DEVELOPING AND ADOPTING NUTRIENT MANAGEMENT GUIDELINES FOR SUGARCANE GROWN ON ALLUVIAL SOILS DERIVED FROM VOLCANIC PARENT MATERIAL IN NICARAGUA

A Thesis submitted by

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ABSTRACT

Sugarcane is produced along the Pacific coast of Nicaragua, adjacent to a chain of volcanoes that runs from north to south. This has resulted in distinct soils, typically derived from recent volcanic parent material and influenced by the sedimentary coastline. San Antonio is the biggest sugar mill company in Nicaragua, with approximately 33,000 ha. Nutrient inputs have traditionally been based on guidelines developed elsewhere. Modified nutrient management guidelines were investigated to ensure sustainable sugarcane production. Interim N, P, K, and S guidelines for San Antonio were developed by considering existing nutrient management systems that could be used as examples for sugarcane production in San Antonio. This was intended to be a tentative nutrient management strategy until R&D-based guidelines were available from this project. A series of replicated small plot nitrogen (N) x potassium (K) and phosphorus (P) experiments were established in 2015 to investigate the N, P, and K requirements. The treatments applied to a series of field trials included 0, 75, 150, 225 kg N/ha as urea and 0, 60, 120 and 180 kg K/ha as muriate of potash, and 0, 20, 40, 60 kg/ha as diammonium phosphate (DAP). Responses to applied N occurred at most of the trial sites and for P and K in some ratoons. These differed from each other and were influenced by climate variability. N and P rates were lower than interim nutrient guidelines, and K was marginal or similar. These locally derived N and P rates are lower than the N and P rates previously used, except for K. Interim nutrient guidelines developed in this study improved nitrogen use efficiency (NUE) by decreasing kg N applied/tc from 2.08 to 1.54 kg N applied/tc. This represented 1,753,770 kg of N less since the improvements were adopted and US $1,517,330 in savings due to N reduction, with higher average productivity in terms of cane and sugar yield. This approach provides an example for other developing countries to establish their own nutrient management guidelines rather than adopting those developed elsewhere.

CERTIFICATION OF THESIS

I Maria Alejandra Caldera Dominguez declare that the PhD Thesis entitled "*Developing and adopting nutrient management guidelines for alluvial soils derived from volcanic parent material in Nicaragua"* is not more than 100,000 words in length including quotes and exclusive of Tables, Figures, appendices, bibliography, references, and footnotes. The thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Date: 19 September 2023

Endorsed by:

Prof Bernard Schroeder

Principal Supervisor

Assoc Prof Troy Jensen

Associate Supervisor

Student and supervisors' signatures of endorsement are held at the University.

ACKNOWLEDGEMENTS

I would like to thank my parents, Marlene Dominguez, and Roberto Jose Caldera, who encouraged me to love the agricultural world since I was a little girl. And my sister, Maria Cristiana Caldera, who encouraged me day by day to make my dreams come true and made me feel like she was my fan# 1. To San Antonio sugarcane growers and APRICO (Asociación de Productores Privados de Caña de Azúcar de Occidente), thanks for the professional respect and support. Thanks to all my vitamin friends who made the journey more calm and easier. I would like to thank my advisor, Prof. Bernard Schroeder, for pushing me on my journey to becoming a better researcher and person. Since day one, you have believed in me and guided me through this long journey that is now a reality that we can see in approximately 17,000 hectares of Nicaraguan sugarcane fields and hopefully in more Nicaraguan growers as well. I would like to thank my work colleagues, especially Reynaldo Alvarado, Claudia Garcia, and Javier Cruz, who helped me set up this project, and Noel Sacasa (San Antonio CEO), who gave me the opportunity to extrapolate this study to commercial fields. I also would like to thank Dr. Troy Jensen for his guidance and support and extend my gratitude to the San Antonio Sugar Mill Company and Mr. Carlos Pellas for providing funding support to develop the first study in sugarcane of this magnitude.

DEDICATION

I dedicate this project to my beloved grandmother, Coco. I know that you are celebrating this success with me. I definitely know that throughout these six years, you have never left me alone. I hope I have made you proud.

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CHAPTER 1: INTRODUCTION

1.1 General introduction to sugarcane production in Nicaragua

The details presented in this Chapter provide background information to justify the need for the study and the outputs and outcomes that were generated by the investigation. It provides a summary description of:

- World and Nicaraguan sugarcane production,
- Location of the Nicaraguan sugar industry,
- Nicaraguan sugarcane-producing soils,
- General climatic conditions in Nicaragua,
- Nicaraguan sugar industry's operating environment, and
- General aspects of nutrient and fertilizer management affecting sugarcane production in Nicaragua.

1.2 Summary of world and Nicaraguan production

Sugarcane is a valuable crop grown in tropical and subtropical climates worldwide mostly to produce sugar (Skocaj *et al*., 2013). About 26.5 million hectares (ha) of sugarcane were harvested worldwide in 2020 (Figure 1). This resulted in world sugar cane production of about 1.86 billion metric tonnes of sugarcane (Anon, 2018a).

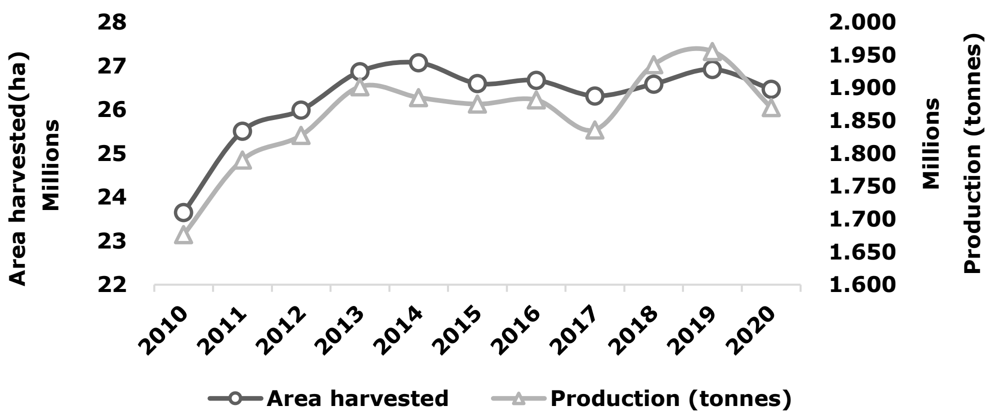

Figure 1. *Sugarcane production and area harvested worldwide. Data from 2010-2020 (Anon, 2018a).*

Sugarcane production contributes markedly to the world economy with a particularly high influence in Third World countries, such as Nicaragua, where agriculture accounts for about 20% of the gross domestic product (GDP) (Sánchez and Vos, 2009). According to Cómite Nacional de Productores de Azúcar (CNPA), the Nicaraguan sugar cane industry covers approximately 73,000 ha. This includes land farmed by growers and four sugar milling companies. It generates more than 35,283 direct jobs and more than 135,000 indirect jobs. It contributes to more than 4% of the calculated local GDP, with an investment of more than US $ 210,000,000 (Anon, 2018b). The sugarcane industry has increased in the last 10 years by about 18,000 hectares (Figure 2).

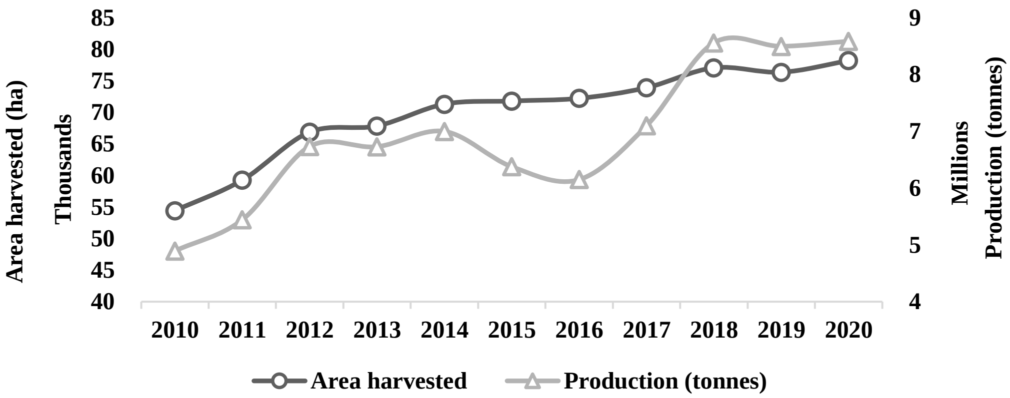

Figure 2. *Nicaraguan sugarcane production and area harvested. Data from 2010-2020* (*Anon, 2018a).*

1.3 Location of sugarcane production in Nicaragua

Nicaragua is in Central America, between latitudes 10°30’and 15°10’ N and longitudes 83°25’ and 87°50’ W (Incer Barquero, 1995).

It borders on the Atlantic Ocean in the east and the Pacific Ocean in the west, between Honduras to the north and Costa Rica to the south. It is the largest country in Central America with a land area of 130,700 square kilometers. It is divided into three regions, namely, the Pacific, Central, and Atlantic Regions.

Sugarcane is produced along the Pacific coast of Nicaragua adjacent to a chain of fourteen volcanoes that runs from north to south, six of them are still active (Figure 3). These volcanos have resulted in distinct soils typically derived from recent volcanic parent material (Joergensen and Castillo, 2001), both in *situ* and due to alluvial and colluvial action. Marine influences have also contributed to the characteristics of the soils closer to the coast.

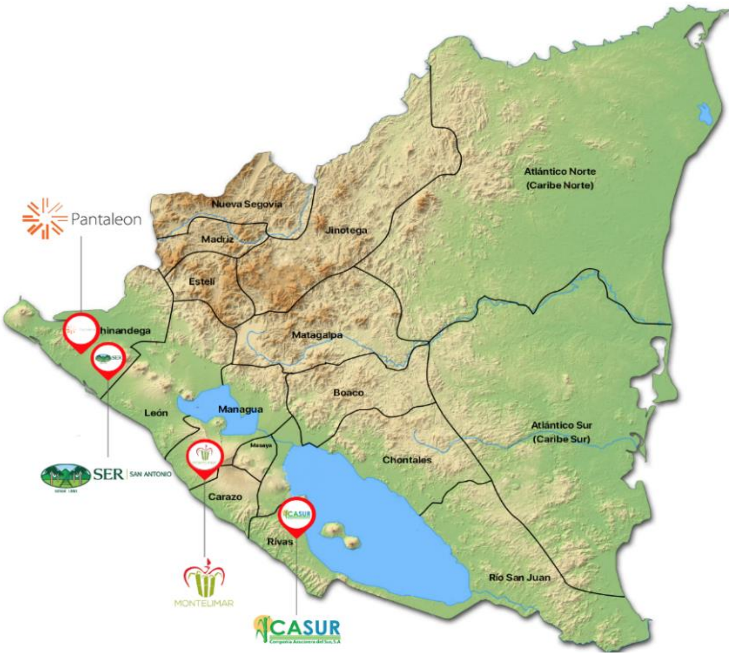

Figure 3. *Map of Nicaragua: showing sugar milling companies along the chain of volcanoes located in the Pacific Coast.*

The main sugar milling companies are San Antonio, Monte Rosa, Montelimar and Casur. In 2016, these companies were supplied with cane harvested from about 74,000 ha (Anon, 2018b). The Nicaraguan sugar milling companies have diversified, generating byproducts such as energy, molasses, ethanol, and biofuel. Three of the four sugar mills have biomass energy plants and sell electricity to the national grid (Bolaños, 2018).

The largest sugar milling company is San Antonio with a mill supply area of 33,000 ha. It is located at Chichigalpa within the city of Chinandega. San Cristobal is the tallest active volcano in Nicaragua (1745m), and it is situated 15 km northeast of the Chinandega city centre. It exhibits persistent activity with moderate eruptive events (Conde *et al*., 2015).

1.4 General description of sugarcane producing soils in Nicaragua

The ash fallouts from the volcanic activity, particularly from San Cristobal contribute to constant rejuvenation of soils in western Nicaragua. From a taxonomic perspective, these soils can be referred to as 'volcanic' in nature. However, this term includes a wide range of soil types with different properties (Nanzyo *et al.,* 1993) depending on the nature of the volcanic material (ash, basalt, granite, etc.) and the length of time since volcanic activity.

According to the United States Department of Agriculture (USDA) Soil Classification System, young volcanic soils that have formed in or from volcanic ash and tephra or volcaniclastic materials are called Andisols. They are typically composed of forms of amorphous aluminium silicates and colloids that include minerals such as allophane, imogolite and ferrihydrite (Leamy *et al*., 1980; Shoji, 1986). Transition of Andisols to some other soil orders such as Oxisols or very highly weathered soils that are found primarily in the intertropical regions of the world and rich in Fe and Al oxide minerals, can occur under the strong influence of climate and vegetation, or with ongoing weathering (Kimble and Eswaran, 1988; Otsuka *et al*., 1988; Shoji *et al*., 1988).

Based on the young volcanic nature of Nicaraguan soils there were expectations that they would logically be classified as Andisols as described above (Anon, 1972). However, many of the soils of the Pacific region in Nicaragua are identified as Vertisols, Mollisols and Entisols that include clay-rich soils with marked shrink-swell characteristics, soils with thick dark horizons due to long-term additions of organic matter, and soils that markedly reflect their parent materials with little profile development, respectively. Inceptisols that include young alluvial soils (deposited by water-action/flooding) and littoral soils (found in areas adjacent to the ocean high tide mark) are also present in the Chinandega landscape.

The sedimentary/depositional coastline adjacent to the 'volcanic' soils in the relief and drainage zone extends from the Cosigüina Peninsula (northwest of Chinandega) to the Soledad River in southern Mexico, in a northwest-southeast direction over approximately 150 km (Anon, 1972). The lack of a predominance of classic Andisols is probably due to the San Cristobal volcanic activity being characterised by ongoing expulsion of relatively small quantities of smoke and ash. Thick layers of volcanic ash that characteristically form Andisols are essentially absent in the Chinandega/Chichigalpa landscape.

1.5 Nicaraguan climate

Nicaragua has a tropical climate, with two seasons: the dry season (November to April) and the rainy season (May to October). In the Pacific region, annual rainfall ranges between 1000 mm and 2000 mm (Anon, 2012). At Chinandega, the annual precipitation is 1835 mm, with incidences of high precipitation during September and October, and a dry period called 'Canicula' between mid-July to mid-August. Average temperature ranges between 26 °C to 30 °C, maximum temperatures can reach 36 °C (Data recorded at San Antonio weather station). Based on recorded data (1971 – 2000) average relative humidity in Chinandega is approximately 70% (Anon, 2012).

1.6 Operating environment

Nicaragua's sugarcane production is surpassed only by Guatemala and El Salvador in Central America. In the last ten years, investments in mechanization, irrigation and training have resulted in considerable increases in yield and planted area. Mechanical harvesting is up to 95% in some of the most productive area and where the design and condition of the farms permit. Elsewhere, approximately 40% of harvesting is still done by hand. Harvesting is performed with machinery owned by the sugar milling companies and operated by company staff. Independent growers do not have the access to private mechanical harvester services.

Sugarcane is a perennial crop that is generally harvested each year for at least four consecutive seasons after planting. Some of the independent growers (approximately 600 growers) practice rotational cropping with legumes such as peanuts. Despite this and limited transition of some land to banana production, the sugarcane production area remains relatively consistent from year to year.

While the sugar milling companies have up to 70% irrigated areas, roughly half of the independent growers have invested in irrigation systems. The remainder of farms rely exclusively on rainfall. Precipitation distribution and absence of hurricanes and storms, plays a fundamental role in productivity.

Nicaraguan sugar production for 2021-2022 was approximately 794,770 MT between the four sugar milling companies (Figure 4). Typically, about 40 percent of total sugar production is consumed domestically in the Nicaraguan market and 60 percent is exported (Anon, 2023).

The Government of Nicaragua does not set sugar prices, nor does it provide subsidies nor special credit programs for sugar production or export. However, sales are higher than world prices in Nicaragua and income from biomass energy production have essentially insulated the Nicaragua’s sugar industry from fluctuations in international sugar pricing (Anon, 2023).

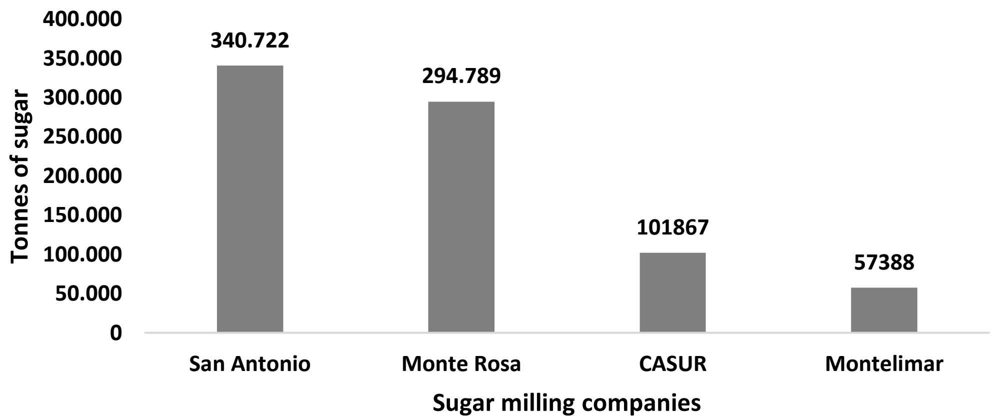

Figure 4. *Nicaraguan sugar production by sugar milling companies. Data from harvesting season 2021-2022 (Anon, 2023).*

Impacts of the ongoing COVID-19 pandemic, increase of fertilizer prices with corresponding lower rates of application of fertilizer, higher fuel prices that affect cultural practices, and one of the wettest years in the last decade have contributed to decreases in Nicaraguan sugarcane yields during the 2022-2023 season.

However, the introduction of sugarcane cultivars, like the drought-tolerant Guatemalan-developed CG-02163, and those high in sucrose content like CP-892143 and CP-001101 that can be grown in irrigated fields, should generate sustained agronomic yield increases in the years ahead.

1.7 General aspects of nutrient and fertilizer management in Nicaragua

In Nicaragua, fertilizer management prior to 2015 was mainly focused on nitrogen (N), and there was a belief that more N equated to production of more biomass. The concept of balanced nutrition based on soil and foliar analyses was not widely adopted. Soil characterization and research of agro-ecological zones had also not been fully explored (Anon, 1972) and most of the fertilizer recommendations were based on information from elsewhere.

In particular, nitrogen (N), phosphorus (P) and potassium (K) rates used in Nicaragua were derived from studies conducted by research centres such as CENGICAÑA in Guatemala. Although that information was important, it pertained largely to the soils and cultivars (Pérez and Melgar, 2000) to that specific country. Further examples of relevant but not Nicaraguan-specific information was from CENICANA in Colombia that covered their particular cultivars (Cassalett-Dávila, *et al.*, 1995). Although the effects of macronutrient deficiencies/imbalances and their importance in crop nutrition are relatively well understood worldwide, their interactions with different type of soils, cultivars and weather conditions have not been studied in Nicaragua.

1.8 Conclusions

In summary and conclusion:

- Sugarcane production continues to increase worldwide. In Nicaragua the area planted to sugarcane has increased by about 25% in the last 10 years.

- In Nicaragua sugarcane is produced along the Pacific coast adjacent to a chain of volcanoes some of which exhibit persistent activity.

- The weather, relief and constant ash fallout from volcanoes such as San Cristobal have resulted in good quality soils specific to the region.

- Based on the young volcanic nature of Nicaraguan soils, it was expected that they would generally be classified as Andisols. However, many of the soils in the Chinandega/Chichigalpa region are identified as Vertisols, Mollisols and Entisols.

- Climate variability, increased fertilizer costs, environmental concerns and fluctuation in sugarcane prices are challenges that are markedly influencing sugarcane production. They are also leading to a need for increased efficiency.

- Weather conditions and water supply are major factors influencing sugarcane production. However, other factors, such as on-farm practices and nutrient management are often more manageable.

- After water, optimum nutrient management is arguably the most important factor in crop and sugar production. Over-application of fertilizers not only affects profitability, but also causes environmental concerns due to losses of applied nutrients.

1.9 Thesis overview

In response to those conclusions, the main objective of the thesis is to improve nutrient management in alluvial soils derived from volcanic parent material in Nicaragua and specially at San Antonio, by improving productivity, profitability and environmental sustainability of sugarcane.

This thesis had the following specific objectives:

- Increase nutrients (N, P and K) use efficiency by matching nutrients supply and nutrients demand of the sugarcane crop.
- Improve productivity in terms of tons of cane and sugar yield, using nutrients more efficient.
- Increase profitability of San Antonio and Nicaraguan growers by lowering cost and increasing yield.
- Improve environmental concerns by reducing nutrient losses through the environment.
- This thesis is composed of six chapters:
- CHAPTER 1: Introduction is presented in Chapter 1 and provides an overview of the sugarcane production system in Nicaragua, sugarcane fields and sugar mills companies location, climatic conditions, Nicaraguan soil types, operating environment, and general aspects of nutrient fertilizer management.
- CHAPTER 2: Literature review is presented in Chapter 2 and provides an explanation of the growing and nutrient requirements of the sugarcane crop, essential nutrients (N, P and K) their process, losses and factors that can influence their availability. It also contemplates agricultural practices and infrastructure for effective nutrient management.

- CHAPTER 3 suggest interim nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) guidelines for sugarcane production at San Antonio. The initial work within this study therefore aims to develop interim site and soil specific N, P, K, S guidelines. This was intended to be a tentative nutrient management strategy, until R&D-based guidelines were available from this project.

- CHAPTER 4 and 5 intends to develop soil-specific guidelines for nitrogen (N), phosphorus (P) and potassium (K) for alluvial soils derived from volcanic parent material in Nicaragua. Nutrient management guidelines for N, P and K are investigated to ensure sustainable sugarcane production into the future, and to ensure that nutrient inputs are based on locally derived recommendations. The investigation consisted of a series of replicated small plot N x K (Chapter 4), and P (Chapter 5) experiments. The study was conducted for 3 years minimum. Nutrients uptake, agronomic variables (weight, population cane and sugar yield) and nutrient efficiency indexes are provided in those Chapters, respectively.

- CHAPTER 6 suggest San Antonio sugar mill company as a model to generate nutrient management guidelines for specific circumstances. The objective of this Chapter is to take in consideration all the information provided in Chapter 1-5 and analyse if interim guidelines for N, P and K can be fine tuning and extrapolate to elsewhere and be adopted for Nicaraguan sugarcane growers.

- CHAPTER 7 provides a discussion of results and integrates the research outcomes, and future work identified in Chapter 4 and 5.

- CHAPTER 8 is a summary of the main conclusions of this research project.

CHAPTER 2: LITERATURE REVIEW

2.1 Understanding the sugarcane crop: nutrient and growing requirements

Any study that aims to develop nutrient management guidelines for growing a crop in specific circumstances needs a good understanding of the main growth characteristics and nutrient requirements of the crop. This Chapter therefore provides a high-level review of:

- Sugarcane growth and production systems,
- Soil types and properties,
- Essential nutrients, particularly the major nutrients (N, P and K) and factors affecting their availability, and
- Practices and infrastructure that affects nutrient management planning.

2.2 Sugarcane growth and production systems

Sugarcane is a large, perennial, tropical/subtropical grass that grows under conditions of high sunlight, high temperatures and large quantities of water. It is therefore best adapted to climatic zones around the world between 35° north and south of the equator (Moore, *et al*., 2013).

Sugarcane crops are harvested several times within a crop cycle before replanting is required. The first crop within a particular crop cycle is referred to as the "plant crop". Subsequent crops are called "ratoons" (Cock, 2003). Although sugarcane is propagated asexually via stem cuttings (or setts) for commercial purposes, many cultivars flower and set seed. With commercial production flowering is not desirable due the reduction in sucrose content and cane yields (Moore and Nuss, 1987).

Sugarcane has four growth phases: Germination and establishment, tillering, major growth phase and ripening. In the germination stage, a primary shoot is produced from a bud on the planted sett. Under field conditions, germination starts from 7-10 days after planting, and usually lasts for about 30-35 days (Botha and Moore, 2014).

The major drivers of germination are soil moisture, soil temperature and aeration. Optimum temperature for germination is about 28-30 ^{o}C (Bonnett, 2013).

Tillering is a physiological process of repeated underground branching. Tillering of sugarcane in the tropics begins soon (15-20 days) after initial germination. In some cultivars, this stage lasts for up to 4 months. The primary shoot and tillers grow to produce a 'stool' that consists of stalks of varying weight, height, and diameter (Matsuoka and Stolf, 2012). During the major growth phase, maximum tiller population and elongation occurs about 120 days after planting and lasts for up to 270 days in a 12-month crop (Vasantha *et al*., 2012). By 150-180 days, at least 50% of the shoots die and a stable population is established. Cultural practices such as row-spacing, fertilizer practices, water availability and weed control influence tillering (Singels *et al*., 2005). Out of the total tillers produced only 40-50% survive after 150 days and form millable cane stalks (Bell and Garside, 2005; Bonnett, 2013).

The final stage before harvest is ripening. During ripening, stalk elongation slows down and sucrose concentration increases. At that stage, relative cool and dry weather conditions are desirable (Van Heerden *et al*., 2013). High rainfall or heavy irrigation in the ripening stage is undesirable, and could result in intense growth, decreases in sucrose accumulation and delayed ripening (Cardozo and Sentelhas, 2013).

Sugarcane yields can be affected significantly by weather conditions such as temperature, relative humidity, precipitation, and solar radiation. Optimum temperature for sugarcane growth is between 26 and 30 °C. Temperatures below 21 °C delay growth and influence sucrose accumulation (Cassalett-Dávila *et al*., 1995).

Sugarcane crops require about 1,500-2,500 mm of available water during a crop period (approximately 12 months) with peak requirements during tillering and the major growth phase (Cassalett-Dávila *et al*., 1995).

2.3 Soil types and properties

Sugarcane can grow in a wide range of soil types and is adaptable to different soil conditions. Of the 12 recognized USDA soil orders, 10 occur in the world sugarcane-producing countries (Table 1). These soil orders and their suborders cover soils with widely differing physical, chemical, and biological properties (Anon, 2022a, c). Therefore, depending on their genesis and location sugarcane-producing soils have ranges in colour, texture, structure, parent materials, position in the landscape, bulk density, water-holding properties, pH, organic matter contents (Org C), cation exchange capacity (CEC), phosphorus (P) sorbing capacities, non-exchangeable potassium (K) release characteristics, salinity, and sodicity (Table 2).

The occurrences of adverse soil properties, often at the limits of the ranges shown in Table 2, result in soil constraints that need attention to ensure that crop growth is not compromised. Constraints such as low fertility, acidity, salinity and sodicity, can in most cases, be corrected, but poor physical soil conditions are much more difficult to ameliorate (Humbert, 1968). Some constraints affect multiples aspects of crop growth. For example, compacted soils influence root penetration, water availability and nutrient uptake. Other properties have optimum values or conditions that best suit particular crops. For instance, sugarcane will grow in soils with pH values ranging from 4 to 9, but the risk of yield losses is minimized when soil pH is maintained at about 5.5 – 6.0 (Wood *et al*., 2003).

Table 1. *Brief description of USDA soil orders and location of soils in different sugarcane producing countries after Anon. (2022a).*

USDA soil orders	**Description**	**Examples of locations**
Alfisols	Soils formed under forests with extensive horizon development and accumulation of clay in the subsoil.	Australia, India
Andisols	Soils formed from volcanic ash that are not well weathered. They typically have low bulk densities.	Mexico, Reunion
Aridisols	Soils of desert/arid regions with evidence of accumulation of calcium carbonate ($CaCO_3$).	Egypt, Iraq, Israel
Entisols	Soils with little horizon development – often sands or in steep slope positions.	Nigeria, Pakistan
Histosols	Very high organic water saturated soils and anaerobic conditions.	USA (Florida)
Inceptisols	Soils with evidence of early stages of horizon development.	Colombia, Thailand
Mollisols	Dark soils with high base saturation and rich in organic material.	Argentina, Nicaragua
Oxisols	Highly weathered soils found in high rainfall areas. They contain low base cation and high acidity and Al^{3+}.	Brazil, Colombia, Zambia
Ultisols	Intensely weathered soils with low base cations and high H+ and Al^{3+} found in warm and humid climate zones.	Australia, Brazil China, India, Thailand
Vertisols	High clay content soils with marked shrink and swell properties	Australia, India, Sudan, Nicaragua, Swaziland

Table 2. *Summary of common soil physical, chemical, and biological properties. After [1]Schroeder et al., (2020), [2] Panitz et al., (2014).*

Soil property	**Range**		**Comment**
Texture[1,2]	Sand	Heavy clay	This is not a linear range as various combinations occur including those with silt components.
Colou1R’[2]	Light grey	Black	This is not a linear range but also includes yellow, red, and bluish-grey soils and mottles.
Structure[1,2]	Weak fine structure	Strong coarse structure	Natural aggregation of soil particles. The shape of the structural units include crumb, blocky and columnar.
Parent material[2]	In-situ	Alluvial deposits	Parent material includes different types of rock, minerals and deposits.
Position in the landscape[1]	Crest	Bottomland	Allowance is also made for proximity to rivers, streams, and marine coasts.
Bulk density[2]	Low	Very high	High bulk density in soils is often associated with compaction due to uncontrolled in-field traffic.
Water-holding properties[2]	Well-drained	Waterlogged	Intermittent moisture contents also occur.
pH[2]	4	9	Soils naturally range from acidic to alkaline.
Organic matter content[1]	Very low (<0.4% org C)	Very high (>15% org C)	Consequent of animals and plant breakdown. Organic C values reflect stable forms such as those determined by Walkley and Black (1934).
Phosphorus sorption[2]	Weak	Very strong	Phosphorus sorption (or fixation) is dependent on parent material, soil pH, org C content and CEC.
Non-exch. potassium release characteristics[2]	Low	High	Non-exchangeable K held within clay minerals is released into the soil solution as exchangeable K is depleted by to plant uptake and/or leaching.
Salinity[1,2]	Very low	Very high	Saline refers to the accumulation of salts in the soil profile.
Sodicity[1,2]	Very low	Very high	Soil sodicity is dependent on the ratio of the exchangeable Na^+ to the other nutrient cations.

2.4 Essential nutrients, particularly nitrogen (N), phosphorus (P) and potassium (K), and factors affecting their availability

Sixteen nutrients are essential for optimum plant growth. Carbon (C), hydrogen (H) and oxygen (O) are found in air and water. The other nutrients are divided into six macronutrients [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S)] and seven micronutrients [zinc (Zn), boron (B), manganese (Mn), iron (Fe), chlorine (Cl) and molybdenum (Mo)] as shown in Figure 5 (Calcino *et al*., 2018). These two groups of nutrients are based on the quantities of acquisition by the plant, rather than their significance in promoting plant growth (Rice *et al.,* 2006). Macronutrients are needed in relatively large quantities by the plant. In sugarcane production, elements that are of nutritional concern include N, P and K based on their amount of acquisition by the plant, loss pathways and nutrient/soil interactions. Nitrogen has been reported as one of the primary nutrients limiting sugarcane production throughout the world. The recommended rates of N fertilizer for sugarcane production vary between 45 and 300 kg/ha (Srivastava and Suarez, 1992).

Much time and research has been devoted to understanding and developing appropriate N, P and K rates for sugarcane grown in different types of soil and cultivars around the world, and in trying to determine the economic optimum ratios for high yield and sugar quality (Bell, 2015; Cavalot, *et al*., 1990; Wood, 1990).

As sugarcane is principally produced as a monoculture, nutrient removal occurs repeatedly. Depending on physical and chemical soil properties, nutrient interactions may differ from soil to soil (El-Tilib, *et al*., 2004; Izquierdo-Hernández *et al*., 2016).

Also, sugarcane cultivars differ in their ability to extract nutrients from soils and in their yield responses to applied N, P and K (Bharatha Lakshmi, *et al*., 2003; El-Tilib *et al*., 2004; Hajari, *et al*., 2015; Izquierdo-Hernández *et al*., 2016; Madhuri *et al*., 2011).

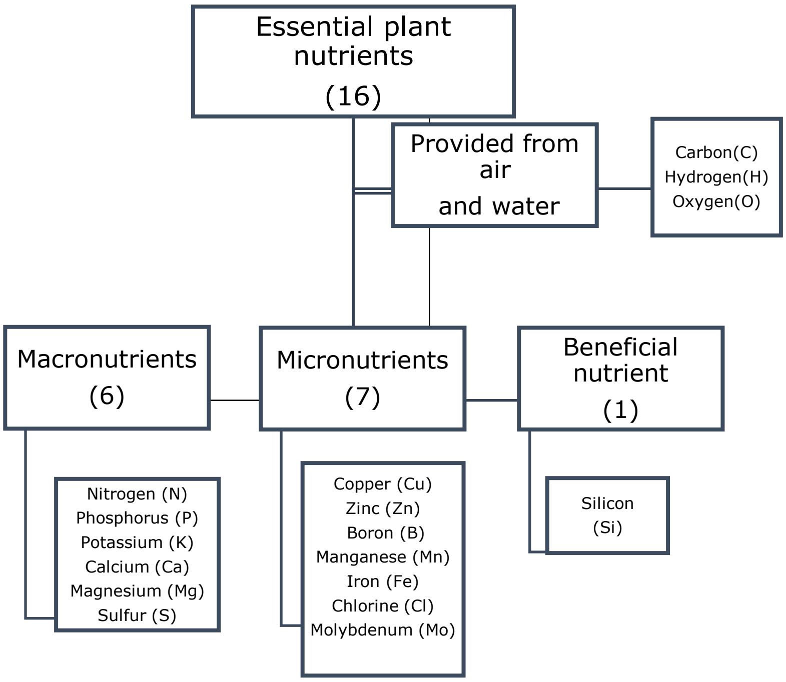

Figure 5. *The essential plant nutrients (Calcino et al., 2018).*

A deficiency or excess of one or more essential nutrients may compromise the availability of the other elements. In comparison silicon (Si) is known to be a beneficial element that can mitigate a range of abiotic and biotic stressors (Liang *et al*., 2007).

Cobalt, selenium, fluorine, iodine and sodium are taken up by plants but are not required for plant growth. Carbon, H and O make up to 90-95 percent of the dry matter of plants. The other 13 nutrients are obtained from the soil by the roots and make up to 5 to 10 percent of the remaining of the dry weight. (Kaur *et al*., 2016).

An average crop of sugarcane removes approximately 208, 53, 280, 30, 3.4, 1.2, and 0.6 kg of N, P, K, S, Fe, Mn and Cu, respectively, from the soil to yield about 100 tonnes of cane per hectare (tc/ha), depending on their environmental and agronomic conditions (Gopalasundaram *et al*., 2011). As demonstrated by Gopalasundaram *et al*., (2011), sugarcane removes substantial quantities of N, P and K in comparison with the other elements. To achieve sustainable sugarcane production, it is essential to understand the functions and transformations of these nutrients.

2.4.1 Nitrogen (N)

Nitrogen (N) is one of the most abundant elements and a main constituent of nucleic acids, proteins, and enzymes. It supports the uptake of other nutrients and stimulates the activity and the development of the root system (Kingston, 2014).

Biomass production is highly correlated with N concentrations. When N is deficient, the whole sugarcane plant is affected. Thin, stunted culms, reduced number of tillers and chlorosis are typical N deficiency symptoms (Anderson and Bowen, 1990). On the other hand, excess of N can cause low sucrose concentration, increased levels of reducing sugars and problems in the milling process. It also causes the production of amino-N compounds such as asparagine that are involved in the formation of colourants in sugar (Chapman *et al*., 1996). Colourants are the most important impurity in raw sugar and are often costly to remove (Meyer and Wood, 2001).

Excess N can lead to inefficient use of the resource and losses to the environment. To achieve a sustainable production using N and minimise losses is essential to understand the transformations of nitrogen in the soil as shown in Figure 6.

Nitrogen is taken up by plants as NO_3^- (nitrate) and NH_4^+ (ammonium). The main N source found naturally in soil is organic matter.

Mineralization of organic matter to NH_4^+ and NO_3^- is a continuing process, and the amount released depends on the amount of organic matter and microbial activity (Masclaux-Daubresse *et al*., 2010).

Rate of mineralization depends on temperature, moisture, soil type, organic matter residues and pH. Mineralization is slower in acidic soil (Abdelmagid, 1980; Schimel and Bennett, 2004; Stanford and Smith, 1972). The released N is available for plant uptake and should be considered within N fertilizer recommendations.

Nitrate levels vary considerably in the soil. They rise after fertilization and decrease by crop removal and after heavy rainfall (by leaching and runoff), waterlogging (denitrification) and ammonia volatilization (Wood *et al*., 2003) as can be seen in Figure 6.

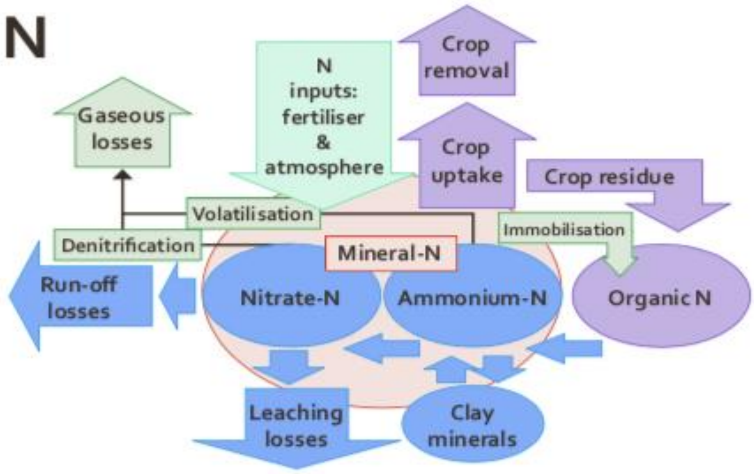

Figure 6. *Diagram of nitrogen cycle (Wood et al., 2003).*

For a better understanding of the N-cycle, it is necessary to know what factors can influence the inputs and outputs associated with the system. Outputs are generally represented by the losses via ammonia volatilization, denitrification and NO_3^- leaching.

Ammonia volatilization: It is mainly associated with urea applied to the soil surface and losses can be as high as 30-40% (Black, *et al*., 1985; Huang *et al*., 2017; Rochette *et al*., 2013). The main factors that influence volatilization are:

- **Soil pH**: High soil pH increases the reaction. Calcareous soils, with naturally high pH, can lose significant amounts of ammonia gas; however, neutral or acid pH soils may also lose substantial amounts of ammonia when urea is surface applied (Black *et al*., 1985).

  When urea is applied to the soil surface the hydrolysis reaction produces a sharp increase in pH (Cameron *et al*., 2013).

- **Soil cation exchange capacity (CEC)**: Soil cation exchange reactions retain NH_4^+ ions on the surface of clays and organic matter through electrostatic attraction. This mechanism helps to store NH_4^+ in soil and reduces the soil solution concentration of ammonium. The CEC also helps to buffer the soil against pH change; thus, when urea hydrolysis occurs in a clay soil (which has a high CEC) there is a smaller increase in pH than would occur in a sandy soil (which has a low CEC) (Daftardar and Shinde, 1980; Whitehead and Raistrick, 1993). Thus, the ammonia volatilization potential of a clay soil (high CEC) is generally lower than that of a sandy soil (low CEC).

- **Soil moisture**: Wetting a dry soil can increase the rate of urea hydrolysis. However, 20 mm or more is enough to wash most of the urea through the trash blanket (Vlek and Carter, 1983; Reynolds and Wolf, 1987).

- **Denitrification:** Under waterlogged conditions (anaerobic), nitrates are chemically altered to nitrous oxide and N gas and easily escape to the atmosphere. Under these conditions, anaerobic bacteria use NO_3^- instead of using O_2, as the terminal electron acceptor during respiration. This causes NO_3^- to be reduced producing, in turn, nitrite, nitric oxide (NO) nitrous oxide and finally dinitrogen (Martens, 2005).

- **Nitrate leaching:** Occurs mainly on freely drained sandy soils. However, leaching of nitrate to lower levels is possible in all soil types.

Loss of N not only reduces soil fertility and sugarcane yields, it also can lead to harmful environmental effects. Ammonia volatilization into the atmosphere contributes to acid rain. Nitrate leaching to groundwater has a significant impact on drinking water quality and can cause an excessive growth of aquatic weeds and algae, which can reduce fish populations (Cameron *et al.*, 2013).

Nitrous oxide produced by denitrification is also known as ozone-depleting gas (Allen *et al*., 2010; Ravishankara *et al*., 2009).

Generally accepted rates of N fertilizer for sugarcane production across the world vary between 0 and 200 kg N/ha/year, trying to suit N demand with N rate applications as shown in Table 1 (Meyer *et al*., 1986; Schroeder *et al*., 2005).

Table 3. *Guidelines for N application rates for sugarcane industries around the world. [Adapted from Bhadha and Schroeder, 2018 (citing Kingston, 2000)].*

Country	O. M (%)	Nitrogen Mineralization potential	Plant (kg N /ha)	Ratoon (kg N /ha)
South Africa[1]	<2	Low	120-140	160-200
	2- 4	Moderate	100-120	140-160
	2- 4	High	80	120
	>4	Very high	60	100
Australia[2]	<0.7	Very Low	140	160
	0.7-1.4	Low	130	150
	2.1-2.8	Moderate	110	130
	3.5-4.2	High	90	110
USA (Florida[3])	<35%	Moderate	120	120
	35-85%	Very high	34	34
	>85%	Very high	0	0

[1] Meyer *et al*., (1986), [2] Schroeder *et al*., (2005), [3] Anderson *et al*., (1990)

2.4.2 Phosphorus (P)

Phosphorus (P) is taken up as $H_2PO_4^-$ or HPO_4^{2-} ions (Busman, 1997; Menzies and Lucia, 2009). An average sugarcane crop takes up about 20 kg P/ha on average. Although P is taken up in small quantity compared with the other macronutrients, it plays an important role in photosynthesis, root development and tillering (Meyer and Wood, 2001). It is also required for energy-rich bonds (ADP and ATP) and contribute to maturation of crops (Kingston, 2014).

Unlike N, P is not susceptible to loss by volatilization (Wood *et al*., 2003). However, biological processes such as mineralization, immobilization and plant uptake do occur. Microorganisms play an important role in the P-cycle being responsible for mineralization and immobilization reactions that convert P into organic and inorganic forms (Mullen, 2005). Phosphorus can be lost by soil erosion and becomes unavailable by a process called P-sorption (Figure 7). P-sorption occurs when the orthophosphates, $H_2PO_4^-$ and HPO_4^{2-}, are strongly attached to soil particles. As phosphate is an anion, particles that have an anion exchange capacity will bind with phosphate. Example of soil particles with anion exchange capacity are aluminum and iron oxides, kaolin clays and amorphous materials (Anon, 2018c).

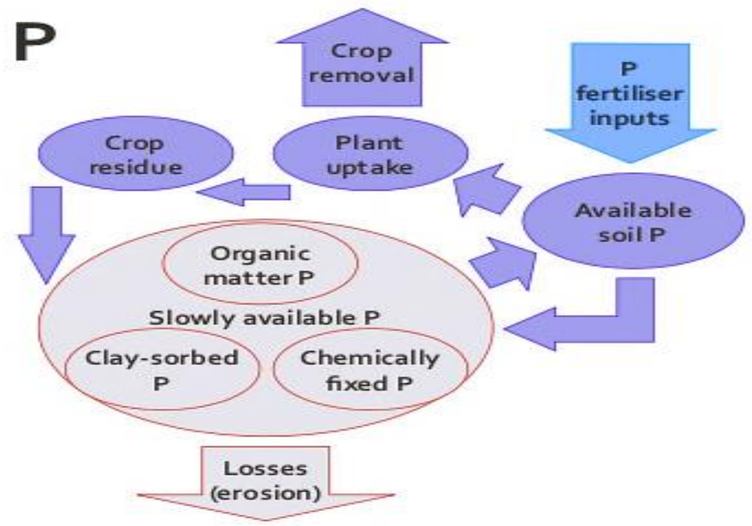

Figure 7. *Diagram of soil phosphorus cycle (Wood et al., 2003).*

Phosphorus deficiency is first observed in older leaves due to the mobility of this element into the plant. Bronzed/purple colour and die-back from the tips often appear. Leaves are thinner, narrower, and shorter and may appear more erect than normal. Tillering is poor. Cane from phosphorus-deficient fields produces juice low in P and in some cases, phosphoric acid may be added during the milling process to assist formation of calcium phosphate flocs to improve juice clarification (Burr *et al*., 1957; Kingston, 2014).

Guidelines for P-rate applications are based on critical soil values that differ among countries according to different analytical methods (Table 4).

Table 4. *Recommendations of phosphorus application rates based on different analytical methods, adapted from (Botha and Moore, 2014).*

Crop	Australia	USA (Florida)	Brazil
Critical soil	<10 mg/kg (BSES)	<14 kg/ha (Bray 2)	<10 mg/dm^3 (anion exchange resin)
Optimal soil	>20 mg/kg (BSES)	-	-
Plant cane (kg P/ha)	0-80	0-36	0-53
Ratoon cane (kg P/ha)	0-80	0-36	0-13

2.4.3 Potassium (K)

Sugarcane crop requires large quantities of potassium (K). This nutrient is essential for plant growth and photosynthesis and is involved in osmotic balance, helping the plant to use water more efficiently (Zorb *et al*., 2014). It also controls the movement of sugars in the plant and promotes root development (Wang *et al*., 2013; Zeng *et al*., 2018).

A deficiency of K first appears in older leaves and the leaf margins. Symptoms as scorching of edges, reddish midribs, thin stalks, and stunted growth often appears as well (Humbert and Martin, 1955).

On the other hand, excess of K can interfere with sucrose concentration and the milling process (Korndorfer, 2009). Processing molasses with high levels of K may inhibit the crystallization of sucrose. Excessive K uptake by sugarcane contributes to high ash levels in raw sugar.

Most soils contain large amount of K. However, only a relatively small amount is available for plants. In addition to releasing K, soil minerals can also fix K, significantly affecting K availability.

The degree of K-fixation in soils depends on the type of clay mineral and its charge density, moisture content, competing ions, and soil pH. Potassium is presented in three distinct forms within soils: readily available K (soil solution K and exchangeable K), slowly available (non-exchangeable K) that is frequently referred as fixed K and relatively unavailable K (Lattice K). Lattice K represents more than 90% of the total K in the soil and it is usually found in micas and feldspar. Over long periods, this soil mineral break down and K is released. However, the process is slow. Potassium losses are possible by leaching (from sandy soils) and by erosion (Korb *et al*., 2002). A diagram of the K-cycle is shown in Figure 8.

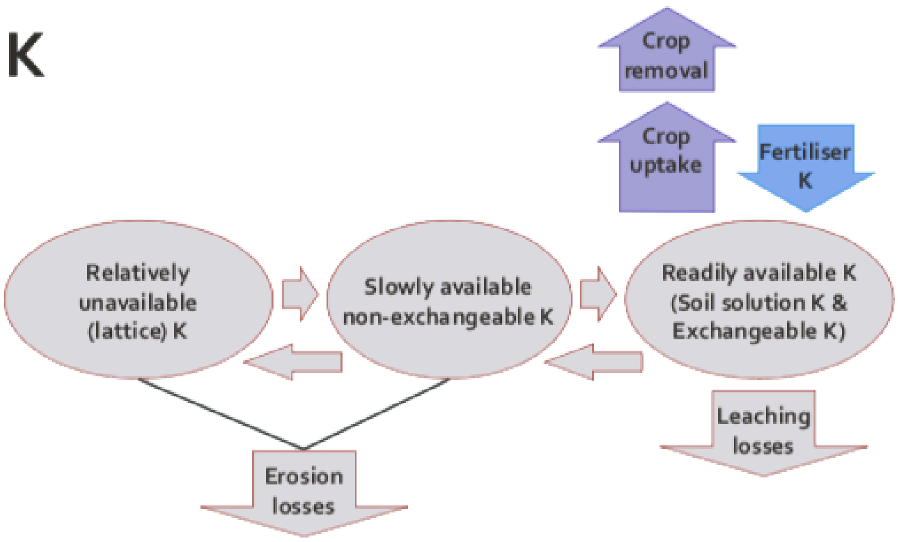

Figure 8. *Soil potassium cycle (Wood et al., 2003).*

Several countries have established different threshold values based on soil exchangeable K to give recommendations for K fertilizer application (as shown in Table 5).

Table 5. *Guidelines for K application rates, according to soil exchangeable K. Adopted from Kingston (2014).*

Threshold soil	**Australia**	**Brazil**	**USA(Hawaii)**
	< 0.24 ($cmol_c/kg$)	**< 1.2–2.3 ($cmol_c/dm^3$)**	**< 0.35 ($cmol_c/kg$)**
Plant cane (kg/ha)	0-100	0-116	0-375
Ratoon cane (kg/ha)	0-120	0-108	0-375

2.5 Practices and infrastructure that affects nutrient management planning

Nutrient management is one of the principal factors responsible of sugarcane productivity; however, cane also needs practices that help manage disease, pest, weed, and irrigation when precipitation is not enough.

Irrigation decreases the dependency on rainfall and allows a better planification and flexibility of agricultural practices. Pivot irrigation, overhead sprinklers, drip and furrow irrigation are typical irrigation systems found in sugarcane industries (Holden and McGuire, 1998).

Pivot and drip irrigation are usually systems that can be used for fertigation by allowing frequent irrigation and nutrient application. Drip irrigation wet only the plant root zone and has the potential to save water and be more efficient with applied fertilizers, by synchronizing nutrient supply and crop demand. Nutrients that are supplied through irrigation water, they are already in soluble forms accessible for plant uptake (Holden and McGuire, 1998).

Furrow irrigation is the most widely used irrigation system for sugarcane. It has low equipment costs and is simple to operate. However, efficiency is very variable and when is not well managed it can result in nutrient losses by run-off and denitrification (Holden and McGuire, 1998).

2.6 Conclusions

In summary and conclusion:

- Sugarcane is a large, perennial, tropical/subtropical grass that grows under conditions of high sunlight, high temperatures and large quantities of water (Botha and Moore, 2014).

- Sugarcane can be grown in a wide range of soil types and is adaptable to different soil conditions. However, the occurrences of adverse soil properties, often at the limits of the ranges, result in soil constraints that need attention to ensure that crop growth is not compromised.

- Sugarcane productivity can be improved through the use of best practice farming systems. Irrigation systems and infrastructures that allows a better placement and timing of fertilizer application should be considered in nutrient management.

- Soils are complex physical, chemical and biological systems that are not static. They store and release nutrients for crop growth. Nutrient guidelines strategies for N, P, K need to take into account the amount and rate of release of nutrients from different soils and the reactions between soils and fertilizers. The main objective of this Chapter was to recognise these processes and sources of nutrient to ensure a sound bases for the study. This was particularly relevant to the development of appropriate N, P, K guidelines for appropriate for alluvial soils derived from volcanic parent material in Nicaragua.

CHAPTER 3: ESTABLISHING INTERIM NITROGEN (N), PHOSPHORUS (P), POTASSIUM (K) AND SULFUR (S) GUIDELINES FOR SUGARCANE PRODUCTION AT SAN ANTONIO

3.1 Introduction

The information presented in Chapter 1 was generally applicable to the farming system used at San Antonio, Nicaragua Sugar Estates Limited. As mentioned earlier, nutrient management at San Antonio was determined from sets of inputs based on rules of thumb, and practices and rates based on information from other countries.

Although staff at San Antonio started collecting soil samples (0-20 cm) from the mill-owned blocks (referred to as administered plots) in 2009, the resulting data from almost 39% of the approximately 17,000 ha were, unfortunately, not used in formulating annual nutrient inputs. These samples were processed and analyzed at a commercial laboratory and categorized according to commonly determined physical (texture) and chemical properties. However, it was difficult to visualize all the information because the reported data was essentially paper based.

In addition to this underutilized resource, stagnated sugarcane yields at about 100 tc/ha despite relatively high N application rates prior to 2018 (Figure 9), decreasing profitability according to management records (not presented here), and increased environmental awareness and responsibility resulted in recognition that there was a need for improved nutrient management.

The initial work within this study therefore aimed to develop interim site and soil specific N, P, K, S guidelines. This would enable tentative nutrient management strategies at San Antonio until R&D-based guidelines were available from this project.

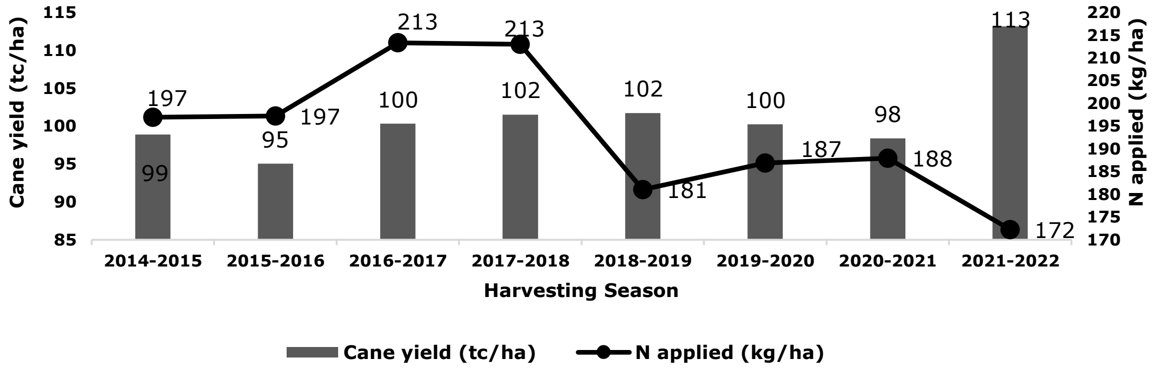

Figure 9. *Average N rates applied (kg/ha) during 8 harvesting seasons and their result in cane yield (tc/ha).*

3.2 Review of information from soil analysis

The identified objectives were achieved by undertaking several interlinked activities. These included the following:

- Soil sampling strategy at San Antonio was reviewed,
- Major soil types were identified based on soil physical and chemical properties,
- Soil properties were linked to sugarcane productivity data,
- A basis for the interim guidelines was developed by integrating the above and considering existing systems that would potentially be relevant for Nicaraguan conditions.

3.3 Results and discussion

3.3.1 Expansion and improvement of soil sampling

By the end of the 2008–2009 harvesting season, about 39% of the total area (approx. 17,000 ha) had been soil sampled (Figure 10). From 2011 to 2015 the remainder of the total area was sampled for the first time.

This effectively doubled the soil sampling intensity, with at least one sample collected from most of the administered plots at San Antonio. It ensured that a sound basis for soil-specific nutrient management guidelines existed.

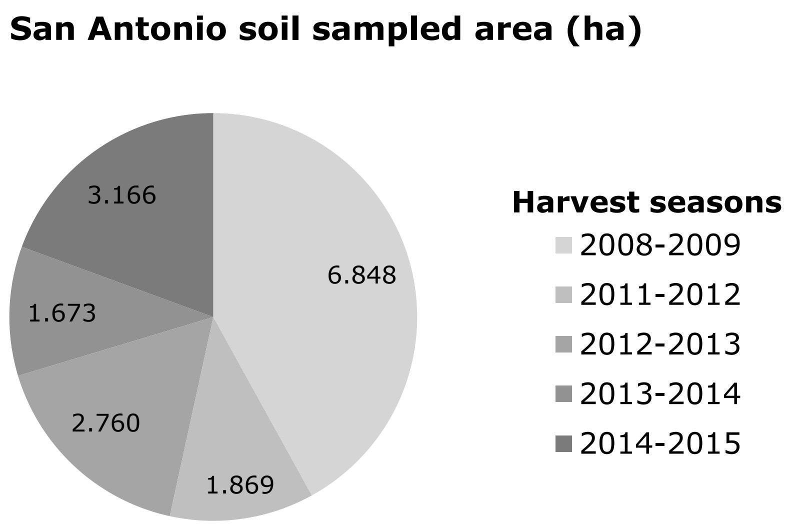

Figure 10. *San Antonio soil sampled area (ha) from 2008 to 2015 harvest seasons.*

In 2014, all the paper-based soil analysis data were digitalized and stored in a database contained in a software program (BIOSALC) for further analysis. Soil analyses were categorized according to nutrient sufficiency [low (L), normal (N) and high (H)] using Fundación Hondureña de Investigación Agricola (FHIA) parameters and classes (Appendix 3). An example of a report is shown in Table 6. This enabled access to summary information for each of the administered plots, easier visualization of data and sufficiency levels, identification of trends, and a sound basis for decision-making. Importantly, the BIOSALC allowed for further data to be added to the database and ongoing interrogation of the data for improving nutrient management at San Antonio.

Table 6. *Example of a BIOSALC nutrient sufficiency report based on soil analyses.*

Code	Site Name	Sample Code	Area (ha)	Texture	pH	Range	O.M (%)	Range	N (%)	Range	P (ppm)	Range	K (meq/100g)	Range	S (ppm)	Range
11002	BORREL N	1434	16.86	Loam	6.5	N	5.5	N/H	0.28	L/N	25.4	N/H	0.9	N/H	9.4	L
11002	BORREL N	1435	16.86	Loam	6.8	N/H	5.7	N/H	0.29	L/N	24.1	N/H	2.3	H	17.2	L/N
11005	BORREL S	1493	20.86	Clay	6.7	N	4.9	N	0.24	L/N	75.7	H	1.5	N/H	9.9	L
11005	BORREL S	1494	20.86	Clay	6.6	N	7.2	H	0.36	N	43.3	H	1.5	N/H	9.5	L
11012	BORREL B	1530	31.53	Loam	6.7	N	4.5	N	0.22	L/N	38.0	N/H	1.7	H	6.1	L
11012	BORREL B	1531	31.53	Loam	6.6	N	5.1	N/H	0.26	L/N	38.3	N/H	1.6	H	6.1	L
11012	BORREL B	1532	31.53	Loam	7.2	H	5.1	N/H	0.25	L/N	25.2	N/H	0.8	N	17.0	L/N

The initial sampling guidelines indicated that soil samples should be collected and tested from each block every four years. In addition, blocks that were subject to earthworks and levelled were resampled. However, neither of these conditions were applicable at that time (2008/2009). In 2015 these guidelines were expanded. Apart from retaining the four-year timeframe and prerequisite for levelled fields, the procedure also included the following:

- Soil samples and cores should be georeferenced via a geographic positioning system (GPS).
- One soil sample should cover 10-12 ha or less depending on textural changes.
- Soil cores were increased from 15 cores to 20-25 core per soil sample.
- Every field should have a soil sampling map with chemical and physical properties result using their GPS coordinates. The resulting information should be integrated into the appropriate IT platform. (Appendix 5.)

During the 2019–2020 harvesting season further soils sampling at SAN Antonio was undertaken according to the revised guidelines described above. Soil sampling maps were developed inclusive of georeferencing. An example is shown in Figure 11.

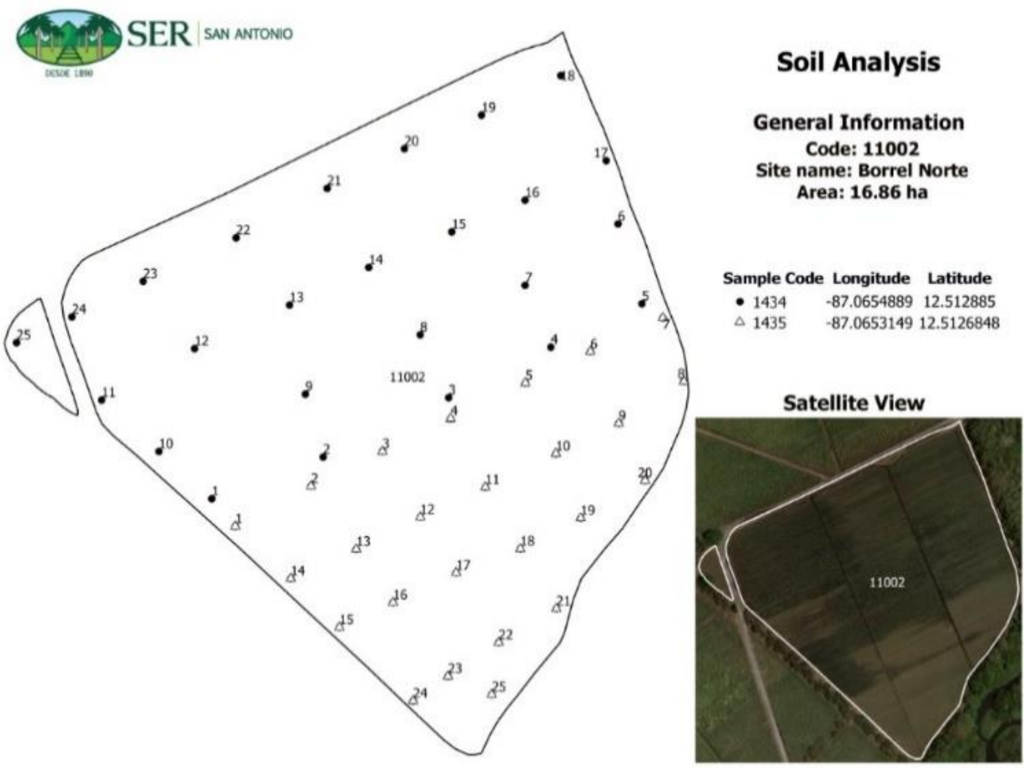

Figure 11. *Soil sampling map showing two georeferenced samples (1434 and 1435) with their GPS coordinates.*

The combination of the database and mappings identified ten different textures groupings (clay loam, loam, clay, sandy clay loam, sandy loam, silty loam, silty clay loam, loamy sand, sandy clay and sand) among the samples and, hence, across the San Antonio estate (Figure 12). However, the main soil textures were clay loam, loam, and clay. The soil chemical properties ranked according to the FHIA classes (Table 7) showed that the principal nutrient deficiencies were:

- N in almost 95% of the area (16,305 ha),
- S in 89% of the area (15,250 ha),
- Boron (B) in approximately 86% (14,839 ha),
- K in 37% of the area (6,342 ha), and
- Phosphorus 26% (P) (4,388 ha)
- Organic matter (OM) was also to found to be low in 49% of the area (8,380 ha).

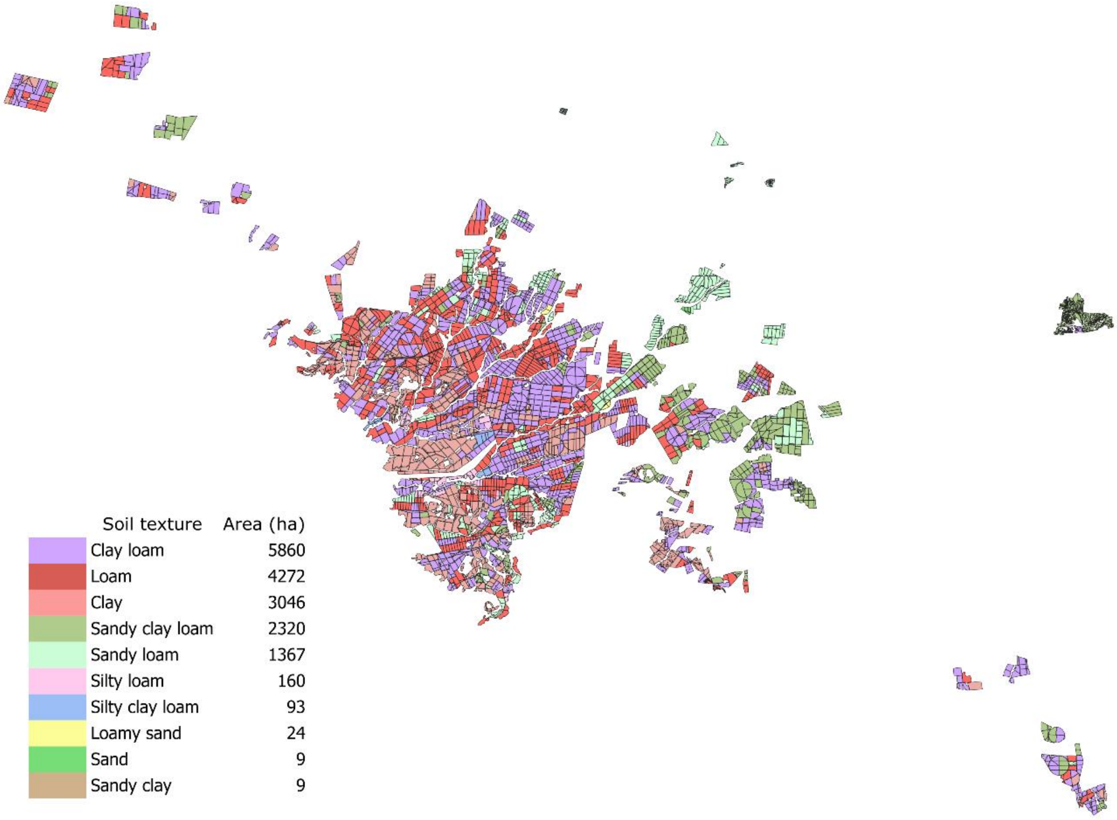

Figure 12. *San Antonio soil textural classification map.*

Table 7. *San Antonio soil analyses result distributed by FHIA soil fertility ranges.*

Nutrient	Low	Low/ Normal	Normal	Normal/ High	High	Total Area (ha)
OM	3,498	4,881	5,704	2,489	586	17,159
N	7,661	8,645	757	-	97	17,159
P	369	4,019	6,626	3,285	2,861	17,159
K	2,999	3,343	2,115	4,596	4,106	17,159
S	11,797	3,454	1,891	-	18	17,159
B	4,900	9,939	2,234	86	-	17,159
Zn	581	1,859	12,893	1,259	568	17,159
Ca	-	86	15,854	564	655	17,159
Cu	-	-	-	712	16,447	17,159
Fe	-	3	9	189	16,958	17,159
Mg	66	30	426	2,786	13,850	17,159
Mn	100	460	7,475	5,474	3,649	17,159
pH	-	550	8,914	5,404	2,291	17,159

3.3.2 Linking soil analyses to productivity

Productivity data expressed as tonnes cane per hectare (tc/ha) plotted against soil analysis data (OM, P, K and S) from eight harvesting seasons (2006-2007 to 2013-2014) for the three main soil texture groups (clay, loam, and clay loam) are shown in Figure 13. The relationships indicated that productivity increased with increased OM in clay and clay loam soils, with increased P in clays, and with increased S in clay and clay loam soils. Little or no effect was observed with K. The marked drop in productivity observed with very high S values in loams suggested that after an initial positive productivity response at lower S values, S may have reached toxicity levels thereafter.

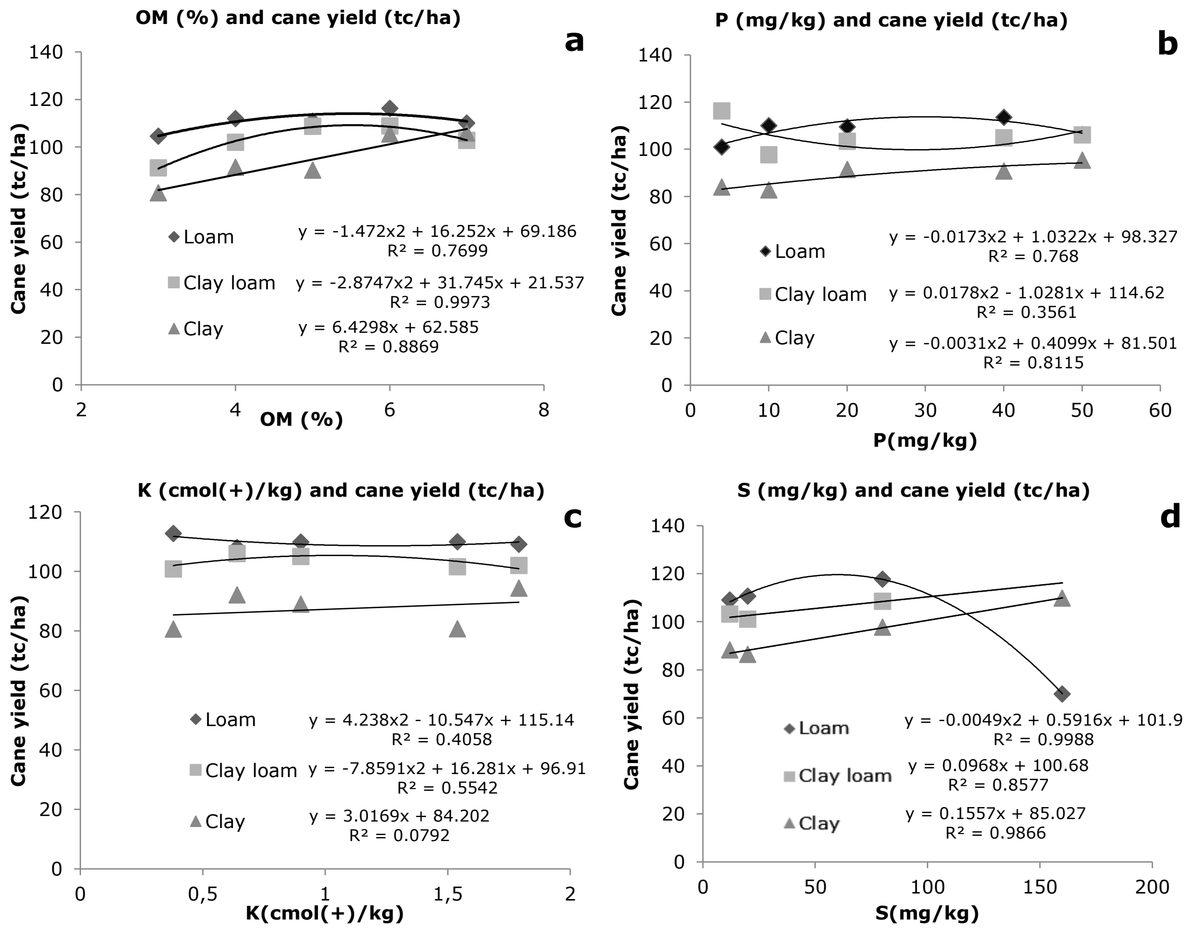

Figure 13. *Cane yield (tc/ha) determined across eight harvesting seasons plotted against soil analysis data: (a) OM (%), (b) P (mg/kg), (c) K (cmol(+)/kg) and (d) S (mg/kg).*

3.3.3 Establishing interim N, P, K and S guidelines

Interim N, P, K and S guidelines for San Antonio were developed by considering existing nutrient management systems that could be used as examples for sugarcane production at San Antonio. These included the Australian SIX EASY STEPS® program (Schroeder *et al*., 2018) and nutritional guidelines developed for the Louisiana sugar industry (Viator *et al*., 2013).

Within the SIX EASY STEPS program, the N fertilizer guidelines are determined from established baseline N requirement for the different regions using district yield potential (DYP) values (Schroeder *et al*., 2005). The DYP is estimated highest average annual district yield multiplied by an index of 1.2. The N requirement suggested by Keating *et al*. (1997) of 1.4 kg N/t cane/ha up to 100 t cane/ha and 1 kg N/t cane/ha is then used in combination with the DYP to set the baseline N requirement. The percentage organic carbon (OC) from soil-test results is used to determine the N mineralization index of the soil and refine the baseline N requirement (Table 8). At San Antonio, the interim N guidelines were based on OM rather than OC.

Table 8. *Australian N guidelines (kg N/ha) based on district yield potential (DYP), organic matter (OM), the equivalent organic carbon (OC) after Schroeder et al., (2005).*

Baseline N guidelines					
OM (%)	**≤ 3.00**	**3.10 – 4.00**	**4.10 – 5.00**	**5.10 – 6.00**	**> 6.00**
OC (%)	**≤1.80**	**1.81 – 2.40**	**2.41 – 3.00**	**3.01 – 3.60**	**> 3.60**
DYP (tc/ha)	**N rates (kg/ha)**				
120	170	160	150	140	130
140	190	180	170	160	150
160	210	200	190	180	170

Louisiana N guidelines are based on yield, crop class (plant and ratoon), soil texture (heavy and light) and response data associated with commercial sugarcane varieties on light and heavy soils (Table 9).

Table 9. *Louisiana N guidelines (kg N/ha) based on LSU AgCenter field trials yield (tc/ha), organic matter (OM), the equivalent organic carbon (OC), crop age (plant and ratoon) and soil texture classification, after Viator et al., (2013).*

N guidelines							
OM (%)			**≤ 3.00**	**3.10-4.00**	**4.10-5.00**	**5.10-6.00**	**>6.00**
OC (%)			**≤1.80**	**1.81-2.40**	**2.41-3.00**	**3.01-3.60**	**>3.60**
Yield (tc/ha)	**Crop age**	**Soil Texture**	**N rates (kg/ha)**				
120	Plant	Light	160	150	140	130	120
		Heavy	170	160	150	140	130
	Ratoon	Light	140	130	120	110	100
		Heavy	150	140	130	120	110
140	Plant	Light	180	170	160	150	140
		Heavy	190	180	170	160	150
	Ratoon	Light	160	150	140	130	120
		Heavy	170	160	150	140	130
160	Plant	Light	200	190	180	170	160
		Heavy	210	210	190	180	170
	Ratoon	Light	180	170	160	150	140
		Heavy	190	180	170	160	150

Table 10. *Phosphorous (P_2O_5) rate recommendation for sugarcane in Louisiana based on Mehlich 3 extraction (B. Tubana, personal communication, October 2014).*

Soil Test Category	**Rate (kg/ha)**
Very low (less than 10 ppm)	50
Low	0
Medium	0
High	0
Very high	0

Table 11. *Potassium (K_2O) rate recommendation for sugarcane in Louisiana based on Mehlich 3 extraction (B. Tubana, personal communication, October 2014).*

Soil Test Category	**Plant cane (kg/ha)**	**Ratoon cane (kg/ha)**
Very low	135	157
Low	123	135
Medium	90	90
High	0	0
Very high	0	0

Table 12. *Sulphur (S) rate recommendation for sugarcane in Louisiana based on Mehlich 3 extraction (B. Tubana, personal communication, October 2014).*

Soil Test Category	Plant cane (kg/ha)	Ratoon cane (kg/ha)
Low (less than 10 ppm)	27	27
High	0	0

Louisiana P, K, and S guidelines are based on Mehlich 3 (M3) extraction (Table 10 - 12). On the other hand, in Nicaragua, for the P soil test, Bray 2 is used for values of soil pH ≤7 or Olsen (sodium bicarbonate) for soil pH > 7, potassium is based on exchangeable potassium (ammonium acetate) and sulphur is tested in a turbidimeter method (monocalcium phosphate extraction). Soil testing methodologies sometimes vary among laboratories and countries and depend on soil types. Therefore, one must know what soil test method was employed before developing fertilization guidelines. In the case of phosphorus, in geographic areas where soils vary in chemical properties, especially in calcareous soils versus noncalcareous, can produce erroneous results when Bray 1 test is used instead of the Olsen test (calibrated for available P in calcareous soil). The M3 test can be used for P and other nutrients across acid, neutral, and high-pH soils.

The M3 extracts the same amount of K as the currently used ammonium acetate test. On the other hand, P soil tests, like the Bray test, produce erroneously low P values in many calcareous soils (Sawyer and Mallarino, 1999).

P guidelines (Table 10) from Louisiana consider application only when soil test levels are less than 10 ppm (same thing for S) and considers that sugarcane removes approximately 0.45 kg of P_2O_5 per ton of cane from the soil. Despite sugarcane removing high quantities of K, (1.36 kg of K_2O per ton of cane from the soil), recommendation nonetheless are linked to the price of potash (Table 11).

Given the above, the following interim N, P, K and S guidelines were established within this study for use at San Antonio:

Nitrogen (N)

N guidelines were based on the highest average yield of preceding two years multiplied by the 'N guidelines factors' provided in Table 13. These 'N factors' are based on a combination of the guidelines from Australia and Louisiana (Table 8 and 9). In the interim guidelines, yields under 120 tc/ha were multiplied by a factor of 1.25 kg N/t cane/ha and the minimum N application rate was 120 kg N/ha, when yield was lower than 100 tc/ha (e.g 80 tc/ha*1.25 kg N/tc=100 kg N/ha, instead apply 120 kg N/ha).

The 'N application factor' decreases as soil OM and OC increase (Table 13). It is higher in heavy textured soils (e.g. clay and clay loam) and in ratoons than in light textured soils (e.g. loam) and in plant cane.

Table 13. *Interim N guidelines based on productivity, OM (%), crop age and texture. Crop yield lower than 120 tc/ha is multiplied by 1.25 kg N/tc.*

OM (%)			**≤ 3.00**	**3.10-4.00**	**4.10-5.00**	**5.10-6.00**	**>6.00**
OC (%)			**≤1.80**	**1.81-2.4**	**2.41-3.00**	**3.01-3.60**	**>3.60**
Yield (tc/ha)	**Crop age**	**Texture**	**N guidelines (kg N/tc)**				
120 - 140	Plant	Light	1.35	1.27	1.19	1.12	1.04
		Heavy	1.40	1.32	1.24	1.15	1.08
	Ratoon	Light	1.44	1.36	1.28	1.20	1.12
		Heavy	1.48	1.40	1.32	1.24	1.16
> 140	Plant	Light	1.28	1.22	1.16	1.09	1.03
		Heavy	1.31	1.25	1.19	1.13	1.06
	Ratoon	Light	1.34	1.28	1.22	1.16	1.09
		Heavy	1.38	1.34	1.25	1.19	1.13

Phosphorus (P)

The interim P rate guidelines (Table 14) were developed to reflect crop class (plant and ratoon), based on Bray 2 P soil test values for soil pH ≤7 or Olsen (sodium bicarbonate) P soil test values for soil pH > 7.

Phosphorus can become unavailable by a process called P-sorption and it can roughly be determined based on the texture of the soil, organic matter content, or if the soil is classified as old (e.g. ultisol and oxisol – which are not commonly found in San Antonio) vs young soils. However, soils with high clay and organic matter content, and classified as old are sometimes categorized as high P Sorption Class. Even though analytical procedures can determine the amount of P release for every unit of P fertilizer added, it is not available in Nicaraguan soil laboratories. In the absence of definitive P-sorption data, P application rates were assumed for moderately P-sorbing soils, since more than 50% of the area have high clay content.

Table 14. *P recommendations rates based on Bray 2 (pH≤7) and Olsen (pH > 7) P test values and moderate P sorption characteristics.*

Phosphorus sorption category	**Crop**	**Bray 2(pH ≤7) and Olsen (pH > 7) (mg/kg)**			
		<= 4.00	**4.10 – 10**	**11 - 30**	**>30**
		Application rate P (kg P_2O_5/ha)			
Moderate	Plant	50	40	30	0
	Ratoon	40	30	20	0

Potassium (K)

The interim K guidelines reflected the particularly low levels of exchangeable K in soil based on the soil analysis data reported in Table 7. As shown in Table 15, K guidelines were based on soil texture (e.g., clay, clay loam, and loam) and crop age (plant or ratoon). It was recommended when soil tests were lower than 250 mg/kg, as shown in Table 15. Higher K rates were recommended for heavy textures and ratoons.

Table 15. *Interim K guidelines based on soil exchangeable K test and texture.*

Texture class	Crop age	Exchangeable K (mg/kg)					
		< 75	75 – 100	100 - 125	125 –150	150 - 250	>250
		K guidelines (kg K_2O)					
Loam	Plant	100	75	50	0	0	0
	Ratoon	125	100	75	50	0	0
Clay loam	Plant	125	100	75	50	0	0
	Ratoon	125	100	100	75	50	0
Clay	Plant	125	100	100	75	50	0
	Ratoon	150	125	100	75	50	0

Sulphur (S)

The interim S guidelines (Table 16) were based on FHIA parameters and S (mg/kg) in soil analysis result (shown in Chapter 2, Table 7) and fine tuning based on Louisiana S recommendations, suggesting that soils with less than 10 ppm of S in soil should be applied (Table 16).

Table 16. *Sulphur guidelines (kg SO_4 /ha) based on organic matter (OM), organic carbon (OC) and Sulphur (S).*

S (mg/kg)	OM (%)		
	≤3.00	3.10 – 6.00	>6.00
	OC (%)		
	≤1.80	1.80 – 3.60	>3.60
<5	20	16	10
5 – 10	15	10	0
>10	0	0	0

3.4 Conclusions

In summary and conclusion:

- By reviewing the information from soil analysis from 2009 to 2015 of San Antonio farms, a lack of information and the necessity to improve soil sampling methodology and resources was observed. Improvements would result in a better understanding of major soil types and their nutrient management and losses.

- Expansion and improvement of soil sampling and data capture resulted in improved identification of major soil types and their physical and chemical properties. Block/plots and farms with deficiency and sufficiency of nutrients could be identified and fertilizer rates could be stablished based on soil requirements.

- Linking productivity associated with eight years of yield data to soil chemical properties such as OM, P, K and S provided a basis for establishing so-called 'red flags' alerting farm management to problem areas and potential issues. This initiative also identified where possible responses to nutrients could occur.

- Interim guidelines were established for N, P, K and S that provided potential for improved use of soil analyses and productivity data. Prior to this study and the development of the interim guidelines, SAR San Antonio used a limited number of fertilizer formulations across the approximate 17,000 ha. After this study, based on soil analyses and productivity, all administered plots have individual nutrient management plans that meet specific requirements.

- The interim guidelines provided a basis for calibration and validation via further investigations and field trials.

CHAPTER 4: DEVELOPING SOIL-SPECIFIC GUIDELINES FOR NITROGEN (N) AND POTASSIUM (K) FOR ALLUVIAL SOILS DERIVED FROM VOLCANIC PARENT MATERIAL IN NICARAGUA

4.1 Introduction

As mentioned previously, sugarcane is produced along the Pacific coast of Nicaragua adjacent to a chain of volcanoes that runs from north to south. This has resulted in distinct soils typically derived from recent volcanic parent material and influenced by the sedimentary coastline. San Antonio is the biggest sugar mill company in Nicaragua with approximately 33,000 ha including commercial farms. Nutrient management guidelines for N and K were being investigated to ensure sustainable sugarcane production into the future, and to ensure that nutrient inputs are based on locally derived norms. Nitrogen has been reported as one of the primary nutrients limiting sugarcane production throughout the world. The recommended rates of N fertilizer for sugarcane production vary between 45 and 300 kg/ha/year (Srivastava and Suarez, 1992). Research by Gopalasundaram *et al*., (2011) demonstrated that sugarcane requires large quantities of potassium as 280 kg K/ha and Donaldson *et al*., (1990) conducted experiments where K fertilization increased biomass production by 20% to 31%.

Most of the Nicaraguan sugarcane industry does not have a clear understanding between fertilizer applied, and the yield resulting from soil fertility.

Nutrients efficiency factors have been described previously by Ladha (2005) and Bell (2015) in terms of N. In this study efficiency factors were also determined for various factors are described in Table 17.

Table 17. *Nitrogen (N) and potassium (K) yield and efficiency factors definitions. Adapted from Ladha (2005) and Bell (2015).*

N and K yield and efficiency factors	Definition
kg N or K applied/tc	Kilograms of N or K per tonne of cane
Crop N or K uptake (kg of N or K/ha)	N or K uptake by the plant according to foliar analyses
Fertilizer N or K uptake (kg of N or K/ha)	Fertilizer N or K uptake compare to zero fertilizer application (e.g soil N or K reserves)

This Chapter covers:

- Development of interim guidelines based on existing expertise, review of soil analyses, and concepts of sugarcane nutrient management and soil fertility as explained on Chapter 3,
- N and K efficiency factors and,
- Establishment of a series of soil calibration trials conducted specifically on alluvial soils derived from volcanic parent material at San Antonio, to determine locally derived guidelines.

4.2 Methodology

4.2.1 Location

The study was conducted in San Antonio sugar mill company located at Chichigalpa, Nicaragua at latitude of 12°31′ 37.32" N and 87°03′07.88" W.

4.2.2 Site selection

Three sites from commercial blocks of sugarcane were chosen based on: K deficiency, low organic matter content and three different textures (loam, clay and clay loam). Soil chemical and physical properties were available from previous soil analyses (Table 18). Sites were chosen according to the type of irrigation system (flood irrigation) to avoid future problems of irrigation schedule and agronomic practices with the commercial field.

Table 18. *Previous soil analyses from experimental sites, showing soil texture, nitrogen (N), organic matter (OM), potassium (K), pH and cation exchange capacity (CEC).*

Site Code	Soil sampling Year	Soil Texture	N (%)	OM (%)	K	pH	CEC (cmol (+) kg)
					(cmol (+) Kg)		
71175	2015	Clay	0.13	2.6	0.2	6.7	52.7
71141	2015	Clay Loam	0.18	3.6	0.4	7.2	30.2
65042	2015	Loam	0.12	2.4	1.1	7.0	26.7

4.2.3 N x K field trial

The investigation consisted of a series of replicated small plot N x K experiments. The study was conducted for 3 years minimum; including one plant crop (PC) and two ratoons (R). Two different sugarcane varieties (CP-731547 and CP-722086) from Canal Point, Florida were used for the field trial.

The treatments applied for N and K were at the rates of 0, 75, 150, 225 kg N/ha as urea and 0, 60, 120 and 180 kg K/ha as muriate of potash, respectively. The treatments were arranged in a randomized factorial complete block design with four replications. This resulted in a total of 64 small plots (Table 19). Row-spacing depended on the previous design of the commercial field (1.50 or 1.75 m). The plot areas at some sites were 90 m^2 (6 rows with a row spacing of 1.50 m and 10 m long), and in others 105 m^2 (6 rows with a row spacing of 1.75m and 10 m long). Gaps of 10 m were established between each plot. The N and K treatment were applied by hand and side dressing to the emerging cane plants at 45 days of age.

Table 19. *General description of N x K experimental sites.*

Site Code	Soil Texture	Sugarcane Variety	Row Spacing (m)	Treatment	#Treatments	#Replicates	#Plots
71175	Clay	CP-731547	1.50	N x K	16	4	64
71141	Clay Loam	CP 731547	1.50	N x K	16	4	64
65042	Loam	CP-722086	1.75	N x K	16	4	64

4.2.4 Planting

The seed cane used for the project was treated with hot water at 51° C for 30 minutes. Once the seed cane was planted it was irrigated to promote germination. All the experimental sites were irrigated by flood irrigation. A quantity of 12-14 eyes/meter were hand planted in all the plots.

4.2.5 Field trials maintenance

Experimental sites were treated as commercial field for agricultural practices except that ripeners and flowering inhibitors were not applied. During the study period, weeds and pests were controlled on an 'as-needs' basis. After mechanical harvesting, empty spaces (depopulation) of more than 1 m were gap-filled with sugarcane billets (seed cane). This agricultural practice is well stablished and recognised as a standard agricultural practice in Central America.

4.2.6 Data collection (Growing phase)

Crop measurements (height and diameter) were recorded during the growing phase of each trial at 5 months. This was done by selecting fifteen stalks from the three middle rows (5 stalks per each row) and were labeled.

4.2.7 Harvesting and yield data

At 345 days, plot yield (tc/ha) was determined by weighting the fifteen stalks already selected and by counting the population of stalks of 5 m from the three centre rows.

The following formula was used to determined plot yield:

$$Cane\ yield\ (tc/ha) = \frac{(number\ of\ stalks/m\ *weight/stalks\ (kg) * effective\ meters/ha)}{1000\ kg}$$

Formula Description:

- 1 ha= 10,000 m^2
- Effective meters/ha= 10,000 m^2/row spacing (e.g 1.50 or 1.75 m)

Two scenarios for calculating cane yield (tc/ha) were used based on the gap-filling practice. The first scenario considered the population (stalk/m^2) results of each small plot from the experimental sites that were gap-filled as needed depending on the depopulation (spaces greater than or equal to 1 m) after mechanical harvesting. As germination is not always 100% efficient and the mechanical harvester did not remove sugarcane stools in all the small plots, the population was variable, thereby a second scenario was proposed. This aimed to manage population (stalks/m^2) through an improved gap-filling practice with good seed germination. This enabled average population per year across the different N and K treatments.

For sugar yield (kg/tc), 5-stalk samples (from the 15 stalks) were collected for commercial cane sugar (CCS) analysis that were performed at San Antonio milling laboratory. The fifteen stalks from the middle rows were cut from the stools, by hand. The sugarcane was not burn pre-harvest. After sampling collection, the rest of the trial was mechanically harvested using a John Deere CH3520 harvester.

4.2.8 Crop nitrogen (N) and potassium (K) uptake

Nitrogen and potassium uptake by the crop (kg N/ha and kg K/ha) was determined from the N and K percent dry matter (% DM) of the 5-stalk biomass samples/plot (stalks, leaves and tops) collected from the first and second ratoon (1R and 2R, respectively).

The 15 stalks, previously selected were divided into: millable stalks and tops which included cabbage and green leaves.

The millable stalk and cabbage, were separated by cutting between the 5th and 6th dewlaps for stalks that had not flowered, or the 7th and 8th dewlaps for stalks that had flowered. All green leaves, even those attached to the millable stalk, were included in the top sample.

Samples were weighed separately using a crane scale (CR-200 kg). Five millables stalks, five tops and two bags of leaves were randomly selected from the fifteen stalks. Samples were washed and weighed (fresh weight) and then were dried in a PREMLAB® oven set at 60 °C. Dry weights were recorded. Shredded sub samples were sent in a paper bag to the laboratory for N and K analysis content. Millable stalks were shredded with a Thomas Model 3 Wiley® mill. Fibre samples with juice (fibre cake), from those samples were also dried and sent to the laboratory for N and K analysis.

4.2.9 Statistics

All trial data was analyzed using Statistix Version 10.0. Analyses of variance was used to determine differences in cane and sugar yield resulting from N and K treatments. Means were separated using Tukey's HSD test. The quadratic functions fitted to the data allowed appropriate N and K application rates to be determined for each trial by determining values corresponding to 99% of the predicted maximum yields on plant and ratoons. The three trials within this study were not considered sufficient to use the usual 95% agronomic discriminator.

4.2.10 Rainfall and weather conditions

Rainfall and other weather conditions were monitored using a Spectrum WatchDog ® 2900ET weather station installed near the experimental sites at San Antonio. Pluviometers installed near the experimental sites were also monitored to check if local weather variations influenced sugarcane productivity.

4.3 Results and discussion

4.3.1 Growing Phase Data

Details of the stalk height and diameters measured during the growing phase (up to 150 days) are provided on Appendix 1.1 to 1.6.

As shown in Table 20, height stalks were significantly taller when N was applied (75, 150, and 225 kg N/ha) versus zero rate in the PC and R crops grown in the three types of soil texture (clay loam, clay, and loam).

In lighter soil textures (clay loam and loam), higher heights were obtained in the 150 and 225 kg N/ha treatments. There was no apparent significant difference between N rates in the case of clay texture. Weather conditions could influence N response in clay texture during the major growth phases. Heavy rainfall is usually associated comes with extreme waterlogging, especially in heavy clays. Such conditions affect crop growth and increase N losses by denitrification (Martens, 2005).

Decreased stalk heights occurred when N was not applied for several years (ratoons) in the clay and clay loam. This was most likely due to soil's physical properties rather than a lack of nutrient reserves. This was in contrast to the loam site where acceptable heights occurred despite no N applied for three years.

Plant crop heights for clay and loam texture were lower than the ratoons. Usually, germination takes about 30 days. This means that ratoon cane at 150 days is taller than corresponding plant crops. Excessive rainfall recorded during the germination and establishment phase for the clay and loam site, also affected growth.

These results showed the need for N to be applied annually, even though the height response on the clay was lower than in the clay loam and loam as shown in Table 20. N x K interactions occurred mainly for clay and loam, as shown in Appendix 1.1 to 1.3.

Table 20. *Effect of nitrogen(N) application rates (kg/ha) on sugarcane height (cm) at growing phase.*

Soil Texture	Crop	Height (cm) by N applied (kg/ha)							
		0		75		150		225	
Clay Loam	PC	185.64	C	183.85	C	192.23	B	212.19	A
	1R	141.00	C	168.47	B	180.10	A	171.88	B
	2R	121.09	D	148.60	C	160.61	B	178.66	A
	3R	89.80	C	118.73	B	127.65	A	125.17	A
	4R	89.44	C	113.82	B	123.77	A	122.68	A
Clay	PC	100.10	B	111.35	A	113.18	A	111.48	A
	1R	141.41	B	153.24	A	145.74	B	145.27	B
	2R	151.17	B	162.65	A	162.65	A	162.06	A
	3R	135.75	C	145.69	A	140.56	B	144.34	AB
	4R	126.80	B	131.73	AB	133.40	A	134.61	A
Loam	PC	170.76	C	178.33	B	184.18	A	184.32	A
	1R	211.55	C	221.00	B	242.29	A	241.67	A
	2R	217.36	C	246.98	B	258.11	A	258.63	A

A, B, C, D *Means accompanied by the same letter in a group are "not significantly different".*
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3, 4R: ratoon 4.*

Smaller stalk diameters were observed when zero N fertilizer was applied to all three soil textures (Table 21). Significantly higher diameters of 2.7 mm differences were found in clay loam texture when 225 kg N /ha was applied in 3R, compared to zero N fertilizer. The same trend was found for clay and loam texture with differences of approximate 1 mm in diameter when some N was applied compared to the zero N treatment. As explained by Chapman *et al*., (1996), sugarcane biomass production is highly correlated with N concentrations. Thin and stunted plants are produced when N is deficient.

Table 21. *Effect of nitrogen (N) application rates (kg/ha) on sugarcane stalk diameter (mm) at growing phase.*

Soil Texture	Crop	Stalk diameter (mm) by N applied (kg/ha)							
		0		75		150		225	
Clay Loam	PC	29.38	A	29.00	A	29.20	A	29.16	A
	1R	27.95	B	28.49	A	28.60	A	29.09	A
	2R	28.13	C	29.04	B	28.85	B	29.72	A
	3R	27.33	B	29.48	A	29.94	A	30.03	A
	4R	28.61	B	30.03	A	30.20	A	30.51	A
Clay	PC	27.17	B	28.28	A	28.39	A	27.65	AB
	1R	27.87	B	28.88	A	28.81	A	28.49	AB
	2R	26.53	B	27.60	A	27.30	A	27.83	A
	3R	26.76	B	27.80	A	27.65	A	27.33	AB
	4R	28.14	A	28.00	A	28.26	A	28.15	A
Loam	PC	27.93	A	27.33	B	27.42	AB	27.75	AB
	1R	25.41	B	26.61	A	26.18	A	26.30	A
	2R	25.32	B	26.43	A	26.68	A	26.45	A

$^{A, B, C, D}$ Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3, 4R: ratoon 4.*

4.3.2 Cane stalk population and weight response to nitrogen (N) and potassium (K) application

At San Antonio, sugarcane yield is often estimated using the cane weight and stalk population. It is of significant concern that these two variables should be analyzed separately. Mechanical harvesting, bad germination, seed health, and other factors can lead to a low population. In contrast, cane weight is less influenced by these factors and is more related to nutritional requirements.

Even though some significant responses in sugarcane population (stalks/m^2) were obtained, population was not influenced by N or K application rates in the three types of soil texture (clay, clay loam, and loam) as shown in Table 22 and Appendix 1.7 to Appendix 1.9.

A relevant factor was the decrease in population after mechanical harvesting associated with all the treatments and the increase in population influenced by agricultural practices such as gap filling as needed (as explained in methodology 4.2.5).

Despite the same number of eye buds at establishment, a lower stalk population was found in the clay soil compared to the clay loam and loam (Table 22). Germination is influenced by soil moisture, temperature, and aeration (Bonnett, 2013). Clay soils usually drain slowly, causing restricted aeration. As the experimental site was established with flood irrigation and heavy rainfall was also recorded, these factors could have contributed to the decrease in germination in the clay soil.

Table 22. *Effect of nitrogen (N) application rates (kg/ha) on sugarcane population (stalks/m²).*

Soil Texture	Crop	Population (Stalks/m²) by N applied (kg/ha)							
		0		75		150		225	
Clay Loam	PC	6.46	B	6.70	A	6.48	B	6.26	C
	1R	5.92	BC	6.20	A	6.11	AB	5.89	C
	2R	6.46	A	6.37	A	6.28	A	6.34	A
	3R	6.57	A	6.46	A	6.27	B	6.17	B
Clay	PC	5.62	B	5.67	B	5.69	B	5.99	A
	1R	5.92	C	6.77	A	6.26	B	6.39	B
	2R	5.68	B	5.93	A	5.58	B	5.99	A
	3R	5.96	B	5.95	B	6.12	A	5.98	B
Loam	PC	6.82	A	6.45	B	6.49	B	6.83	A
	1R	7.14	B	7.44	A	7.18	B	6.73	C
	2R	6.81	B	7.10	A	6.89	B	6.59	C

A, B, C Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

The increased weights in plant cane were obtained with 150 kg N/ha rate for clay loam and loam, and 225 kg N/ha for clay texture (Table 23). N requirement in clay loam increased in older ratoons with 150 kg N/ha in 1R and 225 kg N/ha in 2R and 3R. In contrast, 150 kg N/ha was the optimum rate in ratoons for clay and loam.

Lower weights were obtained in the clay when compared to the clay loam and loam. It was also observed that despite the same amount of N being applied over the years weights generally decreased from the PC to the ratoons. As seen in Table 23, generally lower weights were obtained in the 1R and 2R crops compared to the PC at the clay and clay loam sites.

Previous research by Chapman *et al*., (1996) reported that good draining soils produce longer ratoon crops than soils with compaction problems and bad drainage as in heavy soils.

Table 23. *Effect of nitrogen (N) application rates (kg/ha) on sugarcane weight/stalks (kg).*

Soil Texture	**Crop**	**Weight/stalks (kg) by N applied (kg/ha)**							
		0		**75**		**150**		**225**	
Clay Loam	PC	1.81	B	1.71	C	1.93	A	1.98	A
	1R	1.32	C	1.52	B	1.65	A	1.58	B
	2R	1.40	D	1.49	C	1.56	B	1.72	A
	3R	1.59	C	1.84	B	1.82	B	1.96	A
Clay	PC	1.45	C	1.45	C	1.54	B	1.59	A
	1R	1.18	B	1.32	A	1.27	A	1.27	A
	2R	1.36	c	1.50	B	1.63	A	1.45	B
	3R	1.27	C	1.41	B	1.45	A	1.45	A
Loam	PC	1.73	C	1.79	B	1.83	A	1.83	A
	1R	1.44	B	1.48	B	1.56	A	1.53	A
	2R	1.29	B	1.32	B	1.41	A	1.42	A

[A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

High precipitation (mm) in combination with low solar radiation (MJ/m^2) during critical physiological phases (germination and establishment, tillering, and major growth phase) can influence biomass production (Tables 24 and 25). As seen in Table 23, lower weights were obtained in 1R and 2R for clay and clay loam sites. The highest accumulated precipitation and lower solar radiations in comparison with previous years were also found in 1R and 2R. Moore *et al*., (2013) described research performed by Glaz *et al*., (2004), in which the effect of flooding reduced cane and sugar yield. Castro (2010), in studies performed in Guatemala (Central America), related solar radiation (MJ/m^2/day) to productivity, concluding that years with higher solar radiation in critical physiological phases from tillering to major growth phase, resulted in improved sugarcane productivity.

Table 24. *Accumulated precipitation (mm) distributed by sugarcane phenological stages in three experimental sites (loam, clay loam and clay). Data was recorded by the nearest pluviometer established in San Antonio farms.*

Accumulated Precipitation (mm)							
Texture	**Crop**	**Planting / Harvesting Date**	**Germination and establishment**	**Tillering**	**Major Growth Phase**	**Ripening**	**Accumulated Precipitation**
Clay Loam	PC	January 24, 2015	0	20	789	176	985
	1R	January 9, 2016	0	74	916	400	1390
	2R	December 23, 2016	35	0	1192	689	1916
	3R	December 10, 2017	0	2	526	713	1241
Clay	PC	February 19, 2015	0	220	710	43	974
	1R	February 29, 2016	0	598	785	33	1416
	2R	February 22, 2017	0	620	1298	0	1919
	3R	January 21, 2018	0	157	1099	36	1292
Loam	PC	April 30, 2015	190	132	845	116	1283
	1R	May 3, 2016	568	382	574	1	1525
	2R	April 24, 2017	203	691	1025	5	1923

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 25. *Average solar radiation ($MJ/m^2/day$) distributed by sugarcane phenological stages. Data was provided from weather stations installed in San Antonio.*

Average solar Radiation (MJ/m^2)						
Texture	**Crop**	**Planting / Harvesting Date**	**Germination and establishment**	**Tillering**	**Major Growth Phase**	**Ripening**
Clay Loam	PC	January 24, 2015	21	20	18	20
	1R	January 9, 2016	21	18	18	17
	2R	December 23, 2016	20	21	17	17
	3R	December 10, 2017	20	21	18	18
Clay	PC	February 19, 2015	21	19	18	21
	1R	February 29, 2016	20	17	18	20
	2R	February 22, 2017	20	17	17	20
	3R	January 21, 2018	21	19	17	20
Loam	PC	April 30, 2015	18	18	19	19
	1R	May 3, 2016	17	18	18	20
	2R	April 24, 2017	16	17	18	21

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

4.3.3 Response curves for N fertilizer application rates in cane yield (tc/ha) under two population (stalks/m^2) scenarios.

Based on the population studies (section 4.3.2), two scenarios were proposed for developing the yield response curves (tc/ha); scenario a, with field trial population results (stalks/m^2/plot), and scenario b, assuming an average population for the whole year, taking into consideration a homogenous population as San Antonio routinely gap fill in row spaces equal or higher 1 m (Table 26).

Table 26. *Sugarcane population (stalks/m^2) used for response curves. Scenario a: with population data from field trial results. Scenario b: with average population data per year.*

Soil Texture	Crop	Scenario a: Population (stalks/m^2) by N applied (kg/ha)								Scenario b
		0		75		150		225		Average
Clay Loam	PC	6.46	B	6.70	A	6.48	B	6.26	C	6.48
	1R	5.92	BC	6.20	A	6.11	AB	5.89	C	6.03
	2R	6.46	A	6.37	A	6.28	A	6.34	A	6.36
	3R	6.57	A	6.46	A	6.27	B	6.17	B	6.37
Clay	PC	5.62	B	5.67	B	5.69	B	5.99	A	5.74
	1R	5.92	C	6.77	A	6.26	B	6.39	B	6.34
	2R	5.68	B	5.93	A	5.58	B	5.99	A	5.80
	3R	5.96	B	5.95	B	6.12	A	5.98	B	6.00
Loam	PC	6.82	A	6.45	B	6.49	B	6.83	A	6.65
	1R	7.14	B	7.44	A	7.18	B	6.73	C	7.12
	2R	6.81	B	7.10	A	6.89	B	6.59	C	6.85

A, B, C Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Based on statistical analysis results (Appendix 1.13-1.18), higher cane yields (tc/ha) for both population scenarios (a and b) were obtained in the 150 to 225 Kg N/ha range. N x K interactions occurred, indicating that improved responses to applied N were possible when some K fertilizer was applied (Appendix 1.13 to 1.18).

Optimum rate response curves were generated based on cane yield results from experimental sites (clay loam, clay, and loam) using the two population scenarios (a and b) and N and K rate field experiments (Appendix 2.1 to 2.6).

The optimum N rates were often much lower than the interim N rates (Table 27) previously discussed in Chapter 3.3.3. However, the optimum N rates varied from one year to the next in response to changes in climatic conditions, as shown in Tables 24 and 25. The differences in optimum N rates among years show the importance of a more thorough investigation into the impact of climatic conditions on nutrient (N and K) fertilizer requirements.

Table 27. *Cane yield response curves with the 99% of the maximum yield predicted (kg N/ha) results by crop (plant and ratoons) and soil texture (clay loam, clay, and loam). Scenario a: with population data from field trial results. Scenario b: with average population data per year.*

Soil texture and Crop	**Scenario a**			**Scenario b**		
	Cane yield (tc/ha)	**Interim guidelines (kg N/ha)**	**Optimum N rate (kg N/ha)**	**Cane yield (tc/ha)**	**Interim guidelines (kg N/ha)**	**Optimum N rate (kg N/ha)**
Clay loam						
PC	116	144	0	114	143	0
1R	99	124	105	98	123	120
2R	91	114	0	87	120	0
3R	119	148	180	124	173	200
Clay						
PC	81	120	0	82	120	0
1R	85	120	100	83	120	100
2R	91	120	100	92	120	100
3R	90	120	160	90	120	160
Loam						
PC	117	146	90	119	150	90
1R	114	142	160	109	137	110
2R	98	122	140	102	127	390

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

On the other hand, the optimum K rates were often higher than the interim K rates (Table 28) discussed in Chapter 3.3.3.

As shown in Table 15, Chapter 3, K guidelines were based on heavy (e.g., clay, clay loam) and light soil textures (e.g., loam, sandy loam), and it was recommended when soil tests were deficient (e.g., <0.26 cmol (+)/kg K), because of high prices of potash.

Table 28. *Cane yield response curves with the 99% of the maximum yield predicted (kg K/ha) results by crop (plant and ratoons) and soil texture (clay loam, clay, and loam). Scenario a: with population data from field trial results. Scenario b: with average population data per year.*

Soil texture and Crop	**Scenario a**			**Scenario b**		
	Cane yield (tc/ha)	**Interim Guidelines (kg K/ha)**	**Optimum K rate (kg K/ha)**	**Cane yield (tc/ha)**	**Interim Guidelines (kg K/ha)**	**Optimum K rate (kg K/ha)**
Clay loam						
P	123	0	60	122	0	50
1R	91	0	130	92	0	120
2R	98	100	200	98	100	50
3R	114	100	170	115	100	40
Clay						
P	91	125	80	90	125	80
1R	83	150	90	83	150	170
2R	96	75	280	88	75	170
3R	84	100	0	82	100	100
Loam						
P	135	0	390	115	0	0
1R	108	0	120	108	0	160
2R	95	0	100	94	0	120

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

4.3.4 Response curves for nitrogen (N) and potassium (K) application rates in sugar:

Soil nutrient management can be used to maximize sugar concentration. However, Buenaventura (1986) explained that sucrose concentration depends on several factors, such as weather conditions and sugarcane varieties. High sucrose concentrations and low yields or vice versa characterize some varieties.

Although guidelines for N and K rate applications based on sugar response were not developed in the past for San Antonio, information about sugar yields (kg sugar/tc) have continued to be available.

Table 29 shows varietal differences in sugarcane sugar yields. The two sugarcane varieties used for this study (CP -722086 and CP -731547) are lower in sugar content, but were the principal varieties planted in San Antonio, representing more than 40% of the land.

Table 29. *Productivity information of San Antonio principal sugarcane varieties from 2014-2015 harvesting season to 2021-2022.*

Harvest Season	**CP-722086**		**CP-731547**		**CP-001101**		**CP-892143**	
	Yield							
	kg sugar/tc	**tc/ha**	**kg sugar/tc**	**tc/ha**	**kg sugar/tc**	**tc/ha**	**kg sugar/tc**	**tc/ha**
2014-2015	106	88	105	114	118	103	112	110
2015-2016	95	86	103	111	112	105	106	101
2016-2017	99	93	106	119	110	98	106	107
2017-2018	103	93	104	120	114	102	105	111
2018-2019	104	91	108	121	117	108	109	113
2019-2020	103	91	102	125	115	110	108	113
2020-2021	106	91	95	125	115	107	110	106
2021-2022	104	105	103	130	113	121	111	121
2022-2023	105	94	104	107	107	111	111	106

Sugar yield response curves to applied N and K fertilizer are provided in Appendixes 2.7 to 2.12.

Table 30 shows a small yield response to applied N (10 kg N/ha) for N application in heavy textured soils (clay loam and clay) in plant crops, compared to loam texture, where the optimum rate was 170 kg N/ha. Optimum N rates are in the range of 10 to 170 kg N/ha based on response curves and just one case of a high rate of 270 kg N/ha.

Research performed by Muchow and Robertson (1994) has shown that higher rates of N can contribute to continued vegetative growth and reduced sucrose concentration, and Das (1936) described that high N concentrations could also lead to increased amounts of the reducing sugars (glucose and fructose) in juice.

Response patterns to applied N and K differed between plant and ratoon crops and could be related to weather inconsistency. As mentioned previously, the wettest year for the clay and clay loam sites were 1R and

2R (Table 24). Also, high rainfall was recorded during the ripening period in the clay site. High rainfall or heavy irrigation in the ripening stage is undesirable and could result in intense growth, decreases in sucrose accumulation, and delayed ripening (Cardozo and Sentelhas, 2013).

Table 30. *Optimum N and K rates for sugar yield (with the 99% of the maximum yield predicted). Results by crop (plant and ratoons) and soil texture (clay loam, clay, and loam).*

Soil texture and Crop	Response to N		Response to K	
	Sugar yield (kg/tc)	Optimum N rate (kg N/ha)	Sugar yield (kg/tc)	Optimum K rate (kg K/ha)
Clay loam				
PC	153	10	-	0
1R	163	100	-	0
2R	158	110	156	30
3R	153	270	-	0
Clay				
PC	165	10	168	240
1R	166	140	-	0
2R	-	0	158	20
3R	-	0	-	0
Loam				
PC	152	170	-	0
1R	164	170	166	120
2R	-	0	158	130

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

4.3.5 Crop N and K uptake results

The Nicaraguan sugarcane industry needs to differentiate between fertilizer N applied and the cane yield derived from soil fertility. The following results show crop N and K uptake where there is no N and K application and different N and K fertilizer rates.

The amount of N and fertilizer uptake by sugarcane in plant cane and ratoons are reported in Table 31. As expected, the higher N rates tended to have higher crop N uptake (kg N/ha) than the lower N rates. At most sites, except for clay loam 2R, N uptake increased as the crop cycle progressed from first to second (loam site) and third ratoon (clay loam and clay).

N is taken up by plants as NO_3^- (nitrate) and NH_4^+ (ammonium). The primary N source found naturally in the soil is organic matter. Mineralization of organic matter is a continuing process (Masclaux-Daubresse *et al*., 2010) that depends on temperature, moisture, soil type, organic matter residues, and soil pH (Abdelmagid, 1980; Schimel and Bennett, 2004; Stanford & Smith, 1972). As shown in Table 31, increased N uptake was recorded in the loam site than in heavier textures such as clay loam and clay.

N uptake in the first ratoon was higher in clay loam when N fertilizer was not applied than in the other sites. Soil analyses from experimental sites reported in Table 17 show higher OM content (3.6%) in clay loam than in clay (2.6%) and loam (2.4%).

As demonstrated by Gopalasundaram *et al*., (2011), sugarcane removes substantial quantities of N (208 kg N/ha). The highest crop N uptakes found in this study were 187 kg N/ha in clay loam, 175 kg N/ha in clay, and 199 kg N/ha in loam texture. The highest uptake previously reported was found with the highest rate of N fertilizer (225 kg/ha) except for loam texture (150 kg N/ha).

The fertilizer N recovered in these experiments ranged from 5% (4 kg N/ha) in clay to 41% (31 kg N/ha) in loam, as reported in Table 31. Even though urea was applied sub-surface near the cane row, fertilizer recovery was poor in the highest fertilizer rates (150 and 225 kg N/ha) in the clay loam site in the 1R and 2R. N can be lost by ammonia volatilization, denitrification, and NO_3- leaching, as explained previously in Chapter 2.

The potential for N losses in heavier textures as clay and clay loam are higher than in lighter textures as loam, especially in wet years when the crop can experience waterlogged conditions; this is likely to reduce the ability of the crop to acquire N fertilizer and lose N by denitrification.

According to FHIA parameters, OM below 3% is considered low. However, including nil N fertilizer treatments in these experiments allowed us to observe a good contribution of N taken up by the plant. As shown in Table 17, the OM content per site was 2.6, 3.6, and 2.4 for clay, clay loam, and loam, respectively. N uptake in nil N fertilizer treatments ranged from 94 to 134 kg N/ha in clay, 102 to 171 kg N/ha in clay loam, and 98 to 145 kg N/ha in loam texture.

Table 32 presents the K and K fertilizer uptake by sugarcane across plant and ratoon cycles. It was observed that higher K fertilizer rates resulted in greater crop K uptake (kg/ha) compared to lower K rates, except for the loam site. In the loam site, K uptake increased as the crop cycle progressed from the first to the second ratoon. In contrast, for the clay and clay loam site, there was a decrease in K uptake during 2R followed by an increase in 3R.

Table 31. *Crop N uptake (kg N/ha) and fertilizer N uptake (kg N/ha) results by ratoons (1R-3R) soil textures (clay loam, clay, and loam) and N fertilizer rates (75, 150, and 225 kg N/ha).*

Soil texture and N Rate	1R		2R		3R	
	Crop N Uptake (kg N/ha)	Fertilizer N Uptake (kg N/ha)	Crop N Uptake (kg N/ha)	Fertilizer N Uptake (kg N/ha)	Crop N Uptake (kg N/ha)	Fertilizer N Uptake (kg N/ha)
Clay Loam						
0	102	0	78	0	171	0
75	112	10	92	14	179	8
150	113	11	120	42	179	8
225	120	18	103	25	187	16
Clay						
0	94	0	123	0	134	0
75	112	18	127	4	145	11
150	106	12	158	35	170	37
225	145	51	148	25	175	42
Loam						
0	98	0	145	0	-	-
75	119	21	176	31	-	-
150	127	29	199	54	-	-
225	116	18	193	48	-	-

**1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 32. *Crop K uptake (kg K/ha) and fertilizer K uptake (kg K/ha) results by ratoons (1R-3R) soil textures (clay loam, clay and loam) and K fertilizer rates (60, 120, and 180 kg K/ha).*

Soil texture and K Rate	1R		2R		3R	
	Crop K uptake (kg K/ha)	Fertilizer K uptake (kg K/ha)	Crop K uptake (kg K/ha)	Fertilizer K uptake (kg K/ha)	Crop K uptake (kg K/ha)	Fertilizer K uptake (kg K/ha)
Clay Loam						
0	138	0	106	0	280	0
60	149	11	125	19	295	14
120	165	27	133	28	309	29
180	168	30	126	20	315	35
Clay						
0	115	0	98	0	147	0
60	132	17	114	16	222	75
120	154	38	148	49	203	56
180	147	31	156	57	206	59
Loam						
0	222	0	362	0	-	-
60	206	-16	311	-51	-	-
120	232	11	326	-37	-	-
180	227	6	304	-58	-	-

**1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

According to Kee Kwong *et al*., (2006), the amount of K removed by sugarcane plants depends on the soil reserves and several conditions. In Australia, 198 kg K/ha was found in aboveground biomass for a crop of 84 tc/ha (Chapman, 1996), while under rainfed conditions in South Africa, the value was 214 kg K/ha. In the Histosols of Florida, 343 kg K/ha was found (Coale *et al*., 1993), and in South African soils under irrigation conditions, 790 kg K/ha was reported (Wood, 1990).

Table 32 shows that K uptakes of 362 kg K /ha were recorded under an irrigated loam site, with the lowest uptake being 206 kg K/ha. As mentioned earlier in Table 17, the soil analysis conducted in 2015 indicated high K concentrations in the soil [(1.1 cmol(+)/kg) relative to the clay (0.2 cmol (+)/kg) and clay loam site (0.4 cmol(+)/kg)]. As expected, with no K fertilizer application, the recovery rate was higher in the loam site (1R=222 and 2R=362 kg K/ha) compared to clay loam (1R=138, 2R=106 and 3R=280 kg K/ha) and clay (1R=115, 2R=98, and 3R=147 kg K/ha), based on soil analyses.

K fertilizer uptake recovery ranged from full recovery in the 3R clay site with 75 kg K/ha in 60 kg K/ha fertilizer rate to a non-recovery in the loam site when K concentrations in soil were already high.

4.3.6 NUE (kg N applied /tc) and KUE (kg K applied/tc)

Nitrogen use efficiency (NUE) is a new concept in the Nicaraguan sugar industry. The results shown in Table 33 relate exclusively to N applied per tonne of cane by N/tc, but other efficiency indexes such as tc/kg N applied, Agronomic Efficiency of Fertilizer N, among others, have previously been described by Ladha (2005) and Bell (2015). Improvements in NUE should be managed by applying less fertilizer to achieve the same yield, obtain higher yields with less fertilizer, or greater yields with the same amount of fertilizer.

As previously discussed, two scenarios with two different populations were used for cane yield. One used actual data, and the other used a homogenous population for all the plots with gap filling (Table 26). Assuming more stalks/m^2 using this practice was expected to obtain higher cane yields and use less kg N applied/tc, assuming dilution by volume of cane. However, because an average population per year was used, the data from scenario a was sometimes higher than scenario b. Slight differences were found among scenarios based on kg N applied/tc. However, it can be assumed that NUE can be improved by obtaining greater yields based on agricultural practices as gap filling.

According to Table 33 results, it is not efficient to use N fertilizer rates of 225 kg N/ha with the cane yield results obtained in the experimental sites; results are above 2 kg N applied/tc. As suggested by Bell (2015), higher yields (e.g.,> 120 t/ha) are generally associated with a NUE value of 0.8 to 1.2 t cane/kg N, whereas higher NUE values (i.e. > 2 t cane/kg N) are mainly associated with yields < 100 t/ha. Considering Nicaragua’s high urea prices during the last harvesting seasons (bagged urea at US $ 55 USD, US US $2.64 per kg N), it seems unprofitable for the Nicaraguan growers.

As expected, kg N applied/tc are lower in plant cane than ratoons and increase as the crop progresses (Table 33). Also, weather conditions previously explained affected cane yield in 1R and 2R and, consequently, NUE.

Table 33*. Nitrogen use efficiency (kg N applied/tc) using two scenarios (a and b) of population (stalks/m^2) in three types of soil texture (clay loam, clay, and loam), crop age (plant and ratoons) and different N fertilizer rates. Scenario a: with population data from field trial results. Scenario b: with average population data per year.*

N Rate (kg N/ha)	PC		1R		2R		3R	
	a	b	a	b	a	b	a	b
	NUE (kg N/tc)							
Clay Loam								
75	0.66	0.68	0.80	0.84	0.79	0.79	0.63	0.62
150	1.20	1.20	1.48	1.52	1.53	1.52	1.31	1.26
225	1.82	1.76	2.42	2.38	2.06	1.98	1.86	1.84
Clay								
75	0.91	0.90	0.84	0.90	0.84	0.86	0.89	0.89
150	1.69	1.68	1.86	1.80	1.63	1.54	1.64	1.66
225	2.32	2.42	2.73	2.78	2.54	2.68	2.56	2.59
Loam								
75	0.65	0.63	0.68	0.71	0.80	0.84	-	-
150	1.26	1.23	1.34	1.36	1.55	1.56	-	-
225	1.80	1.85	2.18	2.18	2.40	2.38	-	-

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Many terms define potassium (K) use efficiency of plants (White *et al.*, 2021). The most common in agriculture is agronomic KUE (potassium use efficiency), which is crop yield per unit of K available from the soil plus fertilizer. In sugarcane, attention has focused on NUE rather than KUE. Results in Table 34 show KUE data relating K fertilizer applied to cane yield (kg K applied/tc).

As expected, kg K applied/tc are lower in plant crop than ratoons and increase as the crop progresses, with an exception in the clay loam in the 3R crop. Slight differences were found among scenarios based on kg K applied/tc. However, it can be assumed that KUE can be improved by obtaining greater yields based on agricultural practices such as gap filling.

Adverse soil properties affect multiple aspects of crop growth and therefore productivity (tc/ha) and nutrient use efficiency.

For example, compacted soils influence root penetration, water availability and consequently nutrient uptake. Heavier soil textures such as clay loam and clay are more difficult to manage.

Clay soils have smaller pores than lighter soils and have higher water holding capacity, usually with bad drainage and issues related to compaction. To increase nutrient efficiency (e.g N and K) is not just about to apply the right rate at the right time and the right place, it is also to manage the other agronomic practices depending on the soil type as improving drainage and soil structure (e.g compaction). As shown in Table 34, KUE is lower in the loam. It can be assumed that roots can more easily uptake nutrients, plants grow better and as a consequence produce greater yields.

Table 34*. Potassium use efficiency (kg K applied/tc) using two scenarios (a and b) of population (stalks/m^2) in three types of soil texture (clay loam, clay, and loam), crop age (plant and ratoons) and different K fertilizer rates. Scenario a: with population data from field trial results. Scenario b: with average population data per year.*

K Rate (kg K/ha)	**PC**		**1R**		**2R**		**3R**	
	a	**b**	**a**	**b**	**a**	**b**	**a**	**b**
	KUE (kg K/tc)							
Clay Loam								
60	0.48	0.48	0.65	0.63	0.59	0.62	0.52	0.54
120	0.99	1.00	1.31	1.36	1.27	1.19	1.03	0.97
180	1.52	1.50	2.00	2.08	1.82	1.75	1.57	1.54
Clay								
60	0.65	0.67	0.75	0.70	0.70	0.68	0.70	0.72
120	1.34	1.33	1.42	1.54	1.35	1.34	1.44	1.51
180	2.01	2.03	2.24	2.09	1.96	2.06	2.08	2.16
Loam								
60	0.52	0.51	0.53	0.57	0.63	0.66	-	-
120	0.96	0.99	1.12	1.14	1.27	1.27	-	-
180	1.44	1.47	1.72	1.70	2.03	2.05	-	-

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

4.4 Conclusions and final remarks

In summary:

- Optimum N rate based on response curves changed from year to year, mainly because of climate variability and agricultural practices as mechanical harvesting (e.g. depopulation) and gap filling.
- Sugarcane plant crops grown in heavy textured soils (clay and clay loam) did not indicate a response to applied N.
- Sugarcane plant crops grown in loam texture respond to N applications at 90 kg N/ha, lower than ratoons (160 and 140 kg N/ha for 1R and 2R, respectively).
- K uptake among the three types of textures (clay, clay loam and loam) is higher than N uptake, however the impact of K on sugar cane growth and yield is not as marked as that of N.
- Nitrogen and K uptake by the plant can be influenced by abiotic stress like flooding and lower solar radiation.
- San Antonio soils tested in this study indicated good fertility soil reserve, demonstrated by K and N uptake in nil N and K treatments.
- Nutrient use efficiency factor should be taken in consideration for nutrient management decisions.
- Nutrient use efficiency can be improved by maintaining stalk population and managing depopulation by filling gaps.
- Despite promising results from this soil calibration study, further investigation is required to ensure extrapolation of guidelines to a wider range of soil textures, different sugarcane varieties and irrigation management practices including rainfed, drip and pivot irrigation systems.

CHAPTER 5: DEVELOPING SOIL-SPECIFIC GUIDELINES FOR PHOSPHORUS (P) FOR ALLUVIAL SOILS DERIVED FROM VOLCANIC PARENT MATERIAL IN NICARAGUA

5.1 Introduction

The location and genesis of soils within the sugarcane-producing enterprises in north western Nicaragua (as mentioned previously) also have implications for phosphorus (P) fertilizer management. P inputs have traditionally been based on guidelines developed elsewhere. Modified nutrient management guidelines are being investigated on clay, clay loam and sandy loam soils plot to ensure sustainable sugarcane production into the future, and to ensure that nutrient inputs are based on locally derived norms. Although P is taken up in small quantity compared to N and K, it plays an important role in photosynthesis, root development and tillering (Meyer and Wood, 2001). It is also required for energy-rich bonds (ADP and ATP) and contribute to maturation of crops (Kingston, 2014).

This Chapter covers:

- Development of interim P guidelines based on existing expertise, review of soil analyses, and concepts of sugarcane nutrient management and soil fertility as explained on Chapter 3.
- Establishment of a series of soil calibration trials conducted specifically on alluvial soils derived from volcanic parent material at San Antonio.

5.2 Methodology

5.2.1 Location

The study was conducted in San Antonio sugar Mill Company located at Chichigalpa, Nicaragua at latitude of 12°31′ 37.32" N and 87°03′07.88" W.

5.2.2 Site selection

Three sites of commercial blocks of sugarcane were chosen based on: P deficiency and three different textures (clay, clay loam and sandy loam). Soil chemical and physical properties were available from previous soil analyses (Table 35). Sites were chosen according to the type of irrigation system (flood irrigation) to avoid future problems of irrigation schedule and agronomic practices with the commercial field.

Table 35. *Previous soil analyses from experimental sites, showing soil texture, nitrogen (N), organic matter (OM), potassium (K), pH and cation exchange capacity (CEC).*

Site code	Soil sampling year	Soil texture	P (mg/kg)	N (%)	OM (%)	K (cmol (+) Kg)	pH	CEC (cmol (+) kg)
71175	2015	Clay	31.5	0.13	2.55	0.2	6.7	52.7
71141	2015	Clay loam	9.1	0.18	3.63	0.4	7.2	10.1
71131	2015	Sandy loam	24.8	0.1	1.99	1.5	7.0	4.5

5.2.3 P field trials

The investigation consisted of a series of replicated small plot of P experiments. The study was conducted for 3 years minimum; including a plant crop (PC) and two ratoons (R).

The treatments applied for P were at the rates of 0, 20, 40, 60 kg/ha as diammonium phosphate (DAP). The treatments were arranged in a randomized factorial complete block design with four replications. This resulted in a total of 16 small plots (Table 36).

Row-spacing (1.5 m or 1.75 m) depended on the previous design of the commercial field. The area designated for each plot was therefore either 90 m² (6 rows with a row spacing of 1.50 m and 10 m long) or 105 m² (6 rows with a row spacing of 1.75m and 10 m long). Gaps of 10 m were established between each small plot. Plots were fertilized by hand in the planting furrow below the cane setts. They received further N and K fertilizer 45 days of planting (150 kg N/ha and 100 kg K/ha).

Table 36. *General description of P experimental sites.*

Site code	**Soil texture**	**Sugarcane variety**	**Row spacing (m)**	**Treatment**	**#Treatments**	**#Replicates**	**# Plots**
71141	Clay loam	CP 73-1547	1.75	P	4	4	16
71175	Clay	CP 73-1547	1.50	P	4	4	16
71131	Sandy loam	CP 73-1547	1.50	P	4	4	16

5.2.4 Planting

The seed cane used for the project was hot water treated at 51° C for 30 minutes. Once the seed cane was planted it was irrigated to promote germination. All the experimental sites were irrigated by flood irrigation. The same quantity of eye bud/meter (12-14 eyes/m) were planted in all the plots by hand.

5.2.5 Field trials maintenance

Experimental sites were treated as commercial field for agricultural practices except that ripeners and flowering inhibitors were not applied. During the study period, weeds and pests were controlled on an ‘as-needs’ basis. After mechanical harvesting, empty spaces (depopulation) of more than 1 m were gap-filled with sugarcane billets (seed cane).

5.2.6 Data collection (Growing phase)

Crop measurements (height and diameter) were recorded during the growing phase of each trial at 5 months. This was done by selecting fifteen stalks from the three middle rows (5 stalks per each row) and were labeled.

5.2.7 Harvesting and yield data

At 345 days, plot yield (tc/ha) was determined by weighting the fifteen stalks already selected and by counting the population of stalks of 5 m from the three centre rows already selected. The following formula was used to determined plot yield:

$$Cane\ yield\ (tc/ha) = \frac{(number\ of\ stalks/m\ * weight/stalks\ (kg) * effective\ meters/ha)}{1000\ kg}$$

Formula Description:

- 1 ha= 10,000 m^2
- Effective meters/ha= 10,000 m^2/row spacing (e.g. 1.50 or 1.75 m)

5.2.8 Crop P uptake

P uptake by the crop (kg P/ha) was determined from the P percent dry matter (% DM) of 5-stalk biomass samples/plot (stalks, leaves and tops) collected from the first and second ratoon (1R and 2R, respectively).

From the 15 stalks, previously selected, stalks were divided into: millable stalks and tops which included cabbage and green leaves. The millable stalk and cabbage, were separated by cutting between the 5th and 6th dewlaps for stalks that had not flowered or the 7th and 8th dewlaps for stalks that had flowered. All green leaves were included in the sample of tops, even those attached to the millable stalk. Samples were weighed separately using a crane scale (CR-200 kg). Five millables stalks, five tops and two bags of leaves were randomly selected from the fifteen stalks.

Samples were washed and weighed (fresh weight) and then were dried in a PREMLAB® oven set at 60 °C. Dry weights were recorded. Three shredded sub samples were sent in a paper bag to the laboratory for P analysis content. Millable stalks were shredded with a Thomas Model 3 Wiley® mill. Fibre samples with juice (fibre cake), from those samples were also dried and sent to the laboratory for P analysis.

5.2.9 Statistics

All trial data was analyzed using Statistix Version 10.0. Analyses of variance was used to determine differences in cane and sugar yield resulting from P treatments. Means were separated using Tukey's HSD test. The quadratic functions fitted to the data allowed appropriate P application rates to be determined for each trial by determining values corresponding to 99% of the predicted maximum yields on plant and ratoons. The three trials within this study were not considered sufficient to use the usual 95% agronomic discriminator.

5.3 Results

5.3.1 Growing Phase Data

Stalk, diameter and height were measured during the growing phase (150 days). Statistical analyses revealed no significant differences in height and diameter between treatments for clay (Table 37) and sandy loam texture (Table 39) in plant crops. This could be due to normal soil P content (31.5 and 24.8 mg/kg P_2O_5) compared to low P content (9.1 mg/kg P_20_5) in clay loam texture (Table 35).

Increased heights found in sandy loam textures (Table 39) compared to heavier textures (clay and clay loam) shown in Tables 37 and 38, also suggested that independently of similar values of P content in soil (24.8 and 31 mg/kg), poor physical soil conditions can compromise crop growth.

Table 37. *Effects of P applied rates on stalk height (cm) and stalk diameter (mm) in clay texture.*

Clay texture			
Crop	**P applied (kg/ha)**	**Height (cm)**	**Diameter (mm)**
PC	0	112.8^{A}	28.0^{A}
	20	111.8^{A}	28.1^{A}
	40	109.6^{A}	27.5^{A}
	60	115.1^{A}	26.6^{A}
	Means for P applied	**112.3**	**27.5**
	Tukey HSD$^{0.05}$	P = 10.3 (p = 0.5746)	P = 2.0 (p = 0.1823)
1R	0	154.0^{B}	29.3^{A}
	20	149.4^{B}	29.6^{A}
	40	167.2^{A}	29.1^{A}
	60	156.2^{B}	29.6^{A}
	Means for P applied	**156.7**	**29.4**
	Tukey HSD$^{0.05}$	P = 10.3 (p = 0.0001)	P = 1.5 (p = 0.7823)
2R	0	154.2^{A}	27.8^{A}
	20	156.5^{A}	28.5^{A}
	40	160.3^{A}	27.5^{A}
	60	144.0^{B}	28.1^{A}
	Means for P applied	**153.8**	**28.0**
	Tukey HSD$^{0.05}$	P = 8.3 (p = 0.0000)	P = 1.1 (p = 0.0778)

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 38. *Effects of P applied rates on stalk height (cm) and stalk diameter (mm) in clay loam texture.*

Clay loam texture			
Crop	**P applied (kg/ha)**	**Height (cm)**	**Diameter (mm)**
PC	0	172.1^{B}	29.9^{A}
	20	177.5^{B}	30.0^{A}
	40	189.6^{A}	29.9^{A}
	60	194.7^{A}	30.1^{A}
	Means for P applied	**183.5**	**30.0**
	Tukey HSD$^{0.05}$	P = 11.3 (p = 0.0000)	P = 1.3 (p = 0.9545)
1R	0	142.4^{AB}	28.0^{A}
	20	136^{B}	29.0^{A}
	40	153^{A}	29.4^{A}
	60	153^{A}	29.3^{A}
	Means for P applied	**146.1**	**28.9**
	Tukey HSD$^{0.05}$	P = 10.9 (p = 0.0001)	P = 1.5 (p = 0.0704)
2R	0	137.2^{A}	29.4^{B}
	20	137.7^{A}	29.7^{AB}
	40	129.9^{A}	29.4^{B}
	60	135.4^{A}	31.0^{A}
	Means for P applied	**135.0**	**29.9**
	Tukey HSD$^{0.05}$	P = 9.0 (p = 0.0988)	P = 1.4 (p = 0.0093)

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 39. *Effects of P applied rates in height (cm) and diameter (mm) in sandy loam texture.*

Sandy loam Texture			
Crop	**P applied (kg/ha)**	**Height (cm)**	**Diameter (mm)**
P	0	204.5A	29.9A
	20	211.5A	30.0A
	40	216.4A	29.9A
	60	206.6A	30.1A
	Means for P applied	**209.7**	**30.0**
	Tukey HSD0.05	P = 11.985 (p = 0.0539)	P = 1.512 (p = 0.6792)
R1	0	183.8BC	28.0A
	20	178.8C	29.0A
	40	198.2AB	29.4A
	60	199.7A	29.3A
	Means for P applied	**190.1**	**28.9**
	Tukey HSD0.05	P = 15.335 (p = 0.0005)	P = 1.4873 (p = 0.253)
R2	0	211.2B	29.4A
	20	225.1A	29.7A
	40	228.0A	29.4A
	60	235.0A	31.0A
	Means for P applied	**224.8**	**29.9**
	Tukey HSD0.05	P = 11.332 (p = 0.0000)	P = 1.4494 (p = 0.1919)

A, B, C Means accompanied by the same letter in a group are "not significantly different".

**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

5.3.2 Cane yield

The stalk number, weight and yield associated with the P trials in the clay, clay loam and sandy loam soils are presented in Tables 40,41 and 42.Even though sugarcane grown on the clay loam showed a substantial height response to applied P in the PC and 1R (Table 41) during the grand growth phase (150 days), greater yields were not obtained with higher P rates, at harvesting time. The lower weights at higher P rates could have been because there was stalk deterioration with lodging. It was not expected to observe a P response in older ratoons considering P was only applied at planting time and the clay loam texture has low P content in the soil. P applied at 40 kg/ha of P_2O_5 as diammonium phosphate (DAP) produce greater yields in the clay and in the sandy loam field trials. Overall, it seems that population(stalks/m^2) is affected by depopulation produced by mechanical harvesting. As shown in Table 44 to Table 45 an initial decrease in population occurred to depopulation and a slightly increase in the next season due to the gap-filling practice.

Table 40. *Effect of P applied rates (kg P_2O_5/ha) in weight (kg/stalk), stalks/m^2 and cane yield (tc/ha) in clay texture.*

Clay texture				
Crop	**P applied (kg/ha)**	**Weight (kg)**	**Population (Stalks/m^2)**	**Cane yield (tc/ha)**
PC	0	1.77^{A}	5.64^{AB}	97.75^{A}
	20	1.71^{A}	5.24^{C}	94.86^{A}
	40	1.56^{B}	5.82^{A}	86.11^{B}
	60	1.50^{B}	5.43^{BC}	82.81^{B}
	Means for P applied	**1.63**	**5.54**	**90.4**
	Tukey $HSD^{0.05}$	P = 0.1 (p=0.0000)	P = 0.3 (p=0.0000)	P = 5.7 (p=0.0000)
1R	0	1.45^{B}	6.27^{B}	105.79^{B}
	20	1.39^{B}	7.74^{A}	101.97^{B}
	40	1.65^{A}	7.86^{A}	120.78^{A}
	60	1.41^{B}	7.40^{A}	103.24^{B}
	Means for P applied	**1.48**	**7.32**	**108.0**
	Tukey $HSD^{0.05}$	P = 0.1 (p=0.0000)	P = 0.6 (p=0.0000)	P = 6.5 (p=0.0000)
2R	0	1.56^{B}	5.49B	87.41B
	20	1.60^{B}	5.86^{A}	89.62^{B}
	40	1.73^{A}	5.47^{B}	97.00^{A}
	60	1.46^{C}	5.64^{AB}	81.89^{C}
	Means for P applied	**1.58**	**5.61**	**89.0**
	Tukey HSD0.05	P = 0.1 (p=0.0000)	P = 0.2 (p=0.0000)	P = 4.9 (p=0.0000)

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 41. *Effect of P applied rates (kg P_2O_5/ha) in weight (kg/stalk), stalks/m^2 and cane yield (tc/ha) in clay loam texture.*

Clay loam texture				
Crop	**P applied (kg/ha)**	**Weight (kg)**	**Stalks/m^2**	**tc/ha**
PC	0	1.90^{A}	7.39^{A}	123.4^{A}
	20	1.75^{B}	6.18^{B}	113.5^{B}
	40	1.74^{B}	6.3^{B}	112.9^{B}
	60	1.78^{B}	6.07^{B}	115.7^{B}
	Means for P applied	**1.79**	**6.48**	**116.4**
	Tukey $HSD^{0.05}$	P = 0.1 (p=0.0003)	P = 0.4 (p=0.0000)	P = 6.9 (p=0.0003)
1R	0	1.44^{A}	5.89^{A}	80.4^{A}
	20	1.38^{A}	5.41^{BC}	77.1^{A}
	40	1.42^{A}	5.79^{AB}	79.2^{A}
	60	1.45^{A}	5.22^{C}	80.9^{A}
	Means for P applied	**1.42**	**5.58**	**79.4**
	Tukey $HSD^{0.05}$	P = 0.1 (p=0.4780)	P = 0.4 (p=0.0003)	P = 6.8 (p=0.4826)
2R	0	1.68^{AB}	5.47^{A}	92.8^{AB}
	20	1.71^{A}	5.68^{A}	94.4^{A}
	40	1.60^{AB}	5.30^{A}	88.7^{AB}
	60	1.58^{B}	5.69^{A}	87.4^{B}
	Means for P applied	**1.64**	**5.53**	**90.8**
	Tukey HSD0.05	P = 0.1 (p=0.0060)	P = 0.4 (p=0.0458)	P = 5.8 (p=0.0060)

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

Table 42. *Effect of P applied rates (kg P_2O_5/ha) in weight (kg/stalk), stalks/m^2 and cane yield (tc/ha) in sandy loam texture.*

Sandy loam texture				
Crop	**P applied (kg/ha)**	**Weight (kg)**	**Population (Stalks/m^2)**	**Cane yield (tc/ha)**
PC	0	2.68^{AB}	7.66^{A}	208.8^{A}
	20	2.75^{A}	7.51^{A}	209.8^{A}
	40	2.57^{B}	7.31^{A}	191.6^{B}
	60	2.77^{A}	6.69^{B}	185.9^{B}
	Means for P applied	**2.69**	**7.29**	**199.0**
	Tukey $HSD^{0.05}$	P = 0.2 (p=0.0040)	P = 0.5 (p=0.0000)	P = 15.8 (p=0.0001)
1R	0	2.53^{A}	5.84^{A}	150.6^{A}
	20	2.35^{B}	5.61^{AB}	134.5^{B}
	40	2.55^{A}	5.41^{B}	142.2^{AB}
	60	2.32^{B}	5.84^{A}	137.4^{B}
	Means for P applied	**2.44**	**5.67**	**141.2**
	Tukey $HSD^{0.05}$	P = 0.2 (p=0.0001)	P = 0.3 (p=0.0003)	P = 12.9 (p=0.0087)
2R	0	1.75^{B}	5.48^{A}	96.9^{BC}
	20	1.79^{B}	5.04^{B}	91.9^{C}
	40	1.91^{A}	5.25^{AB}	102.9^{AB}
	60	1.93^{A}	5.40^{A}	107.1^{A}
	Means for P applied	**1.84**	**5.29**	**99.7**
	Tukey HSD0.05	P = 0.1 (p=0.0001)	P = 0.3 (p=0.0001)	P = 8.7 (p=0.0001)

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*
**PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3.*

5.3.3 P cane yield and sugar productivity responses curves

The observed optimum P rate associated with cane yield could not be calculated for the PC and ratoons in clay loam and sandy loam (Figure 15 and Figure 16, respectively) because the cane yield response was linear.. On the other hand, for clay texture, optimum rates were found in 1R and 2R, with 30 and 20 kg/ha, respectively as seen on Figure 14.

For sugar content, response for the PC was found on clay and clay loam texture with 30 and 20 kg/ha, respectively (Figure 14 and Figure 15). In the case of the sandy loam textured soil, no optimum P rates were found to be appropriate as the relationships were essentially linear.

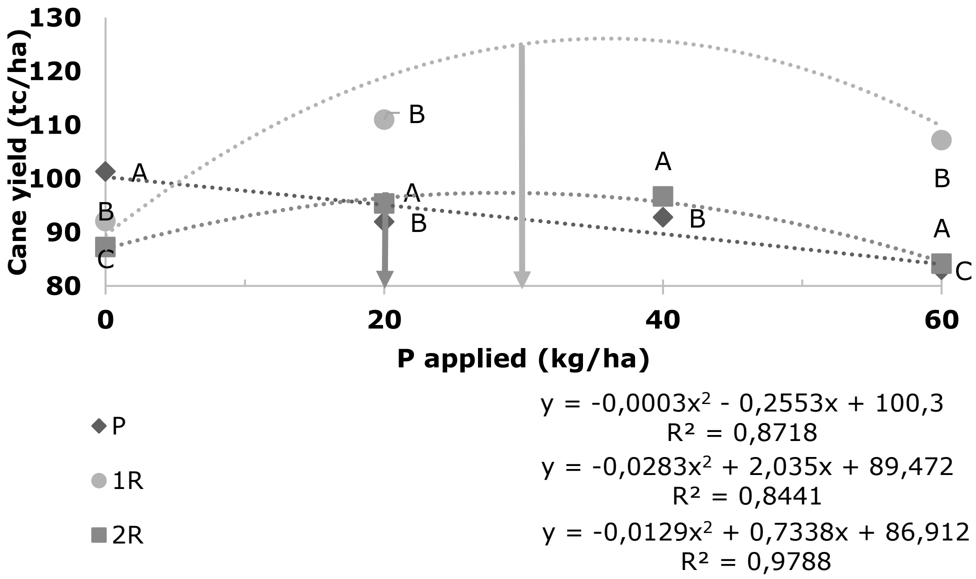

Figure 14. *Cane yield response curves (tc/ha) resulting from P applied to clay trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

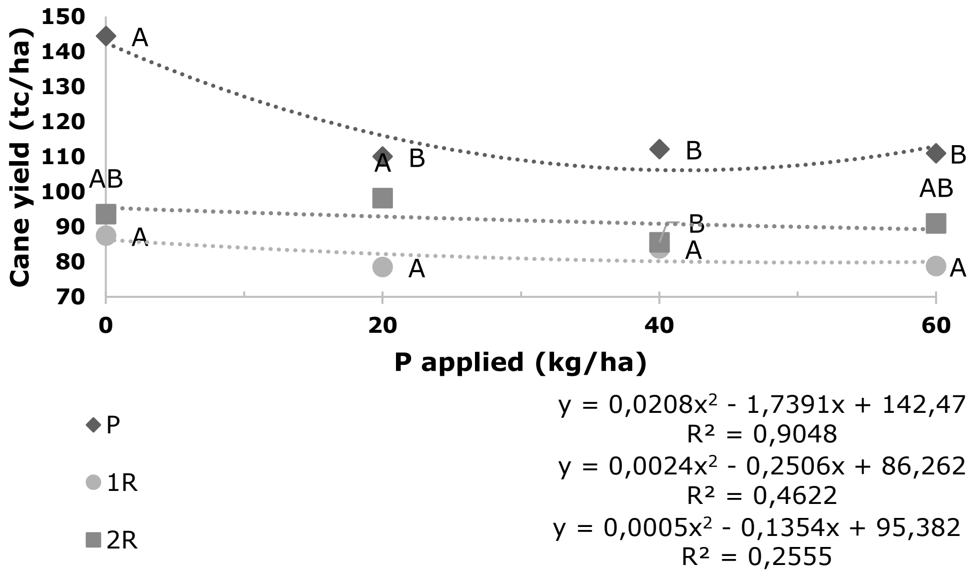

Figure 15. *Cane yield response curves (tc/ha) resulting from P applied to clay loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

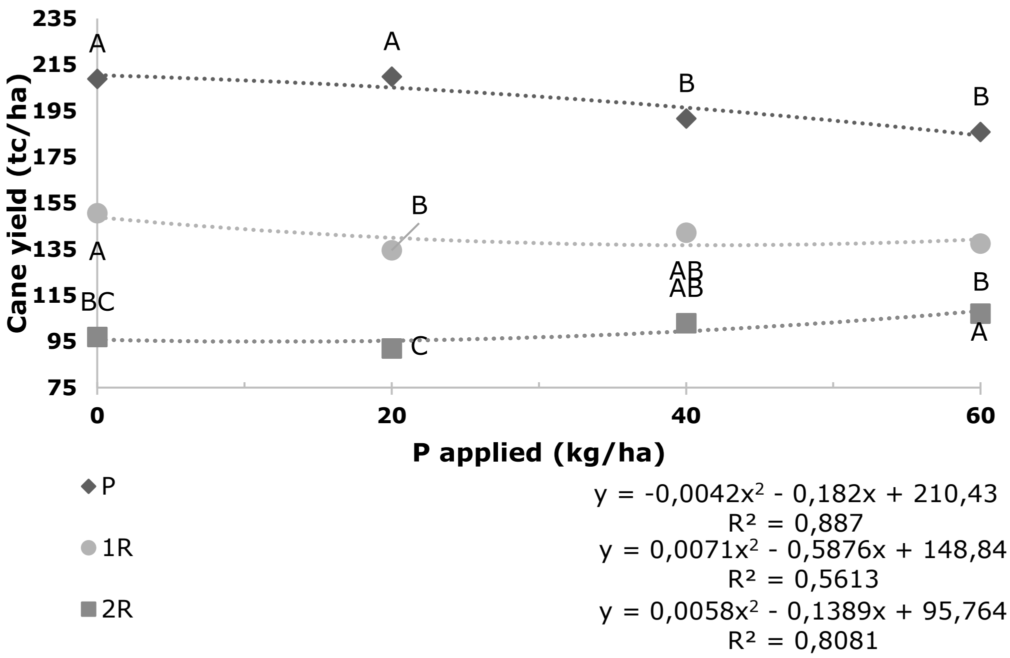

Figure 16. *Cane yield response curves (tc/ha) resulting from P applied to sandy loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

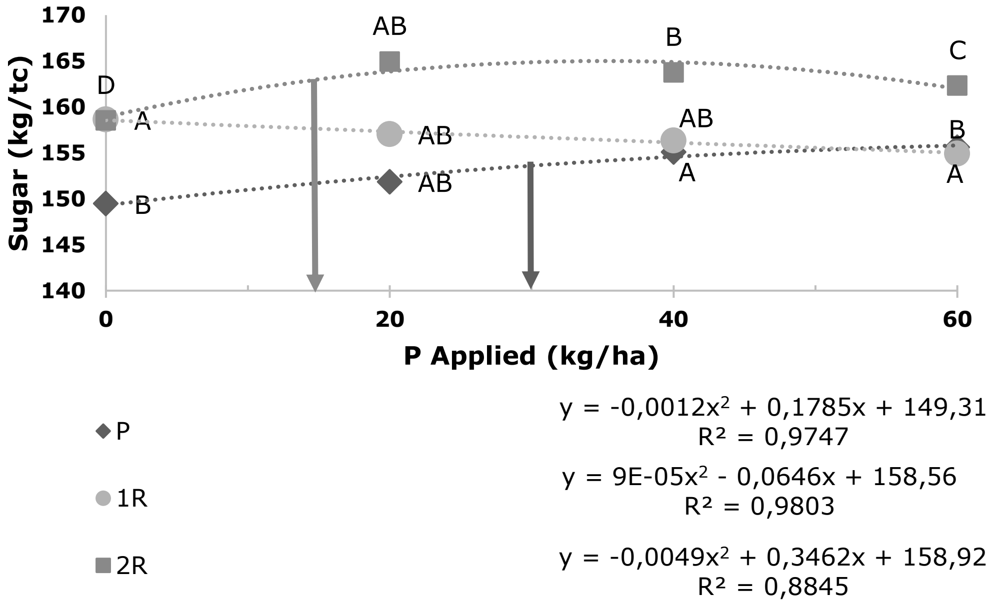

Figure 17. *Sugar yield response curves (kg S/tc) resulting from P applied to clay trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

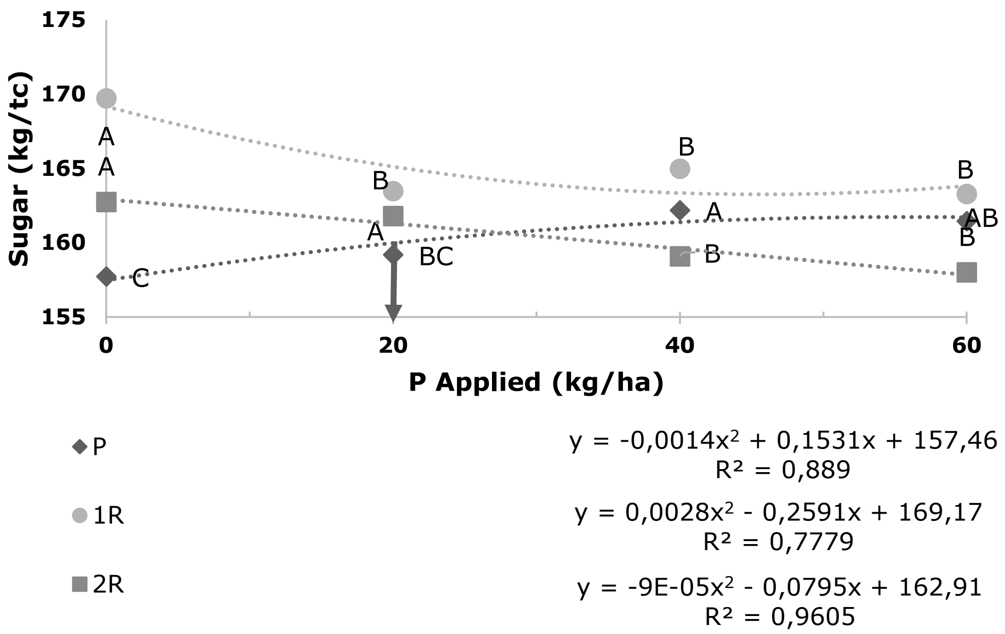

Figure 18. *Sugar yield response curves (kg S/tc)) resulting from P applied to clay loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

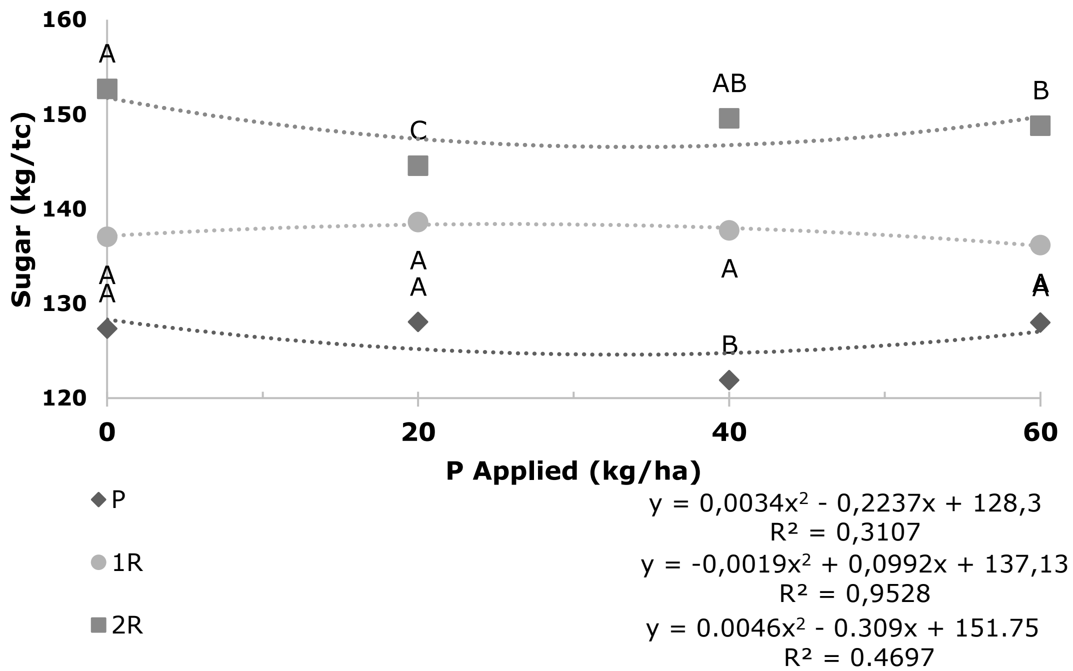

Figure 19. *Sugar yield response curves (kg S/tc) resulting from P applied to sandy loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.* [A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

5.3.4 Crop P uptake results

Crop P uptake was lower on clay loam than clay and sandy loam, this can be related with the P content in soil previously described in Table 43, where clay loam has the lowest content (9 mg/kg) compared to sandy loam (24.8 mg/kg) and clay (31.50 mg/kg).

Table 43. *Crop P uptake (kg/ha) by P applied rates and soil textures.*

Texture	Crop	0	20	40	60
Clay	1R	48.7	51.5	68.7	62.3
	2R	42.3	43.1	47.8	48.9
Clay loam	1R	16.1	15.2	19.1	55.1
	2R	23.3	19.3	22.5	26.7
Sandy loam	1R	74.9	66.2	78.0	75.3
	2R	46.1	49.0	49.4	47.7

5.3.5 Conclusion and final remarks

- No significant yield responses to applied P was identified in plant crop in the three types of textures (clay, clay loam and sandy loam) this could be resulted of P mineralization process.

- No significant yield responses to applied P was identified in ratoons in clay loam and sandy loam.

- The results so far suggest that P application rates somewhat equal or lower (30 and 20 kg/ha) than the traditional P rates (26 kg/ha) are applicable at San Antonio on the clay soils. This appears to correspond to the accepted average crop removal Figure of 20 kg P/ha/yr (Meyer and Wood 2001).

- P needs to be applied to the plant and ratoon crops to maintain appropriate soil P levels during the sugarcane production cycles, since plant continues in constantly uptake.

- As the rates of P were applied to the plant crop only, responses to P may have been influenced during the ratoon crops. P response was expected to occur due to the volcanic origin and possible P-sorption characteristics of the soils (as explained in Chapter 1 and Chapter 2). However, the soils are in fact Vertisols, Mollisols and Entisols and, hence, lacking such characteristics (Chapter 2). Results from this Chapter suggests that the soils at San Antonio have reasonable P reserves that are available for uptake by the crop.

CHAPTER 6: SAN ANTONIO SUGAR MILL COMPANY AS A MODEL TO GENERATE NUTRIENT MANAGEMENT GUIDELINES FOR SPECIFIC CIRCUMSTANCES

6.1 Introduction

Recognition of the need for modified nutrient guidelines for sustainable sugarcane production was the catalyst for develop a robust nutrient management system in San Antonio.

This was achieved using a staged approach by:

- Understanding sugarcane production in Nicaragua and weather influence by monitoring digital weather stations and pluviometers located in San Antonio (Chapter 1).
- Knowing the sugarcane crop, Nicaraguan soil types, essential nutrients (N, P, K) and their process and losses (Chapter 2).
- Considering agricultural practices and infrastructure for effective nutrient management (Chapter 2).
- Establishing interim guidelines for N, P, K, S for approximate 6 years according to soil requirements and productivity, based on improved soil sampling and acquisition of information for more than 17,000 hectares. (Chapter 3).
- Generating response curves for N, P, K in the main soil textures of San Antonio: clay loam (34%) Loam (25%) and clay (18%) of approximate 17000 ha as shown in Chapter 4 and 5.
- Identifying nutrients use efficiency and crop N, P, K uptake under Nicaraguan conditions (Chapter 4 and 5).

The objective of this Chapter is to take in consideration all the information listed above and analyse if the interim guidelines can be fine tuning and extrapolate to elsewhere and be adopted for Nicaraguan sugarcane growers.

6.2 Methodology

6.2.1 Reviewing and analyzing actual stage of interim guidelines

As previously explained in Chapter 3 improved soil analysis data were digitalized and stored in a database contained in a software program (BIOSALC). As an established rule, resulting from this project, soil samples were collected and tested from each block every four years minimum. In addition, blocks that were subject to earthworks and levelled were resampled. Resulting soil analysis data per each commercial field was linked with parameters of interim N, P, K and S guidelines (Chapter 3) to generate a fertilizer recommendation expressed in kg of N, P, K and S and subsequently expressed as kg of the traditional fertilizer sources used in San Antonio (Table 44).

Table 44. *Chemical fertilizers used in San Antonio and % of nutrient content.*

Fertilizer type	N (%)	P_2O_5 (%)	K_2O (%)	S (%)
Urea	46	-	-	-
Diammonium Phosphate (DAP)	18	46	-	-
Monoammonium phosphate (MAP)	12	61	-	-
Potassium chloride (KCL)	-	-	60	-
Ammonium Sulphate ($(NH_4)_2SO_4$)	21	-	-	24

The following rules were used for nutrient management recommendations:

- N fertilizer recommendations were created bases on N interim guidelines that were established based on productivity of the last years, OM content and crop age.
- In the absence of definitive P-sorption data, P application rates were assumed for moderately P-sorbing soils, since more than 50% of the area have high clay content. P fertilizer recommendations were created based on crop age (PC and R) and P content in soil based on on Bray2 (pH≤7) and Olsen (pH > 7) P test values and moderate P sorption characteristics.
- As seen in Chapter 3 (Table 15), K guidelines were based on heavy (e.g. clay, clay loam) and light soil textures (e.g. loam, sandy loam) and it was recommended just when soil test were very low (e.g. <0.26 cmol (+)/kg K), because of really high prices of potash.
- The interim S guidelines were based on S content (mg/kg) according to FHIA parameters, and fine tuning based on Louisiana S recommendations, suggesting that S should be applied to soils containing less than 10 ppm of S. Response curves for S were not evaluated as the main focus of the study was N, P and K.

6.2.2 Development of fertilizer (N, P, K and S) formulas based on interim guidelines

Compound fertilizers contain two or more nutrients. As explained in Chapter 2, sugarcane crop requires sixteen nutrients for optimum growth, however macronutrients as N, P, K and S are of major concern based on on their amount of acquisition by the plant, loss pathways and nutrient/soil interactions (Calcino *et al.,* 2018).

Based on soil analyses results the main nutrient requirements of San Antonio soils are N, P, K and S. Six fertilizer formulas were generated based on N, P, K and S for the approximate 17,000 ha. Variabilities between application of the fertilizer formula and commercial field nutrient requirement was revised.

6.2.3 Interim N, P, K and S guidelines productivity and rates data

Interim N, P, K and S guidelines were used from harvesting season 2016-2017 to harvesting season 2022-2023. A data base was formulated to have records of N, P, K and S fertilizer applied per commercial field and their productivity in the approximate 17,000 ha, including seed production fields.

Since interim guidelines for N rates were based in productivity of the last years. Database of historical productivity was reviewed.

Even though the interim guidelines for N, P and K were accepted in San Antonio, the company decided to use the highest potential yield of the commercial field in the last 10 harvesting seasons.

This was modified by harvesting season 2018–2019, and the last two harvest seasons' productivity was used for N recommendations based on the following:

- Sugarcane varieties adopted per farm were not the same as the used with the highest yield potential
- Changes in type of irrigation systems (e.g from rainfed to drip irrigation) and,
- Variability in climatic conditions

6.2.4 Nutrients use efficiency indexes for N, P and K

NUE indexes as kg N/tc, kg P/tc and kg K/tc were assessed, by dividing average cane yield by average kg of N, P and K respectively. Indexes were recorded per commercial fields and harvest season.

6.2.5 Comparing optimum N, P, K rates from response curves and interim guidelines

A comparison between interim guidelines and the outcomes from the response curves (scenario b) previously discussed in this study (Chapters 4 and 5) for N, P, and K was proposed, assuming the exact yield as response curves, OM, soil texture, and crop age.

6.2.6 Economic assessment

An economic assessment of applying the optimum and interim N, P, and K rates was undertaken by calculating the partial net return per hectare to the industry (sugar milling companies) and the growers using the following calculations.

A new economic assessment for the industry's partial net return was proposed based on the following formula:

- **Industry partial net return economic assessment:** [Sugar yield (kg of sugar/tc) × price of sugar ($/t)] – [fertilizer cost ($) × mass of NPK (kg/ha)] – application of fertilizer cost ($) - [Cane yield (tc/ha) × estimated harvesting cost ($/ha)] - [Cost of tc produced ($/tc/ha) × Cane yield (tc/ha)]

- **Growers partial net return:** [Cane yield (tc/ha) × price of tonnes of cane ($/t) – [fertilizer cost ($) × mass of NPK (kg/ha)]– application of fertilizer cost ($)- (Cane yield (tc/ha) × estimated harvesting cost ($/ha)] - (Cost of tc produced ($/tc/ha) × Cane yield (tc/ha)]

For simplicity, the following values and assumptions were taken into consideration:

- **Sugar yield:** Expressed in kg sugar/tc. The average of the last two harvest seasons of sugar yield of the CP-722086 was used for calculations. As explained in previous Chapters is one of the principal sugarcane varieties grown in San Antonio,

- **Price of sugar:** US$ 418/TM
- **Fertilizer cost:** US$ 1.78 /kg N, US$ 2.90 /kg P and US$ 2.41 /kg K.
- **Application of fertilizer cost:** US$ 57/ha
- **The estimated of harvesting cost:** US$ 4.17/tc
- **Cost of tonnes of cane produced:** US$ 13/tc

In the case of the grower's partial net return, an award for sugar yield was incorporated since, in the Nicaraguan industry, sugar yields higher than 100 kg/tc received a monetary bonus based on the following formula:

- **Award for sugar productivity:** (kg sugar/tc - 100) × (0.545/50) × cane yield price × cane yield (tc/ha)

Savings in interim nutrient guidelines: The economic impact of using interim nutrient management was assessed by checking variations in the quantity of kg of nutrients applied (N, P, and K) and fluctuations in fertilizer prices from 2015–2016 to the 2022–2023 harvest season.
The following concepts were applied for the calculations of quantity variance:

Quantity variance: the subtraction of the standard quantity of N, P, and K fertilizer used in harvest season 2015–2016 from the actual amount used, then multiplying that number by the cost per kg of fertilizer applied.

6.3 Results and discussion

6.3.1 Actual stage of interim guidelines

Interim N, P, K, and S guidelines were used from harvesting season 2016–2017 to harvest season 2022–2023. As shown in Table 45, from harvest season 2015–2016, it increased the average rate of kg N/ha applied, and the other nutrients P, K, and S did not have significant changes.

Even though parameters were established, and a more organized nutrient management system was established based on more soil analyses, the company decided to use the highest yield potential of the last 10 harvesting seasons. It was found that productivity data from seed production fields that are usually harvested twice per year (e.g., every 6-7 months) were duplicated, and the database showed erroneously high yields. Also, the highest productivity in San Antonio was in the 2009–2010 harvest season, when favourable weather conditions were present.

As explained in the methodology, changes for the N application were performed until harvest season 2018–2019. Also, by that time, as explained in Chapter 3, further soil sampling at San Antonio was undertaken according to revised guidelines, and soil sampling maps were developed inclusive of georeferencing, helping to detect errors and being more organized. Additionally, as part of this strategy, urease inhibitors in the form of NutriSphere-N® were added from the factory to all the N fertilizer formulas used in San Antonio.

By organizing, establishing interim guidelines, keeping records, and improving and expanding soil sampling, a reduction of 42 kg of N/ha were decreased in 17000 hectares of sugarcane grown for a total of 714,000 kg of N in the 2022–2023 harvest season.

P fertilizer application had a significant decrease in harvest season 2022–2023 due to price. Just the commercial fields with lower than 20 ppm of P in soil analyses received P applications. K and S did not have major changes in the average rate, just in the area applied, also because of high prices.

Table 45. *N, P, K and S fertilizer rates applied from 8 harvest seasons.*

Harvest season	kg N/ha	kg P_2O_5/ha	kg K_2O/ha	kg SO_4/ha
2015-2016	197	43	75	20
2016-2017	213	43	79	23
2017-2018	214	43	79	23
2018-2019	181	54	74	33
2019-2020	187	42	62	34
2020-2021	188	41	64	43
2021-2022	172	36	75	44
2022-2023	155	30	70	37

6.3.2 Development of fertilizer (N, P, K and S) formulas based on interim guidelines

Six fertilizer formulas were generated based on N, P, K and S for the approximate 17,000 ha (Table 46). San Antonio used to have 3 fertilizers formulas that used to have more variability between requirement as a single nutrient for example just for N and when N has to be in combination with another nutrient as a S in a fertilizer formula (37.67% N + 0% P + 0% K + 8% S). For example, the application of 334 kg of one of the main fertilizer formulas developed (37.67% N + 0% P + 0% K + 8% S) supplies a requirement of 126 kg N/ha and approximately 27 kg of S/ha. As shown in Table 46, more than 500 farms were fertilized with this fertilizer formulas, representing 13,305 hectares and more than 5 million of kg of fertilizer formula in total. The development of more formulas according to the deficiencies of the commercial fields decreased the overapplication of nutrients. The remaining area, more than 3,000 hectares, is established under drip irrigation systems. For that particular system, just one fertilizer formula was used, and it was applied as a single fertilizer product. The drip-irrigation fertilizer formula was composed of 190 kg N/ha as ammonium nitrate and urea, 32 kg $S0_4$ /ha as ammonium sulphate, 78 kg K_2O/h, and

60 kg P_2O_5/ha as phosphoric acid. This formula was used as a rule of thumb until harvest season 2018-2019, when the area under the drip irrigation system was fertilized according to soil analysis requirements.

The new average of fertilizer rates is 180 kg N/ha as ammonium nitrate and urea, 50 kg SO_4 /ha as ammonium sulphate, 70 kg K_2O/h, and 38 kg P_2O_5/ha as phosphoric acid.

Table 46. *San Antonio edaphic fertilization formulas.*

Fertilizer Formula -San Antonio	Number of farms	Area applied (ha)	Fertilizer applied (kg)
37.67% N + 0% P + 0% K + 8% S	250	6,006	2,380,514
31.6% N + 0 % P + 10.35% K + 6.21% S	84	2,451	1,136,127
46% N	71	1,809	519,461
32.58% N + 9.89% P + 0% K + 7.1% S	41	1,245	594,835
27.51% N + 7.41% P + 10.08% K + 6% S	31	693	401,428
22.24% N + 0% P + 23.44% K + 5.56% S	28	570	356,537
20.38% N + 7.11% P + 21.04% K + 4.96% S	23	532	341,677
Total	**528**	**13,305**	**5,730,579**

6.3.3 Comparison of optimum N, P, and K rates and nutrients use efficiency based on response curves and interim rate results

The optimal N rates found in response curves were lower or similar, except for 2R in loam texture, to the ones proposed in interim guidelines, as shown in Table 47. The optimum N rates varied from one year to the next in response to changes in climatic conditions. The differences in optimum N rates over the years show the importance of a more thorough investigation into the impact of climatic conditions on nutrients, as explained in Chapter 4.

A combination of physical and chemical soil properties affects crop results. According to Table 47, greater yields were obtained in loam, which even had a lower OM level (2.4%) than clay loam (3.6%) and clay (2.6%). Although nutrients can be present in enough amounts in the soil, availability to be taken up and climatic conditions are essential.

Sugarcane plant crops grown in heavy-textured soils (clay and clay loam) did not indicate a response to applied N, and the lowest N rate in loam was obtained in PC (Table 47), showing that N responses in PC are lower or nil when compared with ratoons.

The lowest N rate in loam was found in PC (90 kg N/ha), and sugarcane PC grown in clay and clay. Loam did not demonstrate a response to applied N (Table 47); it demonstrates that N responses in PC are lower or nil when compared with ratoons.

This outcome can be attributed to enhanced soil aeration from field preparation, a better soil structure via decompaction that promotes N uptake by roots, and increased availability of soil N reserves (Smith *et al*., 2005).

Interim N guidelines previously explained in Chapter 3 showed less kg N/tc applied when it was a PC rather than a ratoon (Table 13, Chapter 3), which is consistent with earlier reports by Lofton (2012), and Wiedenfeld (1997).

Approximately 20% of the 17,000 ha of San Antonio (3,400 ha) of sugarcane are replanted annually in San Antonio, with an average of 146 kg N/ha. Based on this study's results, it is possible to adjust N suggestion rates for PCs.

The highest crop N uptakes found in this study were 187 kg N/ha in clay loam, 175 kg N/ha in clay, and 199 kg N/ha in loam texture. The highest uptake previously reported was found with the highest rate of N fertilizer (225 kg/ha), except for loam texture (150 kg N/ha). The fertilizer N recovered in these experiments ranged from 5% (4 kg N/ha) in clay to 41% (31 kg N/ha) in loam, as reported in Chapter 4 (Table 31).

The optimal rate determined using response curves in Loam 2R, as shown in Table 47, is 390 kg N/ha, which is 263 more than interim N rates and much higher than the rates obtained for PC and 1R. As was previously demonstrated in Chapter 4, utilizing scenario a (population with field trial findings), the recommended optimal N rate from loam 2R suggested 140 kg N/ha.

One of the major goals of this investigation was to determine whether NUE values were lower than interim N recommendations rates without affecting productivity. As seen in Table 47, overall NUE (kg N/tc) was lower than the N interim guidelines. Improved NUE's may reduce input expense, like fertilizer costs, while also preventing nitrogen from contaminating the environment. Less greenhouse gas emissions, along with reduced nitrate leaching into groundwater, would result from reducing fertilizer inputs.

Interim N rates for yields below 120 tc/ha were 120 kg N/ha, as indicated in Table 47. In the interim N recommendations discussed in Chapter 3, crop yields less than 120 tc/ha were multiplied by a factor of 1.25 kg N/t cane/ha, and the minimum N application rate was 120 kg N/ha, even if crop yield was less than 100 tc/ha (e.g., 80 tc/ha*1.25 kg N/tc=100 kg N/ha; apply 120 kg N/ha instead). Response curves reveal that this factor needs to be lower, as seen in Table 47.

Table 47. *Comparison of response curves optimum rates and N rates proposed in interim guidelines.*

Soil texture	Crop	Optimum yield (tc/ha)	Interim Guidelines (kg N/ha)	Response curves optimum rate (kg N/ha)	Difference (kg N/ha)	NUE Interim guidelines (kg N/tc))	NUE Response curves (kg N/tc)
Clay	1R	83	120	100	20	1.45	1.20
	2R	92	120	100	20	1.30	1.09
	3R	90	120	160	-40	1.33	1.78
Clay loam	1R	98	123	120	3	1.26	1.22
	3R	124	173	200	-27	1.40	1.61
Loam	PC	119	150	90	60	1.26	0.76
	1R	109	137	110	27	1.26	1.01
	2R	102	127	390	-263	1.25	3.82

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

As reported in Chapter 4, earlier studies have discovered K uptakes ranging from 198 kg/ha (Chapman, 1996), 343 kg/ha (Coale *et al*., 1993), and 790 kg/ha (Wood, 1990) in various locations and conditions. In addition, it is widely recognized that sugarcane removes more K than other nutrients. Results from K response curves indicated that overall K rates were greater than those specified in K interim guidelines.

The price of potash fertilizer has regulated K applications in San Antonio. Prior to the establishment of interim K guidelines, the higher rate of 50 kg K/ha was only used on commercial fields with irrigation systems and productivity of more than 80 tc/ha. According to soil texture, interim K recommendations were established, with higher rates for heavier soil textures. Results from response curves for K applied also suggested overall higher K rates in clay than clay loam and loam (Table 48). On top of that, as compared to clay loam (0.4 cmol (+)/kg) and loam (1.1 cmol (+)/kg), the clay texture had the lowest K concentration in soil (0.2 cmol (+)/kg).

Furthermore, in Chapter 3, when productivity and soil analysis were linked, it seemed that K treatments in commercial fields with K contents in soil lower than 1 cmol (+)/kg in clay and clay loam had a response to K application. On the other hand, little or no effect was observed in loam when productivity was linked with soil analyses (Chapter 3). Results from Table 48 suggest a response to K applications in loam texture for 1R (160 kg/ha) and 2R (120 kg/ha), unless, based on soil analyses, there is an adequate amount of K in the soil.

K responses in PC were lower or nil when compared to ratoons, this could be due to the same concept explained for N responses in PC: availability and a better uptake of nutrients thanks to land preparation and a better soil structure (Table 48).

The K response curve results indicated higher K application rates and higher KUE (kg K/tc). Even though clay loam and loam have medium to high K levels in soil analyses, as previously explained, sugarcane constantly consumes large quantities of K that must be replenished, and in certain cases, even though high amounts of K are present in the soil, they are not available to the plant due to several environmental circumstances.

Table 48. *Comparison of response curves optimum K rates (kg K_2O/ha) and K rates (kg K_2O/ha) from interim guidelines and K use efficiency (KUE) by soil texture and crop age.*

Soil texture	Crop	Optimum yield (tc/ha)	Interim Guidelines (kg K/ha)	Response Curves optimum rate (kg K/ha)	Difference (kg K/ha)	KUE Interim guidelines (kg K/tc))	KUE Response curves (kg K/tc)
Clay	PC	90	125	80	45	1.39	0.89
	1R	83	150	170	-20	1.81	2.05
	2R	88	75	170	-95	0.85	1.93
	3R	82	100	100	0	1.22	1.22
Clay loam	PC	122	0	50	-50	0.00	0.41
	1R	92	0	120	-120	0.00	1.30
	2R	98	100	50	50	1.02	0.51
	3R	115	100	40	60	0.87	0.35
Loam	1R	108	0	160	-160	0.00	1.48
	2R	94	0	120	-120	0.00	1.28

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

P response was expected to occur due to the volcanic origin and possible P-sorption characteristics of the soils (as explained in Chapter 1 and Chapter 2). However, the soils are in fact Vertisols, Mollisols and Entisols and, hence, lacking such characteristics (Chapter 2). Table 49 shows interim P guidelines were similar to P applied response curves, except for clay loam and plant crops, which did not show any response for P application.

Johnson *et al*., (2017) found that phosphorus fertilizer did not consistently improve cane or sugar yields in five locations in Louisiana, with P values around 14 mg/kg. It is also mentioned that different results would be obtained if higher levels of soil phosphorus were applied.

Crop P uptake during PC was not evaluated, however clay loam 1R and 2R ratoons had lower crop P uptake (55.1 and 26.7 kg/ha) compared to clay

(62.3 and 48.9 kg/ha) and sandy loam (75.3 and 47.7 kg/ha), as previously described in Chapter 5, where clay loam has the lowest content (9 mg/kg) compared to sandy loam (24.8 mg/kg) and clay (31.50 mg/kg).

This could be due to the low P content in clay loam soils and the application of P fertilizer just during planting time, potentially influencing the nil response, as shown on Table 49.

Even though response curves suggest no P application during PC (Table 49), this is the best moment to apply P because it can be applied in the planting furrow below the cane setts and P has low mobility in the soil. Most of the fertilizer equipment in San Antonio applies fertilizer more than 20 cm apart from the sugarcane stool, obstructing P fertilizer contact with sugarcane roots. Additionally, clay and loam had a response to applying P in ratoons from previous applications in PC, as shown in Table 49; this suggests that P should be applied in PC and followed by ratoons as required. Also, P uptake presented in Chapter 5 supports the fact that sugarcane plants are always taking up P.

As seen in Table 49, response curves for P applied suggest rates not higher than 40 kg P/ha. PUE (kg P/tc) had similar values in response curves and interim P guidelines in some ratoons. However, on PC, there was no response to the P application.

Table 49. *Comparison of response curves optimum P rates (kg P_2O_5/ha) and P rates (kg P_2O_5/ha) from interim guidelines and P use efficiency (PUE) by soil texture and crop age.*

Soil texture	Crop	Optimum yield (tc/ha)	Interim guidelines (kg P/ha)	Response curves optimum rate (kg P/ha)	Difference (kg P/ha)	PUE Interim guidelines (kg P/tc)	PUE Response curves (kg P/tc)
Clay	1R	120	20	30	-10	0.18	0.27
	2R	96	20	20	0	0.21	0.21
Loam	1R	135	20	20	0	0.14	0.14
	2R	94	20	40	-20	0.19	0.38

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

6.3.4 Economic assessment results

The grower and industry partial economic returns (US $/ha) for PC and ratoons in the three main soil textures of San Antonio are shown in Tables 50 to 55 per each nutrient previously described in this study (N, P, and K).

Partial economic returns (US $/ha) for N applied:

As shown in Table 50, the economic analysis indicates that the observed optimum N rate from response curves increases industry partial net returns compared to the interim guidelines rate by US$106/ha in loam. Since the optimum N rate and associated cane yield could not be calculated for clay loam and clay PC because the cane yield response was linear, it also could not be calculated for partial economic returns. However, this finding suggests a lower N rate for clay loam and clay PC and, at the same time, a higher economic return.

As shown in Table 50, for older ratoons like 3R in clay and clay loam texture, the partial net return is US $71/ha and US $47/ha, respectively, lower than in the interim guidelines. Sugarcane's lifecycle usually includes 1 PC and up to 3 ratoons. By considering the whole life cycle rather than just one crop, N response curve suggestions lead to higher crop profitability overall. The same trend was found in growers partial net return shown in Table 51. However, the partial net return is higher in the industry because it considers sugar yield, as previously explained in methodology.

In the case of the grower's partial net return, a prize for sugar was incorporated in the Nicaraguan industry, sugar yields higher than 100 kg/tc received a prize based on the formula previously described in the methodology.

Table 50. *Calculated Industry partial net returns (US $/ha) from applying interim N guidelines rates and optimum N rates from response curves. Equations in 6.2.6 were used to calculate the industry partial net return.*

Soil texture	Crop	Optimum yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	1R	83	2,000	1,965	36
	2R	92	2,235	2,199	36
	3R	90	2,066	2,137	-71
Clay loam	1R	98	2,368	2,362	6
	3R	124	2,912	2,959	-47
Loam	PC	119	2,983	2,877	106
	1R	109	2,672	2,624	47

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

Table 51. *Calculated growers partial net returns (US $/ha) from applying interim N guidelines rates and optimum N rates from response curves. Equations in 6.2.6 were used to calculate the growers partial net return.*

Soil texture	Crop	Optimum yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	1R	83	787	751	36
	2R	92	895	859	36
	3R	90	761	832	-71
Clay loam	1R	98	936	930	6
	3R	124	1,109	1,156	-47
Loam	PC	119	1,246	1,141	106
	1R	109	1,085	1,037	47

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

Partial economic returns (US $/ha) for K applied:

Results from response curves for K applied suggested an overall higher K rate in the three types of textures compared to interim guidelines (Table 48). As was expected, the partial net return to apply K was lower in response curves than in the interim K guidelines for industry and growers, as shown in Tables 52 and 53.

As shown in Appendix 1, Although responses to applied K did not occur *per se*, the N x K interactions that occurred at some sites indicated that improved responses to applied N were possible when at least some K fertilizer was applied. This combination could result in an increase in partial net returns (data not presented).

Table 52. *Calculated Industry partial net returns (US $/ha) from applying interim K guidelines rates and optimum K rates from response curves. Equations in 6.2.6 were used to calculate the industry partial net return.*

Soil texture	Crop	Optimum Yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	PC	90	2,163	2,055	108
	1R	83	1,761	1,809	-48
	2R	88	1,893	2,122	-229
	3R	82	1,901	1,901	0
Clay loam	PC	122	3,094	3,214	-121
	1R	92	2,120	2,410	-289
	2R	98	2,450	2,330	121
	3R	115	2,932	2,787	145
Loam	1R	108	2,453	2,839	-386
	2R	94	2,174	2,463	-289

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

Table 53*. Calculated growers partial net returns (US $/ha) from applying interim K guidelines rates and optimum K rates from response curves. Equations in 6.2.6 were used to calculate the growers partial net return.*

Soil texture	Crop	Optimum yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	PC	90	854	745	108
	1R	83	551	599	-48
	2R	88	612	841	-229
	3R	82	708	708	0
Clay loam	PC	122	1,319	1,439	-121
	1R	92	782	1,071	-289
	2R	98	1,024	904	121
	3R	115	1,257	1,112	145
Loam	1R	108	882	1,268	-386
	2R	94	807	1,096	-289

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2, 3R: ratoon 3

Partial economic returns (US $/ha) for P applied:

No significant yield responses to applied P were identified in PC in the three types of textures (clay, clay loam, and sandy loam), as previously described in Chapter 5, so no economic analysis was calculated for plant crops as well as ratoons in clay loam.

As shown in Tables 54 and 55, the calculated partial net return from industry and growers was lower or similar compared to interim guidelines; however, as previously explained, response curves suggest that P applications can be lower during PC and for clay loam since P was applied during planting time and the response was observed in ratoons.

Table 54. *Calculated Industry partial net returns (US $/ha) from applying interim P guidelines rates and optimum P rates from response curves. Equations in 6.2.6 were used to calculate the industry partial net return.*

Soil texture	Crop	Optimum yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	1R	120	3,074	3,103	-29
	2R	96	2,459	2,459	0
Loam	1R	135	3,507	3,507	0
	2R	94	2,348	2,405	-58

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2

Table 55. *Calculated growers partial net returns (US $/ha) from applying interim P guidelines rates and optimum P rates from response curves. Equations in 6.2.6 were used to calculate the industry partial net return.*

Soil texture	Crop	Optimum yield	Response curves net return (US $/ha)	Interim guidelines net return (US $/ha)	Difference
Clay	1R	120	1,328	1,357	-29
	2R	96	1,062	1,062	0
Loam	1R	135	1,541	1,541	0
	2R	94	980	1,038	-58

* PC: plant crop, 1R: ratoon 1, 2R: ratoon 2

Economic impact and nutrient efficiency of adopting improved interim nutrient management in San Antonio:

As shown in Figure 20, the kg of N applied was reduced from 197 kg/ha to 155 kg/ha in the harvesting season 2022–2023. This decrease represents approximately 719,000 kg of N just in harvesting season 2022–2023, and 1,753,771 kg of N less since all the improvements were adopted in the interim nutrient management program as shown in Table 56. As revealed in Figure 20, the kg N/tc applied decreased from 2.08 to 1.54 kg N/tc. As previously explained in Chapter 2, N is essential for the growth and development of the sugarcane plant (Anderson and Bowen, 1990; Kingston, 2014), and worldwide, it is the most widely used fertilizer. However, as previously explained in Chapter 4, fertilizer N recovered ranged from 5% (4 kg N/ha) in clay to 41% (31 kg N/ha) in loam, while the rest is lost through ammonia volatilization (Black *et al*., 1985; Huang *et al*., 2017; Rochette *et al*., 2013), denitrification (Allen *et al*., 2010; Ravishankara *et al*., 2009), and nitrate leaching (Martens, 2005). The NUE numbers reported in Figure 20 seem to be congruent with the findings previously described.

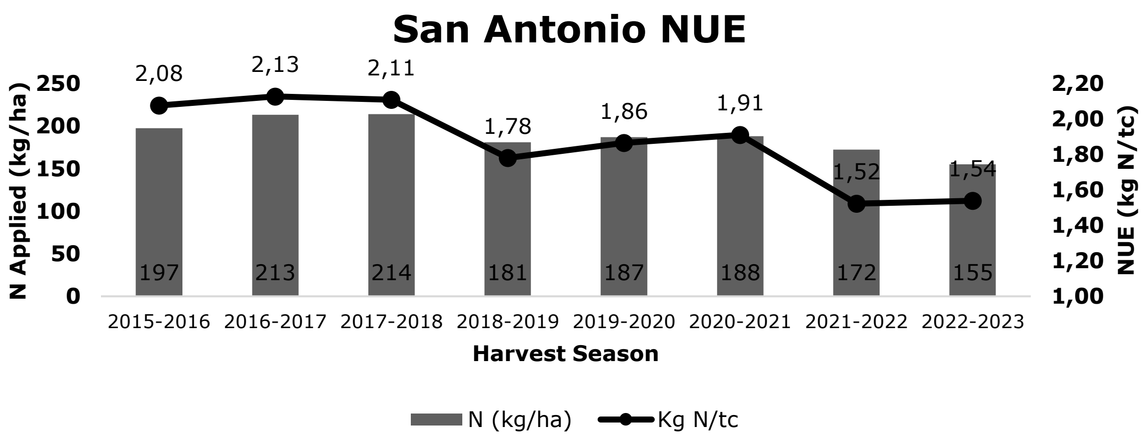

Figure 20. *San Antonio nitrogen use efficiency (NUE) along 8 harvesting seasons.*

As previously explained in methodology, interim nutrient guidelines were adopted during harvesting season 2016–2017; however, the yield potential (the highest cane yield) for N recommendations was taken from the last 10 harvesting seasons. As shown in Table 56, even though it was the first time to use parameters and the recommendations were according to soil analysis requirements, there was an approximate increase in N applied of 273,500 kg. Climate variability in Nicaragua and the rest of the world has a tremendous impact on cane yields and nitrogen losses. Crop size (cane yield) is mostly related to sugarcane varieties, crop age, and whether the crop is rainfed or irrigated, which largely determines how much nitrogen fertilizer should be applied. Conditions change, and nutrition recommendations should change. After having a better understanding of these implications for the harvesting season 2018–2019, interim N guidelines were fully adopted, resulting in less kg of N being applied, as reported in Table 56.

A total of US $1,517,333 was saved by reducing the kg of N applied from the fully implemented interim N guidelines.

Fertilizer costs increased dramatically through 2022 and beyond due to COVID-19-related worker absences, manufacturing closures, and, additionally, Russia's invasion of Ukraine (Anon, 2022b). By the harvest season of 2022–2023, this increase in price could have increased San Antonio's N fertilizer expenditure by almost US $1,277,955 if N interim guidelines did not exist (Table 57).

As previously described in Chapter 3 (Figure 9) even N application has decreased in the last years sugarcane productivity and sugar has been similar or higher and as shown in Figure 21, OM (%) has increased in the last 10 years, in general by 0.1%.

Table 56. *Economic impact of N application in San Antonio.*

Harvest season	Area (ha)	kg N/ha	kg N total	Cost/kg N (US $)	Total cost (US $)	Quantity variance (kg N)	Cost of quantity variance (US $)
2015-2016	17,000	197	3,353,336	0.90	3,004,501	-	-
2016-2017	17,000	213	3,626,835	0.73	2,634,395	273,500	-
2017-2018	17,000	214	3,636,788	0.64	2,315,777	283,452	-
2018-2019	17,000	181	3,077,873	0.61	1,892,043	-275,463	246,808
2019-2020	17,000	187	3,176,995	0.73	2,330,481	-176,341	157,997
2020-2021	17,000	188	3,195,556	0.80	2,543,137	-157,780	141,366
2021-2022	17,000	172	2,928,468	0.79	2,313,742	-424,867	380,670
2022-2023	17,000	155	2,634,016	1.78	4,679,633	-719,320	644,492
						Savings	**1,571,333**

Table 57. *Economic impact of N fertilizer price increases due Covid-19 pandemic and the Russia-Ukraine war.*

Harvest season	kg N total	Actual Cost (US $/kg N)	Total Cost (US $)
2015-2016	3,353,336	1.78	5,957,589
2022-2023	2,634,016	1.78	4,679,633
Savings			**1,277,955**

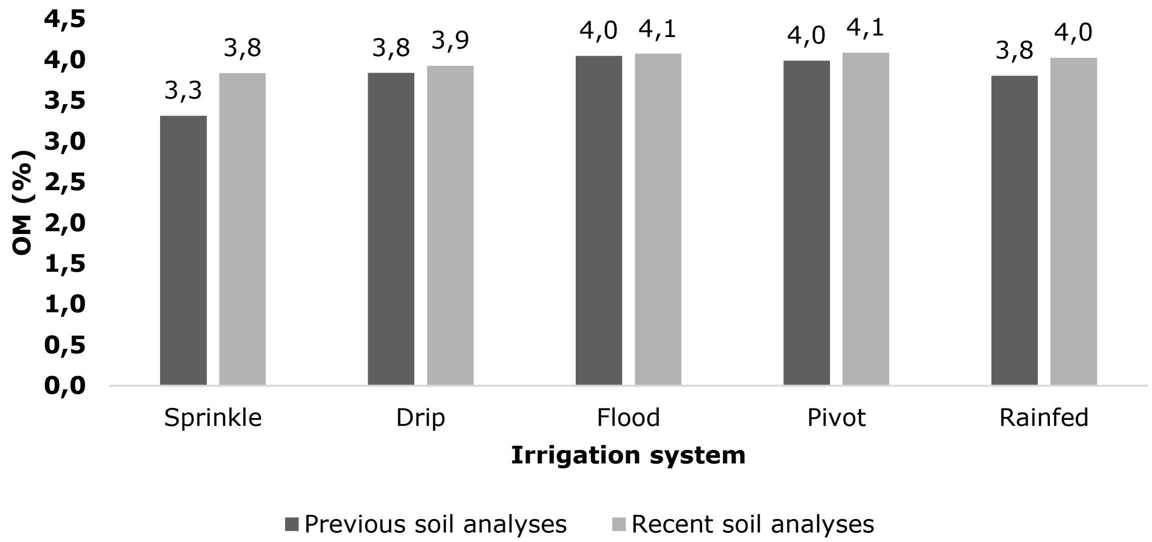

Figure 21. *OM (%) comparison from previous and recent soil analyses by San Antonio irrigation systems.*

Even approximately 4,300 ha of commercial fields in San Antonio were deficient in P (lower than 10 mg/kg) according to FHIA parameters already explained in Chapter 3. Interim P guidelines suggest applications to commercial fields lower than 30 mg/kg, and the highest rate recommended was 50 kg P_2O_5/ha. As shown in Table 58, more than 60% of the commercial fields (11,158 ha) used to be applied with P by harvest season 2015–2016, representing US $700,373. The increase in fertilizer prices in 2022 and 2023 influenced the change in P management strategy, and thanks to the final results of this study, we could support P reduction by just applying commercial fields with less than 20 mg/kg of P in the soil. This generated a decrease in the area applied from 11,158 to 9,028 ha (2,128 ha) and an average P applied rate from 43 kg P_2O_5/ha to 30 kg P_2O_5/ha (13 kg), representing a reduction of 208,868 kg of P. This reduction in the 2022–2023 harvest season represents US $300,769 in savings, even as exposed in Table 58 P, where the budget increased by US $85,062. Also, in commercial drip irrigation fields (3,400 ha), there was a reduction of 22 kg of average P as phosphoric acid, from 60 to 38 kg of P, and a reduction in the applied area. This strategy resulted in US $392,000 in savings for the company.

Table 58. *Economic impact of P application in San Antonio.*

Harvest season	Area (ha)	kg P/ha	kg P total	Cost/kg P (US $)	Total cost (US $)
2015-2016	11,156	43	479,708	1.46	700,373
2022-2023	9,028	30	270,840	2.90	785,436
Difference	**-2,128**	**-13**	**-208,868**	**1.44**	**85,062**

As seen in Figure 22, the last P soil analyses by irrigation systems show an average normal level of P in the soil, supporting the final comparisons between interim guidelines, response curves, and economic assessment to fine-tune the P application rate in San Antonio soils.

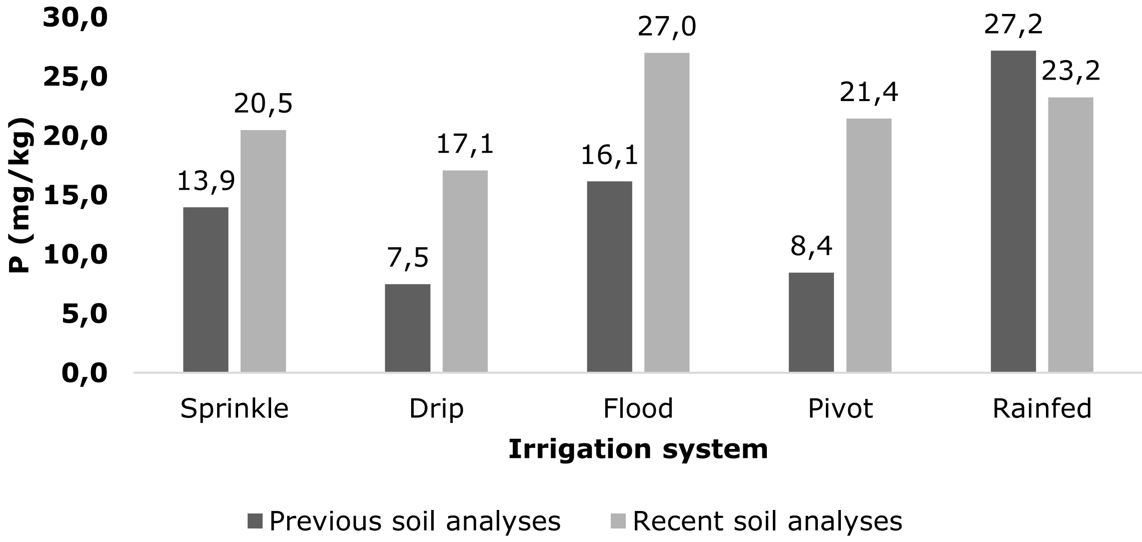

Figure 22. *P (mg/kg) comparison from previous and recent soil analyses by San Antonio irrigation systems.*

K application was not a common practice in San Antonio because of the high prices of potash fertilizer and the lack of knowledge about and responses to this nutrient in cane yield productivity. In contrast with N and P, this element increased in applied area by 3,408 ha, as shown in Table 59, resulting in a difference of US $760,813 influenced by price and quantity. However, as shown in Figure 24, the average sugar yield has increased in the last few years since interim K guidelines were proposed. As shown in Appendix 1.19 to 1.21, N and K interactions in older ratoons have a significant response to sugar. As seen in Figure 23, the last soil analyses showed a normal to high level of K content in soil; however, as exposed in Chapter 3, more than 37% of commercial fields (6,342 ha) are deficient in K, and according to the final results of K uptake and response curves, it would be recommended to increase the K area applied.

Table 59. *Economic impact of K application in San Antonio.*

Harvest season	Area (ha)	kg K/ha	kg K total	Cost/kg K (US $)	Total cost (US $)
2015-2016	2,396	75.32	180,500	1.22	219,532
2022-2023	5,804	70.06	406,646	2.41	980,345
Difference	**3,408**	**-5**	**226,145**	**1.19**	**760,813**

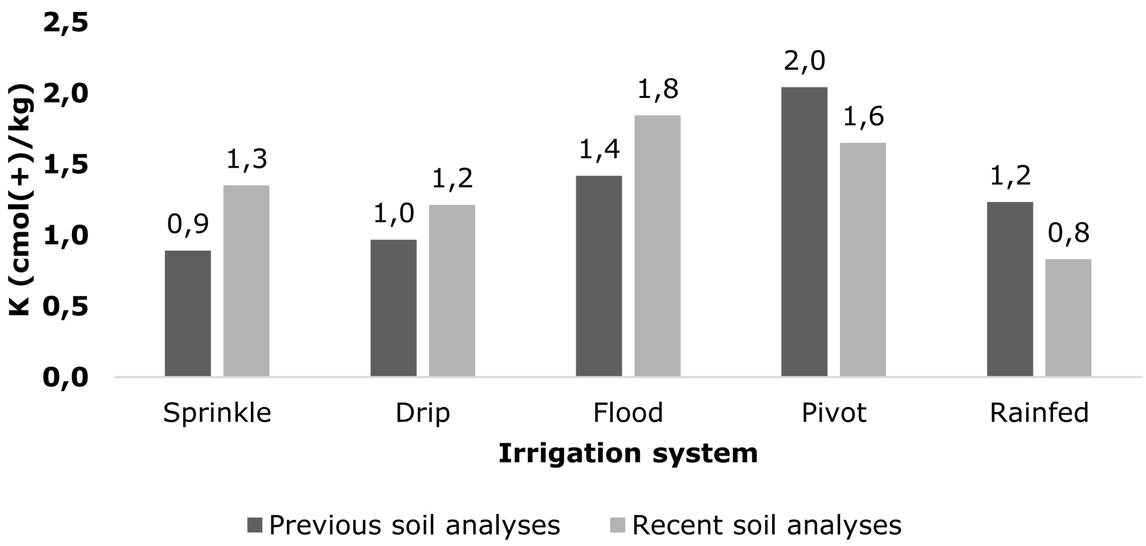

Figure 23. *K (cmol (+)/kg) comparison from previous and recent soil analyses by San Antonio irrigation system.*

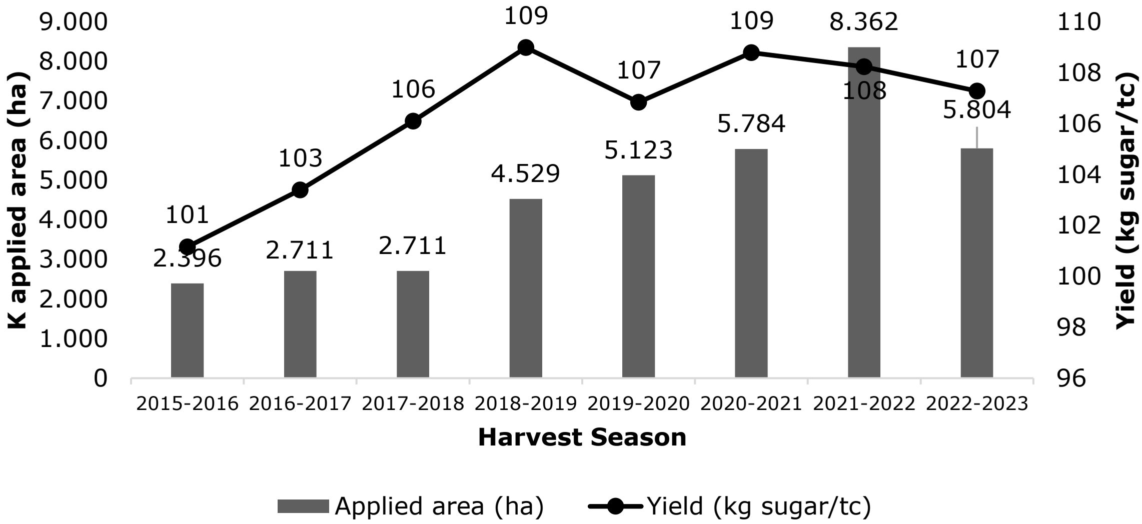

Figure 24. *K applied area by harvest season and sugar yield productivity.*

6.4 Conclusions and final remarks

- The first step in this study was a review of soil and agronomic information in San Antonio, which was one of the principal factors that influenced the success of interim guidelines and the reduction of N application without compromising productivity.

- Responses to applied N, P, and K occurred at most of the trial sites except that for plant crops, they were nil or lower than interim nutrient guidelines

- Agronomic optimum N rates were calculated from the response data and corresponded to the rates of N at 99%. Even though these values varied from each other, they provided a range of N rates for decision-making purposes, especially when viewed in combination with the calculated N-use efficiency (NUE) in terms of kg N applied/tc.

- These locally derived N and P rates from response curves are lower than the interim rates used in San Antonio.

- Although responses to applied K did not occur *per se*, the N x K interactions that occurred at some sites indicated that improved responses to applied N for sugar and cane yield were possible when at least some K fertilizer was applied.

- Interim guidelines had a great impact on profitability and N-use efficiency, but they can still be fine-tuned.

CHAPTER 7: DISCUSSION AND FUTURE WORK

Sugarcane is a valuable crop grown in tropical and subtropical climates worldwide mostly to produce sugar (Skocaj *et al*., 2013). Sugarcane production contributes markedly to the world economy with a particularly high influence in Third World countries, such as Nicaragua, where agriculture accounts for about 20% of the gross domestic product (GDP) (Sánchez and Vos, 2009). Sugarcane production continues to increase worldwide. In Nicaragua the area planted to sugarcane has increased by about 25% in the last 10 years. However, climate variability, increased fertilizer costs, environmental concerns and fluctuation in sugarcane prices are challenges that are markedly influencing sugarcane production. They are also leading to a need for increased efficiency. Even weather conditions and water supply are the major factors influencing sugarcane production, other factors, such as on-farm practices and nutrient management are often more manageable. After water, optimum nutrient management is arguably the most important factor in crop and sugar production. Over-application of fertilizers not only affects profitability, but also causes environmental concerns due to losses of applied nutrients. Much time and research has been devoted to understanding and developing appropriate N, P and K rates for sugarcane grown in different types of soil and cultivars around the world, and in trying to determine the economic optimum ratios for high yield and sugar quality (Bell, 2015; Cavalot, *et al*., 1990; Wood, 1990). In Nicaragua, fertilizer management prior to 2015 was mainly focused on nitrogen (N), and there was a belief that more N equated to production of more biomass. The concept of balanced nutrition based on soil and foliar analyses was not widely adopted. Soil characterization and research of agro-ecological zones had also not been fully explored (Anon, 1972) and most of the fertilizer recommendations were based on information from elsewhere.

Based on the young volcanic nature of Nicaraguan soils, there were expectations that they would logically be classified as Andisols (Anon, 1972), and they have problems with P fixation. However, many of the soils of the Pacific region in Nicaragua are identified as Vertisols, Mollisols, and Entisols.

The scope of sugarcane crop management in Nicaragua and the review of the literature (Chapter 2) highlighted the need to better understand sugarcane principal macronutrients (N, P, and K) fertilizer requirements and their impact in triple bottom line (economic, environmental, and social). In response to these needs, the main objective of the thesis is to improve nutrient management in alluvial soils derived from volcanic parent material in Nicaragua, considering the biggest sugar mill company in the country, San Antonio as a role model, to generate modified nutrient management guidelines derived locally by:

- Economic: By maintaining or increasing sugarcane productivity in terms of cane and sugar yield and increasing profitability by lowering application costs or increasing yield.
- Environmental: Increase nutrient (N, P, and K) use efficiency
- Social: By providing research and knowledge to the Nicaraguan growers of essential macronutrients (N, P, and K) for sugarcane production and their agronomic and economic responses in Nicaraguan soils.

7.1 Economic: By maintaining or increasing sugarcane productivity in terms of cane and sugar yield and increasing profitability by lowering application costs or increasing yield

As explained on Chapter 3 interim nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) guidelines for sugarcane production at San Antonio were suggested. The initial work within this study therefore aimed to develop interim site and soil specific N, P, K, S guidelines until R&D-based guidelines were available from this project. To support this part of the project, it was important to have a better understanding of the sugarcane production system in Nicaragua, climatic conditions, Nicaraguan soil types, and operating environments, compiled in Chapter 1. Also, an explanation of the growing and nutrient requirements of the sugarcane crop, essential nutrients (N, P, K) their process, losses and factors that can influence their availability and agricultural practices and infrastructure for effective nutrient management (Chapter 2). Nutrient guidelines for N, P, K and S developed elsewhere as explained in Chapter 3 and productivity linked with soil analyses were considered for interim nutrient guidelines in San Antonio as well. The expansion and improvement of soil sampling explained in Chapter 3, visualization of nutrient deficiency and a better knowledge of the main soil types in San Antonio could help to improve the nutrient management strategy since interim guidelines by lowering the application of N and increasing productivity.

As shown in Chapter 6 (Figure 20), the kg of N applied was reduced from 197 kg/ha to 155 kg/ha in the harvesting season 2022–2023. This decrease represents approximately 719,000 kg of N just in harvesting season 2022–2023, and 1,753,771 kg of N less since all the improvements were adopted in the interim nutrient management program (shown in Table 56).

A total of US $1,517,333 was saved by reducing the kg of N applied from the fully implemented interim N guidelines. As previously explained in Chapter 6, fertilizer costs increased dramatically through 2022 and beyond due to COVID-19-related, and, additionally, Russia's invasion of Ukraine (Anon, 2022b). By the harvest season of 2022–2023, this increase in price could have increased San Antonio's N fertilizer expenditure by almost US US $1,277,955 if N interim guidelines did not exist.

The increase in fertilizer prices in 2022 and 2023 influenced the change in P management strategy, and thanks to the results of this study, we could support P reduction by just applying commercial fields with less than 20 mg/kg of P in the soil. This generated a decrease in the area applied from 11,158 to 9,028 ha (2,128 ha) and an average P applied rate from 43 kg P_20_5/ha to 30 kg P_20_5/ha (13 kg), representing a reduction of 208,868 kg of P, productivity results are expected in harvesting season 2023-2024.

On the other hand, K interim management suggested an expansion of the applied area, and savings for a reduction in quantity were not found. However, it appears that the concept of balanced nutrition contributed to the improvement of cane and sugar yield.

Even though interim nutrient guidelines helped to increase productivity and lower the cost, R&D-based guidelines suggested that N, P rates in plant crops could be lower than the interim rates used. The average kg of nutrients applied in San Antonio to plant crops for N, and P, is 146, and 47, respectively.

Crop size was one of the main determinants of N fertilizer requirements, but N interim guidelines recommendations were based on potential yields up to 120 tc/ha. Yields under 120 tc/ha were multiplied by a factor of 1.25 kg N/t cane/ha, and the minimum N application rate was 120 kg N/ha, even when crop yield was lower than 100 tc/ha. Response curves for N applied suggest N rates of 100 kg N/ha with yields lower than 120 tc/ha.

Even though response curves suggest no P application during PC (Chapter 6), this is the best moment to apply P because it can be applied in the planting furrow below the cane setts and P has low mobility in the soil. Most of the fertilizer equipment in San Antonio applies fertilizer more than 20 cm apart from the sugarcane stool, obstructing P fertilizer contact with sugarcane roots. Additionally, clay and loam had a response to applying P in ratoons from previous applications in PC. However, results from response curves suggest 20–40 kg P/ha, lower than the average P rate applied in PC (47 kg P/ha).

K responses in PC were lower or nil when compared to ratoons. However, overall, they were higher than the interim guidelines. As shown in Appendix 1, although responses to applied K did not occur *per se*, the N x K interactions that occurred at some sites indicated that improved responses to applied N were possible when at least some K fertilizer was applied. As shown in Figure 24 (Chapter 6), the average sugar yield has increased in the last few years since interim K guidelines were proposed. As shown in Appendix 1.19 to 1.21, N and K interactions in older ratoons have a significant response to sugar.

7.2 Environmental: Increase nutrient (N, P, and K) use efficiency

Most of the Nicaraguan sugarcane industry does not have a clear understanding of the relationship between fertilizer applied and the yield resulting from soil fertility. Fertilizer NUE is a terminology not known in Nicaragua, and there is still the belief that fertilizer requirements calculations can be based on aspirational yield potential without reference to site-specific management and soil analyses.

San Antonio is the first sugar mill company in Nicaragua thanks to this research, which began to focus on this topic by setting experimental plots and investigating nutrient uptake, soil supply, and the relation between kg of fertilizer applied to produce a tonne of cane.

Nutrients efficiency factors have been described previously by Ladha (2005) and Bell (2015) in terms of N as explained in Chapter 4. In this study efficiency factors were also determined for P and K in terms of kg of nutrient applied per tonne of cane.

Interim nutrient guidelines established in San Antonio have helped to increase NUE by decreasing kg N applied/tc from 2.08 to 1.54 kg N applied/tc.

Uptake results (Chapters 4 and 5) show crop N, P, and K uptake where there is no N, P, and K application, giving a powerful tool of knowledge of the soil fertility in Nicaragua and their specific conditions and how much comes from fertilizer and how much from soil reserves.

As demonstrated by Gopalasundaram *et al*., (2011), sugarcane removes substantial quantities of N (208 kg N/ha). The highest crop N uptakes found in this study were 187 kg N/ha in clay loam, 175 kg N/ha in clay, and 199 kg N/ha in loam texture. The highest uptake previously reported was found with the highest rate of N fertilizer (225 kg/ha), except for loam texture (150 kg N/ha).

The fertilizer N recovered in these experiments ranged from 5% (4 kg N/ha) in clay to 41% (31 kg N/ha) in loam, as reported in Chapter 4. Even though urea was applied sub-surface near the cane row, fertilizer recovery was poor in the highest fertilizer rates (150 and 225 kg N/ha) in the clay loam site in the 1R and 2R. N can be lost by ammonia volatilization, denitrification, and NO_3- leaching, as explained previously in Chapter 2.

The potential for N losses in heavier textures as clay and clay loam are higher than in lighter textures as loam, especially in wet years when the crop can experience waterlogged conditions; this is likely to reduce the ability of the crop to acquire N fertilizer and loseN by denitrification.

One of the major goals of this investigation was to determine whether NUE values were lower than interim N recommendations rates without affecting productivity. As seen in Chapter 6, the overall NUE (kg N/tc) from this investigation was lower than the N interim guidelines already established, ranging from 0.76 kg N/tc in PC loam texture to 1.78 kg N/tc in 3R clay texture.

As part of NUE strategy, urease inhibitors in the form of NutriSphere-N® were added from the factory to all the N fertilizer formulas used in San Antonio, since 2018-2019 harvest season.

The K response curve results indicated higher K application rates and higher KUE (kg K/tc); however, it was identified that K application in combination with N positively influences productivity in terms of cane yield and sugar.

As previously explained in Chapter 4, research from some parts of the world has found K uptakes of up to 300 kg k/ha (Coale *et al*., 1993; Wood, 1990), and it's well known that sugarcane removes large quantities of K from the soil. Results from this study suggest the same trend, showing K uptakes of 362 kg K/ha recorded under an irrigated loam site.

Also, it was observed that with no K fertilizer application, the recovery rate was higher in the loam site (1R = 222 and 2R = 362 kg K/ha) compared to clay loam (1R = 138, 2R = 106, and 3R = 280 kg K/ha) and clay (1R = 115, 2R = 98, and 3R = 147 kg K/ha). Based on soil analyses, the loam site has a higher content of K in the soil.

PUE (kg P/tc) had similar values in response curves and interim P guidelines in some ratoons. However, on PC, there was no response to the P application.

Enhancing nutrient use efficiency may reduce input expenses, like fertilizer costs, while also preventing nutrients from contaminating the environment. In the case of N reduction, less greenhouse gas emissions, along with reduced nitrate leaching into groundwater, would result from reducing fertilizer inputs.

Still, we have a long way to go in terms of nutrient use efficiency in Nicaragua; however, these first steps can help growers and industry be aware of environmental concerns without affecting profitability.

7.3 Social: By providing research and knowledge to the Nicaraguan growers of essential macronutrients (N, P, and K) for sugarcane production and their agronomic and economic responses in Nicaraguan soils

As previously explained, sugarcane is produced along the Pacific coast of Nicaragua. The main sugar milling companies are San Antonio, Monte Rosa, Montelimar, and CASUR. These companies represented about 74,000 ha (Anon, 2018b). The largest sugar milling company is San Antonio, with a mill supply area of 33,000 ha, and approximately 47% of that area is planted by private growers. As shown in Figure 3, Chapter 1, Monterosa is near San Antonio, and some private growers share farms with both mill companies. The expansion and improvement of soil analyses explained in Chapter 3 of the approximate 17,000 ha sampled gives a better perception of nutrient deficiencies and main soil texture to the growers that are neighbors to the sampled fields. This strategy has induced growers to do the same practice. Since harvest season 2021–2022, San Antonio growers have started to do soil analyses thanks to an agreement between San Antonio and a Nicaraguan laboratory to get a better price for growers as an incentive to increase this practice. This strategy comes as a bundle composed of a georeferenced soil textural map of the farm and fertilizer recommendations, previously based on interim San Antonio nutrient guidelines. However, as a future work, this recommendation will also be fine-tuned with the results of the last phase of this study.

Since harvest season 2018-2019, nutrient management workshops have been performed explaining the essential nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), and factors affecting their availability, Nicaraguan soil types, and their properties. This has given a better understanding of the chemical processes in the soil and the factors that increase their losses through the environment.

One of the main questions of this study was whether it could be extrapolated to Nicaraguan growers. As shown in Chapter 6.3.4, a partial net return was also calculated for growers with the results from the response curves of the main textures that have been found in commercial fields. This main soil texture represents approximately 76% of the commercial fields in San Antonio; however, the same soil sampling work is recommended for growers.

As observed by Schroeder *et al*., (2006), some perceptions and inefficient practices have also been observed among Nicaraguan growers in terms of nutrient management, including:

- A perception that all soils are similar.
- An assumption that all nutrients react in similar ways and have the same process in the soil.
- A belief that more fertilizer produces higher yields.
- A lack of understanding of nutrient losses, their causes, and their effects.
- Generalized fertilizer applications on the farm—focusing on the worst soil and fertilizing the whole farm according to that requirement
- Uncommon use of soil analyses and leaf testing
- Overapplication of some nutrients (N) and underapplication of others (K).
- Poorly kept records
- No N fertilizer incorporation: urea surface applied.
- Nitrogen rates are not reduced after peanut crops.

Most of these perceptions can be clarified by understanding and practicing Chapters 1 through 6.

7.4 Future Work

This thesis has highlighted the importance of managing the impact of climate variability and the need for more information in terms of uptake and response coming from the seven remaining soil textural classifications in San Antonio.

This study was performed on one PC and at least two ratoons; however, PC uptake was not evaluated, and the response to applying nutrients was overall nil. Future works should take this limitation into consideration.

Sugarcane productivity can be improved through the use of best-practice farming systems. Irrigation systems and infrastructure that allow for better placement and timing of fertilizer applications should be considered. This study was performed only on plots irrigated by flood irrigation. Also, it would be important to consider the study in rain-fed fields.

Foliar analyses are taken in San Antonio; however, the values are compared to indicators of sufficiency or deficiency, generated in Florida. It’s of high importance to check the nutrient content of the soil and what is assimilated by the plant.

As demonstrated in Chapters 5 and 6, even some plots apparently have more sufficiency of one nutrient than another texture (e.g., clay vs. loam), and lighter soil results in better uptake. Rather than just work on defining the rate, it is important to find resources and conduct research to improve nutrient availability (e.g., the effects of decompaction, draining, and the use of microorganisms).

Most sugarcane growers have a crop rotation with peanuts, and some commercial fields in San Antonio are applied with mill mud. This input should be considered.

It was expected to have a high response to P because of the "volcanic genesis" of the soils; however, just about 4,000 hectares were deficient in this nutrient according to FHIA parameters.

Most of the soil in San Antonio has a higher content of calcium. It's recommended to have some soil analyses using Mehlich-3 and the current methodology (Bray or Olsen).

CHAPTER 8: CONCLUSIONS

"You cannot manage what you cannot measure". The first step of this study was to know our soils and identify the major soil types and nutrient deficiencies. Up to 3,000 soil samples were used to define the interim nutrient management. It changed from having obsolete paper-based soil analysis information from 10 years ago covering less than 40% of the total area to having digital, georeferenced, and more representative soil information analyses in the 2018–2019 harvest season for 100% of the total area of San Antonio.

“More is not always better": In the 2021-2022 harvest season, we had the highest productivity of the past ten years with 113 tc/ha and 172 kg N/ha applied on average compared to 213 kg N/ha (a reduction of 424,867 kg N less) and 100 tc/ha, respectively, across the 17,000 hectares. This was achieved with nutrient inputs slightly below the interim guidelines suggested by this study. Response curve results suggest that in PC, N application to the three main soil textures groupings can be lower than the interim guidelines, and that N recommendation for ratoon cane can undergo further fine-tuning.

"It’s about balanced nutrition": For decades, the nutrient management at San Antonio was essentially focused on N, and other macronutrients such as K were applied according to price fluctuations. One or several nutrients should not be applied at the expense of others. According to the results of this study, although responses to applied K did not occur per se, the N-K interactions that occurred at some sites indicated that improved responses to applied N were possible when at least some K fertilizer was applied in terms of cane and sugar yield. Approximately 6,342 ha (37% of the total area of San Antonio) were identified as having low K content in the soil. Some of this area (approximately 5,800 ha) was treated with K in the last few years, and sugar yield has increased by 8 kg/tc on average, as shown in Chapter 6.

In addition, the previous excessive N application could have influenced sugar yield. Excessive N rates will cause continued vegetative growth and reduce the sugar (sucrose) content. The amended K guidelines now consider differences in soil texture. They also recognize that different soils have different amounts of K reserves. These guidelines ensure that K applications do not contribute to excessive crop removal or overexploitation of K reserves.

"It’s just not about fertilizer." Sustainable sugarcane production can only be accomplished through the use of productive and disease-resistant sugarcane varieties in combination with best-practice farming systems and on-farm management. Nutrient management, which is included in full picture, should not be considered separately from other agricultural practices that influence productivity. This includes ripener application, flowering inhibitors, filling the gaps, weed and pest control, and irrigation.

“It’s not a static nutrient management recipe”. It will depend on changes in the environment, resources used, weather and economic conditions. Therefore, it is most important to understand that soils are complex physical, chemical, and biological systems that’s store and released nutrients according to several factors mentioned in Chapter 2.

San Antonio soils are from volcanic parent material, but as mentioned in Chapter 1, we have Vertisols, Mollisols, and Entisols, which lack some Andisol characteristics like P-sorption characteristics. Phosphorus uptake results and P response curves suggest that the soils at San Antonio have reasonable P reserves that are available for uptake by the crop, and the amount of P applied in San Antonio soils should be decreased. Before establishing this study, P fertilizer was applied to more than 11,000 ha. The interim P guidelines have resulted in a reduction of 208,868 kg of P.

Further fine-tuning of the P application rates has the potential for further economic and environmental benefits.

In conclusion, this study has resulted in the development and adoption of nutrient management guidelines specific for sugarcane grown on the volcanic-derived alluvial soils of north-western Nicaragua. This have resulted in improvements in productivity, profitability, and environmental considerations. This work has therefore been instrumental in promoting sustainability in one of the most important agricultural crops in Central America. This approach could provide the bases for other developing countries to establish their own nutrient recommendation guidelines rather than adopting for elsewhere.

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APPENDIX 1. EFFECT OF NITROGEN (N) AND POTASSIUM (K) APPLICATION RATES IN CLAY, CLAY LOAM AND LOAM TEXTURE.

Appendix 1.1. Effect of N and K application rates on sugarcane height (cm) in clay texture

Crop	K applied (kg/ha)	Clay texture / Height (cm)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	85.42	104.02	117.65	112.08	104.79^{B}
	60	101.65	116.73	111.22	112.32	110.48^{A}
	120	108.07	111.45	113.32	110.17	110.75^{A}
	180	105.27	113.20	110.55	111.35	110.09^{A}
	Means for N applied	100.10^{B}	111.35^{A}	113.18^{A}	111.48^{A}	
	Tukey $HSD^{0.05}$: N = 4.88 (P=0.0000); K = 4.88 (P=0.0041); N x K = 13.03 (P=0.0000)					
1R	0	139.00	147.78	132.17	141.37	140.08^{C}
	60	144.03	159.18	146.82	125.95	144.00^{BC}
	120	148.93	152.32	157.30	160.50	155.76^{A}
	180	133.68	153.68	146.67	153.25	146.82^{B}
	Means for N applied	141.41^{B}	153.24^{A}	145.74^{B}	145.27^{B}	
	Tukey $HSD^{0.05}$: N = 6.28 (P=0.0000); K = 6.28 (P=0.0000); N x K = 16.75 (P=0.0000)					
2R	0	136.70	154.82	144.00	163.80	149.83^{B}
	60	160.00	170.65	162.75	156.22	162.40^{A}
	120	165.42	160.02	171.33	166.43	165.80^{A}
	180	142.55	165.10	172.52	161.78	160.49^{A}
	Means for N applied	151.17^{B}	162.65^{A}	162.65^{A}	162.06^{A}	
	Tukey $HSD^{0.05}$: N = 6.04 (P=0.0000); K = 6.04 (P=0.0000); N x K = 16.10 (P=0.0000)					
3R	0	125.35	151.83	133.55	142.25	138.25^{B}
	60	146.07	137.02	144.72	132.82	140.15^{B}
	120	145.07	140.27	145.10	150.85	145.32^{A}
	180	126.53	153.65	138.88	151.43	142.63^{AB}
	Means for N applied	135.75^{C}	145.69^{A}	140.56^{B}	144.34^{AB}	
	Tukey $HSD^{0.05}$: N = 4.66 (P=0.0000); K = 4.66 (P=0.0007); N x K = 12.42 (P=0.0000)					
4R	0	128.52	120.42	126.80	127.93	125.92^{C}
	60	117.02	131.20	130.30	140.10	129.65^{BC}
	120	128.62	131.02	139.20	138.17	134.25^{AB}
	180	133.07	144.30	137.28	132.25	136.73^{A}
	Means for N applied	126.80^{B}	131.73^{AB}	133.40^{A}	134.61^{A}	
	Tukey $HSD^{0.05}$: N = 5.25 (P=0.0008); K = 5.25 (P=0.0000); N x K = 14.003 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.2. Effect of N and K application rates on sugarcane height (cm) in clay loam texture

Crop	K applied (kg/ha)	Clay loam texture / Height (cm)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	153.17	184.78	185.40	207.60	182.74^{C}
	60	197.28	188.75	197.43	216.28	199.94^{A}
	120	209.00	178.35	192.60	213.25	198.30^{AB}
	180	183.12	183.53	193.48	211.62	192.94^{B}
	Means for N applied	185.64^{C}	183.85^{C}	192.23^{B}	212.19^{A}	
	Tukey HSD$^{0.05}$: N =6.05 (P=0.0000); K = 6.05 (P=0.0000); N x K = 16.13 (P=0.0000)					
1R	0	137.43	177.27	189.97	177.13	170.45^{A}
	60	144.93	162.72	175.70	183.12	166.62^{A}
	120	146.03	166.78	183.97	166.02	165.70^{A}
	180	135.58	167.12	170.75	161.23	158.67^{B}
	Means for N applied	141.00^{C}	168.47^{B}	180.10^{A}	171.88^{B}	
	Tukey HSD$^{0.05}$: N = 6.89 (P=0.0000); K = 6.89 (P=0.0002); N x K = 18.37 (P=0.0005)					
2R	0	120.65	150.08	164.70	179.97	153.85^{A}
	60	124.25	146.23	158.60	181.08	152.54^{A}
	120	120.25	151.37	161.93	178.22	152.94^{A}
	180	119.22	146.72	157.20	175.38	149.63^{A}
	Means for N applied	121.09^{D}	148.60^{C}	160.61^{B}	178.66^{A}	
	Tukey HSD$^{0.05}$: N = 5.76 (P=0.0000); K = 5.76 (P=0.27); N x K = 15.37 (P=0.87)					
3R	0	91.00	116.38	132.47	126.95	116.70^{A}
	60	89.72	115.25	121.68	130.05	114.18^{A}
	120	89.45	120.05	127.27	125.57	115.58^{A}
	180	89.05	123.22	129.20	118.12	114.90^{A}
	Means for N applied	89.80^{C}	118.73^{B}	127.65^{A}	125.17^{A}	
	Tukey HSD$^{0.05}$: N = 5.38 (P=0.0000); K = 5.38 (P=0.66); N x K = 14.35 (P=0.27)					
4R	0	95.83	109.18	125.78	121.73	113.13^{A}
	60	87.77	105.48	123.67	128.37	111.32^{A}
	120	85.30	122.57	123.43	122.27	113.39^{A}
	180	88.87	118.05	122.18	118.35	111.86^{A}
	Means for N applied	89.44^{C}	113.82^{B}	123.77^{A}	122.68^{A}	
	Tukey HSD$^{0.05}$: N = 4.94 (P=0.0000); K = 4.94 (P=0.66); N x K = 13.18 (P=0.0000)					

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".

Appendix 1.3. Effect of N and K application rates on sugarcane height in loam texture

Crop	K applied (kg/ha)	Loam texture / Height (cm)				
		N applied (kg/ha)				Means for K applied
		0	**75**	**150**	**225**	
PC	0	169.68	180.83	186.37	185.45	180.58^{AB}
	60	169.98	182.58	188.92	186.35	181.96^{A}
	120	173.15	174.93	183.73	183.05	178.72^{AB}
	180	170.22	174.95	177.70	182.43	176.33^{B}
	Means for N applied	170.76^{C}	178.33^{B}	184.18^{A}	184.32^{A}	
	Tukey HSD$^{0.05}$: N =5.03 (P=0.0000); K =5.03 (P=0.0260); N x K = 13.43(P=0.5072)					
1R	0	202.82	227.40	245.98	247.00	230.80^{A}
	60	214.57	207.47	230.40	236.73	222.29^{B}
	120	210.87	223.12	246.57	236.40	229.24^{A}
	180	217.95	226.03	246.22	246.53	234.18^{A}
	Means for N applied	211.55^{C}	221.00^{B}	242.29^{A}	241.67^{A}	
	Tukey HSD$^{0.05}$: N =5.76 (P=0.0000); K =5.76 (P=0.0000); N x K =15.36 (P=0.0000)					
2R	0	210.12	248.45	254.52	259.05	243.03^{BC}
	60	212.35	247.77	250.23	252.67	240.75^{C}
	120	219.10	245.63	264.88	255.77	246.35^{B}
	180	227.87	246.07	262.82	267.05	250.95^{A}
	Means for N applied	217.36^{C}	246.98^{B}	258.11^{A}	258.63^{A}	
	Tukey HSD$^{0.05}$: N = 4.34(P=0.0000); K = 4.34(P=0.0000); N x K =11.58 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.4. Effect of N and K application rates on stalk diameter (mm) in clay texture

Crop	K applied (kg/ha)	Clay texture / Diameter (mm)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	26.80	28.37	28.47	29.20	28.21^{A}
	60	26.88	28.93	27.93	27.00	27.69^{A}
	120	27.98	27.30	28.70	26.87	27.71^{A}
	180	27.00	28.52	28.45	27.53	27.88^{A}
	Means for N applied	27.17^{B}	28.28^{A}	28.39^{A}	27.65^{AB}	
	Tukey HSD$^{0.05}$: N = 0.78 (P=0.0001); K = 0.78 (P=0.0041); N x K = 2.08 (P=0.0000)					
1R	0	27.27	28.53	27.58	28.90	28.07^{B}
	60	28.90	28.92	29.27	27.30	28.60^{AB}
	120	28.98	29.05	29.42	29.18	29.16^{A}
	180	26.33	29.02	28.97	28.58	28.23^{B}
	Means for N applied	27.87^{B}	28.88^{A}	28.81^{A}	28.49A^{B}	
	Tukey HSD$^{0.05}$: N = 0.76 (P=0.0022); K = 0.76 (P=0.0011); N x K = 2.01 (P=0.0000)					
2R	0	26.17	27.78	25.27	27.18	26.60^{B}
	60	27.47	27.13	28.57	27.88	27.76^{A}
	120	26.98	27.70	27.32	28.15	27.54^{A}
	180	25.52	27.80	28.05	28.08	27.36^{A}
	Means for N applied	26.53^{B}	27.60^{A}	27.30^{A}	27.83^{A}	
	Tukey HSD$^{0.05}$: N = 0.75 (P=0.0001); K = 0.75 (P=0.0005); N x K = 1.99 (P=0.0000)					
3R	0	26.42	27.58	27.52	27.85	27.37^{A}
	60	26.98	27.52	28.18	26.88	27.39^{A}
	120	27.20	27.87	27.90	27.18	27.54^{A}
	180	26.43	28.23	27.02	27.38	27.27^{A}
	Means for N applied	26.76^{B}	27.80^{A}	27.65^{A}	27.33^{AB}	
	Tukey HSD$^{0.05}$: N = 0.71 (P=0.0008); K = 0.71 (P=0.7924); N x K = 0.32 (P=0.1881)					
4R	0	28.20	27.58	28.62	28.30	28.18^{A}
	60	28.48	28.70	27.90	27.72	28.20^{A}
	120	28.12	27.93	28.37	27.90	28.08^{A}
	180	27.77	27.80	28.17	28.68	28.10^{A}
	Means for N applied	28.14^{A}	28.00^{A}	28.26^{A}	28.15^{A}	
	Tukey HSD$^{0.05}$: N = 0.62 (P=0.7633); K = 0.62 (P=0.9527); N x K = 1.65 (P=0.0871)					

$^{A, B}$ Means accompanied by the same letter in a group are "not significantly different".

Appendix 1.5. Effect of N and K application rates on stalk diameter(mm) in clay loam texture

Crop	K applied (kg/ha)	Clay loam texture / Diameter (mm)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	29.17	28.95	29.42	28.90	29.11^{A}
	60	29.72	29.55	29.20	29.25	29.43^{A}
	120	29.03	29.17	29.17	29.62	29.25^{A}
	180	29.58	28.32	29.00	28.87	28.94^{A}
	Means for N applied	29.38^{A}	29.00^{A}	29.20^{A}	29.16^{A}	
	Tukey HSD$^{0.05}$: N = 0.67 (P=0.54); K = 0.67 (P=0.28); N x K = 1.77 (P=0.54)					
1R	0	27.73	27.73	28.82	28.57	28.21^{A}
	60	28.02	28.63	28.92	29.12	28.67^{A}
	120	27.82	29.50	28.20	29.48	28.75^{A}
	180	28.22	28.10	28.48	29.18	28.50^{A}
	Means for N applied	27.95^{B}	28.49^{A}	28.60^{A}	29.09^{A}	
	Tukey HSD$^{0.05}$: N = 0.68 (P=0.0003); K = 0.68 (P=0.19); N x K = 1.82 (P=0.12)					
2R	0	28.00	29.00	28.62	29.03	28.66^{A}
	60	27.97	28.72	29.32	30.03	29.01^{A}
	120	28.48	29.35	28.47	29.77	29.02^{A}
	180	28.08	29.10	29.00	30.03	29.05^{A}
	Means for N applied	28.13^{C}	29.04^{B}	28.85^{B}	29.72^{A}	
	Tukey HSD$^{0.05}$: N = 0.62 (P=0.0000); K = 0.62 (P=0.33); N x K = 1.66 (P=0.42)					
3R	0	27.43	28.63	29.38	29.23	28.67^{B}
	60	27.10	29.45	29.98	30.35	29.22^{AB}
	120	27.97	30.25	30.47	29.88	29.64^{A}
	180	26.82	29.60	29.93	30.65	29.25^{AB}
	Means for N applied	27.33^{B}	29.48^{A}	29.94^{A}	30.03^{A}	
	Tukey HSD$^{0.05}$: N = 0.74 (P=0.0000); K = 0.74 (P=0.01); N x K = 1.97 (P=0.26)					
4R	0	28.53	29.88	29.37	30.63	29.60^{A}
	60	28.93	29.97	30.80	31.12	30.20^{A}
	120	28.20	30.00	30.12	30.35	29.67^{A}
	180	28.77	30.27	30.53	29.95	29.88^{A}
	Means for N applied	28.61^{B}	30.03^{A}	30.20^{A}	30.51^{A}	
	Tukey HSD$^{0.05}$: N = 0.69 (P=0.0000); K = 0.69 (P=0.11); N x K = 1.84 (P=0.38)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.6. Effect of N and K application rates on stalk diameter in loam texture

Crop	K applied (kg/ha)	Loam texture / Diameter (mm)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	27.83	27.17	27.42	27.77	27.55^{A}
	60	28.05	27.60	27.17	27.40	27.55^{A}
	120	27.37	27.22	27.83	28.33	27.69^{A}
	180	28.47	27.35	27.27	27.50	27.65^{A}
	Means for N applied	27.93^{A}	27.33^{B}	27.42^{AB}	27.75^{AB}	
	Tukey HSD$^{0.05}$: N =0.58 (P=0.0293); K =0.58 (P=0.9053); N x K =1.56 (P=0.1179)					
1R	0	25.18	26.08	26.42	26.57	26.06^{AB}
	60	24.55	26.10	26.18	26.07	25.73^{B}
	120	26.38	26.85	25.68	26.10	26.25^{AB}
	180	25.53	27.42	26.43	26.48	26.47^{A}
	Means for N applied	25.41^{B}	26.61^{A}	26.18^{A}	26.30^{A}	
	Tukey HSD$^{0.05}$: N =0.65 (P=0.0000); K =0.65 (P=0.0261); N x K =1.73 (P=0.0302)					
2R	0	24.82	25.87	26.27	26.78	25.93^{B}
	60	24.83	26.27	26.58	25.73	25.85^{B}
	120	25.78	26.63	26.62	26.47	26.38^{AB}
	180	25.85	26.97	27.25	26.82	26.72^{A}
	Means for N applied	25.32^{B}	26.43^{A}	26.68^{A}	26.45^{A}	
	Tukey HSD$^{0.05}$: N =0.65 (P=0.0000); K =0.65 (P=0.0017); N x K =1.73 (P=0.5837)					

$^{A, B}$ Means accompanied by the same letter in a group are "not significantly different".

Appendix 1.7. Effect of N and K application rates on sugarcane stalks/m^2 in clay texture

Crop	K applied (kg/ha)	Clay texture / Stalks/m^2				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0.00	5.54	5.78	5.20	5.83	5.59^C
	60.00	5.64	6.24	5.70	5.93	5.88^A
	120.00	5.58	5.08	5.99	6.23	5.72^{BC}
	180.00	5.70	5.57	5.86	5.98	5.78^{AB}
	Means for N applied	5.62^B	5.67^B	5.69^B	5.99^A	
	Tukey HSD$^{0.05}$: N =0.15 (P=0.0000); K = 0.15 (P=0.0000); N x K = 0.40 (P=0.0000)					
1R	0	5.84	6.81	7.14	6.37	6.54^A
	60	5.74	6.53	6.10	5.83	6.05^B
	120	6.32	6.79	5.98	7.31	6.60^A
	180	5.78	6.96	5.82	6.03	6.15^B
	Means for N applied	5.92^C	6.77^A	6.26^B	6.39^B	
	Tukey HSD$^{0.05}$: N = 0.28 (P=0.0000); K = 0.28 (P=0.0000); N x K =0.75 (P=0.0000)					
2R	0	5.67	5.92	5.43	6.23	5.81^A
	60	5.23	6.36	5.13	5.53	5.56^B
	120	6.06	5.42	5.70	6.36	5.88^A
	180	5.74	6.00	6.06	5.83	5.91^A
	Means for N applied	5.68^B	5.93^A	5.58^B	5.99^A	
	Tukey HSD$^{0.05}$: N =0.19 (P=0.0000); K =0.19 (P=0.0000); N x K =0.51 (P=0.0000)					
3R	0	5.66	5.57	5.96	5.82	5.75^C
	60	6.07	6.08	6.21	6.20	6.14^A
	120	5.94	6.19	6.37	6.04	6.14^A
	180	6.19	5.96	5.94	5.86	5.99^B
	Means for N applied	5.96^B	5.95^B	6.12^A	5.98^B	
	Tukey HSD$^{0.05}$: N =0.12 (P=0.0009); K =0.12 (P=0.0000); N x K =0.33 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.8. Effect of N and K application rates on sugarcane stalks/m^2 in clay loam texture

Crop	**K applied (kg/ha)**	**Clay loam texture / (stalks/m^2)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	5.98	6.72	6.64	6.47	6.45^{AB}
	60	6.68	6.67	6.37	6.11	6.46^{AB}
	120	6.60	7.06	6.44	6.29	6.60^{A}
	180	6.58	6.37	6.46	6.17	6.39^{B}
	Means for N applied	6.46^{B}	6.70^{A}	6.48^{B}	6.26^{C}	
	Tukey $HSD^{0.05}$: N =0.18 (P=0.0000); K =0.18 (P=0.03); N x K =0.48 (P=0.0000)					
1R	0	5.62	6.51	6.17	5.99	6.07^{A}
	60	6.22	6.01	5.87	5.73	5.96^{A}
	120	6.08	5.91	6.17	5.77	5.98^{A}
	180	5.77	6.38	6.24	6.07	6.11^{A}
	Means for N applied	5.92^{BC}	6.20^{A}	6.11^{AB}	5.89^{C}	
	Tukey $HSD^{0.05}$: N =0.19 (P=0.0000); K =0.19 (P=0.13); N x K = 0.52 (P=0.0000)					
2R	0	6.74	6.26	6.59	6.44	6.51^{A}
	60	6.80	6.40	6.27	6.53	6.50^{A}
	120	5.99	6.31	6.16	6.11	6.14^{B}
	180	6.32	6.51	6.11	6.26	6.30^{B}
	Means for N applied	6.46^{A}	6.37^{A}	6.28^{A}	6.34^{A}	
	Tukey $HSD^{0.05}$: N =0.20 (P=0.11); K = 0.20 (P=0.0000); N x K =0.52 (P=0.0005)					
3R	0	6.58	6.59	6.43	5.90	6.38^{AB}
	60	6.41	6.59	6.29	5.87	6.29^{B}
	120	6.83	6.56	6.17	6.46	6.50^{A}
	180	6.46	6.09	6.20	6.47	6.30^{B}
	Means for N applied	6.57^{A}	6.46^{A}	6.27^{B}	6.17^{B}	
	Tukey $HSD^{0.05}$: N =0.14 (P=0.0000); K =0.14 (P=0.0004); N x K =0.38 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.9. Effect of N and K application rates on sugarcane stalks/m^2 in loam texture

Crop	K applied (kg/ha)	Loam texture / Stalks/m^2				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	6.77	6.30	6.32	6.40	6.45^B
	60	6.60	6.24	6.80	6.37	6.50^B
	120	7.03	6.79	6.35	7.30	6.87^A
	180	6.88	6.47	6.48	7.26	6.77^A
	Means for N applied	6.82^A	6.45^B	6.49^B	6.83^A	
	Tukey HSD$^{0.05}$: N =0.20 (P=0.0000); K =0.20 (P=0.0000); N x K =0.54 (P=0.0000)					
1R	0	7.48	6.81	7.12	6.96	7.09^B
	60	7.62	8.03	7.02	6.68	7.34^A
	120	6.49	7.70	7.30	6.77	7.06^B
	180	6.99	7.23	7.30	6.50	7.00^B
	Means for N applied	7.14^B	7.44^A	7.18^B	6.73^C	
	Tukey HSD$^{0.05}$: N =0.22 (P=0.0000); K =0.22 (P=0.0005); N x K =0.58 (P=0.0000)					
2R	0	6.85	7.19	6.99	6.90	6.98^A
	60	6.88	6.86	6.81	6.83	6.84^B
	120	6.84	7.30	7.11	6.24	6.87^{AB}
	180	6.69	7.07	6.63	6.40	6.70^C
	Means for N applied	6.81^B	7.10^A	6.89^B	6.59^C	
	Tukey HSD$^{0.05}$: N =0.12 (P=0.0000); K =0.12 (P=0.0000); N x K =0.32 (P=0.0000)					

[A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.10. Effect of N and K application rates on sugarcane weight/stalks (kg) in clay texture

Crop	**K applied (kg/ha)**	**Clay texture / Weight/stalks (kg)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0.00	1.23	1.36	1.45	1.54	1.41^{B}
	60.00	1.54	1.45	1.63	1.54	1.54^{A}
	120.00	1.50	1.50	1.50	1.68	1.54^{A}
	180.00	1.50	1.41	1.54	1.63	1.54^{A}
	Means for N applied	1.45^{C}	1.45^{C}	1.54^{B}	1.59^{A}	
	Tukey $HSD^{0.05}$: N = 0.0414 (P=0.0000); K = 0.0414 (P=0.0000); N x K =0.1104 (P=0.0000)					
1R	0	1.04	1.23	1.23	1.23	1.18^{B}
	60	1.27	1.45	1.32	1.18	1.32^{A}
	120	1.23	1.23	1.23	1.36	1.27^{A}
	180	1.23	1.32	1.32	1.32	1.27^{A}
	Means for N applied	1.18^{B}	1.32^{A}	1.27^{A}	1.27^{A}	
	Tukey $HSD^{0.05}$: N =0.0169 (P=0.0000); K =0.0169 (P=0.0000); N x K =0.0339 (P=0.0000)					
2R	0	1.23	1.32	1.45	1.45	1.36^{C}
	60	1.36	1.59	1.63	1.50	1.54^{AB}
	120	1.32	1.50	1.72	1.41	1.50^{B}
	180	1.41	1.50	1.72	1.50	1.54^{A}
	Means for N applied	1.36^{c}	1.50^{B}	1.63^{A}	1.45^{B}	
	Tukey $HSD^{0.05}$: N =0.0162 (P=0.0000); K =0.0162 (P=0.0000); N x K =0.1112 (P=0.0000)					
3R	0	1.27	1.45	1.54	1.59	1.45^{A}
	60	1.36	1.27	1.50	1.41	1.36^{BC}
	120	1.23	1.32	1.41	1.36	1.33^{C}
	180	1.32	1.50	1.45	1.45	1.41^{AB}
	Means for N applied	1.27^{C}	1.41^{B}	1.45^{A}	1.45^{A}	
	Tukey $HSD^{0.05}$: N =0.0500 (P=0.0000); K =0.0500 (P=0.0000); N x K = 0.1333 (P=0.0000)					

$^{A,\ B,\ C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.11. Effect of N and K application rates on sugarcane weight/stalks (kg) in clay loam texture

Crop	K applied (kg/ha)	Clay loam texture / Weight/stalks (kg)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	1.57	1.67	1.90	2.03	1.79^{B}
	60	1.82	1.70	2.15	2.06	1.94^{A}
	120	2.00	1.73	1.84	1.81	1.85^{B}
	180	1.86	1.72	1.81	2.00	1.85^{B}
	Means for N applied	1.81^{B}	1.71^{C}	1.93^{A}	1.98^{A}	
	Tukey HSD$^{0.05}$: N =0.07 (P=0.0000); K =0.07 (P=0.0000); N x K =0.17 (P=0.0000)					
1R	0	1.26	1.53	1.61	1.61	1.50^{AB}
	60	1.43	1.45	1.73	1.61	1.56^{A}
	120	1.30	1.55	1.71	1.55	1.53^{AB}
	180	1.28	1.52	1.55	1.53	1.47^{B}
	Means for N applied	1.32^{C}	1.52^{B}	1.65^{A}	1.58^{B}	
	Tukey HSD$^{0.05}$: N =0.07 (P=0.0000); K =0.07 (P=0.0093); N x K = 0.18 (P=0.0020)					
2R	0	1.30	1.37	1.66	1.65	1.50^{B}
	60	1.52	1.48	1.47	1.77	1.57^{A}
	120	1.41	1.53	1.49	1.72	1.54^{AB}
	180	1.37	1.56	1.59	1.76	1.57^{A}
	Means for N applied	1.40^{D}	1.49^{C}	1.56^{B}	1.72^{A}	
	Tukey HSD$^{0.05}$: N =0.06 (P=0.0000); K =0.06 (P=0.13); N x K = 0.17 (P=0.0000)					
3R	0	1.85	1.66	1.79	1.78	1.77^{A}
	60	1.52	1.87	1.79	2.18	1.84^{A}
	120	1.50	1.92	1.90	1.81	1.78^{A}
	180	1.49	1.91	1.82	2.06	1.82^{A}
	Means for N applied	1.59^{C}	1.84^{B}	1.82^{B}	1.96^{A}	
	Tukey HSD$^{0.05}$: N = 0.09 (P=0.0000); K =0.09 (P=0.13); N x K = 0.23 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.12. Effect of N and K application rates on sugarcane weight/stalks (kg) in loam texture

Crop	**K applied (kg/ha)**	**Loam texture / Weight/stalks (kg)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	1.62	1.74	1.93	1.75	1.76^{B}
	60	1.74	1.77	1.68	1.85	1.76^{B}
	120	1.79	1.78	1.81	1.89	1.82^{A}
	180	1.78	1.86	1.90	1.83	1.84^{A}
	Means for N applied	1.73^{C}	1.79^{B}	1.83^{A}	1.83^{A}	
	Tukey $HSD^{0.05}$: N =0.0382 (P=0.0000); K =0.0382 (P=0.0000); N x K = 0.1018 (P=0.00000)					
1R	0	1.32	1.46	1.52	1.55	1.47^{B}
	60	1.52	1.52	1.53	1.54	1.53^{A}
	120	1.50	1.47	1.57	1.53	1.52^{A}
	180	1.41	1.48	1.59	1.49	1.50^{AB}
	Means for N applied	1.44^{B}	1.48^{B}	1.56^{A}	1.53^{A}	
	Tukey $HSD^{0.05}$: N = 0.0168 (P=0.0000); K =0.0168 (P=0.0006); N x K =0.1149 (P=0.0000)					
2R	0	1.30	1.37	1.38	1.36	1.36^{AB}
	60	1.31	1.26	1.47	1.52	1.39^{A}
	120	1.33	1.30	1.44	1.40	1.37^{A}
	180	1.22	1.33	1.33	1.39	1.32^{B}
	Means for N applied	1.29^{B}	1.32^{B}	1.41^{A}	1.42^{A}	
	Tukey $HSD^{0.05}$: N =0.0485 (P=0.0000); K =0.0485 (P=0.0025); N x K =0.1295 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.13. Effect of N and K application rates on cane yield (tc/ha) in clay texture (WOA)

Crop	**K applied (kg/ha)**	**Clay texture / Cane yield (tc/ha)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	71.75	80.96	77.62	93.32	80.91^{B}
	60	88.49	94.44	96.12	93.92	93.24^{A}
	120	86.87	78.70	93.53	107.77	91.72^{A}
	180	87.45	82.09	94.44	102.05	91.51^{A}
	Means for N applied	83.64^{C}	84.05^{C}	90.43^{B}	99.26^{C}	
	Tukey HSD$^{0.05}$: N =3.58 (P=0.0000); K =3.58 (P=0.0000); N x K =9.54 (P=0.0000)					
1R	0	62.32	85.65	89.78	80.71	79.62^{B}
	60	75.87	95.96	83.10	71.33	81.57^{B}
	120	80.02	86.58	77.05	102.92	86.64^{A}
	180	72.77	95.03	78.66	81.89	82.09^{B}
	Means for N applied	72.74^{C}	90.81^{A}	82.15^{B}	84.21^{B}	
	Tukey HSD$^{0.05}$: N =4.53 (P=0.0000); K =4.53 (P=0.0008); N x K =12.09 (P=0.0000)					
2R	0	73.55	82.27	81.73	94.34	82.97^{C}
	60	74.58	104.98	85.50	87.10	88.04^{B}
	120	84.56	85.52	100.36	91.48	90.48^{AB}
	180	84.76	92.51	108.55	89.47	93.82^{A}
	Means for N applied	79.36^{B}	91.32^{A}	94.04^{A}	90.59^{A}	
	Tukey HSD$^{0.05}$: N =4.21 (P=0.0000); K =4.21 (P=0.0000); N x K =11.22 (P=0.0000)					
3R	0	73.06	84.59	92.81	93.91	86.09^{A}
	60	84.70	80.34	96.34	89.36	87.69^{A}
	120	76.20	86.26	94.03	85.88	85.59^{A}
	180	83.20	92.20	87.86	88.73	88.00^{A}
	Means for N applied	79.29^{C}	85.85^{B}	92.76^{A}	89.47^{A}	
	Tukey HSD$^{0.05}$: N = 4.51 (P=P=0.0000); K = 4.51 (P=0.2155); N x K = 11.89 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.14. Effect of N and K application rates on cane yield (tc/ha) in clay loam texture (WOA)

Crop	**K applied (kg/ha)**	**Clay loam texture / Cane yield (tc/ha)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	94.98	112.49	126.20	131.34	116.25^{B}
	60	120.62	114.16	137.88	125.91	124.64^{A}
	120	132.37	122.13	119.71	114.79	122.25^{AB}
	180	126.37	111.44	117.76	123.79	119.84^{AB}
	Means for N applied	118.59^{BC}	115.05^{c}	125.39^{A}	123.96^{AB}	
	Tukey HSD$^{0.05}$: N = 6.06 (P=0.0000); K = 6.06 (P=0.0034); N x K =16.18 (P=0.0000)					
1R	0	72.04	100.26	98.42	96.61	91.83^{A}
	60	89.50	87.52	101.67	90.80	92.37^{A}
	120	78.93	93.27	106.26	91.04	92.38^{A}
	180	75.78	97.14	95.52	94.08	90.63^{A}
	Means for N applied	79.06^{C}	94.55^{B}	100.47^{A}	93.13^{B}	
	Tukey HSD$^{0.05}$: N = 5.11 (P=0.0000); K = 5.11 (P=0.7950); N x K = 13.64 (P=0.0000)					
2R	0	88.49	85.94	111.64	106.25	98.08^{AB}
	60	104.85	95.81	94.57	115.92	102.79^{A}
	120	85.30	98.57	93.46	105.20	95.63^{BC}
	180	88.31	103.27	97.87	110.46	99.98^{AB}
	Means for N applied	91.74^{C}	95.90^{BC}	99.39^{B}	109.46^{A}	
	Tukey HSD$^{0.05}$: N = 5.86 (P=0.0000); K = 5.86 (P=0.0147); N x K =15.61 (P=0.0000)					
3R	0	122.15	109.38	114.91	104.09	112.63^{A}
	60	98.26	124.51	112.97	127.63	115.84^{A}
	120	102.87	125.35	116.22	116.73	115.29^{A}
	180	97.71	116.58	111.08	133.23	114.65^{A}
	Means for N applied	105.25^{C}	118.96^{AB}	113.79^{B}	120.42^{A}	
	Tukey HSD$^{0.05}$: N = 6.09 (P=0.0000); K =6.09 (P=0.5534); N x K =16.24 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.15. Effect of N and K application rates on cane yield (tc/ha) in loam texture (WOA)

Crop	**K applied (kg/ha)**	**Loam texture / (tc/ha)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	112.30	110.87	125.48	114.45	116.78[B]
	60	118.25	112.87	116.30	120.25	116.92[B]
	120	128.83	123.13	117.03	140.13	127.28[A]
	180	124.86	122.58	126.42	135.25	127.28[A]
	Means for N applied	121.06[B]	117.36[B]	121.31[B]	127.52[A]	
	Tukey HSD$^{0.05}$: N =4.75 (P=0.0000); K =4.75 (P=0.0000); N x K =12.67 (P=0.0000)					
1R	0	101.17	101.86	111.13	109.77	105.98[B]
	60	116.66	122.52	109.05	104.68	11323[A]
	120	99.22	115.44	115.87	105.83	109.09[B]
	180	100.80	109.46	118.48	98.28	106.76[B]
	Means for N applied	104.46[B]	112.32[A]	113.63[A]	104.64[B]	
	Tukey HSD$^{0.05}$: N = 4.12(P=0.0000); K =4.12 (P=0.0000); N x K =10.99 (P=0.0000)					
2R	0	91.02	100.71	98.92	95.84	96.62[A]
	60	92.03	88.16	101.89	105.35	96.86[A]
	120	92.95	96.70	104.85	89.72	96.05[A]
	180	83.25	96.46	90.22	90.72	90.16[B]
	Means for N applied	89.81[B]	95.51[A]	98.97[A]	95.41[A]	
	Tukey HSD$^{0.05}$: N =3.77 (P=0.0000); K = 3.77(P=0.0000); N x K =10.06 (P=0.0000)					

[A, B, C] *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.16. Effect of N and K application rates on cane yield (tc/ha) in clay texture (WA)

Crop	K applied (kg/ha)	Clay texture / Cane yield (tc/ha)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0.00	72.81	78.93	84.44	89.78	81.49^{B}
	60.00	88.56	85.31	94.99	89.08	89.49^{A}
	120.00	87.48	86.70	87.87	97.72	89.94^{A}
	180.00	86.05	82.75	90.73	95.73	88.81^{A}
	Means for N applied	83.72^{C}	83.42^{C}	89.51^{B}	93.08^{A}	
	Tukey HSD$^{0.05}$: N =2.37 (P=0.0000); K =2.37 (P=0.0000); N x K =6.33 (P=0.0000)					
1R	0	67.16	79.09	78.18	79.57	76.00^{B}
	60	81.39	92.07	83.93	76.22	83.40^{A}
	120	77.73	80.15	80.00	87.14	81.25^{A}
	180	78.56	84.31	84.03	84.17	82.77^{A}
	Means for N applied	76.21^{B}	83.91^{A}	81.53^{A}	81.77^{A}	
	Tukey HSD$^{0.05}$: N =2.76 (P=0.0000); K =2.76 (P=0.0000); N x K = 7.36 (P=0.0000)					
2R	0	73.37	78.27	84.80	85.81	80.56^{C}
	60	80.99	93.91	94.83	88.79	89.63^{AB}
	120	78.54	89.31	100.17	81.60	87.41^{B}
	180	82.65	87.30	102.41	87.08	89.86^{A}
	Means for N applied	78.89^{C}	87.2^{B}	95.55^{A}	85.82^{B}	
	Tukey HSD$^{0.05}$: N =2.42 (P=0.0000); K =2.42 (P=0.0000); N x K = 6.45 (P=0.0000)					
3R	0	76.90	89.79	92.65	95.42	88.69^{A}
	60	82.30	77.76	91.15	85.20	84.10^{BC}
	120	74.85	81.66	86.70	83.07	81.57^{C}
	180	79.35	90.38	87.34	89.52	86.64^{AB}
	Means for N applied	78.35^{C}	84.90^{B}	89.46^{A}	88.30^{A}	
	Tukey HSD$^{0.05}$: N = 3.00 (P=0.0000); K = 3.00 (P=0.0000); N x K = 8.01 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.17. Effect of N and K application rates on cane yield (tc/ha) in clay loam texture (WA)

Crop	**K applied (kg/ha)**	**Clay loam texture / Cane yield (tc/ha)**				
		N applied (kg/ha)				**Means for K applied**
		0	**75**	**150**	**225**	
PC	0	101.93	108.00	122.79	131.70	116.11^{B}
	60	118.04	110.21	139.19	133.80	125.31^{A}
	120	129.54	112.26	119.46	116.96	119.56^{B}
	180	120.34	111.82	117.76	129.74	119.91^{B}
	Means for N applied	117.46^{B}	110.57^{C}	124.80^{A}	128.05^{A}	
	Tukey HSD$^{0.05}$: N = 4.25 (P=0.0000); K = 4.25 (P=0.0000); N x K =11.32 (P=0.0000)					
1R	0	75.80	92.54	97.28	97.05	90.67^{AB}
	60	86.29	87.75	104.67	97.10	93.95^{A}
	120	78.49	93.36	103.39	93.77	92.25^{AB}
	180	77.58	91.95	93.59	92.49	88.90^{B}
	Means for N applied	79.54^{C}	91.40^{B}	99.73^{A}	95.10^{B}	
	Tukey HSD$^{0.05}$: N = 3.99 (P=0.0000); K = 3.99 (P=0.7955); N x K = 10.63 (P=0.0000)					
2R	0	83.04	87.18	105.90	104.79	95.23^{B}
	60	97.04	94.30	93.97	112.63	99.49^{A}
	120	89.68	97.81	95.22	109.70	98.10^{AB}
	180	87.09	99.26	101.52	112.01	99.97^{A}
	Means for N applied	89.21^{D}	94.64^{C}	99.15^{B}	109.78^{A}	
	Tukey HSD$^{0.05}$: N = 4.01 (P=0.0000); K = 4.01 (P=0.0111); N x K =10.70 (P=0.0000)					
3R	0	117.90	105.59	114.12	113.59	112.80^{A}
	60	97.12	119.36	113.83	138.67	117.25^{A}
	120	95.63	122.49	120.76	115.51	113.60^{A}
	180	95.05	121.48	116.23	131.59	116.09^{A}
	Means for N applied	101.42^{C}	117.23^{B}	116.23^{B}	124.84^{A}	
	Tukey HSD$^{0.05}$: N = 5.55 (P=0.0000); K =5.55 (P=0.5518); N x K =14.82 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.18. Effect of N and K application rates on cane yield (tc/ha) in loam texture (WA)

Crop	K applied (kg/ha)	Loam texture / Cane yield (tc/ha)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	108.07	115.51	128.48	116.21	117.07^{B}
	60	115.76	118.12	111.94	123.00	117.21^{B}
	120	119.18	118.32	120.23	125.56	120.82^{A}
	180	118.42	123.35	126.52	121.89	122.55^{A}
	Means for N applied	115.36^{C}	118.83^{B}	121.79^{A}	121.67^{A}	
	Tukey HSD$^{0.05}$: N =2.53 (P=0.0000); K =2.53 (P=0.0000); N x K =6.76 (P=0.0000)					
1R	0	94.53	103.85	108.81	110.64	104.46^{B}
	60	108.38	108.76	109.29	110.05	109.12^{A}
	120	107.14	104.45	111.56	109.35	108.12^{A}
	180	100.57	105.58	113.60	106.55	106.57^{AB}
	Means for N applied	102.65^{B}	105.66^{B}	110.82^{A}	109.15^{A}	
	Tukey HSD$^{0.05}$: N =3.06 (P=0.0000); K =3.06 (P=0.0006); N x K = 8.16 (P=0.0000)					
2R	0	89.38	94.25	95.03	93.47	93.03^{AB}
	60	89.69	86.33	100.62	104.45	95.27^{A}
	120	91.56	89.38	98.86	95.96	93.94^{A}
	180	83.48	91.61	91.61	95.44	90.54^{B}
	Means for N applied	88.53^{B}	90.39^{B}	96.53^{A}	97.33^{A}	
	Tukey HSD$^{0.05}$: N =3.33 (P=0.0000); K = 3.33 (P=0.0028); N x K =8.88 (P=0.0000)					

$^{A, B, C}$ Means accompanied by the same letter in a group are "not significantly different".

Appendix 1.19. Effect of N and K application rates on sugar yield (kg/tc) in clay texture.

Crop	K applied (kg/ha)	Clay texture / Sugar (kg/tc)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	161.99	167.14	165.93	160.51	163.89^{A}
	60	167.14	165.11	159.86	160.51	163.15^{A}
	120	165.93	168.79	170.34	163.68	167.19^{A}
	180	161.90	171.06	165.09	166.36	166.10^{A}
	Means for N applied	164.24^{A}	168.02^{A}	165.31^{A}	162.76^{A}	
	Tukey HSD$^{0.05}$: N = 6.37 (P=0.7234); K = 6.37 (P=0.8932); N x K = 17.28 (P=0.5257)					
1R	0	163.16	169.79	165.20	158.06	164.05^{B}
	60	165.01	164.12	160.59	160.25	162.49^{B}
	120	167.25	167.99	169.79	162.81	166.96^{A}
	180	167.60	171.59	165.20	166.46	167.71^{A}
	Means for N applied	165.75^{B}	168.37^{A}	165.20^{B}	161.90^{C}	
	Tukey HSD$^{0.05}$: N =1.7522 (P=0.0000); K =1.7522 (P=0.0000); N x K = 4.6731 (P=0.0000)					
2R	0	155.65	152.68	161.18	163.73	158.31^{BC}
	60	155.73	157.15	155.40	161.45	157.43^{C}
	120	160.15	162.05	164.73	161.80	162.18^{A}
	180	158.03	155.23	158.20	165.08	159.13^{B}
	Means for N applied	157.39^{C}	156.78^{C}	159.88^{B}	163.01^{A}	
	Tukey HSD$^{0.05}$: N =1.47 (P=0.0000); K =1.47 (P=0.0000); N x K =3.92 (P=0.0000)					
3R	0	170.44	167.16	166.49	173.24	169.33^{C}
	60	174.78	176.81	170.94	171.29	173.45^{B}
	120	171.91	173.00	173.75	174.49	173.29^{B}
	180	179.71	173.61	184.64	178.04	179.00^{A}
	Means for N applied	174.21^{AB}	172.65^{B}	173.95^{AB}	174.26^{A}	
	Tukey HSD$^{0.05}$: N = 2.15 (P=0.9330); K = 2.15 (P=0.0067); N x K = 4.45 (P=0.5795)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.20. Effect of N and K application rates on sugar yield (kg sugar/tc) in clay loam texture

Crop	K applied (kg/ha)	Clay loam texture / Sugar (kg/tc)				
		N applied (kg/ha)				Means for K applied
		0	75	150	225	
PC	0	153.87	153.01	153.34	151.41	152.91^{A}
	60	153.34	152.26	157.22	152.58	153.85^{A}
	120	152.25	154.80	151.03	151.28	152.34^{A}
	180	153.01	156.28	157.37	153.67	155.08^{A}
	Means for N applied	153.12^{A}	154.09^{A}	154.74^{A}	152.23^{A}	
	Tukey HSD$^{0.05}$: N = 7.41 (P=0.6183); K = 7.41 (P=0.6406); N x K =20.10 (P=0.9933)					
1R	0	162.32	159.31	164.60	159.41	161.41^{A}
	60	159.15	160.72	163.24	161.32	161.11^{A}
	120	160.30	152.97	164.55	163.20	160.25^{A}
	180	155.71	163.59	167.98	162.32	162.40^{A}
	Means for N applied	159.37^{B}	159.15^{B}	165.09^{A}	161.56^{B}	
	Tukey HSD$^{0.05}$: N = 7.24 (P=0.0078); K = 7.24 (P=0.6851); N x K = 19.63 (P=0.3271)					
2R	0	153.98	151.35	158.68	155.70	154.93^{C}
	60	151.35	152.55	161.75	157.15	155.70^{BC}
	120	158.50	155.20	160.15	156.38	157.56^{A}
	180	152.35	157.80	158.85	157.98	156.74^{AB}
	Means for N applied	154.04^{C}	154.23^{C}	159.86^{A}	156.80^{B}	
	Tukey HSD$^{0.05}$: N =1.67 (P=0.0000); K = 1.67 (P=0.0003); N x K =4.45 (P=0.0000)					
3R	0	148.91	149.79	146.09	161.08	151.47^{A}
	60	147.14	145.48	157.68	148.44	149.68^{B}
	120	146.38	156.66	155.11	153.60	152.94^{A}
	180	145.10	157.96	153.94	153.16	152.54^{A}
	Means for N applied	146.88^{B}	152.47^{A}	153.20^{A}	154.07^{A}	
	Tukey HSD$^{0.05}$: N =1.74 (P=0.0000); K = 1.74 (P=0.0000); N x K = 4.64 (P=0.0000)					

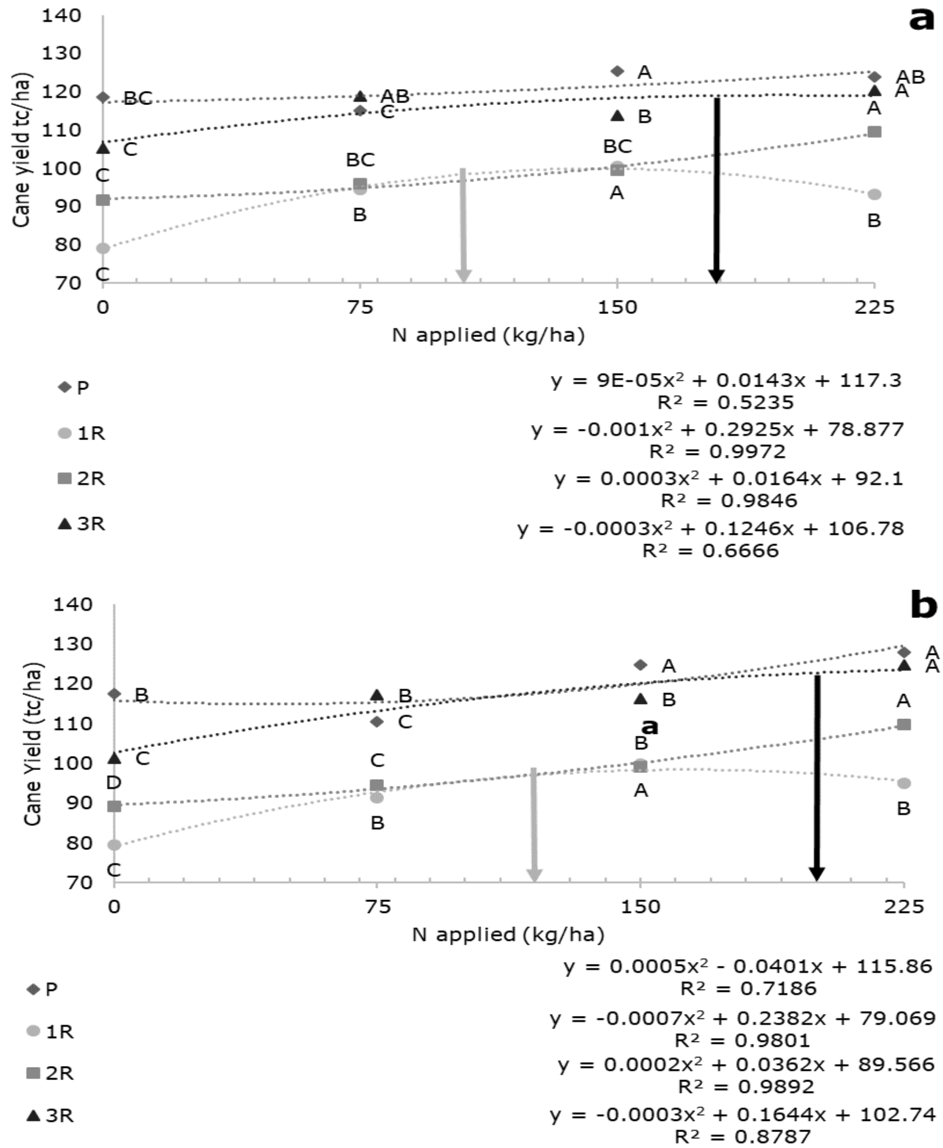
$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

Appendix 1.21. Effect of N and K application rates on *sugar yield (*kg sugar/tc in loam texture.

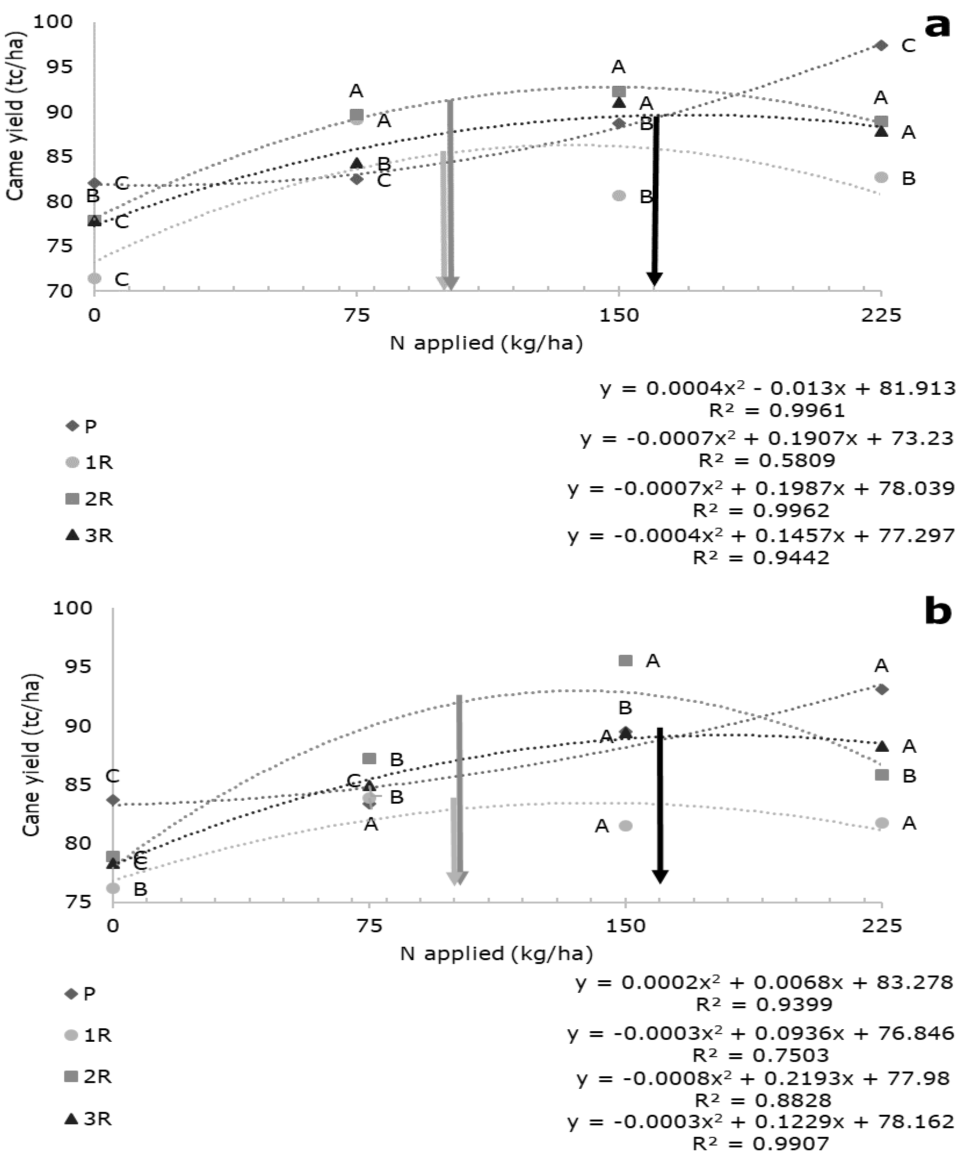
Crop	K applied (kg/ha)	Loam texture / Sugar (kg/tc)				
		N applied (kg/ha)				Means for K applied
		0	**75**	**150**	**225**	
PC	0	155.91	150.66	150.88	148.94	151.60^{A}
	60	152.46	151.03	155.15	149.82	152.12^{A}
	120	148.49	156.92	155.54	153.20	153.54^{A}
	180	149.82	151.15	154.51	150.24	151.43^{A}
	Means for N applied	151.67^{A}	152.44^{A}	154.02^{A}	150.55^{A}	
	Tukey HSD$^{0.05}$: N = 5.22(P=0.4128); K =5.22 (P=0.6524); N x K=14.16 (P=0.3595)					
1R	0	164.17	159.02	160.67	150.98	158.71^{C}
	60	158.40	160.35	165.75	164.76	162.31^{B}
	120	168.58	168.04	165.16	161.31	165.77^{A}
	180	159.46	172.45	164.17	167.13	165.80^{A}
	Means for N applied	162.65^{B}	164.96^{A}	163.93^{AB}	161.04^{C}	
	Tukey HSD$^{0.05}$: N =1.52 (P=0.0000); K =1.52 (P=0.0000); N x K =4.06 (P=0.0000)					
2R	0	156.80	161.65	157.63	154.00	157.52^{B}
	60	164.70	157.90	162.45	155.18	160.06^{A}
	120	162.48	154.68	154.73	156.88	157.52^{B}
	180	161.08	153.05	152.65	152.33	154.77^{C}
	Means for N applied	161.26^{A}	156.86^{B}	156.86^{B}	154.59^{C}	
	Tukey HSD$^{0.05}$: N =1.71 (P=0.0000); K =1.71 (P=0.0000); N x K = 4.56 (P=0.0000)					

$^{A, B, C}$ *Means accompanied by the same letter in a group are "not significantly different".*

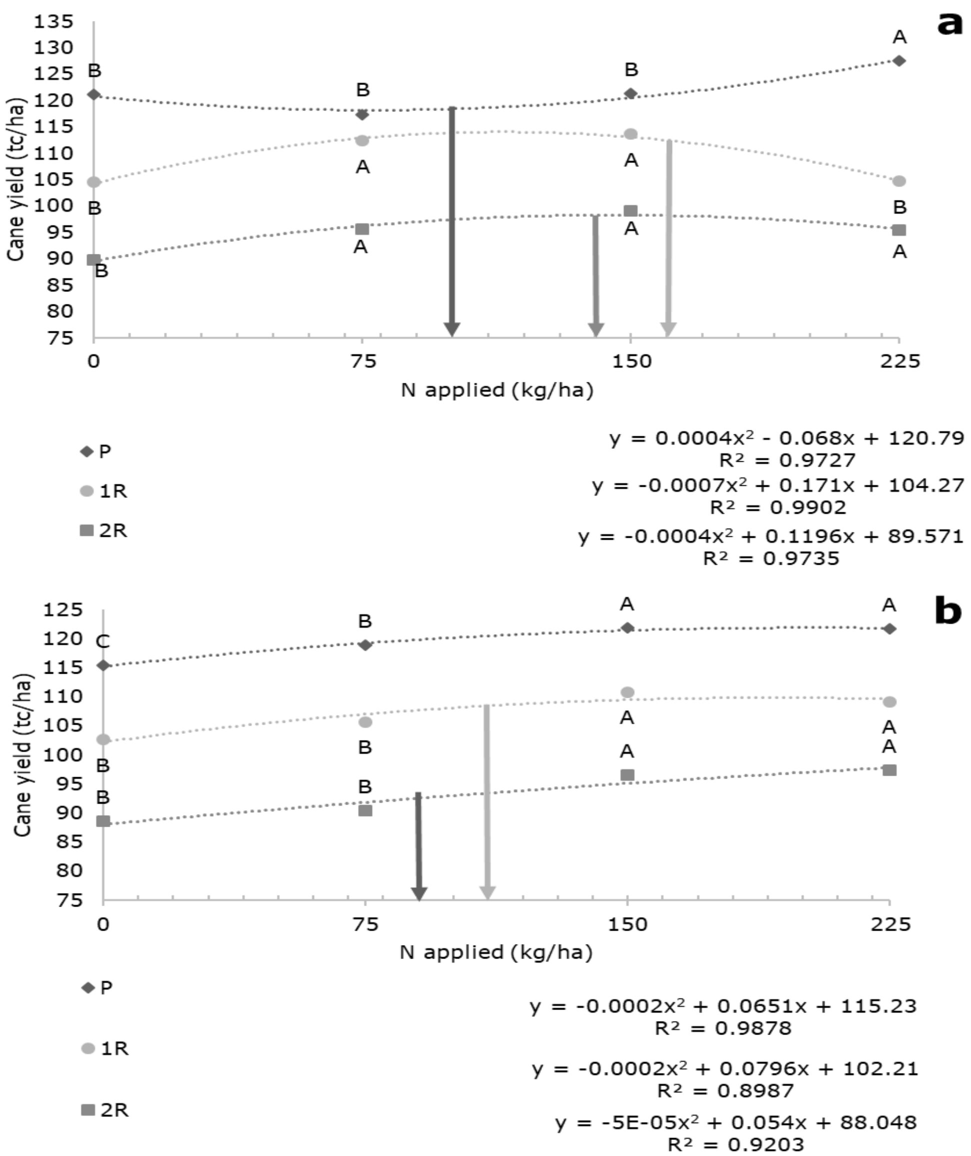
APPENDIX 2. RESPONSE CURVES



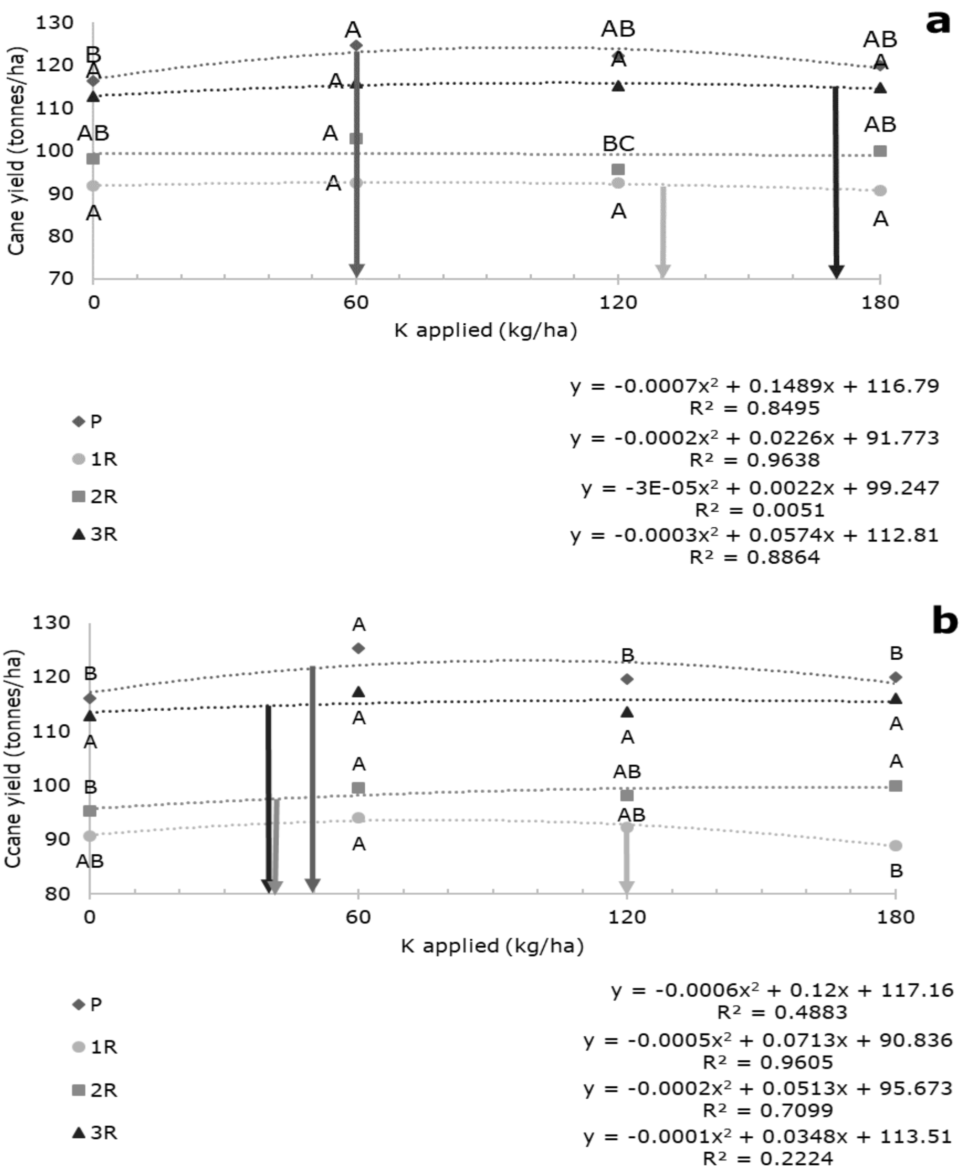
Appendix 2.1. Cane yield response curves (tc/ha) resulting from N applied to clay loam trial. The arrows indicate the application rate corresponding to 99% of the maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data. (b) With average population data per year. [A, B, C] Means accompanied by the same letter in a group are “not significantly different”.



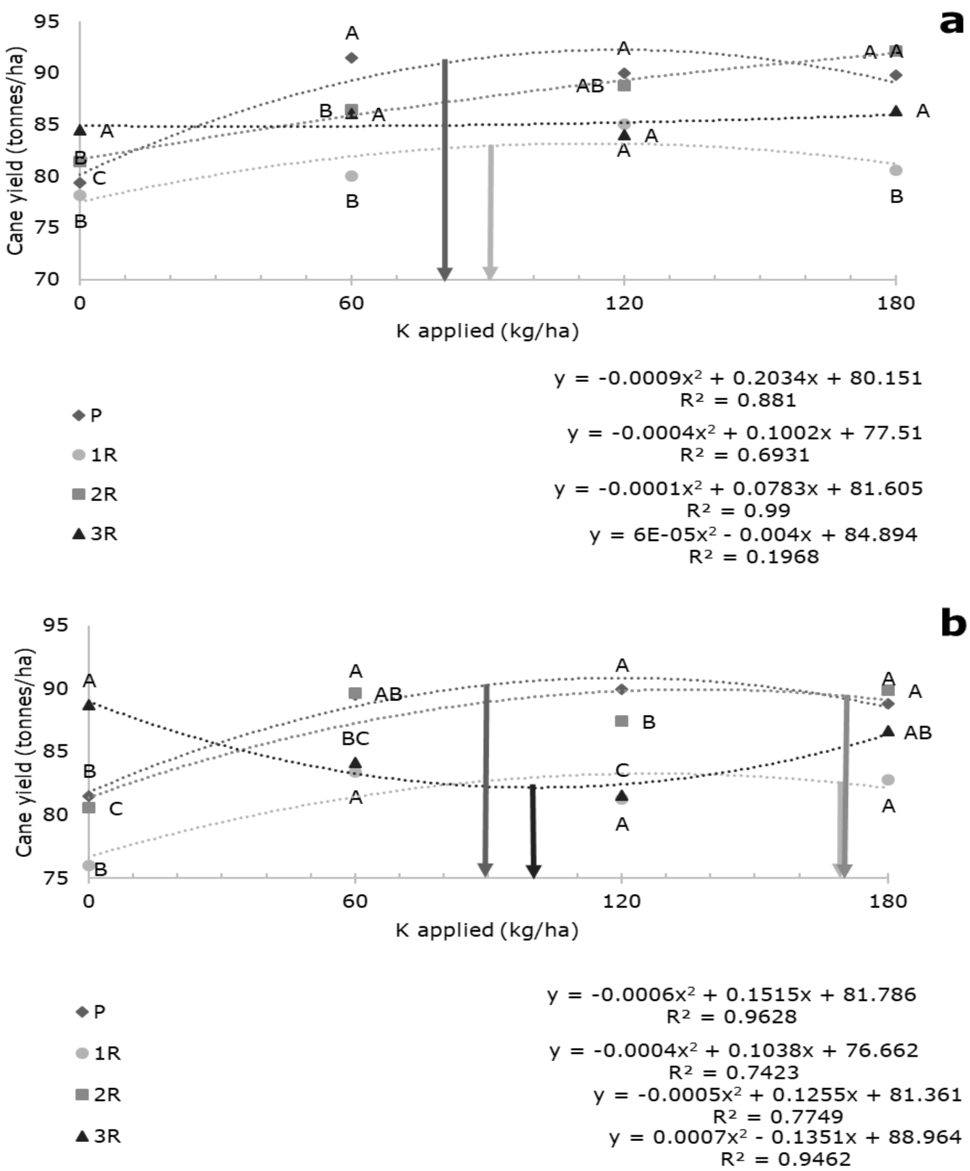
Appendix 2.2. Cane yield response curves (tc/ha) resulting from N applied to clay trial. The arrows indicate the application rate corresponding to 99% of the maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data. (b) With average population data per year. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".



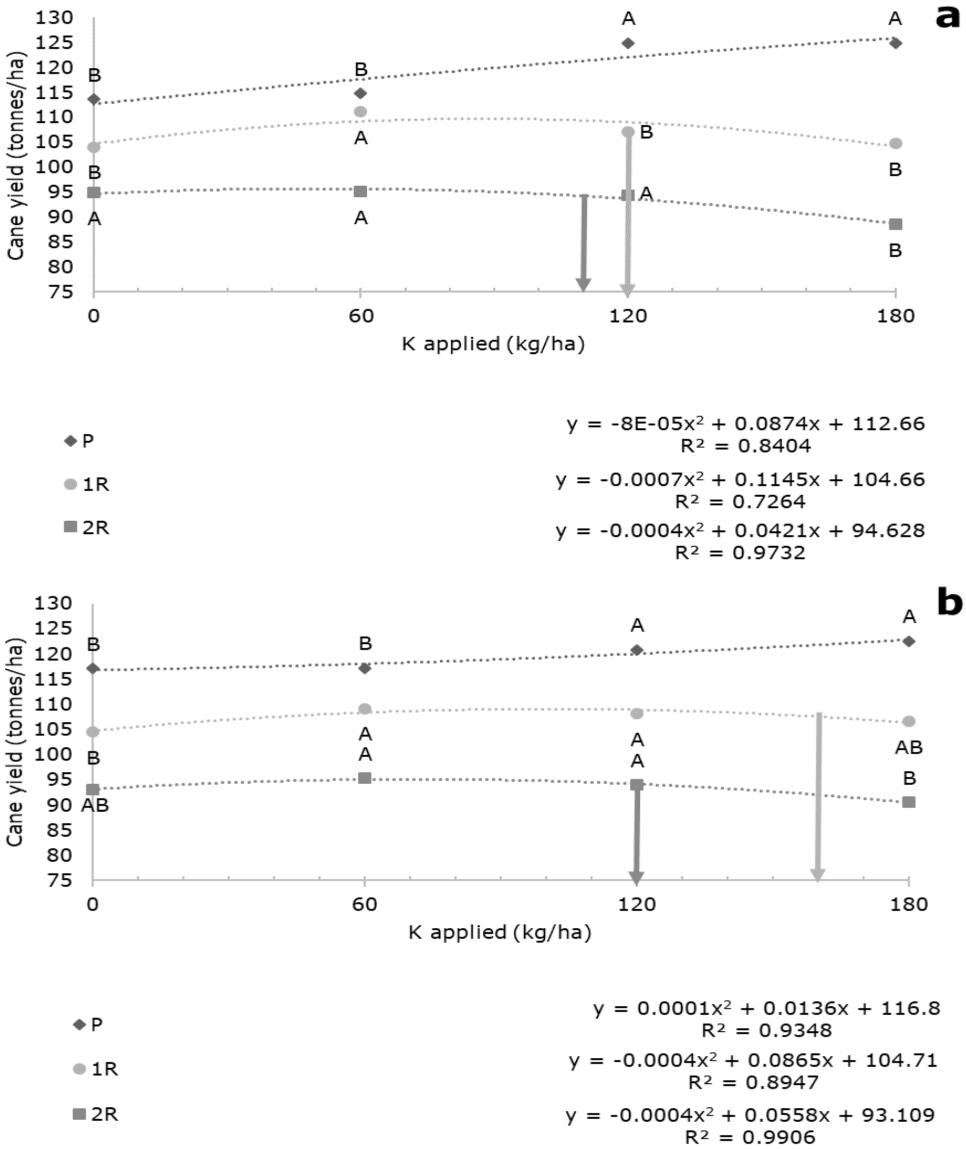
Appendix 2.3. Cane yield response curves (tc/ha) resulting from N applied to loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data. (b) With average population data per year. [A, B] Means accompanied by the same letter in a group are "not significantly different".



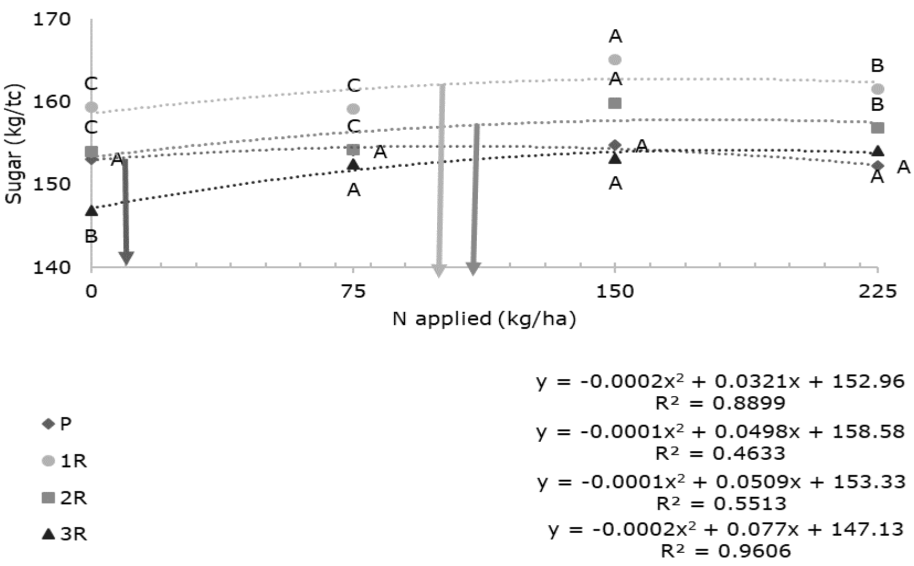
Appendix 2.4. Cane yield response curves (tc/ha) resulting from K applied to Clay Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data provided by plot. (b) With average population data per year. A, B, C Means accompanied by the same letter in a group are "not significantly different".



Appendix 2.5. Cane yield response curves (tc/ha) resulting from K applied to Clay trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data provided by plot. (b) With average population data per year. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".

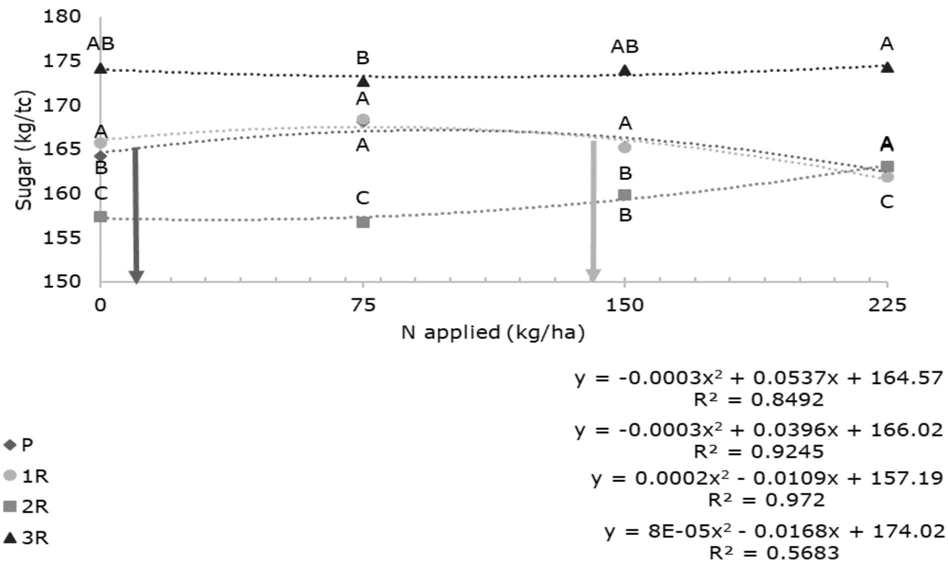


Appendix 2.6. Cane yield response curves (tc/ha) resulting from K applied to Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. (a) With actual population data provided by plot. (b) With average population data per year. [A, B] Means accompanied by the same letter in a group are "not significantly different".

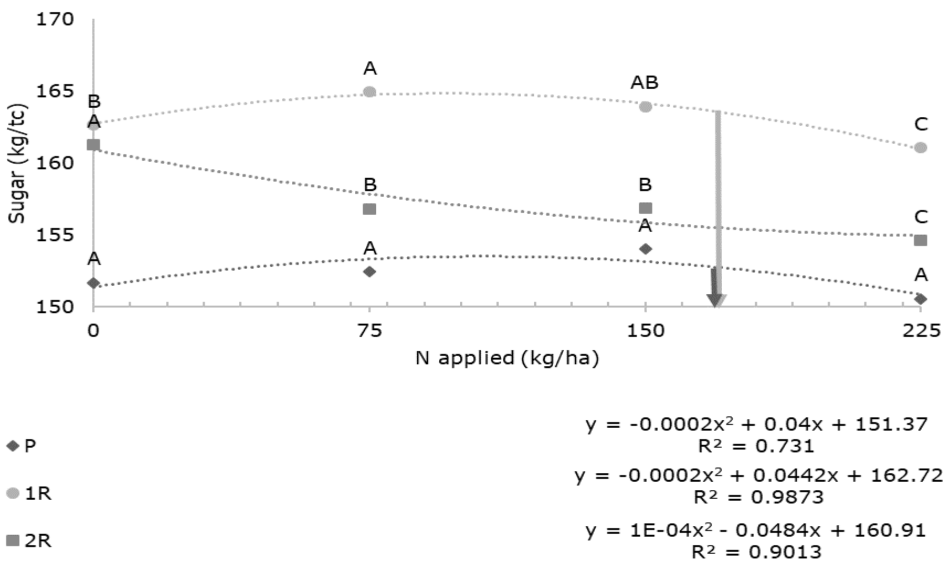


Appendix 2.7. Yield response curves (Kg of Sugar/tc) resulting from N applied to Clay Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points.

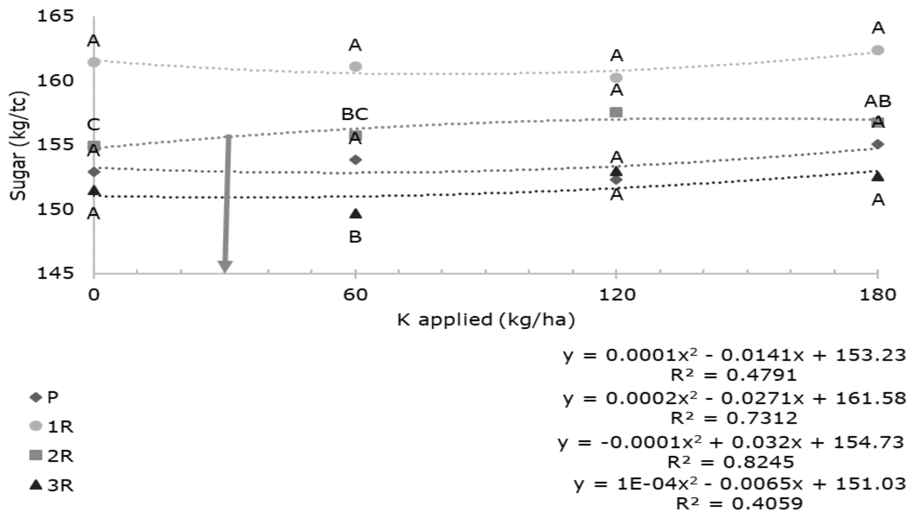
A, B, C Means accompanied by the same letter in a group are "not significantly different".



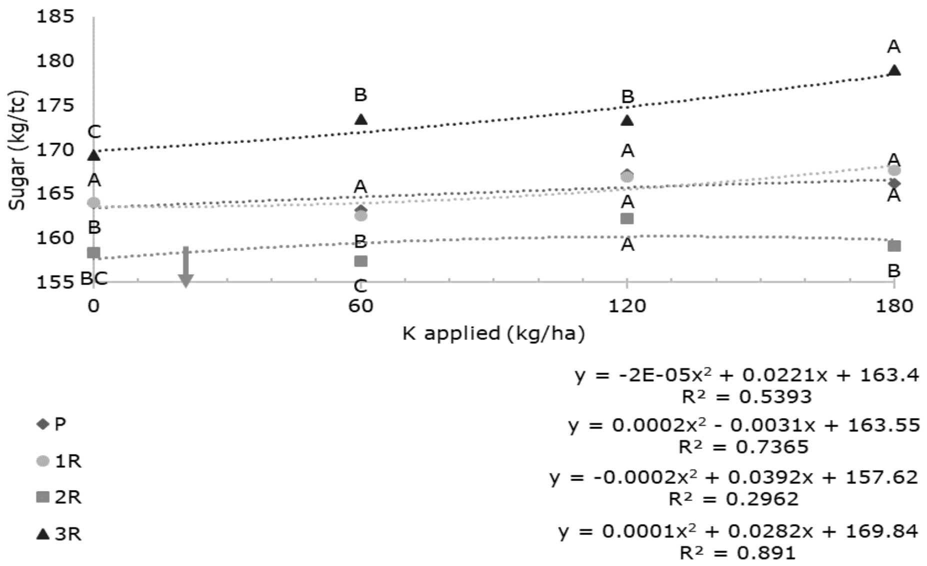
Appendix 2.8. Yield response curves (Kg of Sugar/tc) resulting from N applied to Clay trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. A, B, C Means accompanied by the same letter in a group are "not significantly different".



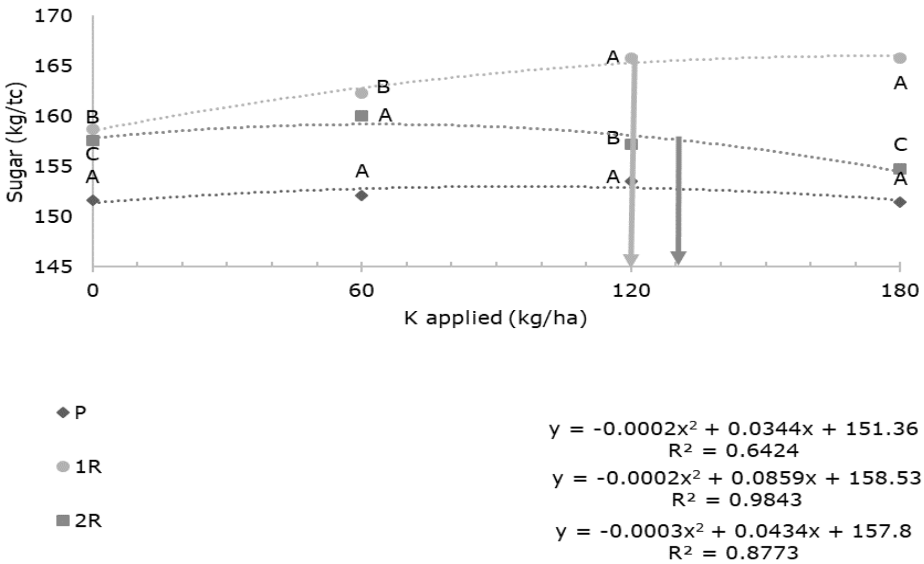
Appendix 2.9. Yield response curves (Kg of Sugar/tc) resulting from N applied to Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".



Appendix 2.10. Yield response curves (Kg of Sugar/tc) resulting from K applied to Clay Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".

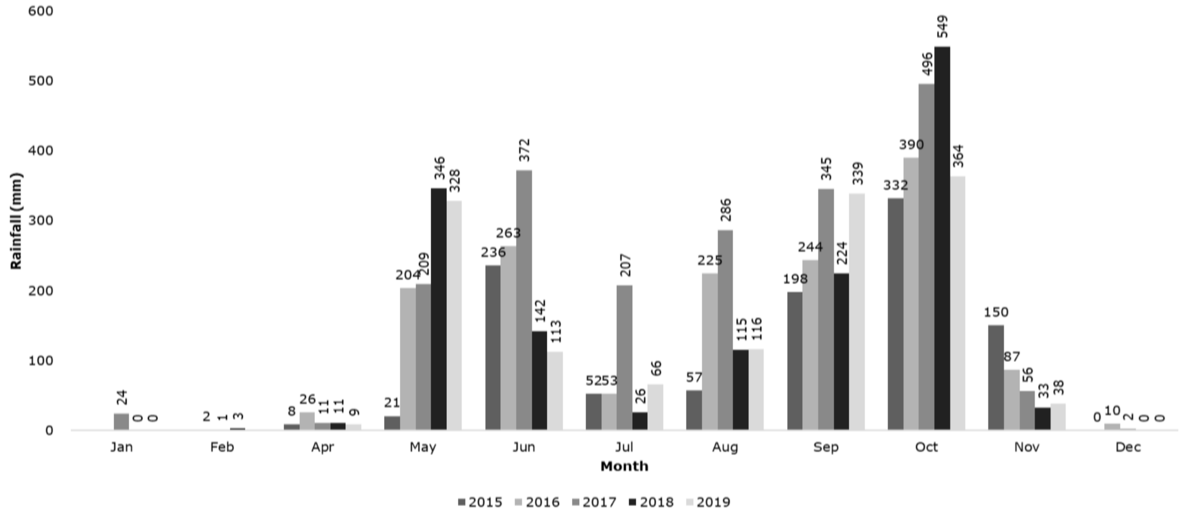


Appendix 2.11. Yield response curves (Kg of Sugar/tc) resulting from K applied to Clay trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".

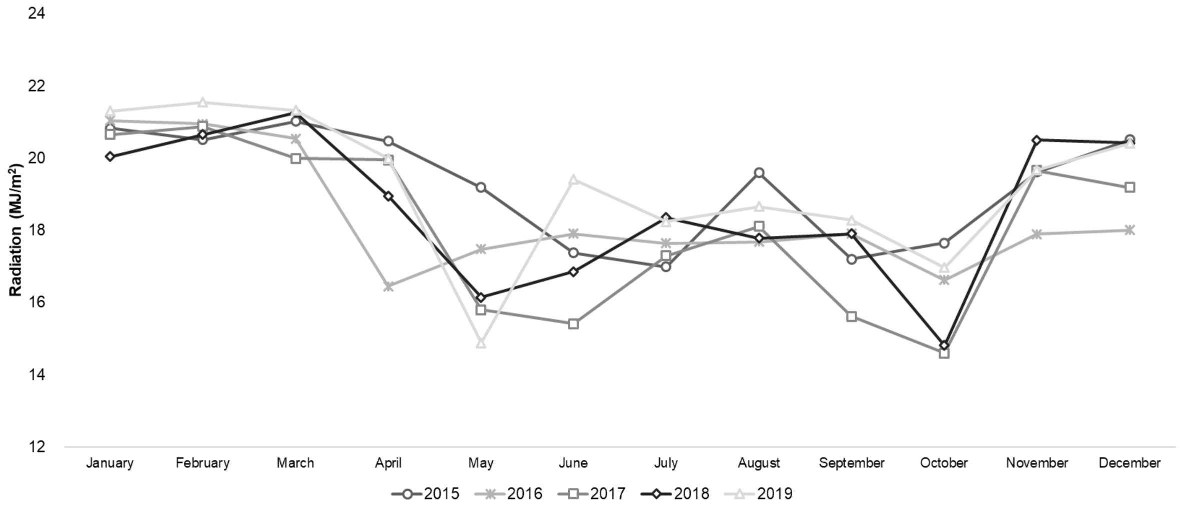


Appendix 2.12. Yield response curves (Kg of Sugar/tc) resulting from K applied to Loam trial. The arrows indicate the application rate corresponding to 99% of maximum yield predicted by the quadratic function fitted to data points. [A, B, C] Means accompanied by the same letter in a group are "not significantly different".

APPENDIX 3. CLIMATIC CONDITIONS IN SAN ANTONIO FROM 2015-2019



Appendix 2.1. Annual Rainfall(mm) in San Antonio by month from 2015-2019.

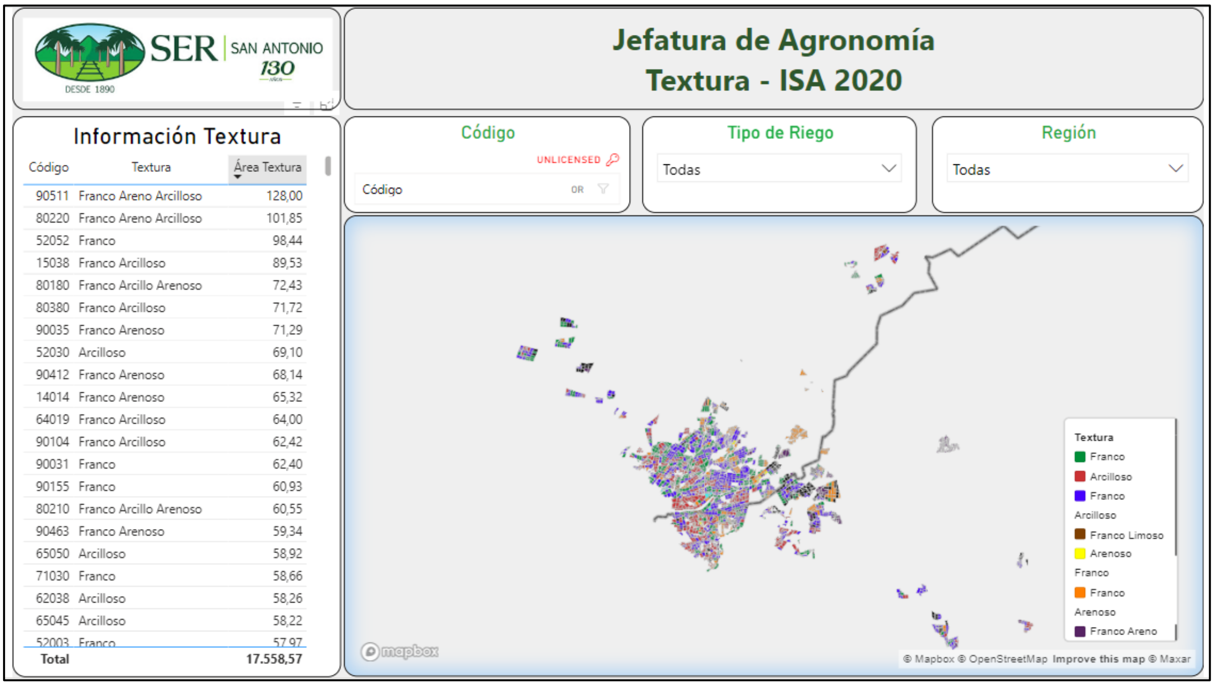


Appendix 2.2. Average solar radiation (Mj/m^2) in San Antonio from 2015-2019.

APPENDIX 4. INTERPRETATION OF SOIL ANALYSIS FERTILITY FOR SUGARCANE. ADOPTED FROM FHIA (FUNDACIÓN HONDUREÑA DE INVESTIGACIÓN AGRÍCOLA).

Nutrient	***Low***	***Low/Normal***	***Normal***	***Normal/High***	***High***
PH	*< 5.0*	*5.0-6.0*	*6.0-6.8*	*6.8-7.2*	*> 7.2*
Nitro. T. %	*< 0.2*	*0.2-0.3*	*0.3-0.4*	*0.4-0.5*	*> 0.5*
Mater.Org. %	*< 3*	*3-4*	*4-5*	*5-6*	*> 6*
P mg/kg	*< 4*	*4-10*	*10-20*	*20-40*	*> 40*
K mg/kg	*< 150*	*150-250*	*250-350*	*350-600*	*> 600*
Ca mg/kg	*< 800*	*800-1000*	*1000-6000*	*6000-10000*	*> 10000*
Mg mg/kg	*< 150*	*150-180*	*180-250*	*250-500*	*> 500*
Fe mg/kg	*< 2.5*	*2.5-5.0*	*5-15*	*15-25*	*> 25*
Mn mg/kg	*< 1.0*	*1-2*	*2-10*	*10-20*	*> 20*
Cu mg/kg	*< 0.2*	*0.2-0.5*	*0.5-1*	*1-10*	*> 10*
Zn mg/kg	*< 0.5*	*0.5-1.0*	*1-5*	*5-15*	*> 15*
S mg/kg	*< 12*	*12-20*	*20-80*	*80-150*	*> 150*
B mg/kg	*< 0.2*	*0.2-0.5*	*0.5-8*	*8-15*	*> 15*

APPENDIX 5. SAN ANTONIO SOIL SAMPLING DATA WITH CHEMICAL AND PHYSICAL PROPERTIES RESULT USING GPS COORDINATES



Código	Textura	Área Textura
90511	Franco Areno Arcilloso	128,00
80220	Franco Areno Arcilloso	101,85
52052	Franco	98,44
15038	Franco Arcilloso	89,53
80180	Franco Arcillo Arenoso	72,43
80380	Franco Arcilloso	71,72
90035	Franco Arenoso	71,29
52030	Arcilloso	69,10
90412	Franco Arenoso	68,14
14014	Franco Arenoso	65,32
64019	Franco Arcilloso	64,00
90104	Franco Arcilloso	62,42
90031	Franco	62,40
90155	Franco	60,93
80210	Franco Arcillo Arenoso	60,55
90463	Franco Arenoso	59,34
65050	Arcilloso	58,92
71030	Franco	58,66
62038	Arcilloso	58,26
65045	Arcilloso	58,22
52003	Franco	57,97
Total		17.558,57

Appendix 5. San Antonio historical productivity.