6, and 8 weeks after fertilization of different N sources, and at harvest for site 4 (2019), Sugar Research Station in St. Gabriel, LA.
Figure 2.19. Leaf N concentration of sugarcane at 2, 4, 6 weeks after fertilization of different N sources, and at harvest for site 5 pooled across crop year (2018-2019), Paincourtville, LA.

2.4 CONCLUSIONS

The outcome of this study showed that sugarcane and sugar yield, quality parameters, and N uptake varied among sites and crop ages. While N application significantly improved sugarcane yield and quality parameters across sites, the effect of N sources, and their interaction were not consistently observed. There were significant N source effects, and granular N sources like NH$_4$ sulfate and urea showed potential options to UAN. This opens a possibility for future evaluations using NH$_4$ sulfate in Louisiana, where pH ranges are higher and there is a need to correct sulfur deficiencies. Juice purity and sugar yield increased regardless of the N sources. However, greater responses were observed with NH$_4$ sulfate and UAN knife-in. Total N uptake was affected by the different N sources across sites and all the crop ages. The use of urea and NH$_4$ sulfate was substantially higher compared to the rest of the N source. Also, lower stalk N uptake was observed in some sites in the second stubble compared to the first stubble crop,
leaving more N fertilizer in the soil. Sugarcane leaves accumulated most of the N uptake early and during the growing season, causing a positive response to N application's leaf N concentration. Nitrogen fertilizers sources had a significant impact on inorganic NH$_4^+$ and NO$_3^-$ concentration in the soil. NH$_4^+$ was the predominant form of N in the soil reported at both soil surface and subsurface compared to NO$_3^-$. High NO$_3^-$ concentration levels were observed throughout the soil profile at the early season; however, reductions indicate possible movement of NO$_3^-$ to the subsoil. The applications of UAN knife-in and NH$_4$ sulfate increased NH$_4^+$ concentration levels in the soil. On the other hand, CaNO$_3$ and UAN knife-in fertilizers application resulted in higher NO$_3^-$ concentration levels at midseason. These findings suggest that fertilizers sources like UAN knife-in and NH$_4$ sulfate can substantially increase the concentration levels of NH$_4^+$ and NO$_3^-$ in the soil.
CHAPTER 3. EVALUATE THE IMPACT OF COVER CROPS ON SOIL AND PLANT NUTRIENT CONTENT AND SUGARCANE PRODUCTIVITY UNDER LOUISIANA CONDITIONS

3.1 INTRODUCTION

Sugarcane (*Saccharum* spp.) is a tropical and subtropical perennial grass (Verheye, 2010). Worldwide sugarcane production in 2015 was estimated at 1980 million Mg harvested from 22 million hectares (Salassi, 2015). Sugarcane is mainly cultivated in tropical and subtropical regions worldwide, having Brazil and India as top producers (Fortes, 2013). Louisiana is the second largest producer of sugarcane in the United States after Florida. The sugar industry represents an annual income of more than $3.5 billion in value to the state's economy. It is cultivated in 24 parishes across the states and processed in 11 sugar mills into raw sugar molasses (Gravois, 2001). The sugarcane acreage in Louisiana has remained at 200,000 hectares for years, with an average yield of 79 Mg ha\(^{-1}\) and sugar recovery of 104 kg sugar ton\(^{-1}\) of cane (Gravois, 2020). In 2019, the production level reached 13 million Mg cane and 1556 million Mg sugar (Deliberto et al., 2020).

Nitrogen (N) is an essential and limiting nutrient for plant growth. It is necessary for biosynthesis of chlorophyll, a pigment necessary for photosynthesis process (Havlin et al., 2005; Kettrings et al., 2003). Currently, N fertilizer recommendations in Louisiana sugarcane production systems are based on crop year/age (plant cane or stubble) and soil type (light or heavy textured soils) (Gravois, 2014). The most common N source of fertilizer is urea-ammonium-nitrate (UAN, 28-32% N) solution, with N recommendation rates ranging 112 to 135 kg of N per ha to meet sugarcane nutrient requirement (Gravois, 2014). On average, sugarcane removes 4.4 kg of N Mg\(^{-1}\) of cane (Tubana et al., 2019).
Potassium (K) fertilizers is commonly applied as muriate of potash (60 % K) at rates depending on the soil test recommendation. Typically, sugarcane removed 3.4 kg $K_2O$ ton$^{-1}$ of cane (Gravois, 2014). Sulfur (S) fertilization is recommended if S soil level is below 10 mg kg$^{-1}$ at rates between 25 to 28 kg S ha$^{-1}$ (Gravois, 2014).

The continuous monoculture production in an intensive farming operation can negatively impact soil nutrient content, pH, and organic matter content and can cause soil erosion and weed resistant problems highlighting the need for more sustainable production practices. Cover crops, by definition, are considered plants that cover the soil and protect it from erosion and loss of nutrients (Reeves, 1994). Cover cropping has become an essential tool that can benefit agriculture in many ways when correctly implemented. Cover crops have been used for centuries to cover and protect the soil from losses due to erosion. The benefits of cover crops are many: pest suppression, providing a habitat for beneficial insects, increasing microbial activity, and improving soil chemical, and physical properties, among others (Tillman et al., 2004; Hooks et al., 2013). Certain cover crop species are more efficient in recovering nutrients from the soil, and after its decomposition, these nutrients will be available for the subsequent crop. For example, legumes cover crops are good at scavenging residual nutrients than other species, thus reducing soil nutrients losses via leaching and improving soil and water quality (Kramberger et al., 2009).

Several studies have reported that nutrient recycling is one of the benefits of cover cropping. Nutrients removed by cover crops are released back to the soil during biomass decomposition within ten weeks after termination (Kleinman et al., 2005; Oliveira et al., 2017). Planting cover crops also reduce N loss by recovering N that would have been otherwise exposed to run-off and erosion on bare ground.
The effect of cover crops on N cycling is well-documented. For example, legumes cover crops, ryegrass (*Lollium perenne*), and brassicas are considered good N scavengers (Brinsfield and Staver, 1991; Shipley et al., 1992; Kramberger et al., 2009). Nitrogen fixation and uptake by the cover crops are influenced by the soil inorganic N content, soil temperature, and humidity. A high soil inorganic N content can reduce the N fixation rate. In contrast, in limited N supply, cover crop species like sunn hemp (*Crotalaria juncea* L.) or iron cowpeas (*Vigna unguiculata*) can fix atmospheric N bringing a significant quantity of N back to the soil at 140 kg N ha\(^{-1}\) (Kramberger et al., 2009). Studies have reported the effect of cover crops on soil K and pH (Nyakatawa et al., 2001; Kramberger et al., 2009). Soil nutrient uptake for the subsequent crop depends on how fast the cover crop is decomposed and the synchrony between the soil nutrient mineralization and the maximum soil-nutrient uptake during the grand growth stage of sugarcane (Gaudin et al., 2013; Thilakarathna et al., 2015)

In Louisiana sugarcane production systems, cover crops have been investigated as a rotational crop in the fallow period or as an intercrop in a newly planted sugarcane. Sugarcane cultivation involves several cultural practices in which soil is intensively disturbed during operations like planting and sugarcane termination. These practices typically leave the soil disturbed and exposed for an extended period causing soil erosion and degradation. Thus, cover crops can play an essential role in improving sugarcane sustainability. Cover cropping can also improve soil fertility, weed suppression, and increase cane and sugar yield. A study by Thawaro et al. (2017) demonstrated that planting sweet sorghum (*Sorghum bicolor* L.), sunn hemp, soybean (*Glycine max* L.), and crimson clover (*Trifolium incarnatum* L.) as cover crops did not impact millable stalks count but increased cane yield in plots grown to rice (*Oryza sativa* L.) and sorghum as cover crops. In another experiment, White et al. (2020) found that cowpea and
sunn hemp grown during fallow periods increased cane and yield and did not negatively impact sugar yield. They reported that sucrose content was improved by 10 to 20% higher than the non-cover crop treatment. Similarly, Webber III et al. (2016) reported that growing kenaf (*Hibiscus cannabinus*) and cowpea as cover crops did not affect millable stalk counts and cane yield. Orgeron et al. (2020) drill seeded a mix of cover crop species after planting new cane crop and recorded a 15% and 12% increase in cane and sugar yield, respectively. With all these recent studies, the specific role(s) of cover cropping on nutrient recycling and sugarcane productivity have not been fully documented nor elucidated. This study evaluated the effect of cover cropping after planting new sugarcane on soil nutrient cycling and sugarcane productivity. The specific objectives were to: (1) quantify the nutrients sequestered by cover crops biomass, (2) monitor soil pH and nutrient content during the 4-year/3-harvest crop cycle after cover crops termination, and (3) document the subsequent response of sugarcane to any soil nutrient content/pH changes using yield and quality components as metrics.

### 3.2 MATERIALS AND METHODS

#### 3.2.1 Site Description, Planting Method, Treatment Structure, and Trial Establishment

This study was conducted at the Louisiana Agricultural Center Sugar Research Station in St. Gabriel, LA, USA (Latitude 30°, '15', 13'' N, Longitude 91°, '06', 05'' W) at four (4) sites. These experimental sites were established on two soil types: Commerce silt loam and Commerce silty clay loam (Fine-silty, mixed, superactive, non-acid, thermic Fluvaquentic Endoaquept). An on-farm demonstration plot (site 5) was conducted with a sugarcane grower at Paincourtville, LA, USA (Latitude 29°, '59', 34'' N, Longitude 91°, '03', 38'' W).
The predominant soil at the site was a Cancienne silt loam soil (Fine-silty, mixed, superactive, non-acid, hyperthermic Fluvaquentic Epiaquepts). Table 3.1 shows the initial chemical properties of soils for all sites.

For all sites, sugarcane variety L01-299 was planted at different years using whole stalk or billets as planting material. At the Sugar Research Station, all the sites were planted using billets. Each plot consisted of three meter wide x 15 meter long beds. Planting beds were opened at 15 cm depth. The opened beds were filled with cut billets measuring between 40 to 50 cm long at the rate of 6 to 8 billets in 50 cm sections down the planting beds. At site 5, three to four whole stalks were planted by hand with overlapped by 8 cm on the next stack of stalks. Each plot consisted of two or three 1.7 meters wide x 170 meters long beds. Following planting, beds were closed up by covering with 8 cm of soil and packed to keep enough moisture for good germination. Table 3.2 provides information on the planting dates and method and agronomic activities for all the sites. After the beds were packed, herbicide application was carried out to seal the soil using a pre-emergence mix of herbicides using metribuzin [4-amino-6-tert-butyl-3-methylthio-1,2,4-triazin-5(4H)-one] at 3 kg a.i. ha⁻¹ and pendimethalin [N-(1-ethyl propyl)-2,6-dinitro-3,4-xylidine] at 3 kg a.i. ha⁻¹.

Table 3.1. Chemical properties of the initial soil samples collected from all the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>‡pH</th>
<th>‡Organic matter g kg⁻¹</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Ca</th>
<th>Mg</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1</td>
<td>17</td>
<td>22</td>
<td>93</td>
<td>14</td>
<td>1633</td>
<td>346</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>18</td>
<td>21</td>
<td>184</td>
<td>12</td>
<td>2896</td>
<td>468</td>
<td>4.1</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>19</td>
<td>64</td>
<td>194</td>
<td>13</td>
<td>2500</td>
<td>524</td>
<td>4.2</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>21</td>
<td>23</td>
<td>196</td>
<td>9.3</td>
<td>2900</td>
<td>553</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>16</td>
<td>22</td>
<td>183</td>
<td>11</td>
<td>2045</td>
<td>343</td>
<td>3.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

⁻ Based on Mehlich 3 (Mehlich, 1984) procedure.
‡ 1:1 w/v soil: deionized water ratio (McLean, 1982)
† Acid-dichromate oxidation (Nelson and Sommer, 1982)
This study was superimposed from a multi-site cover crop x N source study wherein treatments consisted of five N sources including a control (0 N), and with and without cover crops arranged in a split-plot design for sites established at the Sugar Research Station in St. Gabriel, LA. The whole plot was assigned to cover crop treatment, and the subplot was the N source treatment. Site 5 at Paincourtville, LA, consisted of three N sources and two cover crop treatments (with and without). Treatments were replicated three times and arranged in a split-plot design. To address the objectives of this study, only two were selected from the N source treatments, i.e., control and urea-ammonium nitrate (UAN) solution. The choice was made since UAN is the typical source of N in Louisiana sugarcane production systems.

For sites 1-4 at the Sugar Research Station, each field was divided into two blocks; one was planted to cover crops while the other half was not seeded or under native weed species (hereafter termed no cover crops). Within each block, the 5 N sources and control were laid out with four replications. At site 5, the field was divided first into three blocks (replicates), then each replicate was split into two for cover crops treatment before assigning the 3 N sources.

The cover crops were established one month after planting of new sugarcane crop. A mix of three cover crop species was broadcasted by hand on top of each bed's shoulder. The cover crops included a blend of brassicas and legumes: crimson clover (*Trifolium incarnatum*), Hairy vetch (*Vicia villosa*), and oilseed radish (*Raphanus sativus* L.) planted at a seeding rate of 13, 17, and 1 kg ha\(^{-1}\), respectively. Table 3.3 presents all the agronomic information about the establishment of the cover crops study.

The cover crops were terminated eight weeks before sugarcane fertilization in April using first a three-row disk cultivator followed by chemical application of selected herbicides utilizing a mix of metribuzin [4-amino-6-tert-butyl-3-methylthio-1,2,4-triazin-5(4H)-one] at 4 kg a.i. ha\(^{-1}\).
and pendimethalin [N-(1-ethyl propyl)-2,6-dinitro-3,4-xylidine] at 3 kg a.i. ha\(^{-1}\). Two weeks after the herbicides were applied, the furrow and row shoulders were cultivated using a three-row disk sugarcane cultivator. The cover crops residues were incorporate and plowed back into the soil.

Before fertilization in April, both shoulders of the planted row were off-bared with a three-row disk cultivator. The UAN fertilizer was injected or dribbled on each shoulder of the planted row at the rate of 90 kg N ha\(^{-1}\). The application of the other N sources is described in the Materials and Methods section of Chapter 2. Rows were closed immediately after N application to prevent any N loss. Table 3.4 describes the N treatments applied at the Sugar Research Station in St. Gabriel and the 'grower's field in Paincourtville, LA. Fertilization was done in April every year until the last stubble crop (2\(^{nd}\) stubble).

### 3.2.2 Soil Sampling

Soil samples were collected at 0-15 and 15-30 cm depth with a soil probe (JMC; Model No. 641-792-8285). A total of sixteen (16) random soil cores were pulled out from each plot to determine soil inorganic N concentration (kg ha\(^{-1}\)) as nitrate (NO\(_3^{-}\)-N) and ammonium (NH\(_4^+\)-N). A composite soil sample was collected by taking multiple cores on a zig-zag pattern from each block (with cover crops and no-cover crop) for soil nutrient content and pH. Soil sampling was done at midseason and after harvest every year during the study period across sites. Soil samples were dried at 60°C for four days in an oven (Despatch LBB series; model number LBB2-18-1). Later, they were processed with a Humboldt electric flail grinder and sieved through a built-in 2 mm sieve.
Table 3.2. Agronomic practices for all the sites established at the Sugar Research Station and the 'grower's field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Planting date</th>
<th>Planting Material</th>
<th>Crop age</th>
<th>Year</th>
<th>Location</th>
<th>Fertilization date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August 2016</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2017</td>
<td>St. Gabriel</td>
<td>April 28</td>
<td>December 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>Second stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 25</td>
<td>October 20</td>
</tr>
<tr>
<td>2</td>
<td>August 2016</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2017</td>
<td>St. Gabriel</td>
<td>April 28</td>
<td>December 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>Second Stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 25</td>
<td>October 20</td>
</tr>
<tr>
<td>3</td>
<td>August 2017</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2018</td>
<td>St. Gabriel</td>
<td>April 15</td>
<td>December 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Billets</td>
<td>First stubble</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 22</td>
<td>November 18</td>
</tr>
<tr>
<td>4</td>
<td>August 2018</td>
<td>Billets</td>
<td>Plant cane</td>
<td>2019</td>
<td>St. Gabriel</td>
<td>April 15</td>
<td>December 15</td>
</tr>
<tr>
<td>5</td>
<td>August 2017</td>
<td>Whole stalk</td>
<td>Plant cane</td>
<td>2018</td>
<td>Paincourtville</td>
<td>April 19</td>
<td>December 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole stalk</td>
<td>First stubble</td>
<td>2019</td>
<td>Paincourtville</td>
<td>April 17</td>
<td>November 18</td>
</tr>
</tbody>
</table>
Table 3.3. Description of the N sources and rates for the study conducted at the Sugar Research Station and the 'grower's field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatments</th>
<th>N rate (kg ha(^{-1}))</th>
<th>N source</th>
<th>Composition</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Gabriel</td>
<td>†1</td>
<td>0</td>
<td>Control</td>
<td>Granular</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>90</td>
<td>Urea</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>†3</td>
<td>90</td>
<td>UAN</td>
<td>Liquid</td>
<td>Injected</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90</td>
<td>NH(_4^+) sulfate</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>90</td>
<td>Ca(NO(_3))(^-)</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>67 + 23</td>
<td>UAN</td>
<td>Liquid</td>
<td>Injected + Foliar</td>
</tr>
<tr>
<td>Paincourtville</td>
<td>2</td>
<td>90</td>
<td>Ca(NO(_3))(^-)</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
<tr>
<td></td>
<td>†3</td>
<td>90</td>
<td>UAN</td>
<td>Liquid</td>
<td>Injected</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90</td>
<td>NH(_4^+) sulfate</td>
<td>Granular</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

† N treatments used in this study.
Table 3.4. Agronomic practices for the cover crop treatment for all sites in St. Gabriel and Paincourtville, LA.

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Application</th>
<th>Planting date</th>
<th>Termination date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>St. Gabriel</td>
<td>Broadcast</td>
<td>Sept. 5, 2016</td>
<td>Jan. 29, 2017</td>
</tr>
<tr>
<td>2</td>
<td>St. Gabriel</td>
<td>Broadcast</td>
<td>Sept. 5, 2016</td>
<td>Jan. 29, 2017</td>
</tr>
<tr>
<td>3</td>
<td>St. Gabriel</td>
<td>Broadcast</td>
<td>Sept. 22, 2017</td>
<td>Feb. 8, 2018</td>
</tr>
<tr>
<td>4</td>
<td>St. Gabriel</td>
<td>Broadcast</td>
<td>Sept. 11, 2018</td>
<td>Feb. 3, 2019</td>
</tr>
<tr>
<td>5</td>
<td>Paincourtville</td>
<td>Broadcast</td>
<td>Jan. 16, 2017</td>
<td>Feb. 28, 2017</td>
</tr>
</tbody>
</table>
3.2.3 Soil Nutrient Analysis

Soil NO$_3$-N and NH$_4^+$-N concentrations were determined using a spectrophotometric measurement with an automated flow injection system (Lachat QuickChem 8500 series 2). One molar (M) potassium chloride (KCl) was poured into a 125 ml plastic bottle containing five (5) grams of processed soil. The samples were shaken for one hour on a reciprocal shaker (Eberbach; model number-E6010.00) at high speed. After shaking, the soil suspension sample was filtered using No. 42 Whatman filter paper.

Soil nutrients (P, potassium – K, sulfur – S, magnesium – Mg, calcium – Ca, copper – Cu, and zinc – Zn) were extracted based on Mehlich-3 procedure (Mehlich, 1984). Two grams of processed soil were weighed into a 125 ml plastic bottle, then 20 ml of Mehlich-3 solution was added. Samples were then shaken for 5 minutes using a reciprocal shaker at high speed and filtered using a No. 2 Whatman filter paper. The nutrient concentrations in KCl extracts were quantified using the inductively coupled plasma-optical emission spectroscopy (ICP-OES). Soil pH was also determined on a 1:1 ratio, w/v soil: water suspension. Ten 10 grams of processed soil was weighed into a 50-ml centrifuge plastic tube and added with 10 ml deionized water. Soil samples were shaken for one hour at high speed in a reciprocal shaker. After shaking, the soil suspension was left undisturbed for one hour, and the pH was measured using a SevenCompact™ pH/ Ion S220 digital pH meter.

3.2.4 Cover Crops Biomass Sampling

The biomass clippings/roots of the cover crops were collected from the cover crops and no cover crop treatments before termination in mid-February of the following year. Biomass samples were collected from 4 x 1 m$^2$-areas. The biomass samples were separated by species,
washed, oven-dried, and weighed to determine dry biomass yield. In the case of tillage radish, roots were also collected and processed.

Biomass samples were dried at 60°C for seven days in an oven (Despatch LBB series; model number LBB2-18-1). Dry matter (DM) yield was computed as:

\[
\text{Dry matter yield (DM) (kg ha}^{-1}\text{)} = \frac{\text{DM weight (kg)}}{\text{m}^2} \times 10,000 \text{ m}^2/\text{ha}
\]  

(3.1)

3.2.5 **Cover Crops Nutrient Content Analysis**

Oven-dried biomass samples were finely ground using a Wiley mill plant grinder (Model No. 3, Arthur H. Thomas CO. Philadelphia, USA), thoroughly mixed, and passed through a 1 mm sieve before storing in a labeled coin envelope. The nutrient concentration in biomass samples was determined based on nitric acid-hydrogen peroxide digestion procedure followed by ICP-OES analysis. A 0.5 g sample was weighed on a 4 x 4 cm Kim wipe. The sample was wrapped by twisting the 4 corners of the Kim wipe together and then placed into 125 ml-digestion tubes. Samples in the tubes were soaked in 5 ml of concentrated nitric acid for 50 minutes, then mixed using a Fisher Scientific vortex automatic mixer and later was placed into a digestion block at 155°C for 5 minutes. After 20 minutes or soon after the pre-digested samples cooled down, 3 ml of 30% hydrogen peroxide was added before placing them back to the digestion block for 2.5 hours. Fully digested samples were removed from the digestion block, cooled down, and transferred the digest into a 25-ml polyethylene centrifuge tube, then washed the tube with DI a few times and transferred the washing to the tube until it reached the 25-ml mark. Digest samples were mixed and then filtered with a Whatman No 1. Finally, the nutrient concentration in the filtered-digested samples was quantified by ICP-OES analysis.
Nitrogen content on a percentage (%) dry-weight basis was determined by dry combustion. Twenty (20) mg ground plant samples were weighed and placed in tin capsules. The samples in the tin capsules were then pressed and placed in the 90-position carousel set on top of the opening to the reactor column of a CN dry combustion analyzer unit (Elementar Americas Inc, Vario EL Cube).

Biomass nutrient removal rate or content was determined for both macro (N, P, K, S, Ca, and Mg) and micro-nutrients (Cu, iron - Fe, manganese - Mn, nickel -Ni, and Zn) using the following equation:

Macronutrient removal rate (kg ha\(^{-1}\)) =

\[
\text{DM weight (kg ha}^{-1}\text{)} \times \text{concentration (\%)} / 100
\]  
(3.2)

Micronutrient removal rate (kg ha\(^{-1}\)) =

\[
\text{DM weight (kg ha}^{-1}\text{)} \times \text{concentration (mg kg}^{-1}\text{)} / 1 \times 10^6
\]  
(3.3)

Nitrogen content in the stalk (%) and stalk N uptake in kg ha\(^{-1}\) was also determined using the following formula:

\[
\text{N Uptake (kg ha}^{-1}\text{)} = [(\text{cane yield ha}^{-1}) - (\text{cane yield ha}^{-1} \times (\% \text{ moisture/100})] \times [\% \text{ N/100}]
\]  
(3.4)

### 3.2.6 Cane and Sugar Yield and Quality Components

Plots were harvested using a single-row chopper harvester (John Deere 350 model). A modified single axle high dump weigh wagon equipped with load cell sensors (Cameco Industries, Thibodaux, LA) was used to determine stalk weight by row. At site 5 in
Paincourtville, yield data was determined using a yield harvest monitor georeferenced to a precise location point using global positioning system (GPS). Ten stalks were randomly cut by hand from the middle row of each plot. The leaves were stripped off from the stalk, and the top was cut about 10 cm below the apical meristem. The weight of the ten stalks was determined and added to the stalk weight of the 3 or 2 rows to get the total plot yield. Sugarcane stalks were shredded and analyzed using a SpectraCane Near Infrared System (Bruker Corporation, Billerica, Massachusetts) to determine juice quality components (theoretically recoverable sugars -TRS, total soluble solids - BRIX, and sucrose content). Grab samples of the shredded stalk were collected to determine stalk N uptake following the procedure detailed in the previous section (3.2.5). Sampled stalk weight was then used to determine average stalk weight and to estimate sugarcane stalk population using the formula:

\[
\text{Stalks per ha}^{-1} = \left( \frac{\text{Total plot weight/average stalk weight}}{10,000 \text{ m}^2/\text{plot area in m}^2} \right)
\]

(3.5)

3.2.7 Data Analysis

Agronomic variables were subjected to analysis of variance (ANOVA) using PROC MIXED in SAS version 9.4 (SAS Institute, Cary, NC, USA 2012). Nitrogen sources were considered fixed effect, and replicate was treated as a random effect. The main plot (cover crops and no cover crops) was assigned to each half of the field before replication was made. Thus, the different sites were used as replication. The cover crops effect was then evaluated across crop ages (plant cane, first and second stubble). The effect of N fertilization was considered as the subplot, i.e., control and UAN. The least-square means were determined, and the means of significant effects were separated using the PDIF option \((p \leq 0.05)\). Letters grouping was converted using the PDMIX800 (Saxton, 1998).
Soil pH and soil nutrient content effect were evaluated from samples collected at four weeks after fertilization and at harvest within two and three years after cover crops were terminated across sites. However, the trend of soil inorganic N concentration was analyzed by sites and crop age.

3.3 RESULTS AND DISCUSSION

3.3.1 Climatological Data

3.3.2 Cover Crops Biomass Yield and Plant Nutrients Composition

The average monthly temperature and precipitation at the Sugar Research Station in St. Gabriel across crop years are reported in Figures 3.1 and 3.2, respectively. The pattern of monthly average temperature on average were similar between 2017 to 2020 (Figure 3.1). The temperature recorded in January 2018 was the lowest monthly average across years. This is important because a low temperature at the early growth stage of sugarcane can affect its growth vigor later, adding more stress and making it susceptible to insect and disease pressure. The optimal temperature for sugarcane growth is between 30-33°C; at temperatures below 16°C, the sugarcane development is compromised (Bakker, 1999). Conversely, low temperature can enhance the ripening process and accumulate more sugar (Bakker, 1999). Optimal dry matter accumulation and stalk elongation have been reported in for sugarcane temperatures between 17.2 to 22.2 °C (Hunsigi, 1993).

Across all years, June, July, August, and September were the months wherein the highest temperatures were recorded at 26, 28, 29, and 27°C, respectively (Figure 3.1). November 2018 and 2019 had the lowest temperature (approximately 4°C) compared to the other years.
The variety L01-299 has been reported as a medium cold tolerant variety. The highest precipitation recorded was in April and May 2019 (Figure 3.2). In general, the rainfall distribution from 2017 to 2020 at the Sugar Research Station was above the average from the 40-year average precipitation. After N fertilization, the highest rainfall in April and May was reported in 2019 at 20 and 26 cm, respectively. Heavy rainfall events, especially after N fertilization, could lead to N losses by run-off and NO$_3^-$ leaching through the soil profile.

The average monthly temperature and precipitation at the grower's field in Paincourtville across crop years are reported in Figures 3.3 and 3.4, respectively. Overall, the monthly average temperature in 2017 was lower than those observed in 2018 and 2019. The average monthly temperature in August to September across years was 26 and 28 °C, respectively. The precipitation recorded in May, June, July, and August 2017 was higher than in the other years (Figure 3.4). The crop year 2018 was quite dry in early and midseason; however, September, November, and December recorded the highest rainfall among those recorded from other years.

While crimson clover, hairy vetch, and tillage radish are cold cover crop species, low winter temperatures can negatively affect their germination and growth. The temperature during cover crop establishment, i.e., early fall in Louisiana, was more favorable for tillage radish and crimson clover, making them dominant in population than hairy vetch, a late winter cover crop species. Also, both crimson clover and tillage radish suppressed hairy vetch growth. The soil surface temperature is also essential, especially for late planting. This was the case at site 5, where cover crops were planted on January 16, reflecting lower seed emergence and cover crops population than those grown in St. Gabriel. Soil temperature and moisture play a significant influence on cover crop growth and biomass yield production.
The cover crops during springtime can improve soil aeration and infiltration in tilled soil. However, the proper cover crop termination date should be implemented to reduce competition with sugarcane for nutrients and N losses via leaching.

Figure 3.1. Average monthly temperature from January to December 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA.
Figure 3.2. Average monthly precipitation from January to December 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA

Figure 3.3. Average monthly temperature from January to December 2017, 2018, 2019, and 2020 at the grower's field in Paincourtville, LA
Figure 3.4. Average monthly precipitation from January to December 2017, 2018, 2019, and 2020 at the grower’s field in Paincourtville, LA.

3.3.3 Impact of Cover Crops on Sugarcane Productivity and Quality Components

The results on ANOVA for yield, quality component, stalk N content, and uptake of sugarcane across crop age, N treatment, and cover crops treatments at the Sugar Research Station are summarized in Table 3.5. There were 2-way significant interactions of crop age with N treatment or cover crop treatment; thus, Tables 3.6, 3.7, and 3.8 were created to present the mean values and ANOVA for all these parameters for plant cane, first stubble, and second stubble crop, respectively.

The cover crops treatment effect on cane and sugar yields on plant cane was not significant (Table 3.6). Cane and sugar yield were numerically higher where the cover crops were planted (84 Mg ha⁻¹ and 9,097 ha⁻¹) than no cover crop treatment (89 Mg ha⁻¹ and 9,904 kg ha⁻¹). On the other hand, fertilizer N significantly impacted cane and sugar yield compared to the
control or no N in plant cane. Cane and sugar yields with N fertilization averaged 95 Mg ha\(^{-1}\) and 10,369 kg ha\(^{-1}\); compared to the 77 Mg ha\(^{-1}\) and 8,632 kg ha\(^{-1}\) with no N, respectively. There was no significant difference in TRS, Brix, sucrose, stalk N, and N uptake between with cover crops and no cover crops treatments. However, there was a significant increase in stalk N content and uptake when N was applied to cane, increasing these values from 0.28 to 0.33% and 61 to 87 kg N ha\(^{-1}\). Sugarcane quality parameters were not significantly affected by N fertilization.

The millable stalks population was statistically lower where the cover crop was grown (84, 215 stalks ha\(^{-1}\)) than the no cover crop treatment (99, 224 stalks ha\(^{-1}\)). However, population was statistically the same between the control and N fertilized cane.

Both cover crop and N fertilization effects were detected for several measured variables in the first stubble crop (Table 3.7). The interaction effect between these two factors was not significant \((p>0.05)\). Cane and sugar yields were significantly higher where cover crops were planted, averaging 91 Mg ha\(^{-1}\) and 9,618 kg ha\(^{-1}\) than no cover crop treatments 88 Mg ha\(^{-1}\) and 9,457 kg ha\(^{-1}\), respectively. Similarly, cane and sugar yields were higher in N fertilized plots. The millable stalk population was positively affected by cover crop and N fertilization. Neither sugarcane quality parameters (TRS, Brix, and sucrose) nor the stalk N content were affected by cover crop or N fertilization.

Sugarcane N uptake was significantly impacted only by N fertilization. Stalk N uptake was significantly higher with N fertilization than the control at 92 vs. 59 kg N ha\(^{-1}\), respectively. Stalk N uptake between cover crops and no cover crop were similar at values of 77 and 74 kg N ha\(^{-1}\), respectively.
Table 3.5. Probability values from the analysis of variance for the fixed effects and their interactions for all the plant measured variables at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Stalk population</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop age</td>
<td>0.0069</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.003 NS</td>
</tr>
<tr>
<td>N fertilization</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.025</td>
<td>NS</td>
<td>NS</td>
<td>0.015 &lt;0.0001</td>
</tr>
<tr>
<td>Cover crop</td>
<td>0.0011</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0257</td>
<td>0.0091</td>
<td>NS NS</td>
</tr>
<tr>
<td>Crop age*N fertilization</td>
<td>NS</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.019 0.0012</td>
</tr>
<tr>
<td>Crop age*cover crop</td>
<td>0.0243</td>
<td>0.0367</td>
<td>0.0017</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS 0.0354</td>
</tr>
<tr>
<td>Crop age<em>N fertilization</em>cover crop</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS NS</td>
</tr>
</tbody>
</table>

*NS indicates no significant difference at the α=0.05 level of significance.
Table 3.6. Mean and analysis of variance on plant cane yield, quality component, and stalk N content and uptake with and without N under cover and no cover cropping system at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Stalk population</th>
<th>Cane yield Mg ha(^{-1})</th>
<th>Sugar yield kg ha(^{-1})</th>
<th>TRS kg Mg(^{-1})</th>
<th>Brix</th>
<th>Sucrose %</th>
<th>Stalk N</th>
<th>N uptake kg N ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover Crop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover crops</td>
<td>84,215 A</td>
<td>84</td>
<td>9,097</td>
<td>109</td>
<td>18.27</td>
<td>15.39</td>
<td>0.31</td>
<td>71</td>
</tr>
<tr>
<td>No cover crop</td>
<td>99,224 B</td>
<td>89</td>
<td>9,904</td>
<td>111</td>
<td>18.52</td>
<td>15.67</td>
<td>0.32</td>
<td>76</td>
</tr>
<tr>
<td>p-value</td>
<td>0.0102</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>N Fertilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N applied</td>
<td>96,536</td>
<td>95 A</td>
<td>10,369 A</td>
<td>108</td>
<td>18.44</td>
<td>15.31</td>
<td>0.33 A</td>
<td>87 A</td>
</tr>
<tr>
<td>Control</td>
<td>86,903</td>
<td>77 B</td>
<td>8,632 B</td>
<td>112</td>
<td>18.34</td>
<td>15.74</td>
<td>0.28 B</td>
<td>61 B</td>
</tr>
<tr>
<td>p-value</td>
<td>NS</td>
<td>0.0014</td>
<td>0.0113</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0017</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Cover crop*N</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

TRS – theoretical recoverable sugar.
NS indicates no significant difference at the α=0.05 level of significance.
The cover crop treatment significantly affected millable stalk population, cane, and sugar yield in the second stubble, but not sugarcane quality parameters, stalk N content, and neither sugarcane N uptake (Table 3.8). The N fertilization significantly impacted stalk population, cane and sugar yield, and sugarcane N uptake, but not the quality parameters and stalk N content. The cover crop treatment had a mean cane yield of 75 Mg ha\(^{-1}\) and sugar yield of 6,784 kg ha\(^{-1}\) compared to the no cover crop means of 69 Mg ha\(^{-1}\) and 6,318 kg ha\(^{-1}\), respectively. The N fertilization produced higher cane (84 Mg ha\(^{-1}\)) and sugar (7,621 kg ha\(^{-1}\)) yield than the control with mean values of 54 Mg ha\(^{-1}\) and 5,480 kg ha\(^{-1}\). Sugarcane N uptake was significantly affected by N fertilization, but not by the cover crops treatment neither by their interaction effect. Cover crops significantly influenced the sugarcane stalk population and N fertilization treatments. A higher stalk population was observed with the cover crops than no cover crops treatments, 100,016 vs. 92,983 stalks ha\(^{-1}\). Similarly, the N application effect also increased the stalk population from 85,060 to 107,938 stalks ha\(^{-1}\). At site 5 in Paincourtville, plant cane yield and sugarcane quality parameters and stalk and sugarcane N content were affected by N fertilization treatments (Table 3.9). Cane and sugar with cover crops produced higher yields when compared to the unfertilized, no cover crop plots. On average, the N-fertilized cane had a significantly higher yield with cover crops (104 Mg ha\(^{-1}\)) and without cover crops (100 Mg ha\(^{-1}\)) compared to unfertilized cane (78 Mg ha\(^{-1}\)). This result also indicates that the presence of cover crops did not make any difference to cane yield. A similar result was obtained for sugar yield, where the N-fertilized cane with or without cover crops showed a higher yield than the unfertilized cane. The lack of significant difference between cover crop-UAN and no cover crops-UAN indicated N plays' larger impact than cover crop on improving productivity and N uptake as supported by the stalk N content and uptake data.
Table 3.7. Mean and analysis of variance on first stubble yield, quality component, stalk N content, and uptake with and without N under cover and no cover cropping system at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Stalk population Stalk ha(^{-1})</th>
<th>Cane yield Mg ha(^{-1})</th>
<th>Sugar yield kg ha(^{-1})</th>
<th>TRS kg Mg(^{-1})</th>
<th>Brix</th>
<th>Sucrose %</th>
<th>Stalk N kg N ha(^{-1})</th>
<th>N uptake kg N ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropping system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover crop</td>
<td>104,242 A</td>
<td>91 A</td>
<td>9,618 A</td>
<td>107</td>
<td>18.36</td>
<td>15.19</td>
<td>0.30</td>
<td>77</td>
</tr>
<tr>
<td>No cover crop</td>
<td>102,937 B</td>
<td>88 B</td>
<td>9,457 B</td>
<td>109</td>
<td>18.55</td>
<td>15.52</td>
<td>0.29</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>(p)-value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0102</td>
<td>0.001</td>
<td>0.041</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N applied</td>
<td>114,761 A</td>
<td>102 A</td>
<td>10,977 A</td>
<td>108</td>
<td>18.56</td>
<td>15.42</td>
<td>0.31</td>
<td>92 A</td>
</tr>
<tr>
<td>Control</td>
<td>92,418 B</td>
<td>77 B</td>
<td>8,098 B</td>
<td>107</td>
<td>18.34</td>
<td>15.29</td>
<td>0.28</td>
<td>59 B</td>
</tr>
<tr>
<td></td>
<td>(p)-value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0002</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Cover crop*(N)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

TRS – theoretical recoverable sugar.
NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
Table 3.8. Mean and analysis of variance on second stubble yield, quality component, stalk N content, and uptake with and without N under cover and no cover cropping system at the Sugar Research Station in St. Gabriel, LA.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Stalk population</th>
<th>Cane yield</th>
<th>Sugar yield</th>
<th>TRS</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk N</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropping system</td>
<td></td>
<td>Stalk ha(^{-1})</td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>kg Mg(^{-1})</td>
<td>%</td>
<td>kg N ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
</tr>
<tr>
<td>Cover crop</td>
<td>100,016 A</td>
<td>75 A</td>
<td>6,784 A</td>
<td>93</td>
<td>17.69</td>
<td>16.61</td>
<td>0.35</td>
<td>72</td>
</tr>
<tr>
<td>No cover crop</td>
<td>92,983 B</td>
<td>69 B</td>
<td>6,318 B</td>
<td>90</td>
<td>17.67</td>
<td>13.76</td>
<td>0.34</td>
<td>65</td>
</tr>
<tr>
<td>p-value</td>
<td>0.0001</td>
<td>0.0436</td>
<td>0.0321</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fertilization</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N applied</td>
<td>107,938 A</td>
<td>84 A</td>
<td>7,621 A</td>
<td>92</td>
<td>17.61</td>
<td>13.58</td>
<td>0.34</td>
<td>79 A</td>
</tr>
<tr>
<td>Control</td>
<td>85,060 B</td>
<td>54 B</td>
<td>5,480 B</td>
<td>91</td>
<td>17.75</td>
<td>13.79</td>
<td>0.31</td>
<td>57 B</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

| Cover crop*N        | NS               | NS         | NS          | NS  | NS   | NS      | NS      | NS       |

TRS – theoretical recoverable sugar.
NS indicates no significant difference at the \(\alpha=0.05\) level of significance.
Table 3.9. Means and analysis of variance on plant cane yield, quality component, stalk N content, and uptake with and without N under cover and no cover cropping system at the grower's field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Stalk population</th>
<th>Cane yield (Mg ha(^{-1}))</th>
<th>Sugar yield (kg ha(^{-1}))</th>
<th>TRS (kg Mg(^{-1}))</th>
<th>Brix (%)</th>
<th>Sucrose (%)</th>
<th>Stalk N (kg N ha(^{-1}))</th>
<th>N uptake (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (no N, no cover crop)</td>
<td>95,286</td>
<td>78 B</td>
<td>7,785 B</td>
<td>103</td>
<td>17.18</td>
<td>14.43</td>
<td>0.35 B</td>
<td>39 B</td>
</tr>
<tr>
<td>Cover crops-UAN</td>
<td>100,344</td>
<td>104 A</td>
<td>10,213 A</td>
<td>100</td>
<td>16.95</td>
<td>14.08</td>
<td>0.37 AB</td>
<td>52 A</td>
</tr>
<tr>
<td>No cover crops-UAN</td>
<td>93,769</td>
<td>100 A</td>
<td>9,785 A</td>
<td>99</td>
<td>17.35</td>
<td>14.13</td>
<td>0.38 A</td>
<td>50 A</td>
</tr>
<tr>
<td></td>
<td><strong>p-value</strong></td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
<td>NS</td>
<td>0.028</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

TRS – theoretical recoverable sugar.
NS indicates no significant difference at the α=0.05 level of significance.
UAN – urea ammonium nitrate solution.
The N fertilization remained a stronger factor than the cover crops treatment for the first stubble cane and sugar yield and stalk N uptake (Table 3.10). Cane yield was significantly greater where N was applied with or without cover crops reaching yield levels of 98 and 93 Mg ha\(^{-1}\), respectively, compared to control, no cover crops treatment at 56 Mg ha\(^{-1}\). A similar response was obtained for sugar yield wherein the N-fertilized plots with or without cover crops had 10,515 and 10,400 kg ha\(^{-1}\), respectively, compared to no N, no cover crops treatment's 6,361 kg ha\(^{-1}\). It is interesting to note that the presence of cover crops impacted the stalk population such that the count was increased from 101,108 to 117,702 stalk ha\(^{-1}\). There seemed to be also cover crops effects showing up on stalk N content and uptake, but the increase was not statistically significant.

Overall, the outcomes from this study mainly showed the significant effect of cover crops on cane and sugar yields, stalk counts, and N uptake occurred in the first and second stubble crops. This agrees with White et al. (2020). Their study showed that the cowpea and sunn hemp planted during fallow periods in Louisiana increased cane yield; no effect was observed in sugar yield. In an on-farm demonstration study, Orgeron et al. (2020), using a mixture of cover crops planted in a newly sugarcane planted in early fall, reported that the sucrose content and sugar yield were improved by 15 and 13 % higher, respectively, where cover crops were drill seeded compared to the non-cover crops treatment.
Table 3.10. Mean and analysis of variance on first stubble yield, quality component, stalk N content, and uptake with and without N under cover and no cover cropping system at the grower’s field in Paincourtville, LA.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Stalk population Stalk ha(^{-1})</th>
<th>Cane yield Mg ha(^{-1})</th>
<th>Sugar yield kg ha(^{-1})</th>
<th>TRS kg Mg(^{-1})</th>
<th>Brix</th>
<th>Sucrose</th>
<th>Stalk N kg N ha(^{-1})</th>
<th>N uptake kg N ha(^{-1})</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (no N, no cover crops)</td>
<td>93,005 B</td>
<td>56 B</td>
<td>6,361 B</td>
<td>115</td>
<td>18.49</td>
<td>15.95</td>
<td>0.28 B</td>
<td>28 B</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Cover crops-UAN</td>
<td>117,702 A</td>
<td>98 A</td>
<td>10,515 A</td>
<td>110</td>
<td>17.83</td>
<td>15.22</td>
<td>0.37 A</td>
<td>49 A</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>No cover crops-UAN</td>
<td>101,108 B</td>
<td>93 A</td>
<td>10,400 A</td>
<td>113</td>
<td>18.21</td>
<td>15.68</td>
<td>0.34 AB</td>
<td>46 A</td>
<td>0.052</td>
</tr>
</tbody>
</table>

TRS – theoretical recoverable sugar.
NS indicates no significant difference at the α=0.05 level of significance.
UAN- urea ammonium nitrate.
Results from recent studies on cover crops in sugarcane production are contradicting. Webber III et al. (2016) reported that kenaf and cowpea did not affect millable stalk counts and cane yield. On the other hand, Orgeron et al. (2020) showed the positive effect of drill seeded cover crops on plant cane yield in the form of a 15% increase in cane yield and a 12% increase in sugar yield. Typically, most sugarcane growers in Louisiana use soybean during the fallow period as a cash crop and as a means to control weeds such as bermudagrass (*Cynodon dactylon* L.) and johnsongrass (*Sorghum halepense* L.) (Gravois et al., 2014).

### 3.3.4 Impact of Cover Crops on Soil pH

Intercropping cover crops or planting cover crops during the fallow period can alleviate the negative impacts of farming on soil health and fertility status (Snapp et al., 2005; Sarrantonio and Gallant, 2008). Cover crops can produce a lot of biomass, thus remove a lot of nutrients from the soil, including base cations. For this study, the monitoring of soil pH revealed that the cover crops did not affect soil pH across crop years and sampling time (Figure 3.5). A slight increase in soil pH was observed in the no cover crop treatment 4 weeks after N fertilization (WANF) in the third crop year; however, the increase was not significant. At site 5 in Paincourtville, the soil pH values of plots with cover and no cover crops were essentially the same across crop years and sampling time (Figure 3.6). The average soil pH was 6.3 and 6.07 in St. Gabriel and Paincourtville, respectively.
Figure 3.5. Soil pH trend with cover and no cover crops, collected at four weeks after N fertilization and harvest within the three crop years across sites at the Sugar Research Station in St. Gabriel, LA.

Figure 3.6. Soil pH trend with cover and no cover crop treatments collected at four weeks after N fertilization and harvest within two crop years at the grower's field in Paincourtville, LA.
3.3.5 Impact of Cover Crops on Plant Available Nutrients

Soil total inorganic N (NO$_3^-$-N + NH$_4^+$-N) is presented in Figures 3.7 to 3.11. The soil inorganic N at 4 WANF and at harvest for site 1 for each crop year is shown in Figure 3.7. Soil NH$_4^+$-N at four WANF was higher compared to NO$_3^-$-N. In the 2017 plant cane crop, the soil NO$_3^-$-N and NH$_4^+$-N levels were slightly higher at 6.25 and 13.72 kg ha$^{-1}$ respectively, in unfertilized plots with cover crops compared to 3.4 and 11.86 kg ha$^{-1}$ of NO$_3^-$-N and NH$_4^+$-N, respectively of unfertilized plots without cover crops. The soil NO$_3^-$-N and NH$_4^+$-N levels in fertilized plots with and without cover crops were the same (Figure 3.7). Unlike at site 1, the NO$_3^-$-N and NH$_4^+$-N contents of soil collected at harvest were lower and did not vary as much across crop years. In 2018 first and 2019 second stubble crops, there was low to virtually no NO$_3^-$-N measured at 0 to 30 cm at 4 WANF and at harvest (Figures 3.8). In general, soil NO$_3^-$-N and NH$_4^+$-N levels were higher in plots with the cover crops than in plots without cover crops where no N was applied. These increases in both NO$_3^-$-N and NH$_4^+$-N were recorded as early as eight weeks after the cover crops were terminated and at harvest (Figure 3.7). The soil NH$_4^+$-N levels reported at the different sampling times and crop years were, on average higher compared to NO$_3^-$-N concentration at 0 to 30 cm (Figure 3.7).

In general, soil NH$_4^+$-N was the predominant N form at 4 WANF and at harvest across sites and sampling times (Figures 3.7 to 3.11). At site 2, both NO$_3^-$-N and NH$_4^+$-N contents in 2017 were the highest among crop years (Figure 3.8). Without N, the cover crop treatment averaged 6 and 21 kg ha$^{-1}$ NO$_3^-$-N and NH$_4^+$-N, respectively, compared to the no cover crops treatment with only 3 and 16 kg ha$^{-1}$ (Figure 3.8). A drastic reduction in soil NO$_3^-$-N and NH$_4^+$-N levels within the 0-30 cm depth were observed across sampling time in 2018 and 2019. These values were considerably lower than the average levels obtained at sites 1, 3, and 4.
The soil NH$_4^+$-N was the predominant N form at site 3 at both sampling times and crop years (Figure 3.9). Without N fertilization, numerically higher soil NO$_3^-$-N and NH$_4^+$-N levels were observed with cover crops than the no cover crops treatment. A similar observation was obtained when N was applied. At site 4, slightly higher NO$_3^-$-N and NH$_4^+$-N content was measured in soil with cover crops than in no cover crops treatment, with or without N fertilizer (Figure 3.10). The presence of cover crops with N fertilization increased soil NO$_3^-$-N and NH$_4^+$-N content by 35 and 8 %, respectively, in reference to no cover crops treatment (Figure 3.10).

At site 5, the soil NO$_3^-$-N content in the presence of cover crop without N was higher than in the plots without cover crops at values 3 vs. 1.8 kg ha$^{-1}$, respectively, in 2018 and 5 vs. 0.6 kg ha$^{-1}$, respectively in 2019 (Figure 3.11). Similarly, the soil NH$_4^+$-N content with cover crop and N at 0-30 cm had the highest levels across sampling times for both crop years. Overall, changes in soil NO$_3^-$-N and NH$_4^+$-N were varied highly across sampling times, and between N treatment cover crops exhibited lesser impact.

There were indications that cover crops positively impacted the soil inorganic N content as early as eight weeks after the cover crop was terminated. There were several instances that soil NH$_4^+$-N and NO$_3^-$-N levels were improved where the cover crops were grown with and without N fertilization. Similar results were found by Clark et al. (1993), where higher N concentration levels were found in the soil after the early termination date of mixed legumes cover crops with hairy vetch having the highest N concentration and ryegrass, the lowest at 12 and 7 kg ha$^{-1}$, respectively.

Typically, legumes cover crop mixes such as those containing Austrian winter pea (*Pisum sativum*), hairy vetch, and crimson clover, increase cash crop yield while reducing NO$_3^-$-
N loss through leaching and run-off (Clark et al., 1993). Wagger (1998) and Ruffo and Bollero (2003) reported the effect of cover crops mixes on decomposition rate. They found that hairy vetch and crimson clover were fully decomposed after 3.5 months. This research also showed improvement on several physical, chemical, and biological properties such as; increased in microbial activity, lower soil surface temperature, lower bulk density, and increased soil NO$_3^-$ content. The peaks of soil NH$_4^+$-N and NO$_3^-$-N levels observed at 4 weeks in year 1 across sites suggested that there could be high decomposition rates of cover crop biomass and mineralization of organically bound N, which is common in crop biomass with narrow C:N ratios.
Figure 3.7. Soil NO$_3^-$-N and NH$_4^+$-N content at 0-30 cm depth at 4 weeks after N fertilization and at harvest across crop years at site 1, at the Sugar Research Station in St. Gabriel, LA.
Figure 3.8. Soil NO$_3^-$-N and NH$_4^+$-N content at 0-30 cm depth at 4 weeks after N fertilization and at harvest across crop year at site 2 at the Sugar Research Station in St. Gabriel, LA.
Figure 3.9. Soil NO$_3^-$-N and NH$_4^+$-N content at 0-30 cm depth at 4 weeks after N fertilization and at harvest in 2018 and 2019 crop year at site 3 at the Sugar Research Station in St. Gabriel, LA.
Figure 3.10. Soil $\text{NO}_3^-$-N and $\text{NH}_4^+$-N content at 0-30 cm depth at 4 weeks after N fertilization and at harvest in 2018 at site 4 at the Sugar Research Station in St. Gabriel, LA.
Figure 3.11. Soil NO₃⁻-N and NH₄⁺-N content at 0-30 cm depth at 4 weeks after N fertilization and at harvest at site 5 in Paincourtville, LA.
Termination of winter cover crops is always an essential aspect of its N release potential. Several studies reported that with an early cover crop termination, the release of N is faster due to a reduction in C accumulation more than N, so the N release is faster, especially for cover crops species like hairy vetch (Muller et al., 1988; Lemon et al., 1990; Ranelss and Wagger, 1992; Doran and Smith, 1999). Rapid mineralization of N follows after the cover crop is terminated (Clark et al., 1993). The rate of mineralization process speeds up if the cover crop residues are incorporated into the soil and if done during the grand growth stage of sugarcane when the nutrient absorption is at the fastest rate. Conversely, Varco et al. (2009) reported that cover crops slowly release N in dry years on an average of 6 to 8 weeks after the cover crops were terminated. Thus, cover crops have been presented as a potential solution to minimize N losses by volatilization and run-off. Sugarcane production in Brazil had recorded low N recovery values due to N losses by volatilization, immobilization, and leaching (Basanta et al., 2003). Sugarcane can lose on average 40 to 60 % of the total applied N from the soil and plant (Keating et al., 1993; Vallis and Keating, 1994; Ishikawa et al., 2009; Franco et al., 2015).

The cover crops scavenge nutrients other than N. Our results showed that cover crops positively affected soil extractable P, K, S, Ca, Mg, Cu, Mn, Ni, and Zn at both locations (Figures 3.12 to 3.19). The data across sites in St. Gabriel was pooled and presented for each crop year and sampling time. The soil nutrient concentrations mainly were higher in plots with cover crops than in plots without cover crops (Figures 3.12 to 3.19). Soil P, K, Zn, and Cu concentrations were consistently higher in plots with cover crops than in plots without cover crops during the first years after cover crops were terminated. Variations were also noticed on soil S concentration, where cover crops had a positive impact at 4 WANF during the first and second crop years after cover crops termination.
The soil S concentration averaged 25 and 20 mg kg\(^{-1}\) in the first and second year, respectively (Figure 3.14 c). The effect of cover crops on soil Ca and Mg concentration was more pronounced 3 years after cover crops termination. By year 3 at 4 WANF, soil Ca and Mg levels were at 2600 and 500 mg kg\(^{-1}\) in plots with cover crops; these were significantly higher than what were measured in plots with no cover crops with 1900 and 440 mg kg\(^{-1}\), respectively (Figures 3.13 a-b). There was no evident response to cover crops treatments observed for soil Fe, Mn, and Ni except for soil Ni at 4 WANF during the third crop year, wherein a significantly lower level was recorded for the no cover crops treatment (Figures 3.14 a-b and 3.15 a).

At site 5 in Paincourtville, LA, soil nutrient content responded to cover crops treatment (Figures 3.16 to 3.9). As early as 4 weeks in year 1, soil P level was significantly higher by about 4 mg kg\(^{-1}\) in plots with cover crops than plots without cover crops (Figure 3.16 a). Soil K levels ranged from 85 to 100 mg kg\(^{-1}\) two years after cover crop termination (Figure 3.16 b). At 4 WANF each year, the soil S level was higher in plots with the cover crop with values in year 1 at 29 vs. 19 mg S kg\(^{-1}\) which was 50 % higher than no cover crops treatment (Figure 3.16 c). In year 2, soil S concentration decreased with only 20 and 10 mg S kg\(^{-1}\) for cover and no cover crops treatments, respectively (Figure 3.16 c). Similarly, Ca and Mg concentrations were higher in soils from plots with cover crops than those from the no cover crops treatment (Figures 3.17 a and b). Soil Ca and Mg increased each year across sampling time. On average, regardless of the sampling time, soil Ca and Mg concentrations were 1800 and 400 mg kg\(^{-1}\), respectively (Figures 3.17 a and b).
Figure 3.12. Soil P (a), K (b), and S (c) concentrations with and without cover crops at 4 weeks after N fertilization and at harvest within the three crop years pooled across sites at the Sugar Research Station in St. Gabriel, LA.
Figure 3.13. Soil Ca (a) and Mg (b) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the three crop years pooled across sites at the Sugar Research Station in St. Gabriel, LA.
Figure 3.14. Soil Cu (a), Fe (b), and Mn (c) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the three crop years pooled across sites at the Sugar Research Station in St. Gabriel, LA.
Figure 3.15. Soil Ni (a), and Zn (b) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the three crop years pooled across sites at the Sugar Research Station in St. Gabriel, LA.
Figure 3.16. Soil P (a), K (b), and S (c) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the two crop years in Paincourtville, LA.
Figure 3.17. Soil Ca (a) and Mg (b) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the two crop years in Paincourtville, LA.
Figure 3.18. Soil Cu (a), Fe (b), and Mn (c) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the two crop years in Paincourtville, LA.
Figure 3.19. Soil Ni (a) and Zn (b) concentrations with and without cover crops at 4 weeks after N fertilization and harvest within the two crop years in Paincourtville, LA.
A similar increasing pattern was observed in the Cu, Fe, Ni, Mn, and Zn in soil with cover crops (Figures 3.18 to 3.19). On average, soil Cu, Fe, Ni, Mn, and Zn levels were increased by cover crops treatment by 25, 9, 33, 13, and 22 %, respectively, at harvest, two years after cover crops termination (Figures 3.18 to 3.19).

The present study showed the positive effect of cover crops on soil extractable nutrient concentration as early as one year after the cover crops were terminated. In St. Gabriel, soils under cover cropping maintained a higher level for almost all soil nutrients, across sampling times compared to the soil without cover crops. The same case was documented in Paincourtville. Several studies have demonstrated that cover crops can positively affect soil organic matter content (OM), biomass yield, primary crop yield, plant, and soil nutrient content (Mazzoncini et al., 2011; Poeplau and Don, 2015). Mite (2020) reported that cover cropping not only maintained soil nutrients concentration but also increased them, especially the macronutrients such as P, K, and S, just with two consecutive years of planting cover crops in a corn-soybean cropping system.

A study conducted by Chu et al. (2017) in the southeastern region of the US with corn and soybean rotational cropping systems showed that the use of a multiple cover crop species consisting of Austrian winter peas, oilseed radish, red clover, and sunflower (Helianthus annuus L.) had a positive effect on soil OM, P, K, S, Mg, and Ca content, and cation exchange capacity (CEC). Conversely, Villamil et al. (2006) suggested that cover crops may reduce soil P availability due to their transformation to organic compounds. This was not observed in any of the sites in the present study.
3.4 CONCLUSIONS

The results from this study showed that the mix of the winter cover crops species planted in a newly planted sugarcane could grow and produce enough biomass during fall-winter periods. Well-distributed rainfall patterns, soil water conditions, and moderate temperature during the experimental period permitted an excellent cover crop growth performance. Thus, this condition favored and significantly impacted biomass yield and the amount of nutrients recovered by the cover crops.

On average across sites, the cover crops treatment removed significantly higher amount plant essential nutrients compared to the native weed species under the no cover crops treatment. The amount of N, P, K, S, Ca, and Mg recovered by cover crops was 40 to 60 % more than the amount recovered by the native weeds in the no cover crop treatment. Similarly, micronutrients such as Mn, Ni, and Zn recovered by cover crops biomass were also higher than native weeds. The monitoring of soil nutrients concentration with time showed that the recovered nutrients were released within a short period of time most of which peaked during the first two years of the sugarcane cultivation. The soil with cover crops and N application had higher NO₃⁻-N and NH₄⁺-N concentration levels than the no cover crop as early as 4 WANF. The NH₄⁺-N was the predominant form of inorganic N in the soil. It was consistently higher in soil with cover crops and no N, indicating that the N mineralized in the soil was probably coming from cover crops biomass decomposition.

Cane and sugar yield response was affected by both cover cropping and N fertilization. However, significant effects on sugarcane yields by cover crop were observed only in the first and second stubble. On average, cane and sugar yield was higher by 5 Mg ha⁻¹ and 300 kg ha⁻¹
in plots with cover crops than in plots without cover crops. The presence of cover crops had no significant impact on any of the sugar quality components across crop ages.

Integrating cover cropping as part of the sugarcane production systems has the potential to improve soil health and sugarcane productivity. However, research has shown that depending on soil type, the amount of nutrients released by the cover crop to the soil would start decreasing two months later after the decomposition process. Thus, the need to synchronize the release of nutrients removed by the cover crop with the moment of nutrients uptake by sugarcane is essential to impact sugarcane productivity. The presence of plant essential nutrients like N, P, and K recovered by the cover crops biomass and released back to the soil after decomposition showed that there is a potential to increase long-term productivity and soil health goals in sugarcane. Future research directions should revolve around understanding the impact of seeding rates and application methods across soil types using legumes and non-legumes for both summer and winter cover crops in fallow periods or a newly planted cane.
CHAPTER 4. ESTABLISHING THE RELATIONSHIP BETWEEN GROUND SENSOR-AND AERIAL IMAGE-BASED VEGETATION INDEX FOR PRECISION NITROGEN MANAGEMENT IN LOUISIANA SUGARCANE

4.1 INTRODUCTION

Sugarcane (Saccharum spp.) is a tropical and subtropical perennial grass (Verhey, 2010). Worldwide average sugarcane production was estimated at 1980 million Mg harvested from 22 million hectares (Salassi, 2015). Sugarcane is cultivated in many countries, Brazil and India being the top producer (Fortes, 2013). Louisiana is one of the few states in the US that produces sugarcane. The sugar industry represents an annual income of more than $3.5 billion in value to Louisiana's economy. It is cultivated in 24 parishes across the states and currently has 11 mills where the cane is processed into raw sugar molasses (Gravois, 2001).

The sugarcane production in Louisiana is maintained at around 200,000 hectares annually. In 2019, the total cane harvested reached 13 million Megagrams (Mg) producing about 1556 million Mg sugar (Deliberto et al., 2020). The average cane yield in Louisiana runs about 79 Mg per hectare, with an average sugar recovery of 104 kg sugar per Mg cane (Gravois, 2020). Sugarcane under Louisiana production systems is cultivated and harvested for three to four years from the initial planting using whole stalks or billets. The first harvest occurs 16-18 months after the planting and is called plant cane. After the first harvest, the cane is harvested again as stubble crops, for two to three more years with 11 months interval.

Nitrogen (N) is one of the plant-essential nutrients and is considered the most limiting nutrients in crop production except in legume cropping systems. It is necessary for chlorophyll formation, which is needed during the photosynthesis process (Kettrings et al., 2003; Havlin et
Nitrogen is very dynamic in the soil. Many pathways can lead to N losses from the soil: immobilization, leaching, denitrification, and plant-biomass as gas by volatilization (Galloway and Cowling, 2002). Naturally, most plants absorb two inorganic N forms, nitrate (NO$_3^-$) and ammonium (NH$_4^+$). Most of the inorganic N is transported from the soil to the plants throughout the roots by mass flow and diffusion (Engels and Marschner, 1995).

Currently, N fertilizer recommendations for sugarcane in Louisiana are based on crop year/age (plant cane or stubble) and soil type (light or heavy textured soils) (Gravois, 2014). The most common N fertilizer is urea-ammonium-nitrate (UAN, 32%N) solution applied at the rates of 112 to 135 kg ha$^{-1}$ (Gravois, 2014). On average, stalk sugarcane takes up about 2.2 kg N per ton of cane (Tubana et al., 2019). The common potassium (K) fertilizer source is muriate of potash (MOP, 60%K). Broadcast application of MOP is made in early spring at a rate based on the soil test recommendation. On average, sugarcane removes 3.4 kg K$_2$O per ton of cane (Gravois, 2014). Sulfur fertilizers are recommended if soil S test level is below 10 mg kg$^{-1}$ at rates between 25 to 28 kg of S per ha (Gravois, 2014).

Nitrate (NO$_3^-$) is an available form of N for plant uptake; it is very mobile in the soil therefore prone to be lost from the soil through runoff and leaching (Havlin et al., 2005; Zuberer, 2005). On the other hand, ammonium (NH$_4^+$) form is commonly fixed on the soil exchange sites until they are transformed to NO$_3^-$ by the microbes (Havlin et al., 2005). However, just like NO$_3^-$, NH$_4^+$ can be lost from the soil via volatilization which takes place when pH and temperature are high (Brady and Weil, 2003; Havlin et al., 2005). Thus, the best N fertilizer management is designed to achieve optimum yields and minimize N losses. The best N management practices involve applying the right amount of N fertilizer at the right time and place in the field.
Vegetation index or indices (VIs) is the relationship between spectral reflectance measurements at different wavelengths collected from crop canopies (Fox and Walthall, 2008). Vegetation indices like simple ratio (SR), normalized difference vegetation index (NDVI), NDVI red-edge, SR red-edge, and modified red-edge SR are commonly used to predict biomass yield (Blackburn, 1998; Gitelson et al., 2002). The NDVI has been successfully used to monitor plant health status, estimate plant biomass, predict crop N rate requirement, and crop response to N fertilization (Raun et al., 2002; Scharf et al., 2009; Tubana et al., 2011). One of the most common crop canopy sensors used is the GreenSeeker® handheld sensor. This active light sensor uses mainly two wavelength bands, the red (670 ± 10 nm) and near-infrared (NIR, 780 ± 10 nm). Crop active sensors have their source of lights and can estimate plant N status at any time of the day (Singh et al., 2006; Shanahan et al., 2008).

The GreenSeeker handheld sensor is the primary remote sensing tool used to site-specific manage N fertilizer in Louisiana sugarcane production systems. The N working algorithm utilizes both the predicted sugarcane yield potential (YP) and response index (RI) – an in-season estimate of plant-available N for N rate recommendation (Lofton et al., 2012a and 2012b; Tubana et al., 2015). According to Johnson and Raun (2003), crop response to N fertilization is calculated using a RI determined by dividing the average NDVI value collected from the non-limiting reference strip area by the NDVI obtained from the check or area with no N fertilizer applied (Johnson and Raun, 2003). Several studies have used the RI concept to estimate crop N response using NDVI readings (Mullen et al., 2003; Raun et al., 2010; Harrell et al., 2011; Tubana et al., 2012). In another study, Mullen et al., (2003) reported that RI NDVI could be used to predict RI HARVEST.
Yield potential with no N fertilizer (YP0) and with N fertilizer (YPN) are also critical components of the working algorithm (Raun et al., 2002). All these components, YP, YPN, and RI, constitute the sensor-based N rate calculator (SBNC). Several demonstration trials showed the potential of SBNC to improve N fertilizer management in sugarcane in Louisiana. On-the-go N fertilizer applications have positively impacted these recommendations, causing improved cane and sugar yield. On-farm demonstration studies located in Napoleonville and at the LSU AgCenter Sugar Research Station from 2013 to 2015 showed that remote sensing technology using the N-rich-strip resulted in an increase of 11 Mg ha\(^{-1}\) in cane yield and 1,120 kg ha\(^{-1}\) sugar yield compared to the farmers standard N management practices (Tubana et al., 2019).

The acquisition of NDVI from aerial images taken by a digital camera attached to an unmanned aircraft vehicle (UAV) has several advantages. The use of UAVs to acquire images and aerial-NDVI can make optical remote sensing even more powerful due to speed, cost, and area of coverage. However, the reliability of the aerial-NDVI has to be validated since NDVI was developed from bands that are different from bands found in consumer-type cameras. The bandwidth of consumer-type cameras use in aerial imagery is wider than handheld devices and satellites, thus likely to have data contamination from adjacent bands. A UAV mounted with multispectral or hyperspectral sensors shows potential for monitoring crop N status as the crop canopy sensors. Studies support the strong relationship between NDVI readings collected using these two platforms (Quemada et al., 2014).

The ability of these two platforms to measure plant health status has opened an opportunity for developing aerial image-based N recommendations from an existing ground sensor database system. Currently, the remote sensor-based N technology in Louisiana is ready for production’s field adoption but the sensor used to build the database is ground-based.
Nowadays, with the availability of precision ag technologies, there is an opportunity in using drones equipped with a hyperspectral sensor camera to predict sugarcane yield and N fertilizer requirement. Thus, a study was conducted to evaluate the relationship between the ground-based sensor (hereafter termed as GreenSeeker-NDVI) and aerial image-based NDVI (hereafter termed as UAV-NDVI) collected from sugarcane during the growth stage where N fertilizer is applied. The specific objectives were to (1) establish the relationship between UAV and GreenSeeker NDVI, (2) normalize NDVI readings using cumulative growing degree days (CGDD) from fertilization to sensing, and (3) validate the current cane and sugar yield prediction models using converted UAV-NDVI as predictor.

4.2 MATERIALS AND METHODS

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

The data used for this study were collected from N response trials focused on evaluating the impact of various N sources established at several sites at the Louisiana State University Agricultural Center Sugar Research Station in St. Gabriel, LA, USA (Latitude 30°, 15', 13" N; Longitude 91°, 06', 05" W) on two soils: Commerce silt loam and Commerce silty clay loam (Fine-silty, mixed, superactive, non-acid, thermic Fluvaquentic Endoaquept). This also included the trial established on a grower’s field in Paincourtville, LA, USA (Latitude 29°, 59', 21" N; Longitude 91°, 1', 29" W). The predominant soil was Cancienne silt loam (Fine-silty, mixed, superactive, non-acid, hyperthermic Fluvaquentic Epiaquepts). Table 4.1 shows the initial chemical properties of the soils at different depths for all sites.
The Sugar Research Station and grower's field trials were established at different years using either whole stalk and billets of sugarcane variety L01-299 and HoCP96-540. At the Sugar Research, Station research sites were planted using billets on beds in a three-row plot configuration. Each plot contained three (3) 1.83 m-wide by 15-m long beds. The opened beds were filled with stalks cut into 40 to 50 cm-long billets at the rate of 6-8 billets for every 50 cm section down the planting furrow. At the grower's field, sets of three to four whole stalks were laid onto opened (15-cm depth) beds by hand, keeping about 8 cm (3 to 4 internodes)- overlap with the next set of stalks. Each bed had a row space configuration of 1.7 m wide by 170 m long at this site. Following planting, beds were covered with 8 cm of soil and packed to keep enough moisture to have good germination. After beds were packed, herbicide application was carried out to seal the soil using a pre-emergence mix of herbicides using metribuzin [4-amino-6-tert-butyl-3-methylthio-1,2,4-triazin-5(4H)-one] at 3.4 kg a.i. ha\(^{-1}\) and pendimethalin [N-(1-ethyl propyl)-2,6-dinitro-3,4-xylidine] at 2.2 kg a.i.ha\(^{-1}\).

Table 4.1. Chemical properties of the initial soil samples collected from all the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>(^\ddagger)pH</th>
<th>(^\dagger)Organic matter g kg(^{-1})</th>
<th>(^\psi)Extractable Nutrients, mg kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1</td>
<td>17</td>
<td>22 93 14 1633 346 2.7 2.1</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>18</td>
<td>21 184 12 2896 468 4.1 2.4</td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>19</td>
<td>64 194 13 2500 524 4.2 3.4</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>21</td>
<td>23 196 9.3 2900 553 4.4 3.2</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>16</td>
<td>22 183 11 2045 343 3.6 3.1</td>
</tr>
</tbody>
</table>

\(^\ddagger\) Based on Mehlich 3 (Mehlich, 1984) procedure.
\(^\dagger\) 1:1 w/v soil: deionized water ratio (McLean, 1982)
\(^\psi\) Acid-dichromate oxidation (Nelson and Sommer, 1982)
Before fertilization in April, the sides of the beds were off-bared with a three-row disk cultivator. Then, N fertilizer was broadcast onto the soil surface on each side by hand, and liquid fertilizers were either injected or dribbled on each shoulder of the planted beds using a UAN fertilizer applicator at the rate of 90 kg N ha\(^{-1}\). Table 4.2 details the agronomic practices for all the experiments at the Sugar Research Station and Paincourtville from 2018 through 2020.

4.2.2 Remote Sensing Data Collection

Canopy reflectance data were collected three weeks after N was applied using a ground-based four-band (NIR, RED660, RED710, and RED735) GreenSeeker® Handheld Optical Active Sensor (Trimble Navigation, Ltd., Sunnyvale, CA). The GreenSeeker sensor measured canopy reflectance readings at red (670 ± 10 nm) and NIR (780 ±10 nm) wavebands of the spectrum. The sensor was mounted on an ATV (2013 Honda FourTrax Rancher 4x4 ES TRX420FE) approximately one meter above the sugarcane canopy. The readings were collected from every row of each plot at a constant speed, obtaining an average of 235 readings over 15 m-long rows. All the GreenSeeker-NDVI readings were averaged to obtain one reading per 15 m-row plot. Determination of GreenSeeker-NDVI was computed based on equation (1):

\[
\text{NDVI} = \frac{(\rho_{\text{NIR}} - \rho_{\text{Red}})}{(\rho_{\text{NIR}} + \rho_{\text{Red}})}
\]  
(4.1)

Where:

\(\rho_{\text{NIR}}\) = reflectance value at the near-infrared region of the electromagnetic spectrum
\(\rho_{\text{Red}}\) = reflectance value at the red region of the electromagnetic spectrum
Table 4.2. Fertilization and sensing dates and information for all experiments established in St. Gabriel and Paincourtville, LA, USA from 2018 through 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Crop age</th>
<th>Variety</th>
<th>Fertilization date</th>
<th>Sensing Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>1st stubble</td>
<td>HoCP 96-540</td>
<td>April-21</td>
<td>April-30</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>2nd stubble</td>
<td>HoCP 96-540</td>
<td>April-21</td>
<td>April-30</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>April-21</td>
<td>April-30</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>2nd stubble</td>
<td>L 01-299</td>
<td>April-21</td>
<td>April-30</td>
</tr>
<tr>
<td>2018</td>
<td>St. Gabriel</td>
<td>Plant cane</td>
<td>L 01-299</td>
<td>May-01</td>
<td>May-22</td>
</tr>
<tr>
<td>2018</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>May-01</td>
<td>May-22</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>Plant cane</td>
<td>L 01-299</td>
<td>May-19</td>
<td>June-21</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>May-19</td>
<td>June-21</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>2nd stubble</td>
<td>L 01-299</td>
<td>May-19</td>
<td>June-21</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>2nd stubble</td>
<td>L 01-299</td>
<td>May-19</td>
<td>June-21</td>
</tr>
<tr>
<td>2020</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>May-04</td>
<td>June-01</td>
</tr>
<tr>
<td>2020</td>
<td>St. Gabriel</td>
<td>3rd stubble</td>
<td>L 01-299</td>
<td>May-04</td>
<td>June-01</td>
</tr>
</tbody>
</table>
A quadcopter (DJI-Phantom 4 Advanced) equipped with a multispectral 5 bands sensor camera (RedEdge-M™ by MicaSense) was used to collect aerial images. Drone mapping was done using a Drone-deploy flight planner. The narrow-band spectral response of this multispectral sensor camera is listed as: blue (475 nm), green (560 nm), red (668 nm), red-edge (717 nm), and NIR (840 nm). Aerial images were collected at an altitude of 30 meters above the sugarcane canopy, at 12 m/s with a side and frontal overlap of 80%. The sensor camera was calibrated using a reflectance panel before and after each flight. The aerial images were taken between 11 am to 2 pm (local time) in the complete absence of clouds.

Stitching and orthomosaic digitalization image processing were accomplished using photogrammetry Pix4D mapper pro software. Finally, the images-index color map was generated using a formula that combines different bands of reflectance maps. Coordinates of individual points were extracted from both platforms; geotagged images were processed to create NDVI maps. The UAV-NDVI was exported into GIS software (QGIS) to calculate UAV-NDVI values by plot.

4.2.3 Cane and Sugar Yield and Quality Components

The sites at the Sugar Research Station and the grower's field were harvested using a single-row chopper harvester (John Deere 350 model). A modified single axle high dump weigh wagon equipped with load cell sensors (Cameco Industries, Thibodaux, LA) was used to determine stalk weight by row. At the grower's field, yield data was collected from a yield harvest monitor georeferenced to a precise location point using a global positioning system (GPS). Ten stalks were randomly cut from the middle row by hand, leaves were stripped off from the stalk, and the top was cut between the first 10 cm below the apical meristem.
Total plot weight was calculated by adding the weight from the ten stalks to the plot yield. Sugarcane stalks were shredded and analyze using a SpectraCane Near Infrared System (Bruker Corporation, Billerica, Massachusetts) to determine juice quality components (theoretically recoverable sugars (TRS), total soluble solids (BRIX), and sucrose content).

4.2.4 Data Analysis

The relationship between GreenSeeker- and UAV-NDVI was established. Similarly, to normalize NDVI readings by sensing dates, the CGDD were used. The CGDD was calculated as the sum of growing degree days (GDD) from when N was applied until the sensing day. The CGDD was calculated based on equation (4.2):

$$\text{CGDD} = \left(\frac{\text{Temp.}_{\text{max}} - \text{Temp.}_{\text{min}}}{2}\right) - \text{base temperature} \quad (4.2)$$

Where:

\begin{align*}
\text{Temp.}_{\text{max}} &= \text{maximum daily temperature}; \\
\text{Temp.}_{\text{min}} &= \text{minimum daily temperature};
\end{align*}

Base temperature = 19°C considered optimal for sugarcane to growth

The data set (1700) from all the experiments and locations was split into the train (85%) and test (15%) sets using sampling without replacement technique in R-Studio 1.1.456 (RStudio, Inc., 2009-2018). The train set of GreenSeeker and UAV-NDVI (hereafter termed as converted GreenSeeker-NDVI) data were subject to linear regression analysis using Excel. This was done to establish the model or equation for converting UAV-NDVI to GreenSeeker-NDVI and vice versa.
A series of conversion processes using models established from ground-based sensor NDVI, cane tonnage, and sugar yield were predicted from UAV-NDVI readings. For validation, both cane and sugar yield were predicted using yield potential prediction models established in 2015 using NDVI as a predictor (Figure 4.1). The equation models for and were the following:

\[ 12.07e^{1.47 \times NDVI} \] and \[ 2354e^{1.7915 \times NDVI} \] for cane and sugar, respectively.

Figure 4.1. Diagram of the validation and calibration process created to determine if cane and sugar yield prediction models established from GreenSeeker-NDVI (GS) can be used with converted GreenSeeker-NDVI as a predictor.

4.3 RESULTS AND DISCUSSION

4.3.1 Climatological Data

The average monthly temperature and precipitation at the Sugar Research Station in St. Gabriel across crop years are reported in Figures 4.2 and 4.3, respectively. The monthly average temperature on average were similar between 2017 to 2020 (Figure 4.2).
The temperature recorded in January 2018 was the lowest monthly average across years. This is important because a low temperature at the early growth stage of sugarcane will affect its growth vigor later, adding more stress to the plant and making it susceptible to insect and disease pressure. On average, the optimal temperature for sugarcane growth is between 30-33°C; at temperatures below 16°C, sugarcane development is compromised (Bakker, 1999). Conversely, low temperature can enhance the ripening process and accumulate more sugar (Bakker, 1999). Optimal dry matter accumulation and stalk elongation have been reported in temperatures between 17.2 to 22.2 °C (Hunsigi, 1993).

From June to September for all years were the months wherein the highest temperatures were recorded at 26, 28, 29, and 27°C, respectively (Figure 4.2). November 2018 and 2019 had the lowest temperature (approximately 4°C) compared to the other years. The variety L01-299 has been reported as a medium cold tolerant variety. In 2019, April and May recorded the highest precipitation across the years (Figure 4.3). In general, the rainfall distribution from 2017 to 2020 at the Sugar Research Station was different from the 40-year average precipitation. After N fertilization, the highest rainfall in April and May was reported in 2019 at 20 and 26 cm, respectively. Heavy rainfall events, especially after N fertilization, could lead to N losses by run-off and NO$_3$ leaching through the soil profile.

The average monthly temperature and precipitation at the grower's field in Paincourtville across crop years are reported in Figures 4.4 and 4.5, respectively. Overall, the monthly average temperature reported in 2017 was lower than those observed in 2018 and 2019. The average monthly temperature reported in August to September across years was 26 and 28°C, respectively. The precipitation recorded in May, June, July, and August 2017 was higher than those recorded in other years (Figure 4.5). The crop year 2018 was quite dry in early and
midseason; however, September, November, and December recorded the highest rainfall those
from other years.

Several studies have evaluated the relationship between NDVI and weather parameters
such as temperature and rainfall. The results from these studies revealed that NDVI readings
collected at different growing seasons was highly correlated with precipitation at the late season
and a weak negative correlation with temperature during the mid-season (Kawabata, 2001;
Onema and Taigbenu, 2009). Similarly, Wang et al. (2003) observed that NDVI values had a
higher correlation with a climatic variable (rainfall and temperature) in the southern region of the
US measured four weeks after the rainfall event occurred.

Weather variability affects sugarcane growth and productivity hence sensor-based
parameters that can describe them such as NDVI readings. This variation is further confounded
by differences in sugarcane varieties and soil types. The use of a sugarcane yield predictive
model adapted for the Louisiana sugarcane system that considers the different physiological
maturity stages of growth and weather variability within a growing season and year-to-year
variability can be an interesting area to further investigate to make current yield prediction model
more robust.
Figure 4.2. Average monthly temperature from January to December 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA.

Figure 4.3. Average monthly precipitation from January to December 2017, 2018, 2019, and 2020 at the Sugar Research Station in St. Gabriel, LA.
Figure 4.4. Average monthly temperature from January to December in 2017, 2018, 2019, and 2020 at the grower's field in Paincourtville, LA.

Figure 4.5. Average monthly precipitation from January to December 2017, 2018, 2019, and 2020 at the grower’s field in Paincourtville, LA.
4.3.2 Calibration between GreenSeeker and UAV-NDVI

Figure 4.6 shows the slope and the $R^2$ of the linear relationship between GreenSeeker- and UAV-NDVI without adjusting the NDVI values using CGDD. The low $R^2$ value indicated that GreenSeeker-NDVI could explain only 44% of the variation in UAV-NDVI. This low $R^2$ can be attributed to the effect of sugarcane response to Louisiana's climate conditions and the variability of the NDVI readings collected with the GreenSeeker (active light sensor) and the UAV (passive light sensor). Reflectance readings collected with passive light sensors compared to the active sensors can be affected by the intensity of the sunlight, bidirectional reflectance, and environmental conditions (Lelong et al., 2008).

Several other factors could be used to explain this trend, for example, soil type, crop age, and sugarcane variety. Several information has been related to year-to-year sugarcane yield variation due to weather and different varieties (Gravois, 2001). Similar results were found in Louisiana rice (*Oryza sativa* L.) production systems. The lower relationships between GreenSeeker and UAV-NDVI were explained as different changes in environmental conditions, fertility conditions, and multiple rice varieties cultivated year after year (Cooker, 2019). Overall the NDVI values collected from the UAV showed higher saturation of the NDVI measurements than the GreenSeeker readings, especially in the 2019 season where sugarcane was greener, and canopy was fully developed compared to other seasons (2018 and 2020) due to different climate conditions. Due to the different sugarcane physiological properties observed across the different cropping seasons, the climatic variables, mainly daily values of maximum and minimum temperature using GDD, were used to normalize NDVI.
Raun et al. (2011) explained that YP0 and RI are independent of each other due to year-to-year variability, but both are needed to estimate N fertilizer recommendations. At the same time, Mullen et al. (2003) suggested that YP0 is susceptible to a year-to-year variation in environmental conditions, which could cause a low relationship between YP0 and RI.

This study showed that after the NDVI values from both GreenSeeker and UAV were normalized using CGDD from fertilization to sensing time, a significant improvement in the relationship was observed. The $R^2$ of the linear equation was increased to 0.94 (Figure 4.7). With this $R^2$ value, the 94% variation in UAV-NDVI can be attributed to GreenSeeker-NDVI. Several studies have demonstrated that by introducing CGDD, the prediction of yield potential has improved (Raun et al., 2001; Moges et al., 2007).

![Figure 4.6. Relationship between GreenSeeker and UAV-NDVI collected after N fertilization from research plots at the Sugar Research Station in St. Gabriel, LA.](image)
Raun et al. (2001) reported that when sensing is done too early, the crop yield potential is not developed just yet; thus, it is expected that the prediction outcome is poor. On the other hand, canopy closure becomes an issue when sensing is done too late. Late in the season could be too late to determine yield potential due to canopy closure, making it challenging to discriminate variability in canopy due to crop N response.

The improvement observed after the normalization of NDVI can be attributed to faster accumulation of positive growing degrees days from N fertilization to sensing due to warmer temperatures in Louisiana. Using CGDD also normalized and accounted the variability observed on growing patterns due to weather, especially temperature. Thus, improving yield prediction can be achieved across diverse environmental conditions using CDDD as a common denominator. Lofton et al. (2012) reported similar results using CGDD to normalize NDVI and generate sugarcane yield potential predictive equations. They also found that grouping the NDVI readings based on CGDD values before generating the yield potential predictive equation resulted in a higher R² value (0.46) and provided guidance on the optimal time for sense.
The CGDD values observed in this study ranged between 273 to 626 from the day of N application to sensing. Higher CGDD was observed in 2019, which could be explained by the higher temperatures throughout the growing season (Figure 4.2) compared to the 2018 and 2020. This was further reflected from both the higher sugarcane biomass accumulated and response to N fertilization obtained at an earlier time of the season in 2019 than in 2018 and 2020. Raun et al. (2002) found that the optimum growth stage where NDVI had a strong relationship with winter wheat (Triticum aestivum L.) yield was between Feeks 4 to 6. Flowers et al. (2004) suggested that when fertilizer is applied in synchrony with the crop's high nutrient demand, the crop yield potential and response to added nutrient fertilizer will increase. For example, N
fertilizer application in Louisiana is made mainly in April in synchrony with the active tillering stage of sugarcane. However, Earlier study showed that delaying N fertilization till May does not compromise sugarcane yield potential nor N uptake ratios (Lofton et al., 2012).

Several studies proved that linking the physiological growth stages and time of sensing can improve yield prediction (Raun et al. 2001; Raun et al. 2002; Lukina et al. 2003; Teal et al. 2006). Raun et al. (2002) indicated that when NDVI is adjusted using CGDD from planting to sensing, it generates an in-season estimate of yield index called INSEY, the yield potential estimation improved. However, for corn Teal et al. (2006) reported that there was no observed improvement in the relationship between NDVI and grain yield when CGDD was used to adjust NDVI values. Currently, YP0 and RI are the major components of the working algorithm for in-season N recommendations in Louisiana sugarcane production systems. The validation work done from 2013-2015 has shown that GreenSeeker-based N recommendations were more efficient than the standard N practice in sugarcane production in Louisiana (Tubana et al., 2019). The overall reduction in N applied was 36% or 45 kg ha\(^{-1}\) without incurring sugar yield reduction. This can potentially increase profitability in Louisiana N sugarcane industry.

### 4.3.3 Validation of Cane and Sugar Yield Predicted Models using UAV-NDVI

The 15% of UAV-NDVI data collected from eleven sites at the LSU AgCenter Sugar Research Station in St. Gabriel and Paincourtville was used for the validation process. The sites have different soil types and were planted to two of Louisiana's most prevalent varieties, L 01-299 and HoCP 96-540. Three different crop ages were used, plant cane, first and second stubble cane, from 2018 to 2020.
After the aerial images were collected, processed, and transformed, both cane and sugar yield were estimated using the current prediction models for yield potential developed in 2015 for sugarcane under Louisiana conditions using GreenSeeker NDVI as predictor.

Figure 4.8 provides the slopes and $R^2$ of the linear regression between the predicted cane yield at midseason and the measured cane yield at harvest using the converted UAV-NDVI as the predictive variable. A line with a slope of 1 was superimposed on the graph between predicted and measured sugarcane yield. After a linear trendline was fitted to the data points with intercept being forced to 0, the slope value obtained was 0.79 (Figure 4.8). A slope value closer to 1 indicates that the yield prediction was accurate. The graph also shows that the precision of the current yield prediction model was high, with an $R^2$ value of 0.97. Similarly, the prediction for sugar yield achieved a good level of accuracy with a slope value of 0.75, and a high level of precision was recorded with an $R^2$ value of 0.94 (Figure 4.9).

Overall, the results of the validation analysis suggested that UAV-NDVI can be used as a predictor of cane and sugar yield potential using models established from GreenSeeker NDVI. The test set of data came from twelve sites with different soil types, varieties, and crop ages. The value of having knowledge on projected yield allows growers to modify N fertilizer recommendations and help with planning on stalk harvesting and transportation logistics.
Figure 4.8. Validation of cane yield potential prediction model using UAV-NDVI collected during midseason of 2018, 2019, and 2020 crop year across sites in St. Gabriel and Paincourtville, LA.

Results from previous validation work done by Forestieri (2017) showed that the current cane yield potential model established using a GreenSeeker achieved positive $R^2$ values ranged from 0.46 to 0.52 from NDVI collected at 60 days after N application (DANF). However, at 21 DANF, the ranges of $R^2$ decreased (0.30 to 0.51). Therefore, this study demonstrated that the yield prediction made with NDVI collected at 21 DANF can be used to adjust the management of N fertilizer recommendations. Furthermore, at 60 DANF, yield prediction can be used as a potential metric for scheduling harvesting.
Sugarcane growth stages, variety, crop ages, and soil type can cause a change in canopy structure and leaf biophysical elements. The canopy structure of sugarcane is grouped into two, erect (erectophile) and droopy (planophile) (Tew et al., 2005b; Gravois et al., 2008). Several studies reported that NDVI could differentiate sugarcane varieties based on the canopy structure (Tejera et al., 2007; Marchiori et al., 2010). Therefore, the current yield prediction model developed using GreenSeeker NDVI in 2015 for Louisiana sugarcane incorporates the different canopy structures across sugarcane varieties to decrease the variability associated with the different sugarcane leaf architecture designs. For example, the sugarcane variety HoCP 96-540 is considered moderately erect, and L 01-299 is a variety that has a rounded and smooth canopy structure (Gravois et al., 2011).
Table 4.3 shows the slope and $R^2$ of the linear regression between both predicted and measured yield at harvest using converted UAV-NDVI. The sugarcane yield validation results were presented in Table 4.3 were separated by location, soil type, variety, and crop age. In Paincourtville, the YP0 models for cane and sugar better predicted the cane and sugar yield for the 2nd stubble crop for both varieties than the 1st stubble based on the slope and $R^2$ values. On average, for the HoCP 96-50 variety across crop age, the linear regression slope between predicted versus measured yield was 0.80 for cane and 0.68 for sugar yield. For the L01-299 variety, the predicted and measured cane and sugar yield had similar slope values closed to 0.69. Overall, both models were precise in estimating cane and sugar yield across varieties and crop ages.

Table 4.3. Validation of cane and sugar yield potential models using converted UAV-NDVI across years, location, crop age, and variety.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Crop age</th>
<th>Variety</th>
<th>Cane</th>
<th></th>
<th>Sugar</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slope</td>
<td>$R^2$</td>
<td>Slope</td>
<td>$R^2$</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>1st stubble</td>
<td>HoCP 96-540</td>
<td>0.78</td>
<td>0.98</td>
<td>0.68</td>
<td>0.99</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>2nd stubble</td>
<td>HoCP 96-540</td>
<td>0.81</td>
<td>0.97</td>
<td>0.69</td>
<td>0.98</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>0.77</td>
<td>0.98</td>
<td>0.63</td>
<td>0.99</td>
</tr>
<tr>
<td>2019</td>
<td>Paincourtville</td>
<td>2nd stubble</td>
<td>L 01-299</td>
<td>0.86</td>
<td>0.98</td>
<td>0.75</td>
<td>0.99</td>
</tr>
<tr>
<td>2018</td>
<td>St. Gabriel</td>
<td>Plant cane</td>
<td>L 01-299</td>
<td>0.71</td>
<td>0.99</td>
<td>0.57</td>
<td>0.97</td>
</tr>
<tr>
<td>2018</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>0.6</td>
<td>0.97</td>
<td>0.67</td>
<td>0.98</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>Plant cane</td>
<td>L 01-299</td>
<td>0.85</td>
<td>0.96</td>
<td>1.21</td>
<td>0.97</td>
</tr>
<tr>
<td>2019</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>0.69</td>
<td>0.99</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>2019</td>
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<td>2nd stubble</td>
<td>L 01-299</td>
<td>0.82</td>
<td>0.99</td>
<td>1.07</td>
<td>0.98</td>
</tr>
<tr>
<td>2019</td>
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<td>L 01-299</td>
<td>1.05</td>
<td>0.99</td>
<td>1.34</td>
<td>0.98</td>
</tr>
<tr>
<td>2020</td>
<td>St. Gabriel</td>
<td>1st stubble</td>
<td>L 01-299</td>
<td>0.95</td>
<td>0.98</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>2020</td>
<td>St. Gabriel</td>
<td>3rd stubble</td>
<td>L 01-299</td>
<td>0.85</td>
<td>0.96</td>
<td>0.9</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The validation results indicated that for the St. Gabriel location, the level of accuracy and precision of both yield potential predictive models was with an average $R^2$ value of 0.96 and slope of 0.77 cross crop ages (Table 4.3).
There were sites with slope values that were almost equal to 1. The 2nd stubble crop in 2019 had slope values of 1.05 and 1.07 for cane and sugar yield. However, the slope values changed from 0.71 and 0.6 and to 0.85 and 0.69 in plant cane and 1st stubble in the 2018 and 2019 crop years, respectively. Similarly, this study also observed that the model's accuracy declined in the plant cane and 2nd stubble crops of the 2019 season, as shown by the increased slope value from 1.21 to 1.34. The 2015 GreenSeeker-NDVI based prediction models for cane and sugar can be utilized using the converted UAV-NDVI as a predictor. In general, the performance of models was reasonable based on the high level of accuracy and precision of the prediction outcomes.

4.4 CONCLUSIONS

The results from this study showed that UAV-NDVI can discriminate the variation of sugarcane response to N fertilization across locations, crop ages, and sugarcane variety. These results indicated that when after NDVI were normalized using CGDD>0, the GreenSeeker and the UAV-NDVI had a strong linear relationship with an $R^2$ and slope values of 0.94 and 0.84, respectively. For the validation process, UAV-NDVI was collected (and converted) from eleven sites located in two different locations in south Louisiana. On average, the precision of the cane yield prediction observed in both plant cane and stubble crops for both L 01-299 and HoCP 96-540 varieties were high with $R^2$ values of 0.97 and 0.96, respectively. Similar outcomes were obtained for sugar yield prediction across varieties and crop ages with an $R^2$ value of 0.98. Based on the slope values ranging from 0.69 to 1.05 for cane yield and from 0.57 to 1.34 for sugar yield for both HoCP 96-540 and L 01-299 varieties across crop ages indicate medium to high levels of accuracy of the prediction models. The models for yield potential and response index predictors are among the sensor-based N calculator (SBNC) components for sugarcane. Thus, results also
showed that converted UAV-NDVI could be used to derive in-season N fertilizer recommendations. Nevertheless, the validation and refinement (of the models) are vital in implementing need-based, in-season N rate recommendations that can account for both the spatiotemporal and varietal variability in sugarcane production.
CHAPTER 5. GENERAL CONCLUSIONS

In Louisiana, nitrogen (N) recommendations vary depending on crop age and soil type. Multiple research studies were conducted to evaluate different N fertilizer management strategies to improve N use efficiency and yield in sugarcane production in Louisiana. This research was initiated in 2017 at the Sugar Research Station in St. Gabriel and in an on-farm demonstration field with a sugarcane grower at Paincourtville, LA.

The outcome of the first study suggested that the impact of the different N sources on both cane and sugar yield varied across soil type and crop age. Overall, cane and sugar yield were improved using urea and NH₄ sulfate as N sources compared to UAN solution. This response was observed in the experimental plots located in St. Gabriel only. In most cases, cane and sugar yield were numerically higher where urea and NH₄ sulfate were applied. Conversely, UAN knife-in treated plots reported the highest cane and sugar yield compared to NH₄ sulfate at the producer's field in Paincourtville although more often, this impact was essentially the same across the different N sources. The TRS and other quality components were statistically the same across N source treatments. However, in certain sites and crop ages, the TRS and sucrose were higher in the control than the N fertilized plots. In general, sugarcane was very responsive to N application; the highest increase in cane and sugar yield was 118 Mg ha⁻¹ and 12,600 Kg ha⁻¹, respectively. Across sites, both UAN and NH₄ sulfate treated plots achieved the highest increase in cane (115 and 117 Mg ha⁻¹, respectively) and sugar yield (13,283 and 12,236 Kg ha⁻¹, respectively).

The use of NH₄ sulfate needs to be considered an alternative to improve the current soil fertility program in Louisiana sugarcane production system, especially if sulfur (S) is deficient and there is a need to acidulate high pH soil. The different sources of N fertilizer impacted the
inorganic N distribution and movement into the soil. Overall, NH$_4^+$ was the predominant form of N in the soil at the surface and subsurface soil compared to NO$_3^-$. Also, the use of UAN (knife-in) and NH$_4$ sulfate substantially increased the concentration levels of NH$_4^+$ and NO$_3^-$ in the soil.

The study on the effect of planting mixed species of cover crops in a newly planted sugarcane early fall showed that cover cropping increased the nutrient turnover to the soil. The cover crops produced higher amount of biomass than the native plants, thus positively impacted the amount of essential and beneficial nutrients recovered in the biomass of the cover crop, and subsequently, after the decomposition, these nutrients raised the soil’s nutrient content. It was also observed that the group of native plants harvested across locations removed a higher amount of micronutrients, especially iron and manganese, compared to the seeded cover crops. On average, fields planted with cover crops positively impacted the millable stalk population, cane, and sugar yield. This effect was observed only in the first and second ratoon crops. It was also observed that the cover crop did not improve or decrease any sugar quality components across sites and crop ages.

Cover cropping impacted the levels and distribution of NH$_4^+$ and NO$_3^-$ in the soil. wherein higher levels were recorded in plots where cover crops were grown. Across the sampling times, the concentration of NH$_4^+$ was higher than NO$_3^-$. Similarly, the soil P, K, S, Ca, and Mg concentration trend revealed that cover crops had positively impacted the level of these nutrients in the soil as early as the first year after cover crops termination. Nitrogen had the highest impact on sugarcane productivity among the nutrients released from the cover crop residue decomposition. However, this improvement varies across soil types, crops, and management practices. The use of cover cropping as part of the sugarcane production systems is promising. Thus, the need to synchronize the release of nutrients removed by the cover crop with
the time of active nutrient uptake by sugarcane is required to improve soil health and fertility in the Louisiana sugarcane industry. This study found that the winter cover crops can be used as an alternative or supplement to fertilization in increasing productivity and sustainability of sugarcane industry.

The third part of the study aimed to validate the converted aerial image NDVI (UAV-NDVI) as a sugarcane yield potential predictor. The relationship between GreenSeeker NDVI and UAV-NDVI was highly correlated on light and heavy texture soil with stubbles and plant cane crops at the Sugar Research Station. The results from the validation study revealed that cane and sugar yield prediction models using converted UAV-NDVI as a predictor exhibited higher accuracy and precision for ratoon crops and plant cane across soil types, locations, and sugarcane varieties. In addition, adjusting NDVI with CGDD provided a better relationship between GreenSeeker and UAV-NDVI collected across soil types, varieties, and crop ages. These results showed that after NDVI were normalized using CGDD>0, the GreenSeeker and the UAV-based NDVI had a stronger linear relationship with an $R^2$ and slope values of 0.94 and 0.84, respectively. On average, the precision of the cane yield prediction observed in both plant cane and ratoon crops for both L 01-299 and HoCP 96-540 varieties were high with $R^2$ values of 0.97 and 0.96, respectively. Similar outcomes were obtained for sugar yield prediction across varieties and crop ages with an $R^2$ value of 0.98. Based on the slope values ranging from 0.69 to 1.05 for cane yield and from 0.57 to 1.34 for sugar yield for both HoCP 96-540 and L 01-299 varieties across crop ages indicate medium to high levels of accuracy of the prediction models. This study also suggested that converted UAV-NDVI can be used as a predictor for yield potential estimation and possibly, for adjusting N fertilizer recommendation. Nevertheless, the validation and refinement (of the models) are vital in implementing need-based, in-season N rate
recommendations that can account for both the spatiotemporal and varietal variability in sugarcane production.

The importance of investigating the different sources and doses of N fertilizers becomes more and more necessary every day. Understanding the dynamism of the nutrients in the soil to correct a fertilization plan is the challenge today. Studying different N sources, such as NH₄⁺ sulfate, could bring significant advantages to the sugar industry since this nitrogen is in available form (NH₄⁺), and possible levels of S deficiencies in the soil can be corrected. In the same way, the use of soil conservation practice to plan and apply nutrients that increase fertilizer efficiency and reduce nutrient losses. Generating sufficient information on the benefits and application of these technologies will ensure rapid adoption among sugar cane growers in Louisiana.
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Daniel was born in Guayaquil, Ecuador in September of 1988. He attended the Panamerican Agriculture University, Zamorano in Honduras, and received his BSc. in agricultural engineering in 2013. He joined Louisiana State University in August 2014 as a visiting scholar. In Summer 2017, Daniel received his master of science (MS) in the School of Plant, Environmental, and Soil Science under the guidance of Dr. Brenda Tubaña, working on improving nitrogen management in sugarcane production in Louisiana, specifically on establishing the optimum rate, source and application method of nitrogen fertilizer. He also documented the changes in soil conservation, soil and plant nutrient content of row crops under rotation systems with soybeans and cover crops. Lastly, he evaluates the remote sensing technology using active and passive sensors as a decision tool to improve fertilization programs and management practices in Louisiana production systems.