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MURILO DE CAMPOS

**SOIL DEEP STRIP-TILLAGE AND LIME APPLICATION ON SUGARCANE: SOIL
FERTILITY OF CLAYEY SOILS AND YIELD**

**Botucatu
2021**

MURILO DE CAMPOS

**SOIL DEEP STRIP-TILLAGE AND LIME APPLICATION ON SUGARCANE: SOIL
FERTILITY OF CLAYEY SOILS AND YIELD**

Tese apresentada à Faculdade de
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Orientador(a): Carlos Alexandre Costa
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TÍTULO DA TESE: SOIL DEEP STRIP-TILLAGE AND LIME APPLICATION ON SUGARCANE: SOIL FERTILITY OF CLAYEY SOILS AND YIELD

AUTOR: MURILO DE CAMPOS

ORIENTADOR: CARLOS ALEXANDRE COSTA CRUSCIOL

Aprovado como parte das exigências para obtenção do Título de Doutor em AGRONOMIA (AGRICULTURA), pela Comissão Examinadora:

Prof. Dr. CARLOS ALEXANDRE COSTA CRUSCIOL (Participação Virtual)
Produção Vegetal / Faculdade de Ciências Agronômicas de Botucatu - UNESP

Prof. Dr. JULIANO CARLOS CALONEGO (Participação Virtual)
Produção Vegetal / Faculdade de Ciências Agronômicas de Botucatu - UNESP

Prof. Dr. CARLOS ANTONIO COSTA DO NASCIMENTO (Participação Virtual)
Ciência do Solo / Escola Superior de Agricultura Luiz de Queiroz

Pesquisador Dr. ANDRÉ CESAR VITTI (Participação Virtual)
Descentralização do Desenvolvimento / APTA - Pólo Regional de Desenvolvimento Tecnológico do Centro Sul

Pesquisador Dr. HENRIQUE COUTINHO JUNQUEIRA FRANCO (Participação Virtual)
. / CROPAN - Inovação Agrícola

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por tudo.

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“Todas as vitórias ocultam uma abdicação”.

(Simone de Beauvoir)

RESUMO

Uma etapa crucial no plantio da cana-de-açúcar (*Saccharum spp*) é o preparo do solo. A adoção de sistemas de manejo visando a longevidade do cultivo é fundamental, pois após sucessivos cortes, o declínio progressivo da produção culminará na necessidade de replantio. Além do sistema de preparo convencional do solo, o sistema de preparo profundo, feito por encanteirador/sulcador tornou-se possível com tráfego de máquinas controlado. Porém, por se tratar de um manejo inovador, existem incertezas quanto à eficácia do sistema de preparo profundo com ênfase na fertilidade química do solo, uma vez que a maioria dos estudos tem abordado principalmente parâmetros físicos do solo. Nesse sentido, foram avaliados o desempenho na produção de colmos e açúcar da cana-de-açúcar, parâmetros de acidez do solo e efeito residual de longo prazo do calcário no perfil de solos argilosos em duas localidades, sendo Macatuba e Piraju. Três sistemas de preparo do solo (Sistema de preparo convencional do solo (CT); Sistema de preparo profundo do solo (DT) e Sistema de preparo do solo profundo modificado(MDT)) com quatro doses de calcário (controle, sem aplicação de calcário; dose recomendada de calcário (DR); duas vezes a dose recomendada de calcário (2x DR); e três vezes a dose recomendada de calcário (3x DR), todas aplicadas no estabelecimento da cultura) foram realizadas em delineamento de blocos casualizados com quatro repetições para cada local. Logo após as colheitas (18 meses após o plantio (cana planta); 30 meses após o plantio (primeira soqueira); 42 meses após o plantio (segunda soqueira) e 54 meses após o plantio (terceira soqueira)), amostras de solo de 0,0 a 1,00 m, estratificados a cada 0,2 m, foram coletados. Foram realizadas análises de fertilidade química do solo, diagnóstico foliar, fracionamento de alumínio (Al) e componentes do rendimento da cana-de-açúcar. Foram feitas considerações sobre as respostas às doses de calcário para cada sistema de preparo, bem como a comparação entre elas na fertilidade do solo, diagnóstico foliar e componentes da produtividade da cana-de-açúcar. Além disso, foi realizado o fracionamento do alumínio (Al) na solução do solo e na fase sólida, bem como suas correlações com o parâmetro de acidez do solo. No geral, houve maior resposta as doses de calcário nos preparos com aplicação em área total e menor naquele onde a calagem foi realizada localizada em faixas. Comparando os sistemas com a mesma dose de calcário, o MDT se sobressaiu nos parâmetros avaliados devido a maior capacidade de posicionamento do corretivo de acidez. Devido à grande efetividade na correção da acidez, em ambos os preparos foi observado que a fração do Al trocável (Al^{3+}) reduziu drasticamente e evidenciou a fração não-trocável. A fração do Al monomérico solúvel permaneceu 100% complexada às frações orgânicas independente do sistema de preparo do solo.

Palavras-chave: sistema de preparo convencional; sistema de preparo profundo em faixas; aplicação de calcário em faixas; fracionamento de alumínio.

ABSTRACT

A crucial step in sugarcane (*Saccharum* spp) planting is the soil tillage. The adoption of management systems aimed at cropping longevity is essential, since after successive cuts, a progressive decline in production will culminate in the need for replanting. In addition to conventional soil tillage system, deep strip-tillage system made up by a planting furrower became possible under controlled machinery traffic. However, as it is an innovative management, there are uncertainties about the effectiveness of deep tillage system with emphasis on chemical soil fertility, since most studies have been addressed mainly soil physical approaches. In this sense, sugarcane performance on stalks and sugar yields, soil acidity parameters and long-term residual effect of limestone across the clayey soil profile in two locations, Macatuba and Piraju, were evaluated. Three soil tillage systems (Conventional soil tillage system; Deep strip-tillage system; and Modified deep strip-tillage system) with four limestone rates (control, no limestone application; limestone recommended rate (LRR); two times limestone recommended rate (2x LRR); and three times limestone recommended rate (3x LRR), all applied at the sugarcane establishment) were performed by using randomized block design with four replicates for each site. Right after the harvests (18 mo after planting (plant cane); 30 mo after planting (first ratoon); 42 mo after planting (second ratoon) and 54 mo after planting (third ratoon)), soil samples from 0.0 to 1.00 m, stratified every 0.2 m, were collected. Soil chemical fertility analysis, foliar diagnosis, aluminum (Al) fractionation and sugarcane yield components were performed. Considerations about liming rates for each tillage system, as well as the comparison between them on soil fertility, foliar diagnosis and sugarcane yield components were described. In addition, Al fractionation on soil solution and solid phase as well as their correlations with soil acidity parameter were performed. In general, there was a greater response to liming rates in tillage which the lime was applied to the total area and less in those where liming was performed in strips. Comparing the systems with the same liming rate, MDT was shown to correct soil acidity most efficiently, mainly due to the positioning of the lime application. Due to the great effectiveness in correcting acidity, in both tillage systems it was observed the exchangeable Al fraction (Al^{3+}) was drastically reduced and highlighted the non-exchangeable fraction. The soluble monomeric Al fraction remained 100% complexed to organic fractions regardless of the soil tillage system.

Keywords: conventional soil tillage; deep strip-tillage; lime broadcast in bands; aluminum fractionation.

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GENERAL INTRODUCTION

Globally, sugarcane (*Saccharum* spp) is grown in 27.68 million hectares, producing 2.05 billion tons of stalks with an average yield of 72.69 Mg ha⁻¹ (FAOSTAT, 2018). Exploited mainly to produce sugar and ethanol, sugarcane has also been worldwide recognized as an important CO₂ sequester, responsible to produce clean and renewable energy, in addition to generating millions of direct jobs, positively impacting the socioeconomic situation where it is inserted (BORDONAL et al., 2018a).

Brazil is the world's largest sugarcane producer. For the 2020/2021 crop season, a production of 665.1 million tons of stalks is expected, cultivated from 8.6 million hectares, of which approximately 30 billion liters of ethanol and 42 million tons of sugar will be produced (CONAB, 2020). São Paulo is the most important Brazilian sugarcane-producing state, accounting for about 54.3% of total sugarcane produced, with an average yield of 81.65 Mg ha⁻¹ (CONAB, 2020). Despite high Brazilian sugarcane production, its average yield is about 77.92 Mg ha⁻¹ (CONAB, 2020), far below its potential, which can reach about 200 Mg ha⁻¹ (MONTEIRO; SENTELHAS, 2014).

Planning the establishment of crops from planting to harvest defines a series of techniques to be adopted, from varieties, treatments, inputs, mechanization, among others. Especially in perennial or semi-perennial crops, the progressive decline in production after successive cuts will culminate in the need for replanting, which is one of the most expensive treatments, and the adoption of management systems aimed at cropping longevity is essential (CRUSCIOL et al., 2017).

Due to the high impact caused on the soil structure, a crucial step in sugarcane planting is the soil tillage system (SCARPARE et al., 2019). With the advent of controlled machinery traffic, new possibilities of soil tillage systems were opened. The conventional soil tillage system is largely used in sugarcane production. This tillage system consists of revolving soil layers up to about 0.4 m depth by using heavy offset disc harrows, subsoilers, and leveling disc harrows, to incorporate soil amendments and to break compacted layers (SCARPARE et al., 2019; BARBOSA et al., 2021).

More recently, minimum tillage management has been adopted, reserving the inter-rows for machine traffic, mobilizing only planting rows (MARASCA et al., 2015). In this context, planting furrower has been used as a tool that creates a non-restrictive environment for better roots development and that preserves part of the area without disturbance. In general, the planting furrower is equipped with a subsoiling rod that works at 0.8 m depth combined with a rotary hoe that works at 0.40 m depth, making the soil tillage and incorporation of straw. Besides, it can deep locate fertilizers or any soil acidity correctives in fillets positioned between 0.40 and 0.6 m depth, just behind the subsoiler stem (MARASCA et al., 2015).

Under the tropical condition, soil fertility is one of the main limiting factors for sugarcane growth (SANCHES et al., 2021). Recently, the sugarcane crop has been expanded to new agricultural areas, under low fertility and acidic soils, which probably justifies the low yield average (BORDONAL et al., 2018a; BERNARDO et al., 2019). In Brazil, acidic soils account for approximately 60% of the country's surface area (VON UEXKÜLL; MUTERT, 1995; SCHAEFER; FABRIS; KER, 2008), and it is considered the largest territory with acidic soils in a single country (VITORELLO; CAPALDI; STEFANUTO, 2005).

Highly weathered soils under humid tropical climate are affected by losses of basic elements along with the profile, being composed mainly by low-activity 1:1 clay minerals, such as kaolinite, and Fe and Al hydrous oxide (SCHAEFER; FABRIS; KER, 2008). Such soils are pH-dependent, with negative variable charges, which the deprotonation of acidic groups is reached by increasing soil pH above to its point of zero charge (PZC, pH value at which the balance of charges is zero) (KOSMULSKI, 2020).

Several other factors can lead to natural soil acidification, such as the poverty of the parent material, microbial activity, continuous supply of H^+ ions originated by carbonic acid dissociation (carbonic acid formed by the dissolution of CO_2 from air and soil), crop export or losses of basic cations by erosive processes, mineralization of soil organic matter (SOM), and the use of fertilizers with an acidifying effect, such as ammoniacal fertilizers (H^+ generation by the ammonium nitrification process). Therefore, it is essential to alleviate the soil acidity improving the cropping system environment (SORATTO; CRUSCIOL, 2008; TIRITAN et al., 2016).

The aluminum (Al) is considered one of the most important pH buffers in acidic soils (ABREU JR.; MURAOKA; LAVORANTE, 2003). In an aqueous solution, Al can

strongly interact with waters of hydration, however, in acidic solutions, proton activity is high, and its dissociation from the water of hydration is not favored. On the other hand, in alkaline solutions, proton activity is low and hydrolysis, or the dissociation of protons from waters of hydration, is favored. This means when soil pH increases by liming, Al hydrolysis works at a pH buffer, acidifying the solution trying to bring back the balance (HIRADATE, 2004).

The agricultural lime is highly used to alleviate the problems brought by the acidity. Besides, lime application can affect the availability of some elements considered nutrients by plants. In this sense, increasing soil pH values in a range between 5.5 to 6.5 (CaCl_2) can increase Potassium (K), Calcium (Ca), and Magnesium (Mg) availabilities by increasing the effective cation exchange capacity (CEC_e) reducing their losses by leaching; nitrogen (N) sulfur (S) and Boron (B) availabilities due to the favorable effect of organic matter mineralization; Phosphorus (P) availability by increasing negative charges which will compete with phosphate specific adsorption, as well as increase the availabilities of Molybdenum (Mo) and Chlorine (Cl) (SOUZA; MIRANDA; OLIVEIRA, 2007). Conversely, Iron (Fe), Copper (Cu), Manganese (Mn), and Zinc (Zn) may be adsorbed by MOS or complexed by OH^- (hydroxyl form) when pH is raised. Therefore, attention should be given to limed areas, avoiding their deficiencies (SOUZA; MIRANDA; OLIVEIRA, 2007).

Agricultural lime has also fertilization effect, since Ca and Mg are both lime constituents. The Ca plays a fundamental role in cell walls structure and membrane formation. Its association with the chains of poly-galacturonic acids (set known as pectins) forms very stable complexes of calcium pectate (VOINICIUC; PAULY; USADEL, 2018).

Considering the cell membrane, Ca^{2+} interacts with phospholipids, stabilizing the lipid bilayer. This interaction is fundamental for membrane structure and integrity by controlling its permeability through connections between phospholipids and membrane protein (HEPLER, 2005; MERIÑO-GERGICHEVICH et al., 2010).

However, the network of Ca-pectate and Al-pectate differently cross-link with pectin in cell walls. If Al^{3+} is in excess, Ca is strongly replaced by Al, causing modifications in its structure and stability (HEPLER, 2005). Cell walls Al replacement will compromise the membrane extensibility, causing primary and secondary effects (HORST; WANG; ETICHA, 2010). The primary effect is that Al^{3+} will interact with

phosphate contained in the membrane and corrupt the ATPase enzyme functioning. With ATPase corrupted, there won't be active absorption for that cell and the root cells begin losing nutrients. The secondary effect will reflect on the deficiency in active uptake of nutrients (TAIZ; ZEIGER, 2017).

Regarding Mg^{2+} , some studies have shown a direct relation between sucrose leaf accumulation and Mg deficiency (GARCIA et al., 2020). This is because the sucrose transport from leaves (source) to stems and roots (sink) is ATP-dependent (active), and since Mg is an enzymatic activator of ATPase, its deficiency will compromise any energy-dependent physiological processes (CAKMAK; KIRKBY, 2008). Also, Mg is a central atom of chlorophyll molecules, therefore, its deficiency will affect photosynthetic processes (MARSCHNER, 2012).

Concerning the recommendation for soil acidity amendments in sugarcane, they were developed for burned sugarcane harvest system. Currently, the harvest of green sugarcane, without burning, is a reality in Brazil. Accordingly, most authors have been addressed their researches regarding the effects on soil carbon and nutrient dynamics, soil microbiology and microbial communities, land-use change, soil physics parameters and water dynamic, soil macrofauna and pests population and straw removal, all considering new perspectives of sugarcane crop system with mechanized planting and harvesting, but not considering the crop liming and its effect in soil chemical fertility (CHERUBIN et al., 2015, 2021; MENANDRO et al., 2019, 2017; BORDONAL et al., 2018b; CASTIONI et al., 2018, 2019; DE CASTRO et al., 2019; RIGOTTO et al., 2020; BARBOSA et al., 2021; TENELLI et al., 2021a, 2021b; LOVERA et al., 2021; MARTÍNI et al., 2021).

Rates of liming and forms of application may influence sugarcane cropping systems. In the conventional soil tillage system, liming incorporation is limited only at the mobilized layer (about 0.4 m). Considering the sugarcane root system can achieve deeper layers (BATTIE LACLAU; LACLAU, 2009), the liming incorporation only at the surface layers might be ineffective in highly acidic subsurface soils. On the other hand, the possibility of liming placement in depth may contribute to improving its effect, reflecting in gains on stalk and sugar yields.

However, as it is innovative management, there are uncertainties about the effectiveness of the deep tillage system combined with the deep placement of the amendments to controlling the soil acidity, since most studies have been addressed mainly soil physical approaches (BANGITA; RAO, 2012; MARASCA et al., 2015;

EVERTON et al., 2016; SCARPARE et al., 2019). In this sense, more specific assessments on soil chemical fertility and Al dynamics under different soil tillage systems and lime application forms are applicable.

From that, the hypothesis (i) more adequate liming rates may improve soil chemical fertility, (ii) different soil tillage systems under lime application may contribute to soil acidity alleviation due to the better lime positioning, and (iii) Al dynamics may be affected by different soil tillage systems and methods of liming were verified by evaluating sugarcane performance of stalks and sugar yields, soil acidity parameters and long-term residual effect of the lime across the soil profile.

CHAPTER 1 - LIME RATE AND METHODS OF APPLICATION INFLUENCE SOIL CHEMICAL FERTILITY AND SUGARCANE YIELD IN CLAYEY SOILS

Abstract

The sugarcane (*Saccharum* spp.) industry has undergone continuous changes in agronomic management practices, as exemplified by the introduction of mechanized and green harvesting and minimum tillage management. Currently, sugarcane producers have adopted the minimum tillage management, as deep strip-tillage, however, information about adequate rates of liming for deep strip-tillage in sugarcane cultivation is lacking. In the current study, sugarcane performance as measured by stalk and sugar yields as well as soil chemical fertility parameters were assessed in a complete sugarcane growing cycle under increasing liming rates individually for each tillage system. Three experiments in two locations were conducted from April 2015 to October 2019, corresponding to 4 growing seasons. A randomized block design field study was established with four replicates. Four liming rates applied once at the sugarcane establishment, such as: control, no liming; lime recommended rate (LRR); two times lime recommended rate (2x LRR); and three times lime recommended rate (3x LRR), were tested separately for each soil tillage system (Conventional soil tillage system (CT); Deep strip-tillage system (DT) and Modified deep strip-tillage system (MDT). Soil samples from 0.0 to 1.00 m, stratified every 0.2 m, were collected immediately after harvesting plant cane (18 months (mo) after planting); first ratoon (30 mo after planting); second ratoon (42 mo after planting); and third ratoon (54 mo after planting). Leaf material was collected at full vegetative growth stage. Soil chemical fertility, leaf element concentrations, and sugarcane yield components were analyzed. Soil pH, Ca^{2+} and Mg^{2+} concentrations and BS increased with increasing liming rates, but not proportionally. In general, the leaf concentrations of Ca and Mg increased under highest liming rates, whereas the leaf concentrations of Fe, Cu, Zn (Macatuba), and Mn (Piraju) decreased. Nonetheless, in all cases, the concentrations of all analyzed elements were within the ranges proposed by the sugarcane bulletin. All tillage systems adequately amended soil acidity, and the magnitude of the residual effect of liming depended on the liming rate. Regardless of the tillage system, higher yields were achieved at higher BS, suggesting that a review of the recommended BS value is necessary. The distribution of lime in the soil profile differed in each tillage system, and according to stalk and sugar yields, the influence of the liming rate was most pronounced under DT, intermediate under CT and lowest under MDT.

Keywords: Conventional tillage; Deep strip-tillage; Furrower; Minimum tillage.

1.1 INTRODUCTION

Improving yield efficiency while conserving the soil is an intrinsic concern in modern agriculture, and sugarcane (*Saccharum* spp.) cultivation is no exception.

Sugarcane is a semi-perennial crop, and successive cuttings are accompanied by progressively declining stalk and sugar yields, mainly due to reduced soil fertility, soil compaction and ratoon damage caused by machinery traffic (Crusciol et al., 2017). Unlike grain crops, for which no-tillage systems are well established, further research on tillage systems is still needed for sugarcane in order to consolidate yield and soil conservation practices.

Brazil is the world's largest producer of sugarcane (FAOStat, 2018), and Brazilian research has contributed greatly to advances in agronomic management. In the 2020/2021 growing season, production of approximately 665.1 million tons of sugarcane stalks is expected in Brazil (Conab, 2020). Despite this high production, the average yield in Brazil is approximately 81.65 Mg ha⁻¹ (Conab, 2020), far below the potential of up to 200 Mg ha⁻¹ (Monteiro and Sentelhas, 2014). This gap highlights the need to evaluate new practices that can increase the efficiency and profitability of the sugar and energy industry.

Conventional soil tillage is the primary form of tillage management on sugarcane crop. In this practice, the soil layers up to a depth of approximately 0.4 m are turned over on total area using heavy offset disc harrows, subsoilers, and leveling disc harrows to incorporate soil amendments and break compacted layers (Barbosa et al., 2021; Scarpore et al., 2019).

On the other hand, the advent of GPS-controlled machinery traffic has opened new possibilities for soil tillage systems, including minimum tillage management, in which the inter-rows are reserved for machine traffic and only the soil in planting rows is mobilized (Marasca et al., 2015). Minimum tillage management can be combined with deep soil tillage by using a furrower equipped with a subsoiling rod that reaches depths of 0.6–0.8 m and a rotary hoe that works at a depth of 0.40 m. The furrower is used for soil tillage and incorporation of straw and can also position fertilizer or any soil acidity amendment at depths of 0.40 and 0.6 m (Marasca et al., 2015).

Sugarcane is preferentially cultivated in tropical regions with high annual rainfall (Bernardo et al., 2019). The soils in these regions are generally highly weathered and acidic due to leaching of primary mineral elements such as Si, Ca, Mg, Na, and K. The remaining secondary minerals generally comprise less mobile chemical elements, such as Fe oxyhydroxide (goethite), Fe oxides (hematite), Al hydroxide (gibbsite), and kaolinite (1:1), when drainage is relatively inefficient

(Schaefer et al., 2008). Consequently, agronomic management to alleviate soil acidity is indispensable for sugarcane cultivation.

Lime is the most commonly used soil acidity amendment in tropical agriculture and its application is based on guidelines from regional bulletins, however, for sugarcane, the bulletins were calibrated only based on conventional soil tillage system. Currently, sugarcane has passed through constant changes in its agronomic management and some producers have adopted the minimum tillage management, as deep strip-tillage, by applying lime over total area or in concentrated-bands for further strip incorporation on planting furrow, reserving inter-rows specifically for machinery traffic. As a new alternative of soil tillage, solid information about adequate rates and methods of liming for deep strip-tillage in sugarcane cultivation is lacking in the literature.

Accordingly, the authors evaluated the level of response of sugarcane under increasing liming rates individually for each tillage system as measured by stalk and sugar yields and on chemical fertility parameters throughout the soil profile for a complete sugarcane growing cycle.

1.2 MATERIAL AND METHODS

1.2.1 Location, soil, and climatic characterization of experimental areas

Three experiments were carried out in two sugarcane commercial sites belonging to the sugar mill groups: Zilor, in Macatuba (22° 29' S and 48° 47' W), and Raízen, in Pirajú, both in State of São Paulo, Brazil (23°07' S 49°24' W) (fig 1). They were conducted from April 2015 to August 2019, totalizing 4 harvests (plant cane cycle plus three regrowth). The climate for both sites is classified as Cwa, which is predominantly tropical humid with a hot summer, according to the Köppen classification. The average rainfall, temperature, and hydro-climatic balance (Rolim et al., 1998; Thornthwaite and Mather, 1957) recorded during the 2015/2019 growing season is showed in figure 2.

Both soils were classified as clayey-textured Rhodic Hapludox (Soil Survey Staff, 2017), and their chemical (Raij et al., 2001) and texture characterization (Gee and Or, 2002) performed from air-dried soil samples collected from 0 to 1.00 m,

stratified every 0.2 m and passed through a 10 mesh (2-mm) sieve prior setting up the experiments (Table 1).

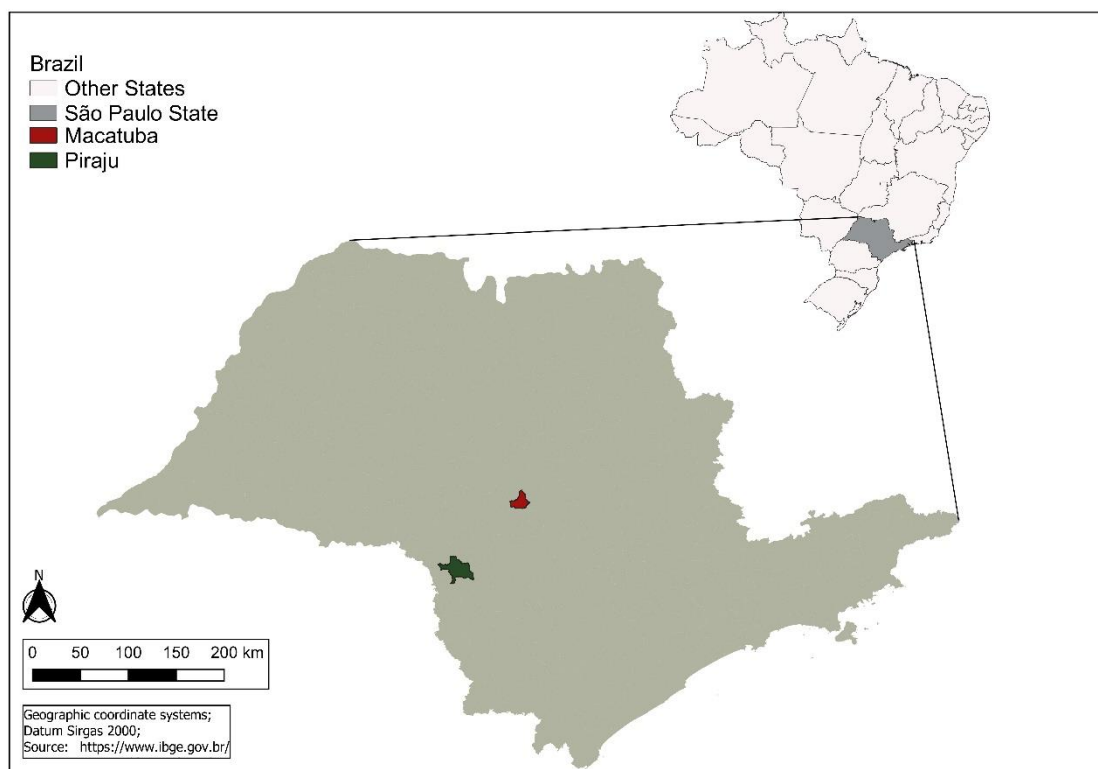


Figure 1. Geographic location of the experimental sites.

1.2.2 Treatments and experimental design

Four treatments as liming rates (control, no liming; lime recommended rate (LRR); two times lime recommended rate (2x LRR); and three times lime recommended rate (3x LRR), all applied at the sugarcane establishment) were tested separately for each soil tillage system (Conventional soil tillage system (CT); Deep strip-tillage system (DT) and Modified deep strip-tillage system(MDT)) using randomized block design with four replicates. The LRR for Macatuba (CaO, 30%; MgO, 17%) and Piraju (CaO, 28%; MgO, 23%) were calculated according to the base saturation method (Cantarella et al., 1998) considering the sum of the soil layers from 0.0 to 0.2 and 0.2 to 0.4 m. For sugarcane, the bulletin recommends a base saturation of 60% (Cantarella et al., 1998; Spironello et al., 1996). The respective lime doses and forms of application are in table 2.

Table 1. Soil chemical attributes and texture characterization prior to the experiment

Attributes	Macatuba Depth (m)					Piraju Depth (m)				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.00	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.00
pH (CaCl ₂)	4.4	4.0	4.0	3.9	4.0	5.0	4.5	4.2	4.2	4.2
OC (g kg ⁻¹)	23	15	12	10	10	19	16	11	9	9
P _{resin} (mg kg ⁻¹)	12	7	4	3	4	8	6	2	2	2
K (mmol _c kg ⁻¹)	2.0	0.8	0.3	0.2	0.7	1.2	0.7	0.1	0.1	0.1
Ca (mmol _c kg ⁻¹)	19	10	6	7	6	33	17	5	5	5
Mg (mmol _c kg ⁻¹)	9	5	3	3	2	15	9	3	4	3
S (mg kg ⁻¹)	21	47	36	50	45	8	18	55	74	68
Fe (mg kg ⁻¹)	23	15	8	7	7	30	27	13	12	7
Cu (mg kg ⁻¹)	3	3.3	2.2	1.8	1.8	1.1	1.2	0.9	0.7	0.6
Mn (mg kg ⁻¹)	9.7	4.3	3	1.2	2	3.6	2.5	0.3	0.3	0.2
Zn (mg kg ⁻¹)	1.1	0.5	0.1	0.1	0.1	0.4	0.3	0.1	0.1	0.1
B (mg kg ⁻¹)	0.2	0.2	0.1	0.1	0.1	0.3	0.2	0.2	0.1	0.1
Al (mmol _c kg ⁻¹)	5	7	8	7	8	0.7	6	10	11	10
H+Al (mmol _c kg ⁻¹)	52	62	64	70	64	45	64	69	71	72
CEC (mmol _c kg ⁻¹)*	82	78	73	80	73	94	91	76	80	78
Base saturation (%)**	37	20	13	13	12	52	28	11	11	9
Al saturation (%)***	14	30	46	40	48	2	27	62	62	64
Clay content (g kg ⁻¹)	358	449	486	469	442	673	735	734	757	746
Silt content (g kg ⁻¹)	154	140	116	124	146	129	93	99	85	92
Sand content (g kg ⁻¹)	488	410	398	407	412	198	173	167	158	163

*Calculated from the equation: CEC (mmol_c kg⁻¹) = Ca²⁺ + Mg²⁺ + K⁺ + (H+Al); ** Base saturation (%) = (Ca²⁺ + Mg²⁺ + K⁺) / (CEC) x 100; ***Al saturation (%) = (Al / (Ca²⁺ + Mg²⁺ + K⁺ + Al³⁺)) x 100.

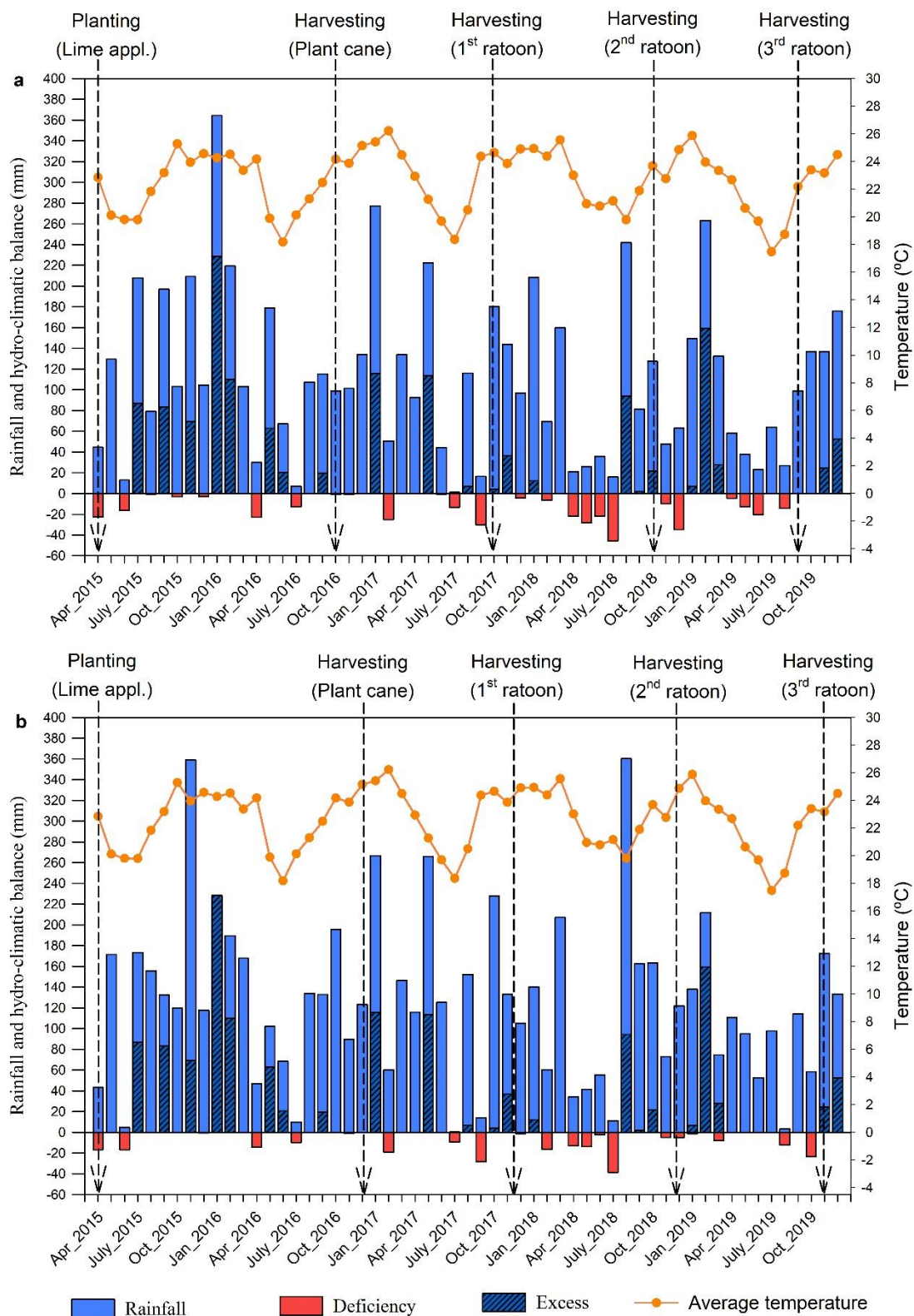


Figure 2. The average of monthly rainfall, temperature and hydro-climatic balance (mm) in the 2015/2019 growing season for (a) Macatuba and (b) Praju.

Table 2. Lime doses and forms of application under different soil tillage systems

Soil Tillage System	CT ¹	DT ²	MDT ³	
Lime application	Broadcasted (over the entire area)	Broadcasted (over the entire area)	Broadcasted on planting furrow	Incorporated
Lime doses	----- Mg ha ⁻¹ -----			
	Macatuba (Rhodic Hapludult)			
Control ⁴	0.0	0.0	0.0	0.0
LRR ⁵	5.0	5.0	3.8	1.2
2x LRR ⁶	10.0	10.0	7.5	2.5
3x LRR ⁷	15.0	15.0	11.3	3.7
	Piraju (Rhodic Acrudox)			
Control	0.0	0.0	0.0	0.0
LRR	4.0	4.0	3.0	1.0
2x LRR	8.0	8.0	6.0	2.0
3x LRR	12.0	12.0	9.0	3.0

¹ Conventional soil tillage system; ² Deep strip-tillage system; ³ Modified deep strip-tillage system;

⁴ No lime application; ⁵ Lime recommended rate (Spironello et al., 1996); ⁶ Two times lime recommended rate; ⁷ Three times lime recommended rate

The tillage systems (treatments) were characterized by the following operations:

The tillage systems were characterized by the following operations:

- (I) Conventional soil tillage system (CT): This is a standard system largely used in sugarcane crops. In this tillage system, the lime was broadcast over the entire area for further incorporation (0.3-0.4 m) using once a heavy offset disc harrow, a subsoiler, and a leveling disc harrow.
- (II) Deep strip-tillage system (DT): The lime was also broadcast over the entire area and strip-deeply incorporated with the furrower only at the planting rows. The furrower has a rotary hoe with a working depth of 0.3 to 0.4 m plus a subsoiling rod with a working depth of 0.6 to 0.7 m. This equipment builds furrows with 1.2 m of width.
- (III) Modified deep strip-tillage system (MDT): The same equipment described in item II (DT) was used. Through a lime storage compartment linked to the subsoiling rod is possible to distribute part of the lime used into the planting furrows at 0.4 and 0.6 m. The term “modified” indicates that the lime was broadcast concentrated in localized bands for further strip-incorporation by the furrower. Approximately $\frac{3}{4}$ was distributed on the soil surface in bands, and $\frac{1}{4}$ was distributed in the soil profile through the subsoiling rod. The rate decreased with depth due to the lower corrected volume since the application occurred concentrated in bands.

A brief scheme is given in Figure 3.

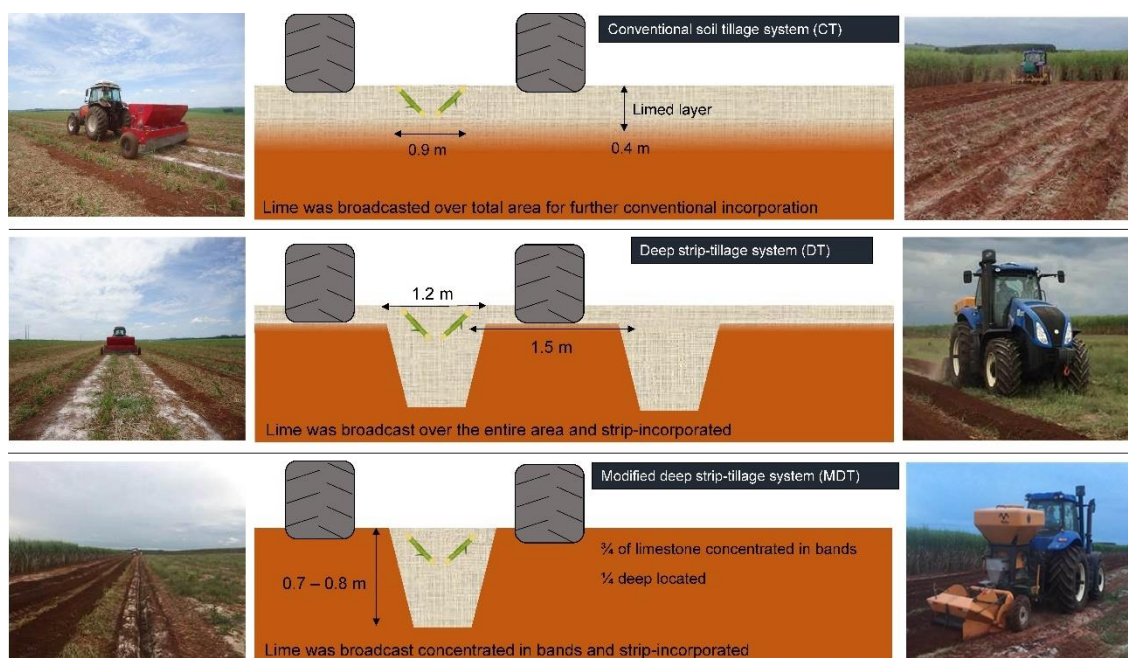


Figure 3. Schematic illustration of the soil tillage systems, agricultural equipment and sugarcane plants disposition.

The sugarcane varieties CTC 20 (Macatuba) and CTC 11 (Piraju) were both mechanically planted immediately after liming at a distribution of 18 viable buds m^{-1} and a depth of approximately 0.3-0.4 m and cultivated with a double-combined row spacing of 1.50×0.90 m under a controlled traffic system. The experimental plots had an area of 240 m^2 , with dimensions of 20 m in length and 12 m in width, and each plot contained 5 double rows. During sugarcane establishment, 500 kg ha^{-1} of NPK fertilizer 06-28-24 (Macatuba) or 600 kg ha^{-1} of NPK fertilizer 10-25-25 (Piraju), plus 40 kg ha^{-1} of S (pastilles of elementary sulfur) was applied in the bottom of the planting furrow. Also, 200 kg ha^{-1} of fertilizer containing micronutrients (Zn, 10%; B, 1.8%; Mo, 0.12%; Cu, 0.6% and Mn, 1.2%) were applied in both areas 40 days after planting. For the ratoons, topdressing applications were performed as NPK fertilizer 18-07-28 and 20-05-28 at rates of 650 and 600 kg ha^{-1} , respectively, for Macatuba and Pirajú, plus 40 kg ha^{-1} of S (pastilles of elementary sulfur) in both sites. Other standard management practices were performed according to sugarcane needs.

1.2.3 Soil chemical analysis

Immediately after the sugarcane harvests, the soil samples at depths from 0.0 to 1.00 m, stratified every 0.2 m were collected using a two-inch tubular sampler only considering the sugarcane planting furrows.

The soil chemical analysis were performed from air-dried soil samples passed through a 10 mesh (2-mm) sieve according to Raij et al (2001), briefly described as follows: pH (0.01 M CaCl_2 solution); exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), extracted by ionic exchange resin and determined by atomic absorption spectroscopy (AAS); exchangeable potassium (K^+), extracted by ionic exchange resin and determined by flame photometry. The exchangeable Al, extracted by 1 mol L^{-1} KCl solution and potential acidity ($\text{H} + \text{Al}$), extracted with 1 mol L^{-1} calcium acetate solution were both determined by titration with ammonium hydroxide (0.025 mol L^{-1}). The percentages of the base saturation (BS) and aluminum saturation (AS) were calculated as follows (equations 1 and 2):

$$\text{Base saturation (BS\%)} = (\text{SB} / \text{CEC}_p) \times 100 \quad (1)$$

Where the SB is the summatory of the basic cations ($\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+$) and the CEC_p is the potential cation exchange capacity of the soil ($\text{CEC}_p = (\text{SB} + (\text{Al} + \text{H}))$).

$$\text{Aluminum saturation (AS\%)} = (\text{Al}^{3+} / \text{CEC}_e) \times 100 \quad (2)$$

Where the Al^{3+} is the exchangeable Al and the CEC_e is the effective cation exchange capacity of the soil ($\text{CEC}_e = \text{BS} + \text{Al}^{3+}$).

1.2.4 Foliar diagnosis

During the period of full vegetative growth of sugarcane, 10 +1 leaves or TVD (Top Visible Dewlap leaf), were collected in the two central rows according to the numbering system (Bataglia et al., 1983). Disregarding the leaf midrib and considering only the middle third of the leaf blade, the material was dried in an oven with forced air circulation at 60 °C until a constant mass was obtained (Spironello et al., 1996). It was then milled and leaf nitrogen (N), phosphorus (P),

potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and boron (B) concentration were determined (Malavolta et al., 1997).

1.2.5 Sugarcane stalk and sugar yields

Before non-burning harvests (Macatuba: plant cane, October/2016; first ratoon, October/2017; second ratoon, October/2018; and third ratoon, September/2019; Piraju: plant cane, December/2016; first ratoon, December /2017; second ratoon, December/2018; and third ratoon, November/2019) the stalk and sugar yields (Mg ha^{-1}) were determined. The stalk yield was determined by weighing the stalks in four sequential meters at two central rows of each plot. The stalks were collected, topped at apical bud height, defoliated, and weighted using a digital scale and the values were extrapolated to hectares. After that, the cleaned stalks were sent to the Middle Tietê Sugarcane Planters Association (ASCANA) Laboratory, in Lençóis Paulista, SP, Brazil and to Raízen Ipaussú Sugar Refining Mill Laboratory, in Ipaussú, SP, Brazil, respectively for Macatuba and Pirajú sites to be processed. The apparent percentage of sucrose (sucrose concentration) and total recoverable sugar (kg of sugar per Mg of stalk) were determined according to the methodology defined in the Sucrose Content-Based Sugarcane Payment System for technological assessments (Fernandes, 2011; Tanimoto, 1964). The Sugar yield (Mg ha^{-1}) was indirectly estimated by the equation 3:

$$\text{Sugar yield (Mg ha}^{-1}\text{)} = (\text{TRS (kg Mg}^{-1}\text{)} \times \text{Stalk yield (Mg ha}^{-1}\text{)}) / 1000 \quad (3)$$

1.2.6 Statistical analysis

Data were subjected to analysis of variance (ANOVA). In cases of significant differences, the Fisher's test, according to the least difference significative (LSD), was used to compared chemical soil attributes separately for each soil depth, foliar diagnosis, and sugarcane stalk and sugar yields for each cropping season. All the tests used a 0.1 level of probability.

1.3 RESULTS

1.3.1 Conventional Soil Tillage System (CT)

1.3.1.1 Soil chemical analysis at Macatuba, SP

Regardless of the application rate, soil pH was higher in all limed treatments than in the control ($p < 0.01$) at all depths in plant cane and up to 0.6 m in all three ratoons. In most of the subsurface layers, there was a significant effect of the liming rate up to second ratoon, and pH was highest under 3x LRR (Fig. 4a, b, c, and d; Table S1).

In plant cane, all liming rates were effective in correcting soil pH. 3x LRR was most effective only up to 0.2 m, and pH was only lower under LRR than under the higher rates from 0.8 to 1.00 m. In first and second ratoon, the residual effect of liming in buffering higher pH values was most evident at the highest liming rates at all depths; similar effects were observed up to 0.6 m in third ratoon.

The range of acidity across the soil layers was classified using a colored acidity scale according to the soil fertility recommendation bulletin of São Paulo State (Raij et al., 1997). At all liming rates, “moderately acidic” pH values were observed up to 0.6 m in plant cane and up to 0.4 m in first ratoon. In second and third ratoon, moderately acidic pH values were only observed under 2 and 3x LRR in the uppermost layers (0.0–0.4 m). “Strongly acidic” pH values were observed at 0.4–0.6 under 2x and 3x LRR in second and third ratoon, whereas soil pH was “extremely acidic” at 0.4–1.0 m in the control and LRR treatments and 0.6–1.0 m at 2x and 3x LRR (Fig. 4a, b, c, and d).

The concentration of Ca^{2+} was higher under liming in plant cane regardless of depth and in all ratoons up to 0.6 m (Fig. 4e, f, g, and h; Table S1). The Ca^{2+} concentration increased as a function of increasing liming rate up to 0.6 m in all growing seasons. In the subsurface layers, the influence of liming decreased in successive growing seasons. Specifically, from 0.4 to 0.6 m, the influence of liming was evident at all rates in plant cane, at 2x and 3x LRR in first and second ratoon, and only at 3x LRR in third ratoon. At greater depths, the effect of liming was significant at 0.6–1.0 m in first ratoon and 0.6–0.8 m in second ratoon

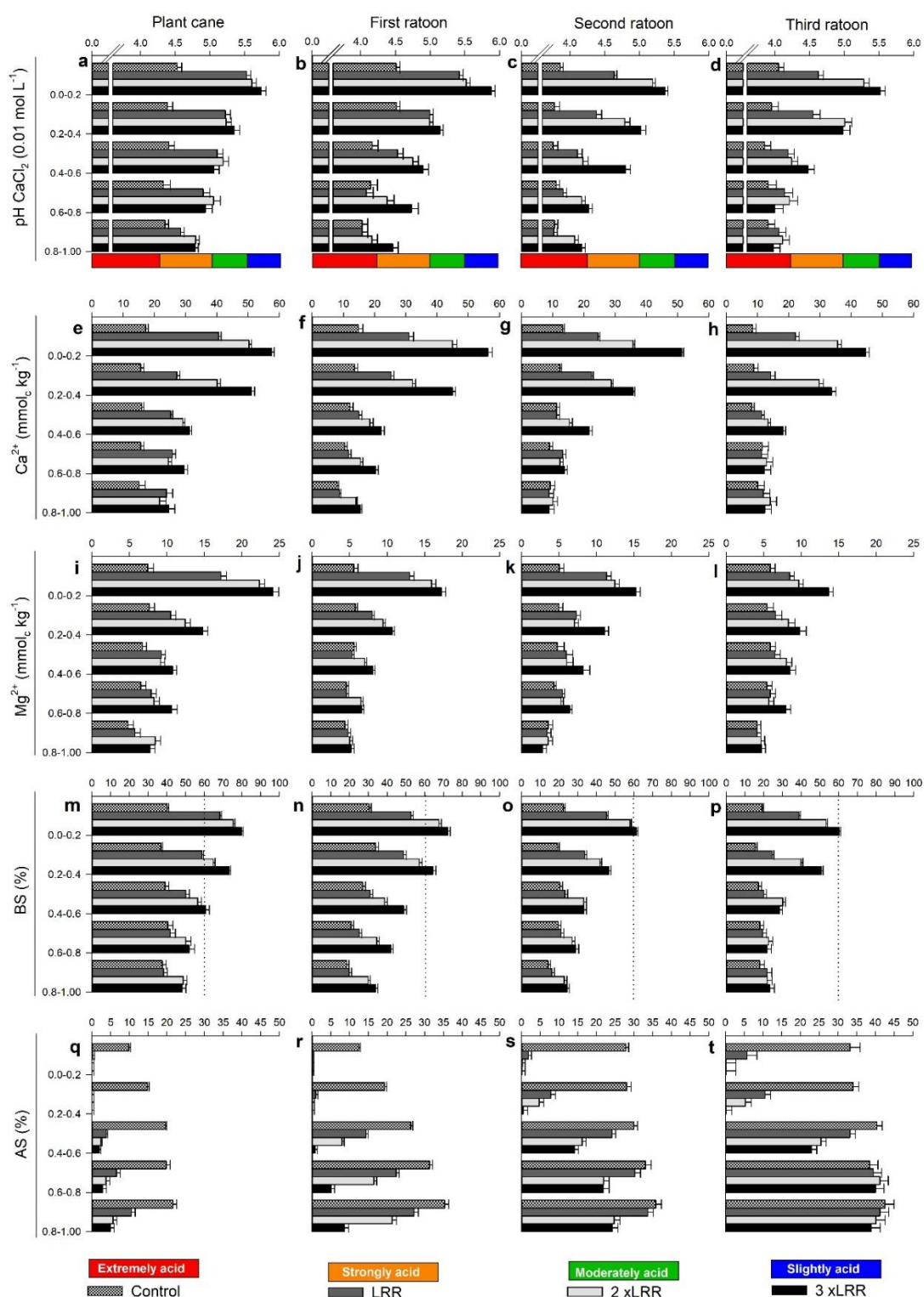


Fig 4. Soil pH $_{\text{CaCl}_2}$ (a, b, c and d), concentration of Ca^{2+} (e, f, g and h) and Mg^{2+} (i, j, k and l), base saturation (BS, m, n, o and p) and Al^{3+} saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on conventional soil tillage systems (CT) for plant cane, first, second and third ratoons in Macatuba. Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raj et al., 1997).

Like Ca^{2+} , liming significantly increased the concentration of Mg^{2+} , with pronounced effects in plant cane and first ratoon; an effect of liming was observed up to 0.4 m in second and third ratoon (Fig. 4i, j, k, and l; Table S1). The effect of the liming rate was most evident in the surface layers, with higher Mg^{2+} concentrations under higher liming rates.

The effects of liming on BS and AS were inversely proportional. As expected, BS increased with the applied liming rate (Fig. 4m, n, o and p; Table S1), whereas AS decreased. AS was highest at depths beyond 0.6 m, mainly in the ratoons (Fig. 4q, r, s, and t; Table S1). BS was significantly higher under liming than in the control up to approximately 0.6 m at LRR and in all layers at 2 and 3x LRR, except in third ratoon, in which significant effects were observed only up to 0.6 m. The threshold BS value of 60% for sugarcane specified in the soil fertility recommendation bulletin of São Paulo State (Cantarella et al., 1998; Spironello et al., 1996) was achieved up to 0.4 m at all liming rates in plant cane and at 2 and 3x LRR in first and second ratoon. In third ratoon, the 60% BS threshold was reached in the surface layer only at 3x LRR.

AS was significantly reduced by liming regardless of rate at all depths in plant cane and first ratoon and up to 0.6 m in second and third ratoon (Fig. 4q, r, s, and t; Table S1). Liming had no significant effect on AS in the two deepest layers in third ratoon. In the uppermost layers (0.0–0.4 m), AS was close to zero in plant cane and first ratoon and below 10% in the subsequent ratoons, demonstrating that CT can efficiently correct surface soil acidity.

1.3.1.2 Leaf analysis at Macatuba, SP

Regardless of growing season, the leaf concentrations of N, P, K, S, Zn, Mn, and B were not affected by the treatments (Fig. 5a, b, c, f, i, j, and k; Table S2). In addition, the concentrations of these elements were within the proposed ranges for sugarcane (Spironello et al., 1996) (18–25 g kg⁻¹ N, 1.5–3.0 g kg⁻¹ P, 10–16 g kg⁻¹ K, 1.5–3.0 g kg⁻¹ S, 10–50 mg kg⁻¹ Zn, 25–250 mg kg⁻¹ Mn, and 10–30 mg kg⁻¹ B).

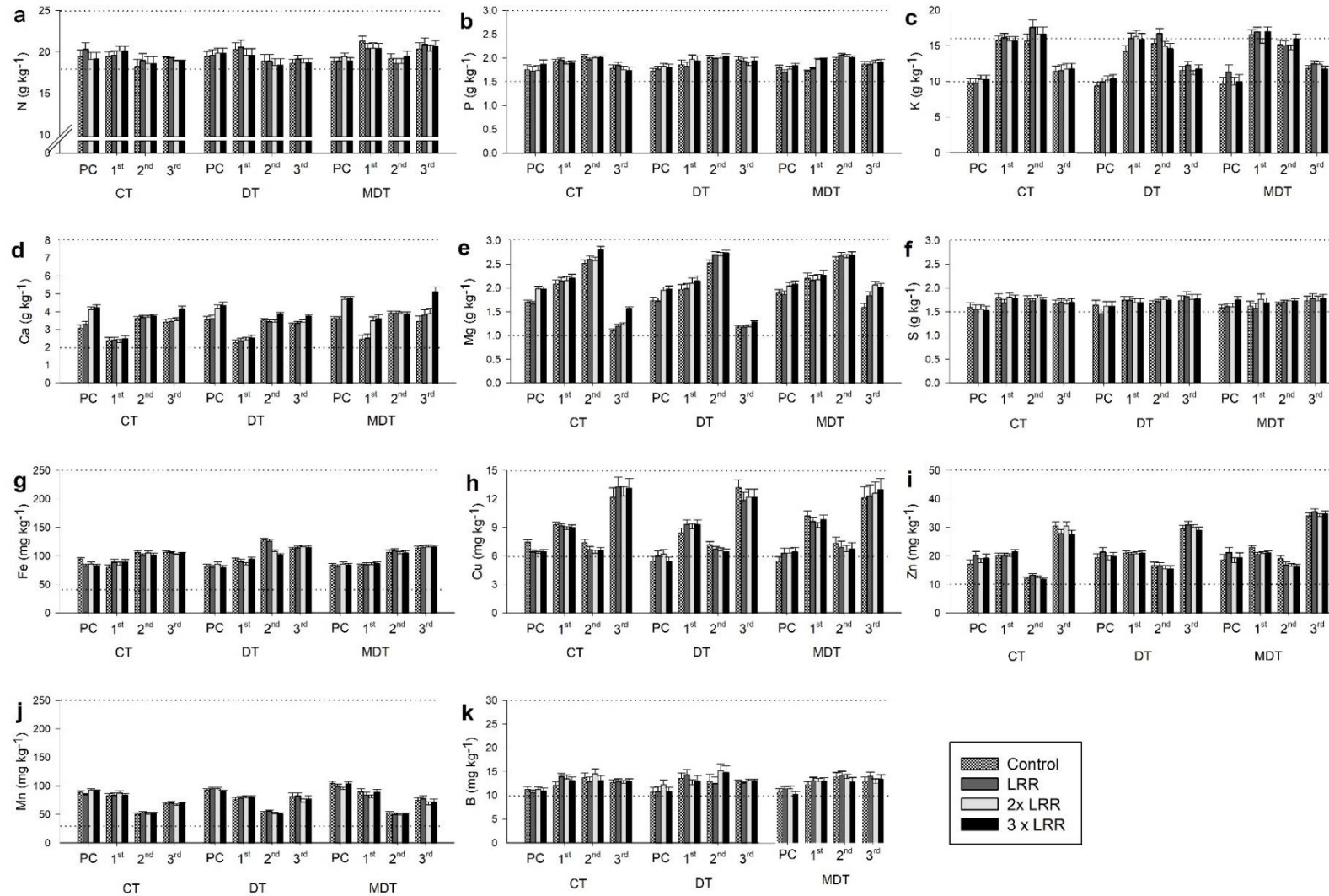


Figure 5. Leaf concentration of elements (a) Nitrogen, (b) Phosphorus (c) Potassium, (d) Calcium, (e) Magnesium, (f) Sulfur, (g) Iron, (h) Copper, (i) Zinc, (j) Manganese and (k) Boron in sugarcane under increasing lime rates and different soil tillage systems (CT, conventional soil tillage system; DT, deep strip-tillage system; and MDT, modified strip-tillage system) for plant cane, first, second and third ratoons (PC, 1st, 2nd and 3rd) in Macatuba. Error bars represent the least significant difference (LSD) $p \leq 0.1$.

The leaf concentration of Ca was significantly increased at 2 and 3x LRR in plant cane ($p<0.01$) and at 3x LRR in third ratoon ($p<0.01$). Similarly, Mg was significantly higher at 2 and 3x LRR in plant cane ($p<0.01$) and at 3x LRR in second and third ratoon ($p<0.01$). In third ratoon, the leaf concentration of Mg did not differ between LRR and 2x LRR but was significantly higher than in the control treatment ($p<0.01$). By contrast, liming decreased the leaf concentrations of Fe (plant cane) and Cu (plant cane and second ratoon) compared with the control, regardless of the liming rate ($p<0.01$). Despite these variations, the concentrations of these elements were within the proposed ranges for sugarcane in all growing seasons: 2.0–8.0 g kg⁻¹ Ca, 1.0–3.0 g kg⁻¹ Mg, 40–250 mg kg⁻¹ Fe, and 6.0–15 mg kg⁻¹ Cu (Spironello et al., 1996).

1.3.1.3 Stalk and sugar yields at Macatuba, SP

The sucrose concentration and TRS were affected by liming in first and third ratoon. In both of these growing seasons, there were no differences in sucrose concentration and TRS among the liming treatments, but all were higher than in the control (Fig. 6a and b, Table S3).

Regardless of rate and growing season, stalk and sugar yields were higher under liming and exhibited similar patterns of variation. Stalk and sugar yields did not differ between 2 and 3x LRR. Compared with LRR, stalk yield was 7.2 and 9.5% higher at 2 and 3x LRR, respectively, in plant cane; 10.4 and 10.3% higher in first ratoon; and 14.8 and 17.1% higher in second ratoon. Sugar yield was 10.1 and 12.4% higher at 2 and 3x LRR, respectively, compared with LRR in plant cane; 9.7 and 7.8% higher in first ratoon; and 14.3 and 14.1% higher in second ratoon. In third ratoon, the yields increased with the liming rate. Compared with LRR, stalk yield was 19.2 and 26.7% higher at 2 and 3x LRR, respectively, and sugar yield was 19.9 and 25% higher. Across all growing seasons, the average stalk yield was 12.1 and 15% higher at 2 and 3x LRR, respectively, than LRR, and the average sugar yield was 12.7 and 14.5% higher, respectively (Fig. 6c and d; Table S3).

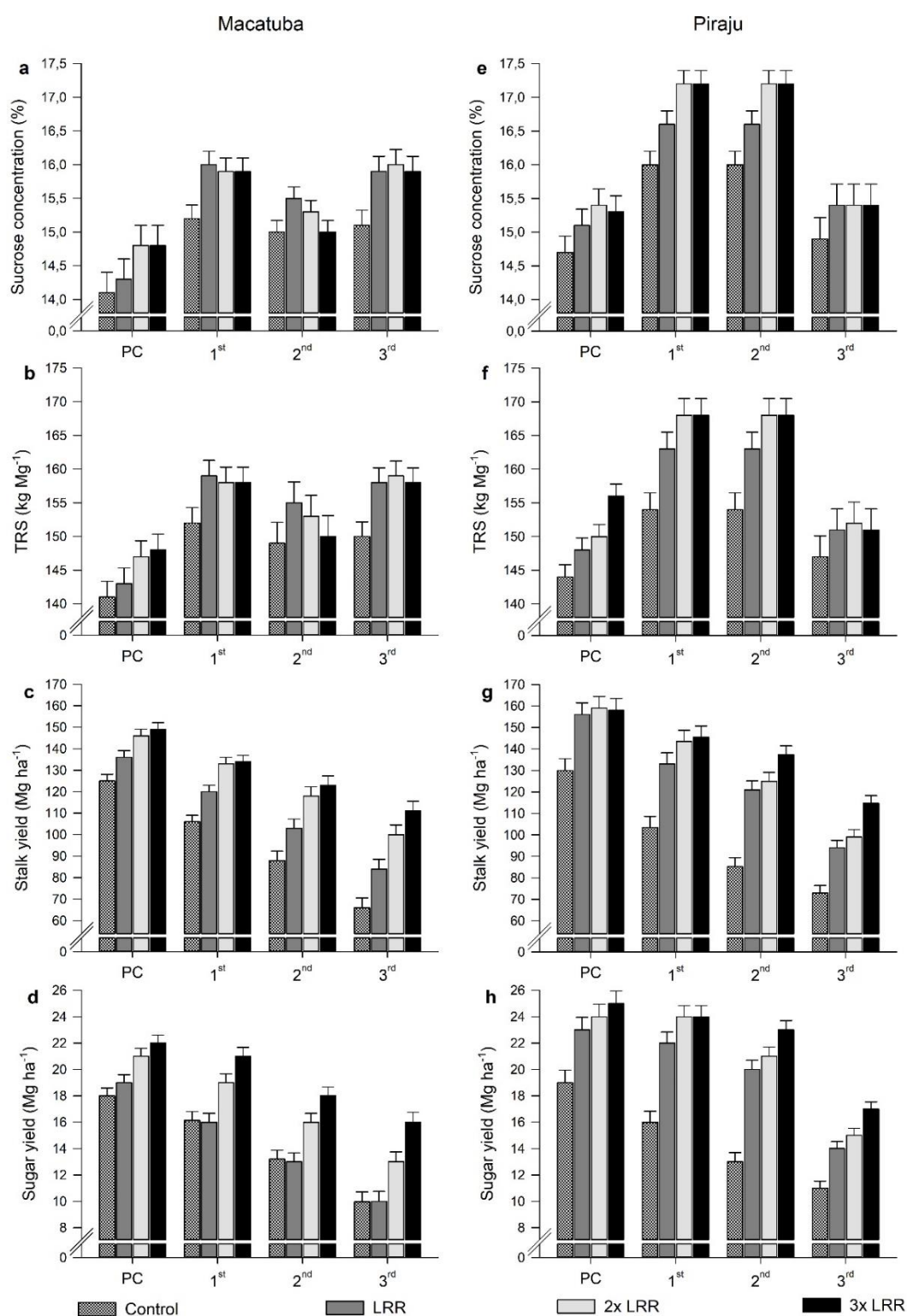


Figure 6. Sucrose concentration (Macatuba, a; Piraju, e), total recoverable sugar (TRS; Macatuba, b; Piraju, f), yield of stalks (Macatuba, c; Piraju, g) and sugar (Macatuba, d; Piraju, h) of sugarcane under increasing lime rates on conventional soil tillage systems (CT) for plant cane, first, second and third ratoons (PC, 1st, 2nd and 3rd). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

1.3.1.4 Soil chemical analysis at Pirajú, SP

The limed treatments were most effective at correcting soil pH up to depths of 0.6 m, regardless of liming rate or growing season (Fig. 7a, b, c, and d; Table S4). In general, pH increased with the liming rate in the uppermost surface layer (0.0–0.2 m). From 0.2 to 0.4 m, 3x LRR had superior effects on soil pH values, whereas LRR and 2x LRR had similar performance. Soil pH classified as “slightly acidic” was observed only at 3x LRR from 0.0 to 0.2 m. By contrast, soil pH in the first layer (0.0–0.2 m) was moderately acidic at LRR and 2x LRR in plant cane and first and second ratoon. In the soil layer from 0.2 to 0.4 m, the soil pH was moderately acidic only at 3x LRR, regardless of the growing season. At depths of 0.4–1.0 m, the pH values were classified as strongly acidic (Fig. 7a, b, c, and d).

Significant effects of the limed treatments on Ca^{2+} concentration were observed only up to 0.4 m regardless of growing season or liming rate, except from 0.0 to 0.2 m at LRR in third ratoon (Fig. 7e, f, g, and h; Table S4). Higher liming rates increased the Ca^{2+} concentration only in the uppermost surface layer in all growing cycles. The Ca^{2+} concentration from 0.2 to 0.4 m was similar at all liming rates in plant cane and first ratoon but was highest at 3x LRR in second and third ratoon. Ca^{2+} concentrations at depths greater than 0.4 m were significantly increased only in plant cane when 2 and 3x LRR were applied.

The Mg^{2+} concentration responded to increasing liming rates up to 0.2 m in all growing seasons and up to 0.4 m in plant cane and first ratoon (Fig. 7i, j, k, and l; Table S4). In second and third ratoon, the Mg^{2+} concentration did not differ between the limed treatments but was higher than in the control. At depths greater than 0.4 m, the Mg^{2+} concentration was increased by 3x LRR in plant cane (0.4–0.8 m) and by all liming rates in first and second ratoon (0.4–0.6 m).

As Ca^{2+} and Mg^{2+} influence BS, the response of this parameter to liming was similar to those of Ca^{2+} and Mg^{2+} . BS increased with the liming rate in the first layer (0.0–0.2 m) and was higher in the limed treatments than the control at all depths in plant cane, up to 0.6 m in first and second ratoon, and up to 0.4 m in third ratoon (Fig. 7m, n, o and p; Table S4). BS values were above 60% in all limed treatments in plant cane, 2 and 3x LRR in first ratoon, and 3x LRR in second ratoon, although only at depths of 0.0–0.2 m in all cases.

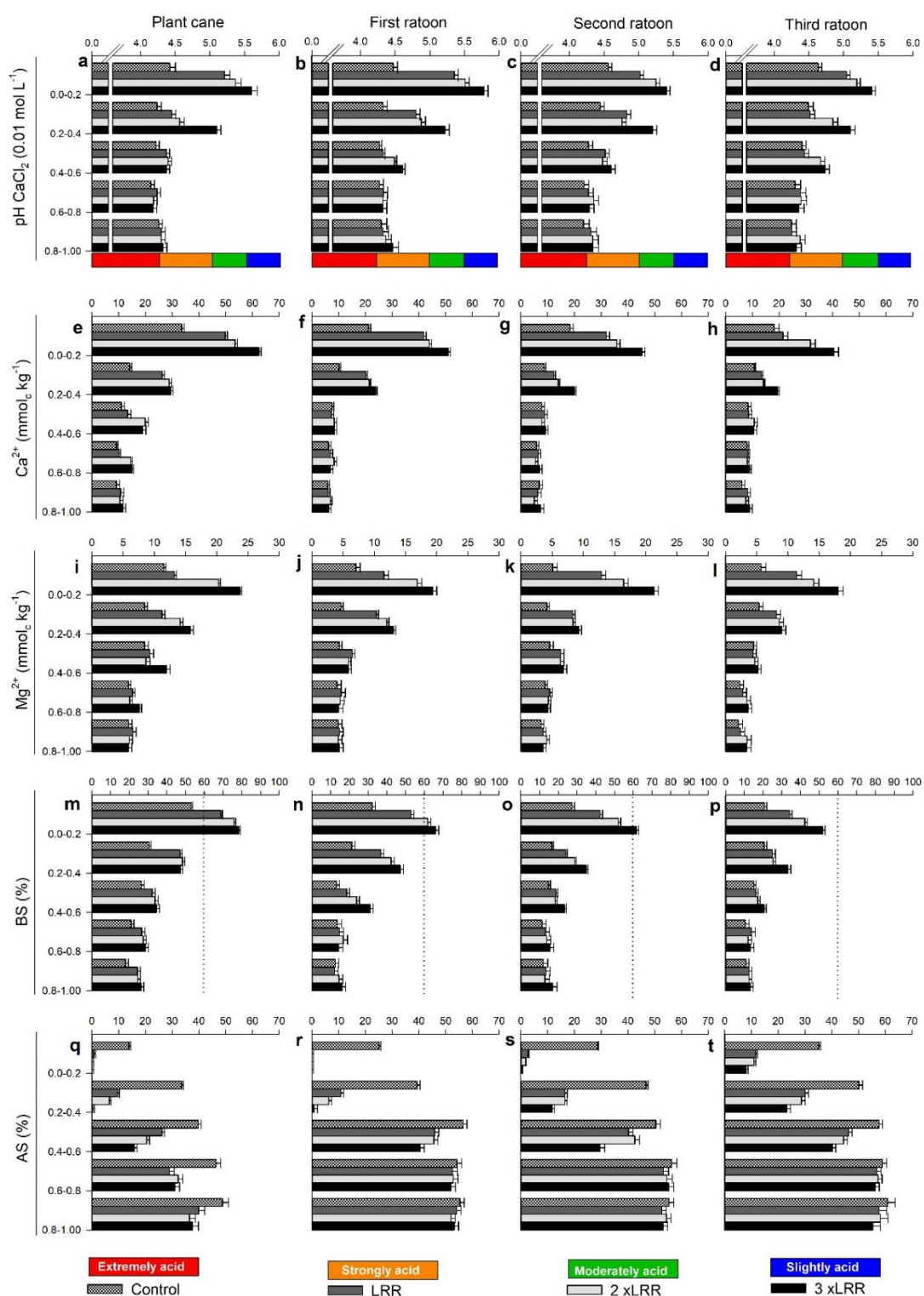


Fig 7. Soil $\text{pH}_{\text{CaCl}_2}$ (a, b, c and d), concentration of Ca^{2+} (e, f, g and h) and Mg^{2+} (i, j, k and l), base saturation (BS, m, n, o and p) and Al^{3+} saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on conventional soil tillage systems (CT) for plant cane, first, second and third ratoons in Piraju. Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raij et al., 1997).

In the limed treatments, the AS value up to 0.2 m was near zero in plant cane and first and second ratoon and less than 10% in third ratoon (Fig. 7q, r, s, and t; Table S4). At 0.2–0.4 m, lime efficiently reacted with Al^{3+} , decreasing its saturation of effective cation exchange capacity in plant cane and first ratoon according to the liming rate. In second and third ratoon, AS did not differ between LRR and 2x LRR and was higher than at 3x LRR. Despite these variations, AS was lower in the limed treatments than in the control across the soil profile (0.0–1.00 m) in plant cane and up to 0.6 m in the three ratoons.

1.3.1.5 Leaf analysis at Piraju, SP

Regardless of growing season, the leaf concentrations of N, P, K, Ca, S, Fe, Cu, Zn, and B were not affected by the treatments (Fig. 8a, b, c, d, f, g, h, i, and k; Table S2) and were within the proposed ranges for sugarcane described above in Section 3.1.2 (Spironello et al., 1996).

Liming significantly increased the leaf concentration of Mg in second ratoon, with the highest concentrations observed at 2 and 3x LRR, followed by LRR ($p < 0.01$). In second and third ratoon, the leaf concentration of Mn was significantly higher ($p < 0.01$) in the control than in the limed treatments, which did not differ. Despite these variations, the concentrations of these elements were within the proposed ranges for sugarcane described above in all growing seasons (Spironello et al., 1996).

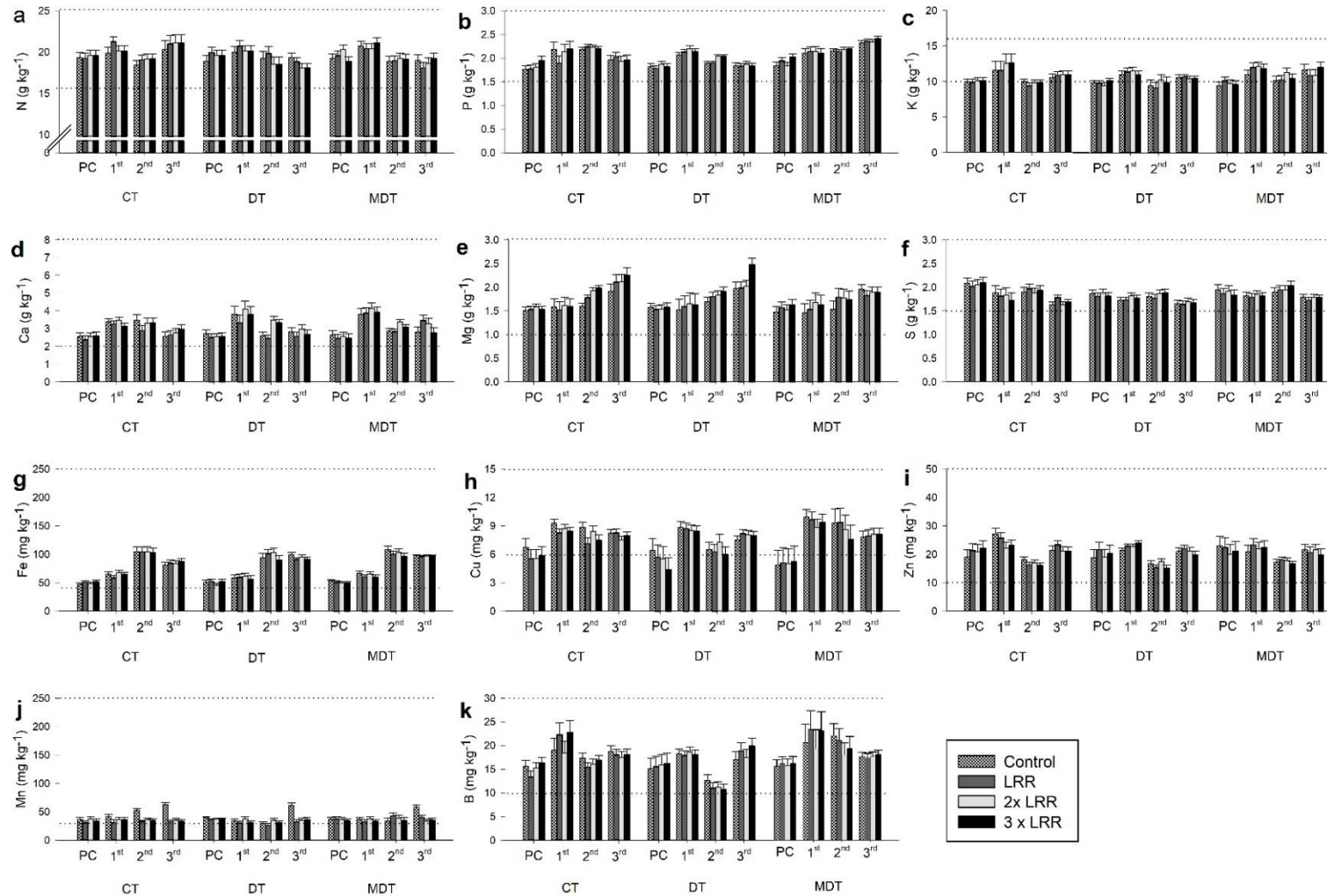


Figure 8. Leaf concentration of elements (a) Nitrogen, (b) Phosphorus (c) Potassium, (d) Calcium, (e) Magnesium, (f) Sulfur, (g) Iron, (h) Copper, (i) Zinc, (j) Manganese and (k) Boron in sugarcane under increasing lime rates and different soil tillage systems (CT, conventional soil tillage system; DT, deep strip-tillage system; and MDT, modified strip-tillage system) for plant cane, first, second and third ratoons (PC, 1st, 2nd and 3rd) in Piraju. Error bars represent the least significant difference (LSD) $p \leq 0.1$.

1.3.1.6 Stalk and sugar yields at Piraju, SP

The sucrose concentration did not differ between 2 and 3x LRR and was higher than at LRR in first and second ratoon. The liming rate had a significant effect on TRS in plant cane and first and second ratoon. In plant cane, TRS was highest at 3x LRR and did not differ between 2x and LRR. In first and second ratoon, TRS did not differ between 2 and 3x LRR and was higher than at LRR (Fig. 6e and f, Table S3).

The effects of liming on stalk and sugar yields varied depending on the growing season. In plant cane, the stalk and sugar yields were similar at all liming rates and were higher than in the control. In first ratoon, the stalk and sugar yields did not differ between 2 and 3x LRR; compared with LRR, stalk yields were 7.8 and 8.0% higher, respectively, and sugar yields were 11.1 and 11% higher, respectively. In second and third ratoon, 3x LRR produced the best yield performance, whereas 2x and LRR had similar effects (Fig. 6g and h; Table S3). In second and third ratoon, 3x LRR increased stalk yield by 13 and 21%, respectively, and sugar yield by 16 and 21%, respectively, compared with LRR. When averaged across all growing seasons, 2 and 3x LRR increased stalk yield by 4.5 and 9.8% and sugar yield by 7 and 13% compared with LRR.

1.3.2 Deep Strip-Tillage System (DT)

1.3.2.1 Soil chemical analysis at Macatuba, SP

Compared with the control, pH was higher ($p < 0.01$) in all limed treatments throughout the soil profile in plant cane and first ratoon and up to 0.2 m in second and third ratoon (Fig. 9a, b, c, and d; Table S1). pH increased with the liming rate only up to 0.4 m in plant cane; however, regardless of growing season, pH was highest at 2 and 3x LRR. Non-significant differences between the treatments were observed from 0.6 m in third ratoon, highlighting the residual effect of liming.

pH values classified as slightly acidic were observed only from 0.0 to 0.2 m in plant cane and first ratoon at 3x LRR, while moderately acidic pH values were attained up to 0.4 m in all limed treatments and growing seasons. In plant cane and first ratoon, the soil pH was considered strongly acidic at depths of 0.6 m and greater in all treatments. By contrast, in second and third ratoon, the soil pH was extremely acidic, with pH values below 4.3 (Fig. 9a, b, c, and d).

The concentrations of Ca^{2+} (Fig. 9e, f, g, and h; Table S1) and Mg^{2+} (Fig. 9i, j, k, and l; Table S1) followed very similar patterns and increased with the liming rate, particularly up to 0.6 m for Ca^{2+} in all growing seasons and for Mg^{2+} in plant cane and first ratoon. No significant differences in Ca^{2+} concentrations were observed from 0.8 to 1.00 m and from 0.6 to 1.00 m in second and third ratoon, respectively. For Mg^{2+} , no significant differences were observed from 0.8 to 1.00 m in first ratoon and from 0.6 to 1.00 m in second and third ratoon.

BS was also influenced by the liming rate. In plant cane, BS did not differ between 2 and 3x LRR up to 0.2 m but was highest at 3x LRR at greater depths. Further supporting the effect of liming, BS was higher in all limed treatments than in the control at all depths in plant cane and first and second ratoon and up to 0.4 m in third ratoon (Fig. 9m, n, o and p; Table S1). The BS threshold of 60% was achieved in all limed treatments only in the first layer (0.0–0.2 m) in plant cane. In addition, when 3x LRR was applied, the BS value reached 60% up to 0.8 m in plant cane, up to 0.4 m in first ratoon, and up to 0.2 m in second ratoon.

Conversely, AS values decreased according to the liming rate (Fig. 9q, r, s, and t; Table S1). In the first layer (0.0–0.2 m), AS was close to zero in plant cane and first ratoon regardless of the liming rate, highlighting the liming effect. The effect of liming was evident across the entire soil profile in plant cane and first ratoon, up to 0.8 m in second ratoon, and up to 0.4 m in third ratoon. A significant effect of liming in the most subsurface layers (0.6–1.00 m) was absent only in third ratoon.

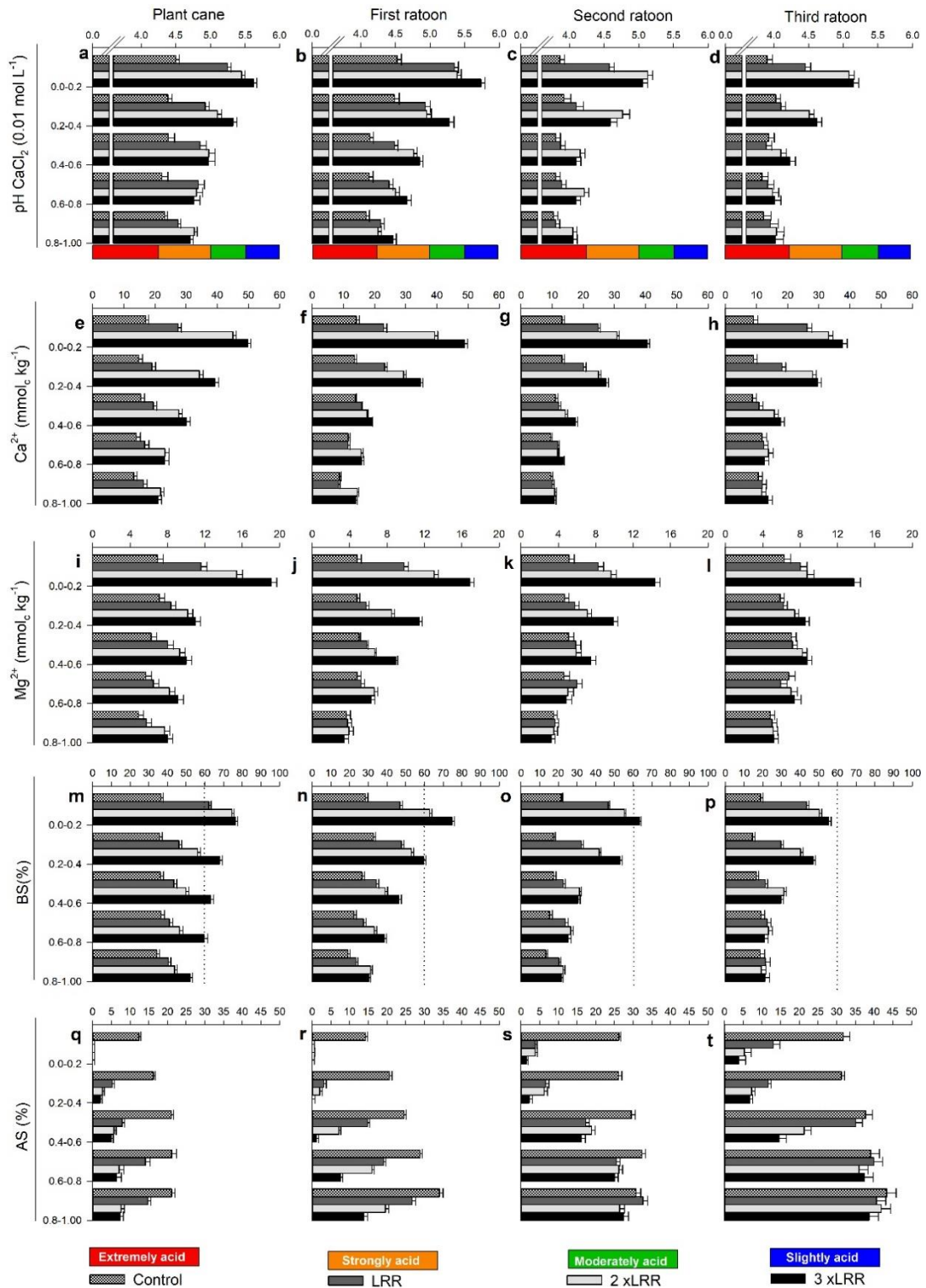


Fig 9. Soil pH_{CaCl₂} (a, b, c and d), concentration of Ca²⁺ (e, f, g and h) and Mg²⁺ (i, j, k and l), base saturation (BS, m, n, o and p) and Al³⁺ saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on deep strip-tillage systems (DT) for plant cane, first, second and third ratoon in Macatuba. Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raij et al., 1997).

1.3.2.2 Leaf analysis at Macatuba, SP

The leaf concentrations of N, P, K, S, Cu, Zn, Mn, and B were not affected by treatment or growing season (Fig. 5a, b, c, f, h, i, j, and k; Table S2) and were within the ranges proposed for sugarcane described above (Spironello et al., 1996). The leaf concentrations of Ca and Mg increased significantly at 2 and 3x LRR in plant cane ($p<0.01$) and at 3x LRR in third ratoon ($p<0.01$). In second ratoon, the leaf concentration of Ca was higher when 3x LRR was applied, whereas the leaf concentration of Mg was significantly increased by all limed treatments ($p<0.01$).

The leaf concentration of Fe ($p<0.01$) was higher in the control and LRR treatments than in the 2 and 3x LRR treatments only in second ratoon. However, the leaf concentrations of Ca, Mg, and Fe were within the ranges proposed for sugarcane (Spironello et al., 1996) in all growing seasons.

1.3.2.3 Stalk and sugar yields at Macatuba, SP

Significant effects of liming on sucrose concentration and TRS were observed in third ratoon. Both parameters were similar at all liming rates and higher than in the control (Fig. 10a and b; Table S3).

The stalk and sugar yields varied among the liming treatments in all growing seasons. In plant cane, the stalk yield was highest at 3x LRR and was similar between 2x and LRR. In all three ratoons, the stalk yield increased with the liming rate. Compared with LRR, 2 and 3x LRR increased the stalk yield by 6.0 and 12.6%, respectively, in plant cane; 9.9 and 15.3% in first ratoon; 12.0 and 18.2% in second ratoon; and 13.6 and 23.8% in third ratoon. Across all growing seasons, the average increase in stalk yield was 10.1 and 17.1% at 2 and 3x LRR, respectively (Fig. 10c, Table S3).

Sugar yield was highest at 2 and 3x LRR regardless of the growing season, except in third ratoon, where the sugar yield increased with the liming rate (Fig. 10d, Table S3). Compared with LRR, 2 and 3x LRR increased sugar yield by 6.7 and 11.8% in plant cane; 9.1 and 15.4% in first ratoon; 15.7 and 17.6% in second ratoon; and 13.6 and 24.0% in third ratoon. When averaged across all growing seasons, 2 and 3x LRR increased sugar yield by 11.0 and 16.9%, respectively.

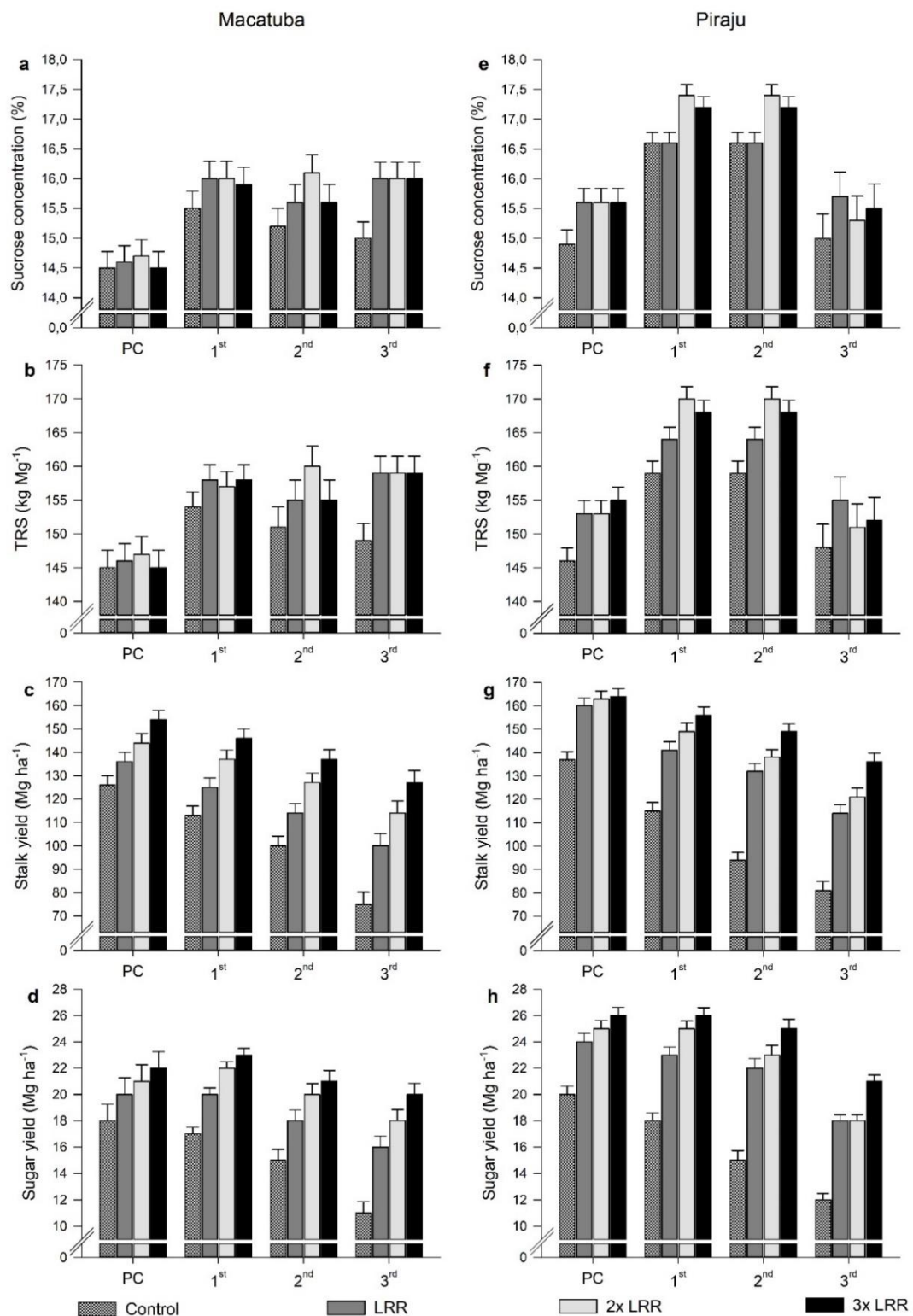


Figure 10. Sucrose concentration (Macatuba, a; Piraju, e), total recoverable sugar (TRS; Macatuba, b; Piraju, f), yield of stalks (Macatuba, c; Piraju, g) and sugar (Macatuba, d; Piraju, h) of sugarcane under increasing lime rates on deep soil tillage systems (DSTS) for plant cane, first, second and third ratoons (PC, 1st, 2nd and 3rd). Error bars represent the least significative difference (LSD) $p \leq 0.1$.

1.3.2.4 Soil chemical analysis at Piraju, SP

Soil pH was significantly altered by all liming treatments up to 0.6 m in plant cane and up to 0.4 m in the subsequent ratoons (Fig. 11a, b, c, and d; Table S4). Soil pH increased with the liming rate mainly in the topsoil layer (0.0–0.2 m), except in the last growing season. In the second layer (0.2–0.4 m), pH was highest at 3x LRR but did not differ between LRR and 2x LRR in plant cane and first and second ratoon. In third ratoon, the effects of the different limed treatments on pH were similar and superior to the control. In the third layer, small effects of liming were observed except in third ratoon.

At 0.0–0.2 m in plant cane and first ratoon, the soil pH was classified as slightly acidic at 3x LRR and moderately acidic at LRR and 2x LRR. From 0.2 to 0.4 m, moderately acidic pH values were observed in plant cane and first ratoon only at 3x LRR. At all other depths and growing seasons, the soil pH was classified as strongly or extremely acidic (Fig. 11a, b, c, and d).

The concentrations of Ca^{2+} (Fig. 11e, f, g, and h; Table S4) and Mg^{2+} (Fig. 11i, j, k, and l; Table S4) exhibited similar patterns as a function of the liming rate. Ca^{2+} increased with increasing liming rate mainly in the topsoil layer (0.0–0.2 m) in all evaluated growing seasons. In plant cane, Ca^{2+} concentrations were similar at LRR and 2x LRR from 0.2 to 0.6 m, whereas 3x LRR increased the Ca^{2+} concentration up to 0.6 m in all growing seasons.

In the uppermost surface layer (0.0–0.2 m), all limed treatments efficiently increased the Mg^{2+} concentration. In plant cane, the effect of liming was observed up to 0.4 m regardless of the liming rate and at all depths at 3x LRR. However, the effect of liming decreased in the subsequent ratoons. Notably, 3x LRR was the only liming rate to increase the Mg^{2+} concentration up to 0.4 m in the last growing season.

Liming increased BS up to 0.4 m in all growing seasons and from 0.4 to 0.6 m in plant cane, regardless of the liming rate. In first ratoon, BS was higher at 2 and 3x LRR from 0.4 to 0.6 m, whereas in second and third ratoon, BS was significantly higher only at 3x LRR (Fig. 11m, n, o and p; Table S4). Liming had no effect on BS at depths greater than 0.6 m. BS values above 60% were observed only up to 0.2 m at all liming rates in plant cane and at 3x LRR in first ratoon.

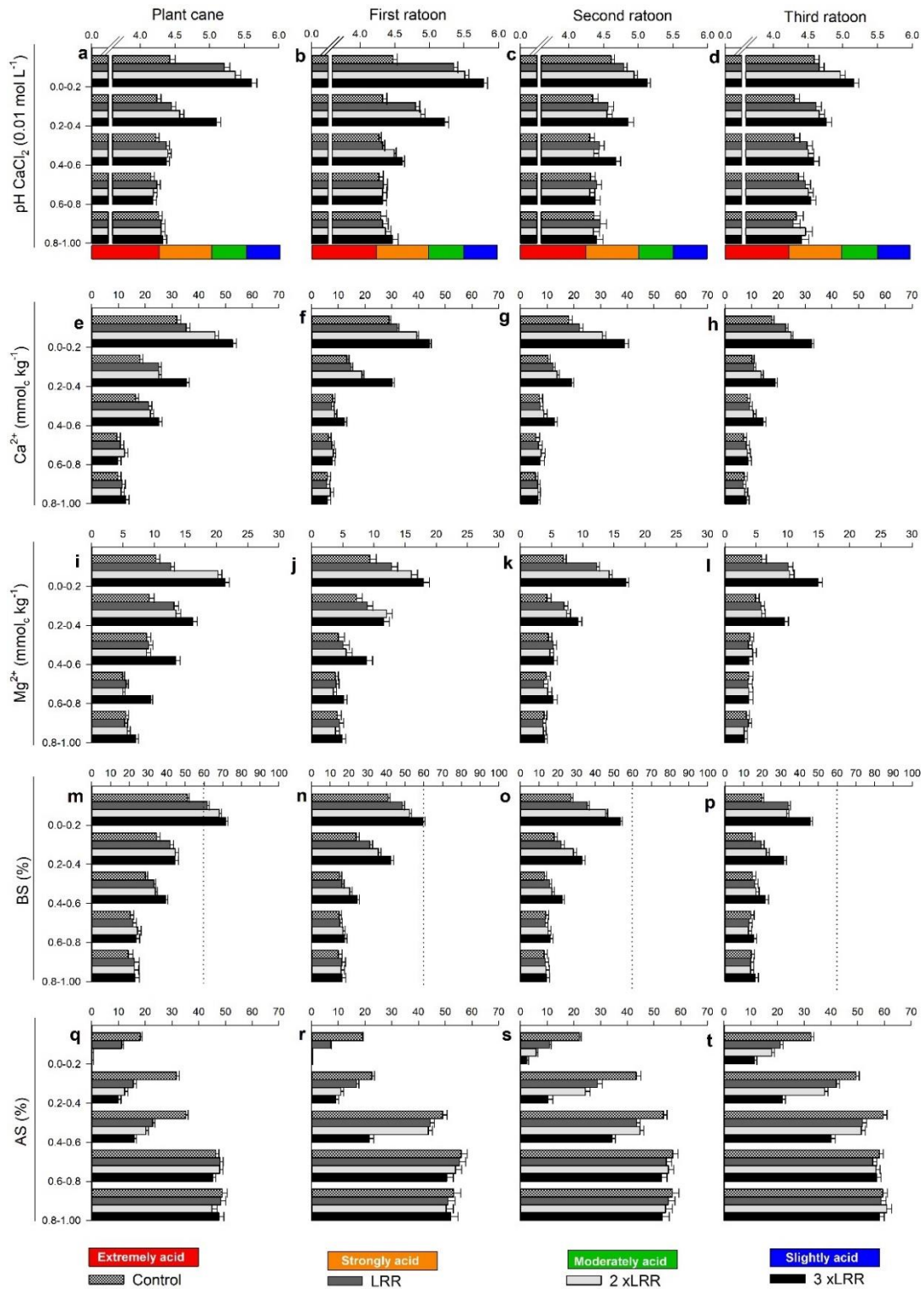


Fig 11. Soil $\text{pH}_{\text{CaCl}_2}$ (a, b, c and d), concentration of Ca^{2+} (e, f, g and h) and Mg^{2+} (i, j, k and l), base saturation (BS, m, n, o and p) and Al^{3+} saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on deep strip-tillage systems (DT) for plant cane, first, second and third ratoons in Piraju. Error bars represent the least significative difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raij et al., 1997).

The limed treatments were effective in decreasing AS up to 0.6 m, regardless of the rate. When 2 and 3x LRR were used, AS values close to zero were observed up to 0.2 m in plant cane and first ratoon; at a liming rate of LRR, AS values in this layer were less than 20%. In the second layer (0.0–0.4 m) in all growing seasons and third layer (0.4–0.6 m) in plant cane, the effect of liming decreased with the liming rate. In deeper layers, liming had no apparent effect on AS (Fig. 11q, r, s, and t; Table S4).

1.3.2.5 Leaf analysis at Pirajú, SP

The leaf concentrations of N, P, K, S, Fe, Cu, Zn, and B did not differ among the treatments in all growing seasons (Fig. 8a, b, c, f, g, h, i and k; Table S2) and were within the ranges proposed for sugarcane (Spironello et al., 1996). Significant increases in the concentrations of Ca (second ratoon, $p<0.01$) and Mg (third ratoon, $p<0.05$) were observed at 2 and 3x LRR and at 3x LRR, respectively. The leaf concentration of Mn ($p<0.01$) was highest in the control and did not differ among the limed treatments. In all growing seasons, the leaf concentrations of Ca, Mg, and Mn were within the ranges proposed for sugarcane (Spironello et al., 1996) in all treatments.

1.3.2.6 Stalk and sugar yields at Piraju, SP

The sucrose concentration and TRS varied significantly from plant cane to second ratoon. In plant cane, the two parameters were similar at all liming rates and higher than in the control. In first and second ratoon, the sucrose concentration increased only at 2 and 3x LRR and did not differ between LRR and the control. TRS did not differ between 2 and 3x LRR and was higher than in the LRR treatment (Fig. 10e and f; Table S3).

The patterns of stalk and sugar yields were identical and varied with the liming rate in all growing seasons. In plant cane, the yields did not differ among the limed treatments and were higher than in the control. In first ratoon, the stalk yield was 5.3 and 9.8% higher at 2 and 3x LRR than LRR, respectively, and the sugar yield was 9.1 and 11.8% higher. In second and third ratoon, the stalk and sugar yields were highest at 3x LRR and were similar between 2x and LRR (Fig. 10g and h; Table S3). In second and third ratoon, the stalk yield was 12 and 17%

higher, respectively, at 3x LRR than LRR, while the sugar yield was 14 and 17% higher. Averaged across all growing seasons, 2 and 3x LRR increased the stalk yield by 4.3 and 10.1% and the sugar yield by 5.8 and 11.3% compared with LRR.

1.3.3 Modified Deep Strip-Tillage System (MDT)

1.3.3.1 Soil chemical analysis at Macatuba, SP

Application of LRR influenced soil pH throughout the soil profile in plant cane, up to 0.8 m in first ratoon, and up to 0.4 m in second and third ratoon. When higher liming rates were applied, significant effects were observed at all depths and in all growing seasons except in the last layer (0.8–1.00 m) in second and third ratoon (Fig. 12a, b, c, and d; Table S1). In general, the spatial and temporal patterns of the effects of liming on soil pH were the same at all liming rates. In the first two growing seasons, the effects of liming were distributed throughout the soil profile, whereas in the last two growing seasons, the residual effect of liming was mainly limited to depths of up to 0.8 and 0.6 m in second and third ratoon, respectively. Regardless of growing season, 2 and 3x LRR buffered the soil pH efficiently above 5.0 and 5.5, respectively, in the uppermost layers (0.0–0.4 m).

When LRR was applied, the soil pH was moderately acidic” up to 0.6 m in plant cane and up to 0.2 in first ratoon. At 2x LRR, the soil pH was slightly acidic up to 0.2 m in plant cane and first ratoon and moderately acidic from 0.4 to 0.8 m in plant cane, from 0.4 to 0.6 m in first ratoon, and up to 0.4 m in second and third ratoon. At 3x LRR, the soil pH was slightly acidic from 0.0 to 0.6 m in plant cane and first ratoon, up to 0.4 m in second ratoon, and up to 0.2 m in third ratoon and was moderately acidic from 0.8 to 1.00 m in plant cane, from 0.6 to 0.8 m in first ratoon and from 0.2 to 0.4 m in third ratoon. In all other growing seasons and depths, the soil pH was classified as strongly or extremely acidic (Fig. 12a, b, c, and d).

Lime application increased the Ca^{2+} concentration throughout the soil profile in plant cane, up to 0.8 m in first and second ratoon, and up to 0.4 m in third ratoon (Fig. 12e, f, g, and h; Table S1). The Ca^{2+} concentration increased with the liming rate at all depths in plant cane and up to 0.8, 0.6, and 0.2 m in first, second, and third ratoon, respectively. There was no effect of liming on the Ca^{2+}

concentration in the most subsurface layers (0.6–1.00 m) in the last growing season.

For Mg^{2+} , the effect of liming was observed mainly up to 0.6 m in plant cane and up to 0.4 m in the subsequent ratoons. However, the effect of 3x LRR was pronounced at all depths in plant cane, up to 0.8 m in first and second ratoon, and up to 0.6 m in third ratoon (Fig. 12i, j, k, and l; Table S1).

Lime application had a positive effect on BS ($p < 0.001$). BS was significantly higher in the limed treatments than in the control regardless of the liming rate, soil depth, or growing season, except at 0.8 to 1.00 m in last ratoon (Fig. 12m, n, o, and p; Table S1). In general, BS increased with the liming rate, even in the most subsurface layers. BS values higher than 60% were observed up to 0.6 m at LRR, up to 0.8 m at 2x LRR, and throughout the entire soil profile (0.0–1.00 m) at 3x LRR in plant cane. In first ratoon, 60% BS was observed up to 0.4 m at 2x LRR and up to 0.6 m at 3x LRR. In second and third ratoon, BS was above 60% in the uppermost layer (0.0–0.2 m) at 2 and 3x LRR and in the second layer (0.2–0.4 m) only at 3x LRR.

AS was significantly controlled by liming at all rates and soil depths in plant cane and first and second ratoon and up to 0.6 m in third ratoon (Fig. 12q, r, s, and t; Table S1). AS values in the uppermost layers (0.0–0.4 m) were close to zero in plant cane and first ratoon regardless of the liming rate and in all growing seasons at 2 and 3x LRR. When LRR was applied, AS was below 10 and 20% at 0.0–0.4 m in second and third ratoon. At the highest liming rates, notable AS levels were observed only at depths of 0.6 m and greater in the last growing season, illustrating the efficiency of lime in controlling AS even in the deepest layers throughout the growing cycle.

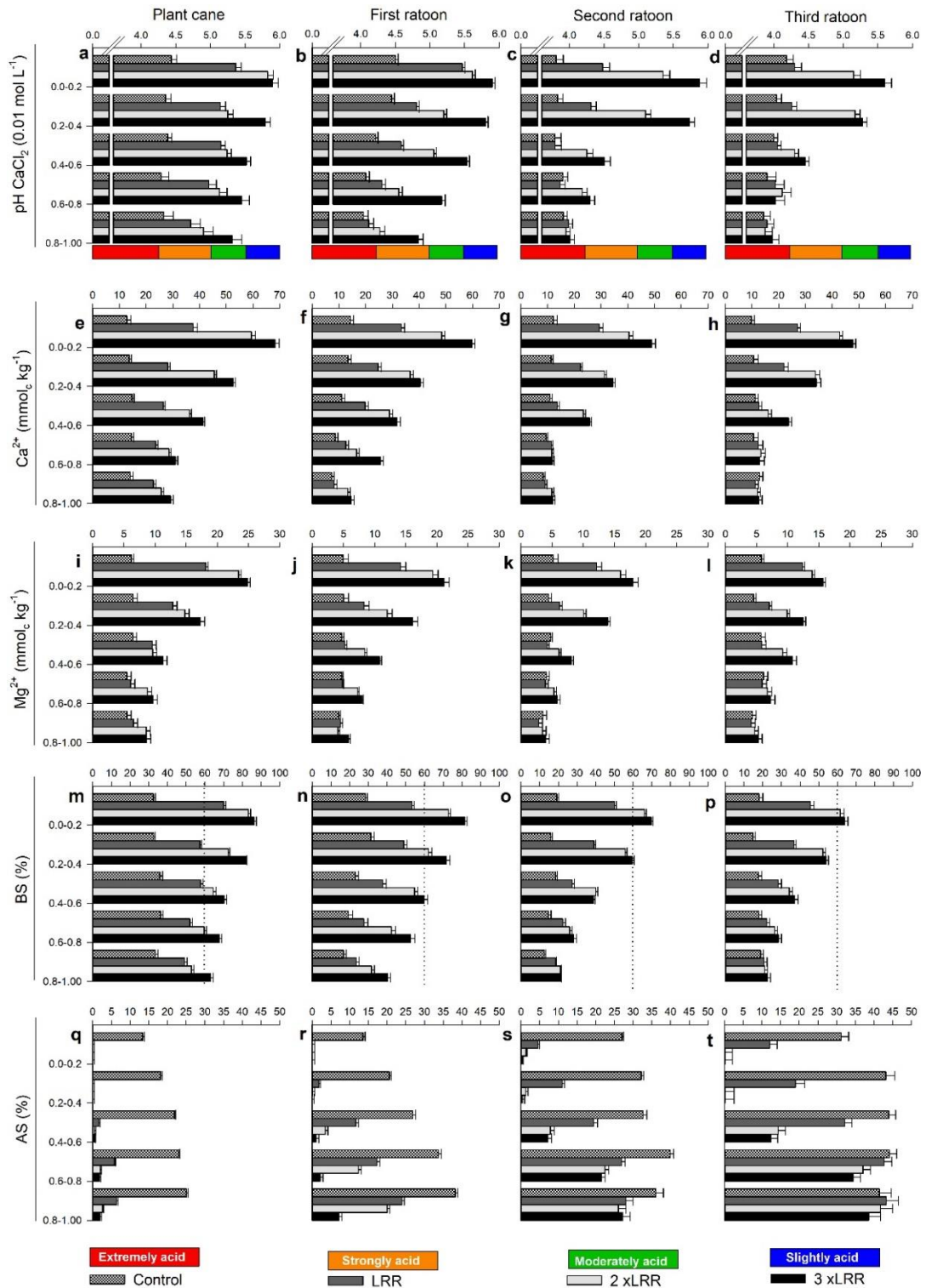


Fig 12. Soil $\text{pH}_{\text{CaCl}_2}$ (a, b, c and d), concentration of Ca^{2+} (e, f, g and h) and Mg^{2+} (i, j, k and l), base saturation (BS, m, n, o and p) and Al^{3+} saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on modified deep strip-tillage systems (MDT) for plant cane, first, second and third ratoons in Macatuba. Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raij et al., 1997).

1.3.3.2 Leaf analysis at Macatuba, SP

Liming had no significant effect on leaf concentrations of N, P, K, S, Fe, Cu, Mn, and B (Fig. 5a, b, c, f, g, h, j, and k; Table S2), which were within the ranges proposed for sugarcane in all growing seasons (Spironello et al., 1996). Applying 2 and 3x LRR significantly increased the leaf concentrations of Ca and Mg in plant cane ($p<0.01$) and Mg in third ratoon. In third ratoon, leaf Ca was highest at 3x LRR, followed by 2x LRR and LRR. The leaf concentration of Zn was significantly higher in the control ($p<0.01$) than in the limed treatments only in second ratoon, whereas the limed treatments did not differ. Nonetheless, the leaf concentrations of Ca, Mg, and Zn were within the ranges proposed for sugarcane (Spironello et al., 1996) in all growing seasons.

1.3.3.3 Stalk and sugar yields at Macatuba, SP

Significant effects of liming on sucrose concentration and TRS were observed only in third ratoon. Neither parameter varied among the limed treatments, and both were higher in the limed treatments than in the control (Fig. 13a and b; Table S3).

The stalk and sugar yields exhibited identical patterns in response to liming in all growing seasons. Neither yield varied significantly among the liming rates in plant cane and first and second ratoon, and both were higher than in the control. In third ratoon, the yields did not differ between 2 and 3x LRR; the stalk yield was 9.5 and 11% higher, respectively, than at LRR, and the sugar yield was 9.0 and 10.3% higher (Fig. 13c and d; Table S3). Across all growing seasons, the average increase in stalk yield was 5.5 and 6.5% at 2 and 3x LRR, respectively, and the average increase in sugar yield was 5.1 and 7.1%.

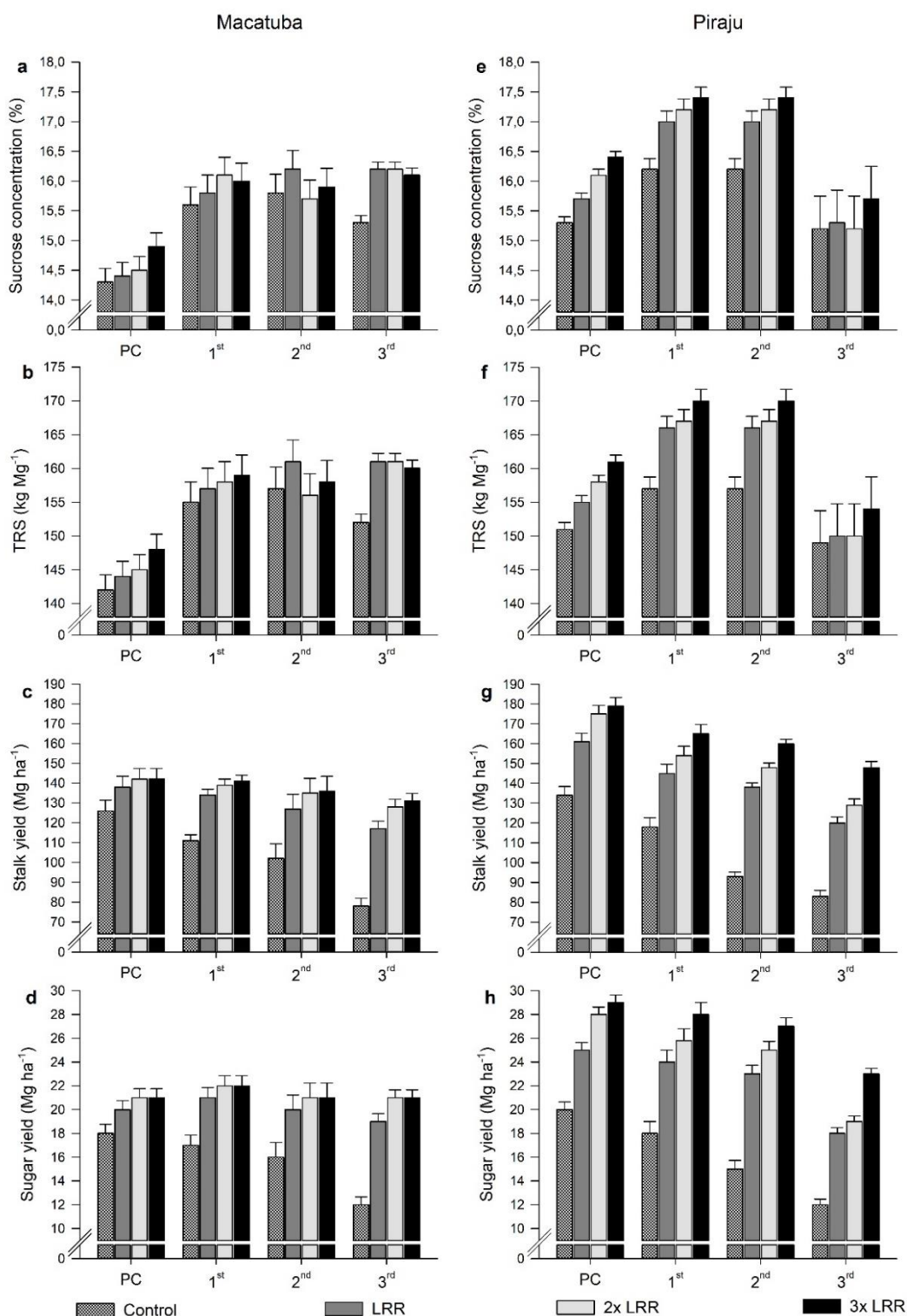


Figure 13. Sucrose concentration (Macatuba, a; Piraju, e), total recoverable sugar (TRS; Macatuba, b; Piraju, f), yield of stalks (Macatuba, c; Piraju, g) and sugar (Macatuba, d; Piraju, h) of sugarcane under increasing lime rates on modified deep strip-tillage systems (MDT) for plant cane, first, second and third ratoons (PC, 1st, 2nd and 3rd). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

1.3.3.4 Soil chemical analysis at Pirajú, SP

Lime application positively affected soil pH up to 0.2 m in all growing seasons but only in plant cane at depths of 0.2–0.4 m. The residual effect of liming on soil pH from 0.4 to 0.6 m was observed mainly at 2 and 3x LRR in plant cane and first ratoon and at 3x LRR in second and third ratoon (Fig. 14a, b, c, and d; Table S4). Liming had no effect on soil pH in the deepest layers (0.6–1.00 m). The soil pH was slightly acidic up to 0.2 m at 2 and 3x LRR in plant cane and first ratoon and at 3x LRR in second and third ratoon. The pH was moderately acidic in the first layer (0.0–0.2 m) in all growing seasons when LRR was used. In the second layer, moderately acidic pH values were observed only at 2 and 3x LRR in plant cane and first ratoon and at 3x LRR in second and third ratoon. At all other depths and growing seasons, the soil pH was strongly or extremely acidic (Fig. 14a, b, c, and d).

The concentration of Ca^{2+} increased according to the liming rate throughout the soil profile (0.0–1.00 m) in plant cane and up to 0.2 m in all growing seasons (Fig. 14e, f, g, and h; Table S4). From 0.2 to 0.4 m, the Ca^{2+} concentration was higher at 2 and 3x LRR, with pronounced effects until the last ratoon.

The concentration of Mg^{2+} increased with the liming rate up to 0.4 m in all growing seasons. In plant cane, lime application had a positive effect on the Mg^{2+} concentration at all rates up to 0.8 m and at 3x LRR up to 1.00 m (Fig. 14i, j, k, and l; Table S4).

Liming significantly increased BS up to 0.6 m regardless of the liming rate and growing season, except from 0.2 to 0.6 m in third ratoon, for which only 2 and 3x LRR had significant effects (Fig. 14m, n, o and p; Table S4). In the most subsurface layers (0.6–1.00 m), BS values were altered only at 3x LRR. In plant cane, BS values above 60% were obtained in all limed treatments only up to 0.2 m; 60% BS was achieved up to 0.4 m at 2 and 3x LRR. In first ratoon, 60% BS was obtained up to 0.2 m at 2 and 3x LRR and up to 0.4 m at 3x LRR. In second ratoon, 60% BS was reached only up to 0.2 m by applying 3x LRR.

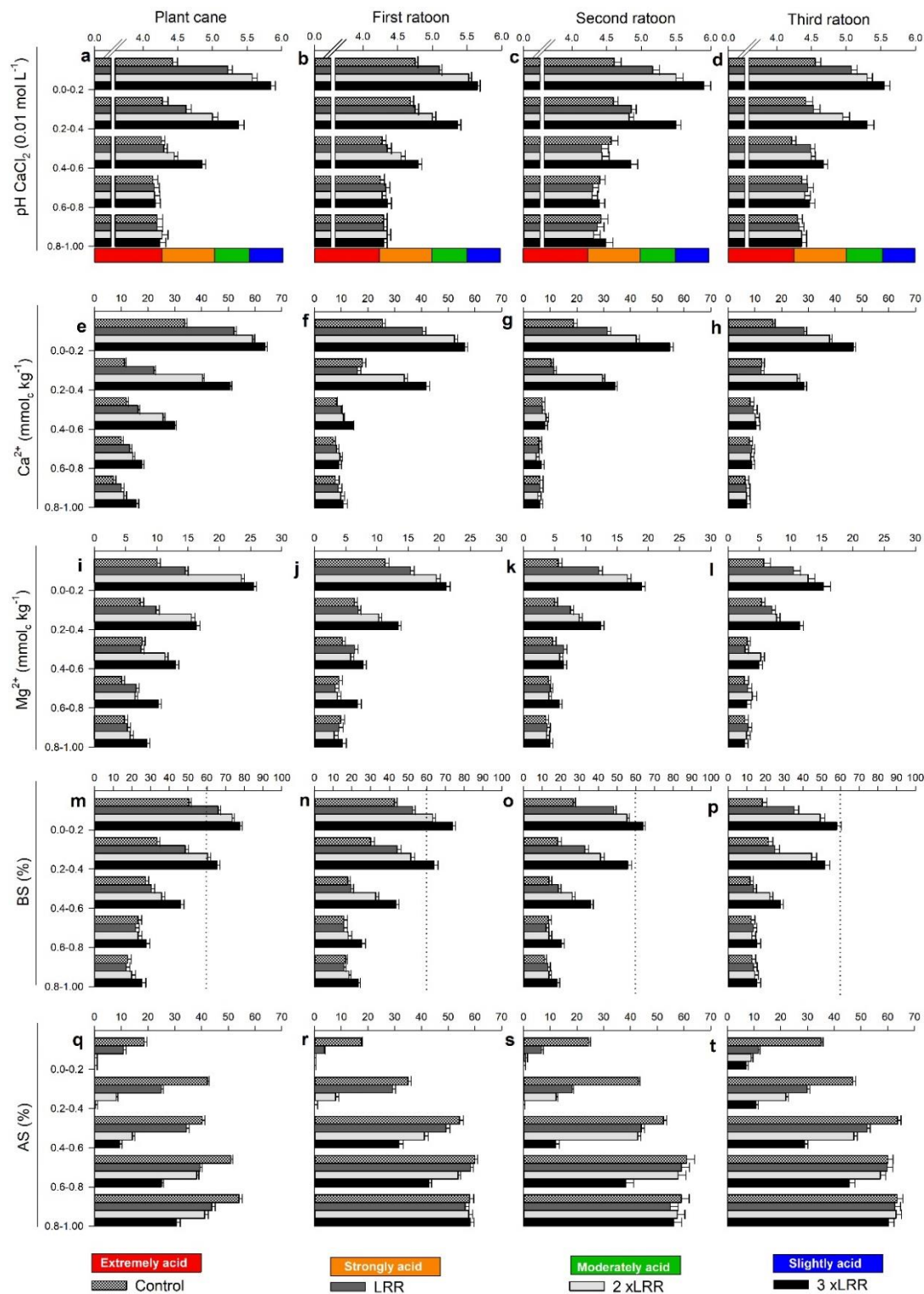


Fig 14. Soil pH_{CaCl2} (a, b, c and d), concentration of Ca²⁺ (e, f, g and h) and Mg²⁺ (i, j, k and l), base saturation (BS, m, n, o and p) and Al³⁺ saturation (AS, q, r, s and t) across the soil profile under increasing lime rates on modified deep strip-tillage systems (MDT) for plant cane, first, second and third ratoons in Piraju. Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale classification (Raij et al., 1997).

Lime application effectively controlled AS regardless of the liming rate at all depths in plant cane and up to 0.6 m in all ratoons. At 0.6-0.8 m, 3x LRR had the best performance, whereas at 0.8–1.00 m, no effect of liming was observed (Fig. 14q, r, s, and t; Table S4). AS values were near zero up to 0.2 m at 2 and 3x LRR and up to 0.4 m at 3x LRR in plant cane and first and second ratoon. In addition, at LRR, AS was below 10% even in last ratoon, illustrating the residual effect of liming throughout the growing cycle.

1.3.3.5 Leaf analysis at Piraju, SP

There was no significant effect of liming on leaf concentrations of N, P, K, Mg, S, Fe, Cu, Zn, and B (Fig. 8a, b, c, e, f, g, h, i, and k; Table S2), which were within the ranges proposed for sugarcane (Spironello et al., 1996) in all growing seasons. The leaf concentration of Ca in second ratoon was significantly higher ($p<0.01$) at 2 and 3x LRR. The leaf concentration of Mn was significantly higher in the control ($p<0.01$) in third ratoon and did not differ among the limed treatments. In all growing seasons, the leaf concentrations of Ca and Mn were within the ranges proposed for sugarcane (Spironello et al., 1996).

1.3.3.6 Stalk and sugar yields at Piraju, SP

In the first three growing seasons, significant effects of liming on sucrose concentration and TRS were observed. In plant cane, both parameters increased with the liming rate. In first and second ratoon, sucrose concentration and TRS did not differ among the limed treatments and were higher than in the control (Fig. 13e and f; Table S3).

The patterns of stalk and sugar yields were similar to one another and indicated an effect of liming in all growing seasons (Fig. 13g and h; Table S3). In plant cane, the stalk and sugar yields did not differ between 2 and 3x LRR; the stalk yield was 8.7 and 10.2% higher, respectively, than in the LRR treatment, and the sugar yield was 11 and 14.5% higher. In first ratoon, stalk and sugar yields were higher at 3x LRR and did not differ between 2x and LRR. In first ratoon, the stalk and sugar yields were 12.8 and 15.2% higher, respectively, at 3x LRR than LRR. In second and third ratoon, both parameters increased with the liming rate. Compared with LRR, the stalk

yield was 8 higher in second and third ratoon, respectively, at 2x LRR and 15 and 22% higher, respectively, at 3x LRR

Sugar yield was 8 and 7% higher in second and third ratoon, respectively, at 2x LRR and 17 and 24% higher, respectively, at 3x LRR. Among all growing seasons, the average increase in stalk yield was 8 and 14% at 2 and 3x LRR, respectively, whereas the average increase in sugar yield was 9 and 17%, respectively, compared with LRR.

1.4 DISCUSSION

As detailed above, liming increased parameters favorable for soil chemical fertility, such as pH, Ca^{2+} , Mg^{2+} , and BS, while decreasing AS. In general, these effects were observed regardless of site or soil tillage system but varied in intensity according to the liming rate and the specific tillage system.

Moderately to slightly acidic values of soil pH at least 0.4 m are important for sugarcane cultivation. At Macatuba, the soil pH values were maintained in the moderately and slightly acidic range in plant cane and first ratoon regardless of the tillage system and liming rate. In subsequent growing seasons, LRR was not sufficient to buffer the pH except in the uppermost layer (0.0–0.2 m) in all tillage systems. Liming rates of 2 and 3x LRR provided better performance at depths up to 0.4 m in all growing seasons.

At Piraju, a more pronounced effect of liming was observed in the first soil layer, and higher rates were more effective in the second layer. Although there were clear differences between the tillage systems, the highest liming rates were able to maintain a greater residual effect in all systems.

Soil pH affects the availability of elements considered nutrients for plants, and pH values within a moderately (5.0–5.5) or, preferably, slightly (> 5.5) acidic range are ideal for increasing the availabilities of K, Ca, and Mg by increasing the effective cation exchange capacity (CEC_e), thus reducing their losses by leaching; N, S and B due to the favorable effect of soil organic matter (SOM) mineralization; P, by increasing negative charges that compete with phosphate-specific adsorption; as well as molybdenum (Mo) and chlorine (Cl) (Souza et al., 2007). Conversely, Fe, Cu, Mn, and Zn may be adsorbed by SOM or CEC when pH increases. Therefore, attention is

needed to prevent deficiencies of cationic micronutrients in limed areas (Souza et al., 2007).

Liming was expected to increase the leaf concentrations of Ca and Mg by increasing their concentration and availability in the soil. The leaf concentrations of cationic micronutrients including Fe, Cu, Zn (Macatuba), and Mn (Piraju) were reduced by liming but remained within the ranges considered sufficient for sugarcane.

The soil concentrations of Ca^{2+} and Mg^{2+} and BS were influenced by the liming rate at both sites, regardless of the tillage system. Although the magnitudes of the effects differed depending on the specific conditions, increasing the liming rate increased these three parameters under all tillage systems. Higher rates of liming were efficient in reaching deeper layers, particularly in plant cane, and intermediate layers in the subsequent ratoons. These findings are important since the proliferation of plant roots tends to be concentrated in soil layers with higher fertility levels and high-water availability. A crucial symptom of Ca deficiency is necrosis of young meristematic regions such as root tips, which will compromise the efficient uptake of water and nutrients (Taiz and Zeiger, 2017). This symptom occurs because Ca^{2+} interacts with the phospholipids of the cellular membrane to stabilize the lipid bilayers and control membrane permeability, which influences the ability of root cells to absorb and retain solutes (Hepler, 2005).

Mg^{2+} participates in sucrose synthesis (inorganic P (Pi) partitioning between starch synthesis and the transport of triose phosphates in the cytosol for sucrose production) and sucrose transport from the leaves to the stalks. Mg^{2+} directly participates in cellular energy generation as a substrate for ATPase, coordinating the binding of ADP with Pi to form ATP. Therefore, in addition to P and K, cellular energy generation and storage depend on Mg^{2+} (Cakmak and Kirkby, 2008; Taiz and Zeiger, 2017). As the main objective of sugarcane cultivation is sucrose yield, efficient transport of sucrose from the leaves to stems is essential, and Mg^{2+} plays a fundamental role in energy-dependent transport (Cakmak et al., 1994).

The liming process added equivalent amounts of Ca^{2+} and Mg^{2+} under CT and DT but not MDT. Under CT and DT, the Ca^{2+} and Mg^{2+} inputs were 1,065 and 510 kg ha⁻¹ for LRR; 2,130 and 1,020 kg ha⁻¹ for 2x LRR; and 4,260 and 2,040 kg ha⁻¹ for 3x LRR, respectively, in Macatuba and 850 and 550 kg ha⁻¹ for LRR; 1,700 and 1,100 kg

ha⁻¹ for 2x LRR; and 3,400 and 2,200 kg ha⁻¹ for 3x LRR, respectively, in Piraju. However, under MDT, the same rates calculated for the total area were applied as concentrated bands. Given a row spacing of 1.5 x 0.9 m (i.e., 2.4 m) and a furrower working width of 1.2 m, a double dose was strip-incorporated by the furrower. Accordingly, under MDT, the Ca²⁺ and Mg²⁺ inputs were 2,130 and 1,020 kg ha⁻¹ for LRR; 4,260 and 2,040 kg ha⁻¹ for 2x LRR; and 8,520 and 4,080 kg ha⁻¹ for 3x LRR, respectively, in Macatuba and 1,700 and 1,100 kg ha⁻¹ for LRR; 3,400 and 2,200 kg ha⁻¹ for 2x LRR; and 6,800 and 4,400 kg ha⁻¹ for 3x LRR, respectively, in Piraju.

Although the soil concentrations of Ca²⁺ and Mg²⁺ did not increase proportionally under MDT compared with CT and DT, the residual effect of liming throughout the growing seasons was highest under MDT. Lime reactivity is favored at pH values below approximately 4.6 to 5.0 (CaCl₂) (Rheinheimer et al., 2000). When soil pH is raised by liming, the lime reaction decreases, contributing to downwards or lateral displacement of the unreacted lime particles. When acidity is restored, the reactivity of the excess lime will be recovered (Rheinheimer et al., 2018, 2000). For perennial or semi-perennial crops, a greater liming residual effect is desirable due to the progressive decline in soil fertility (Crusciol et al., 2017).

BS above 60% is considered adequate for sugarcane (Spironello et al., 1996) and provides greater availability of base cations and reduced availability of acidic cations. As the LRR was calculated by summing the liming necessary for the uppermost surface layers (0.0–0.2 + 0.2–0.4 m), BS values reaching at least 60% were expected in these layers. In general, adequate results were observed in plant cane under all tillage systems when LRR was used; however, in subsequent growing seasons, BS was less than 60% under LRR even in the first layer, regardless of the tillage system. When higher liming rates were used, a greater residual effect was observed, mainly in first ratoon under CT and DT and in all ratoons under MDT. The BS values varied between the sites and were highest in the first layer. Higher yields were observed under higher BS, which suggests that the value of 60% may not be sufficient, especially in clayey soils with higher pH buffer capacity. AS and BS are inversely proportional and thus equally important. When lime was applied, the soil pH increased and Al³⁺ saturation decreased due to its complexation into Al-hydroxides (Li and Johnson, 2016). Therefore, reducing Al³⁺ and exchangeable H⁺ is as important as inputting Ca²⁺ and Mg²⁺.

Even though the concentrations of Ca^{2+} and Mg^{2+} were greater than required for sugarcane, the yields were higher under the highest liming rates. In general, the dependence on higher-than-recommended liming rates was greatest under DT, as the stalk and sugar yields increased as the liming rate increased. Because lime was broadcast over the entire area for further strip-incorporation only in planting furrows under DT, reaction of part of the lime may be not favored. In addition, since the lime was deeply mobilized, a higher lime dose than recommended may be necessary to attain a higher soil concentration.

Conversely, under CT and MDT, the stalk and sugar yields varied with increasing liming rate only in third ratoon at Macatuba, where they were higher at 2 and 3x LRR than LRR, and at 3x LRR at Piraju. In contrast to DT, lime was not only broadcast but also incorporated over the entire area under CT, resulting in a better distribution of lime and favoring its reaction. Compared to LRR, higher stalk and sugar yields were observed at 2x LRR but not always at 3x LRR. When 3x LRR was used, a greater residual effect was observed, mainly in third ratoon.

A similar pattern was observed under MDT. At Macatuba, the stalk and sugar yields were lower in the LRR treatment only in third ratoon. By contrast, at Piraju, stalk and sugar yields did not differ between LRR and 2x LRR in most growing seasons and were higher at 3x LRR. As noted above, the application of lime in concentrated bands was equivalent to a double dose at the planting furrow, resulting in higher yields under MDT even when LRR was used. In other words, when lime was broadcast over the total area, a greater influence of the liming rate on sugarcane yield was observed.

Our findings provide adequate information for clayey soils, however, solid information on chemical assessment for medium-textured and sandy soils is also necessary due to the great representation of these soils in the sugarcane industry.

1.5 CONCLUSION

The present study assessed chemical fertility parameters throughout the soil profile for a complete sugarcane growing cycle and evaluated sugarcane performance under different tillage systems and liming rates. In general, all tillage systems adequately amended soil acidity, and the highest liming rates provided a more pronounced residual effect.

As the lime recommended rate (LRR) was calculated based on the base saturation (BS) method, the findings suggest that a review of the recommended BS value is necessary since, in most cases, higher yields were achieved at higher-than-recommended BS, regardless of the tillage system.

The distribution of lime in the soil profile differed in each tillage system. The influence of the liming rate on stalk and sugar yields was most pronounced in the deep strip-tillage system (DT), intermediate in the conventional soil tillage system (CT) and lowest in the modified deep strip-tillage system (MDT).

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CHAPTER 2 - DEEP TILLING AND LOCALIZED LIMING IMPROVE SOIL CHEMICAL FERTILITY AND SUGARCANE YIELD IN CLAYEY SOILS

Abstract

The selection of an appropriate soil tillage system for improving yields and longevity is an important decision in sugarcane cultivation. In the present study, the effects of different soil tillage systems and methods of applying lime on sugarcane stalk and sugar yield performance as well as soil fertility parameters were evaluated throughout the sugarcane crop cycle. The experiments were established in two locations in April 2015 and conducted until August 2019, corresponding to a total of 4 growing seasons. A field study with a randomized block design was established with four replicates considering 4 treatments: conventional soil tillage system (CT), deep strip-tillage system (DT) and modified deep strip-tillage system (MDT), all with the same liming rate; and a standard treatment (control, CT without liming). Immediately after harvesting plant cane (18 months (mo) after planting), first ratoon (30 mo after planting), second ratoon (42 mo after planting) and third ratoon (54 mo after planting), soil samples were collected from a depth of 0.0 to 1.00 m, stratified every 0.2 m. Leaf material was sampled during the period of full vegetative growth. Analyses of soil chemical fertility, leaf concentrations of elements, and sugarcane yield components were performed. MDT was found to correct soil acidity most efficiently, mainly due to the positioning of the lime application. Under high aluminum saturation (AS), especially in deeper layers, deep lime placement was more effective and resulted in the best distributions of calcium (Ca^{2+}) and magnesium (Mg^{2+}), the highest base saturation (BS) and the lowest AS compared with the other treatments. Lime application was more important than the tillage system for improving the sucrose concentration and total recoverable sugar (TRS), whereas the tillage system affected the stalk yield and, consequently, the yield of sugar. Compared with DT and CT, the average stalk yield was 4.1 and 9.4% higher, respectively, under MDT at Macatuba and 6.3 and 15.3%, higher, respectively, under MDT at Piraju. Similarly, MDT improved average sugar yield by 3.7 and 10.4% at Macatuba and 6.1 and 16.3% at Piraju. Overall, long-term assessments, which are important for semi-perennial crops like sugarcane, showed that the both deep strip-tillage were most effective.

Keywords: Conventional soil tillage; Deep strip-tillage; Lime application in bands; Base saturation; Aluminum saturation.

2.1 INTRODUCTION

Brazil is the world's largest producer of sugarcane (*Saccharum* spp.) and accounts for approximately 30% of global production (Conab, 2020; FAOStat, 2018). In the 2020/2021 crop season, stalk production of 665.1 million tons is expected, which will be used to produce approximately 30 billion liters of ethanol and 42 million

tons of sugar (Conab, 2020). São Paulo produces approximately 54.3% of all sugarcane in Brazil, with an average yield of 81.65 Mg ha⁻¹, making it the most important sugarcane-producing state in Brazil (Conab, 2020). Monteiro and Sentelhas (2014) mapped the potential and actual productivity of sugarcane in the different producing regions of São Paulo and found that the potential sugarcane yield is greater than 200 mg ha⁻¹, much higher than the actual scenario.

Agricultural sustainability is of great socio-environmental importance for Brazil, which has motivated continued research on sustainable production systems, especially adequate soil management and conservation practices (Carvalho et al., 2017; Cherubin et al., 2015; Crusciol et al., 2017). Better management practices are also essential for increasing profitability and yields. The adoption of new technologies such as precision agriculture (Sanches et al., 2021) in combination with different soil tillage systems (De Moraes et al., 2019; Marasca et al., 2015; Scarpore et al., 2019) can mitigate deficiencies in the physical and chemical properties of soil and provide better conditions for plant development and the use of agronomic inputs.

Sugarcane is a semi-perennial crop, and its ratoons will remain in the field for several years until replanting is agronomically and economically warranted. Consequently, the soil tillage system is a fundamental parameter for ensuring greater sugarcane yields and field longevity (Barbosa et al., 2021). Currently, the conventional soil tillage system is widely used to establish sugarcane crops. However, the sugar and alcohol industries are implementing changes in cultivation practices such as green (no burn) and mechanical harvesting and controlling machine traffic to improve crop resilience in the face of environmental stresses and maintain better environmental conditions (Bordonal et al., 2018; Carvalho et al., 2017). To enable deeper root access, new agricultural equipment for constructing planting furrows (i.e., furrower) has been developed and tested in Brazil. This equipment distributes soil chemical amendments only in the planting row; the inter-rows are reserved for machine traffic (Scarpore et al., 2019).

New soil tillage systems were initially developed with a focus on the physical properties of soil in order to obtain the best conditions for further exploration of the sugarcane root system (Cury et al., 2014; De Soares et al., 2015; Everton et al., 2016; Marasca et al., 2015; Scarpore et al., 2019). By comparison, the impact of these systems on the chemical properties of soil has received relatively little

attention, especially in tropical agriculture. Sugarcane is preferentially cultivated in tropical regions with high rainfall, as the crop does not tolerate low temperatures (Bernardo et al., 2019). Tropical soils are generally highly weathered and acidic (Schaefer et al., 2008). In addition, weathered acidic soils typically have high levels of exchangeable aluminum (Al^{3+}), and Al^{3+} toxicity has long been recognized as a significant and increasing constraint in the sugarcane industry around the world (Borges et al., 2020).

To amend soil acidity, lime application is the most recommended practice (Crusciol et al., 2017). In general, lime is broadcast superficially and incorporated to a depth of approximately 0.4 m by using a heavy offset disc harrow, a subsoiler, and a leveling disc harrow, which limits lime placement to the mobilized layer only. By contrast, a furrower allows deep liming placement in the planting furrow. However, solid evidence supporting this innovative management practice is still lacking in the sugarcane industry. Such evidence is important because the shift to new agricultural systems requires the adoption of multiple types of new machinery and thus incurs high costs. In addition, due to the peculiarities of sugarcane cultivation, a multiyear approach addressing aspects of tillage management is needed. Accordingly, the present study aimed to evaluate sugarcane performance as measured by stalk and sugar yields throughout the crop cycle as well as soil fertility parameters under different soil tillage systems and methods of lime application.

2.2 MATERIAL AND METHODS

2.2.1 Location of the experimental areas and soil and climate characteristics

The experiments were established in April 2015 and conducted until August 2019, corresponding to a total of 4 growing seasons (plant cane plus three regrowth canes (ratoons)), in two sugarcane commercial sites belonging to the Zilor sugar mill group in Macatuba (22° 29' S and 48° 47' W), and the Raízen sugar mill group in Piraju, both in State of São Paulo, Brazil (23°07' S 49°24' W) (Fig. 1). The climate at both sites is classified as Cwa, i.e., predominantly tropical humid with hot summers, according to the Köppen classification. Figure 2 presents the average rainfall, temperature and hydro-climatic balance (Rolim et al., 1998; Thornthwaite and Mather, 1957).

The Macatuba and Piraju soils were both classified as clayey-textured Rhodic Hapludox (Soil Survey Staff, 2017). Soil chemical (Raij et al., 2001) and texture characterizations (Gee and Or, 2002) were performed using air-dried soil samples collected from depths of 0 to 1.00 m, stratified every 0.2 m. The soil samples were passed through a 10 mesh (2-mm) sieve prior to characterization (Table 1).

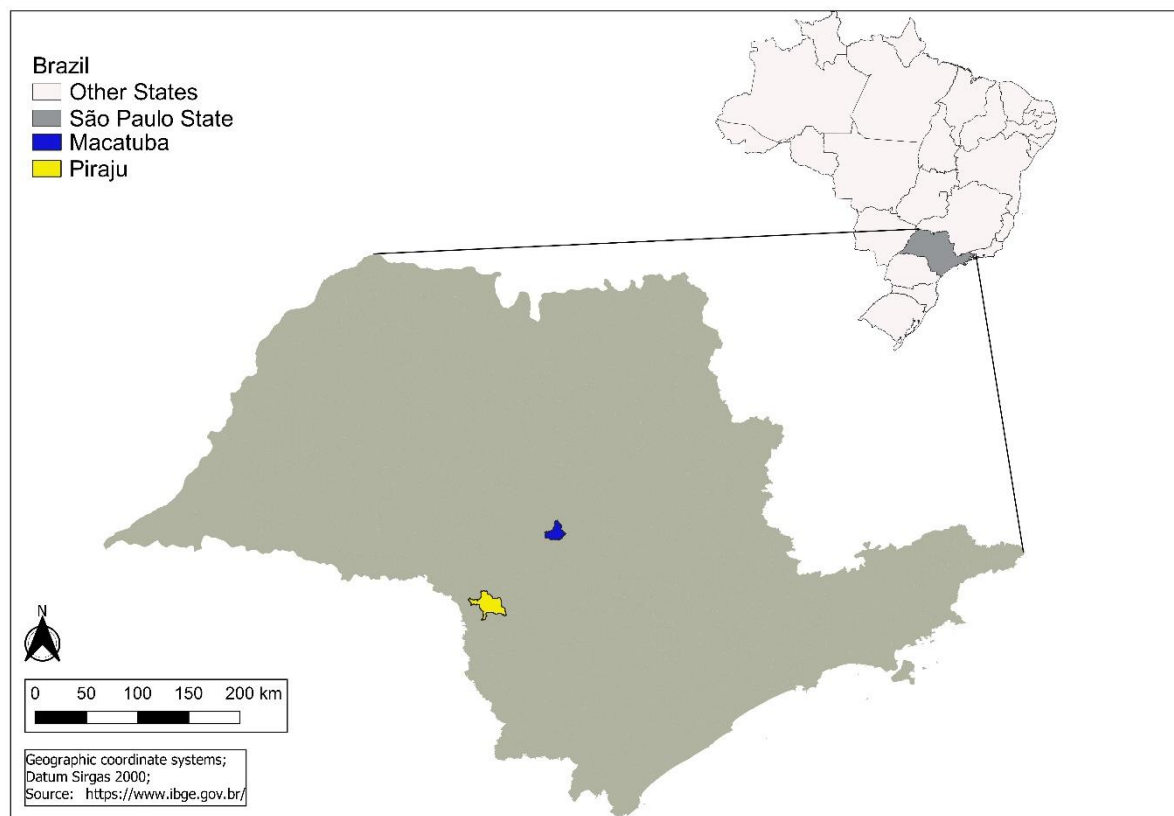


Figure 1. Geographic location of the experimental sites.

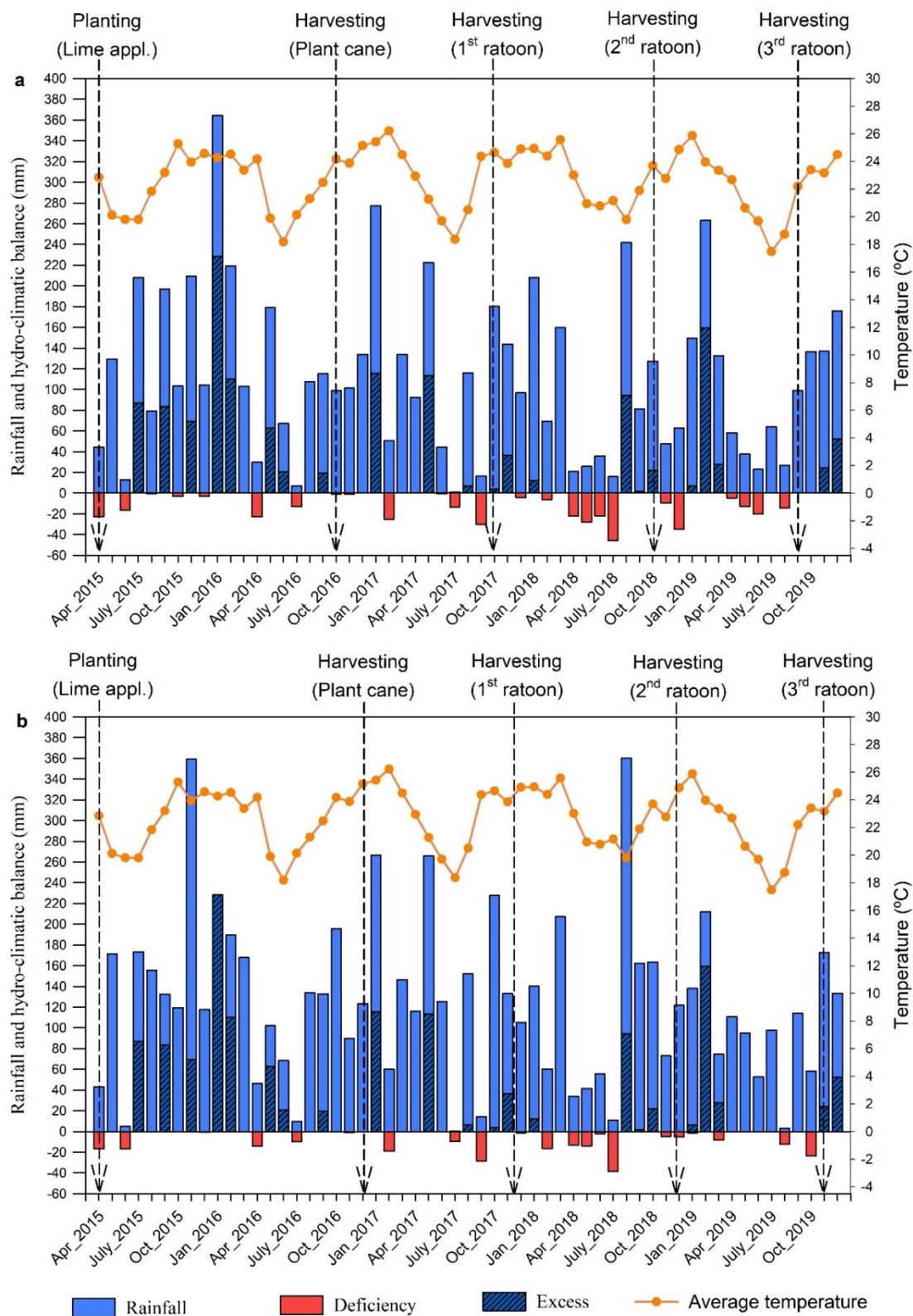


Figure 2. The average of monthly rainfall, temperature and hydro-climatic balance (mm) in the 2015/2019 growing season in (a) Macatuba and (b) Piraju.

Table 1. Soil chemical attributes and texture characterization prior to the experiment

Attributes	Macatuba Depth (m)					Piraju Depth (m)				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.00	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.00
pH (CaCl ₂)	4.4	4.0	4.0	3.9	4.0	5.0	4.5	4.2	4.2	4.2
OC (g kg ⁻¹)	23	15	12	10	10	19	16	11	9	9
P _{resin} (mg kg ⁻¹)	12	7	4	3	4	8	6	2	2	2
K (mmol _c kg ⁻¹)	2.0	0.8	0.3	0.2	0.7	1.2	0.7	0.1	0.1	0.1
Ca (mmol _c kg ⁻¹)	19	10	6	7	6	33	17	5	5	5
Mg (mmol _c kg ⁻¹)	9	5	3	3	2	15	9	3	4	3
S (mg kg ⁻¹)	21	47	36	50	45	8	18	55	74	68
Fe (mg kg ⁻¹)	23	15	8	7	7	30	27	13	12	7
Cu (mg kg ⁻¹)	3	3.3	2.2	1.8	1.8	1.1	1.2	0.9	0.7	0.6
Mn (mg kg ⁻¹)	9.7	4.3	3	1.2	2	3.6	2.5	0.3	0.3	0.2
Zn (mg kg ⁻¹)	1.1	0.5	0.1	0.1	0.1	0.4	0.3	0.1	0.1	0.1
B (mg kg ⁻¹)	0.2	0.2	0.1	0.1	0.1	0.3	0.2	0.2	0.1	0.1
Al (mmol _c kg ⁻¹)	5	7	8	7	8	0.7	6	10	11	10
H+Al (mmol _c kg ⁻¹)	52	62	64	70	64	45	64	69	71	72
CEC (mmol _c kg ⁻¹)*	82	78	73	80	73	94	91	76	80	78
Base saturation (%)**	37	20	13	13	12	52	28	11	11	9
Al saturation (%)***	14	30	46	40	48	2	27	62	62	64
Clay content (g kg ⁻¹)	358	449	486	469	442	673	735	734	757	746
Silt content (g kg ⁻¹)	154	140	116	124	146	129	93	99	85	92
Sand content (g kg ⁻¹)	488	410	398	407	412	198	173	167	158	163

*Calculated from the equation: CEC (mmol_c kg⁻¹) = Ca²⁺ + Mg²⁺ + K⁺ + (H+Al); ** Base saturation (%) = (Ca²⁺ + Mg²⁺ + K⁺) / (CEC) x 100; *** Al saturation (%) = (Al / (Ca²⁺ + Mg²⁺ + K⁺ + Al³⁺)) x 100.

2.2.2 Treatments and experimental design

A randomized block design field study was established with four replicates considering 4 treatments: standard (conventional soil tillage system without liming as a control); conventional soil tillage system with liming (CT); deep strip-tillage system with liming (DT); and modified deep strip-tillage system with liming (MDT). The conventional soil tillage system used in this study is the standard for sugarcane cultivation in Brazil. The liming recommended rates (LRR) for Macatuba (CaO, 30%; MgO, 17%) and Pirajú (CaO, 30%; MgO, 23%) were calculated according to the base saturation method (Cantarella et al., 1998) considering the sum of the soil layers from 0.0 to 0.2 and 0.2 to 0.4 m. For sugarcane, the bulletin recommends a base saturation of 60% (Spironello et al., 1996). Based on a previous study (data not shown) that tested four liming rates (no liming, LRR based on Spironello et al. (1996), 2× LRR and 3× LRR), 2× LRR was used as the liming rate in the limed treatments. The respective lime amounts and forms of application are presented in Table 2.

Table 2. Lime doses and forms of application under different soil tillage systems

Soil Tillage System	CT1	DT2	MDT3	
Lime application	Broadcast (over the entire area)	Broadcast (over the entire area)	Broadcast (in bands)	Deep-incorporated
Lime doses	----- Mg ha ⁻¹ -----			
	Rhodic Hapludult (Macatuba)			
Control ⁴	0.0	0.0	0.0	0.0
2x LRR ⁵	10.0	10.0	7.5	2.5
	Rhodic Acrudox (Piraju)			
Control	0.0	0.0	0.0	0.0
2x LRR	8.0	8.0	6.0	2.0

¹ Conventional soil tillage system; ² Deep strip-tillage system; ³ Modified deep strip-tillage system; ⁴ No liming; ⁵ Two times liming recommended rate (Spironello et al., 1996).

The tillage systems (treatments) were characterized by the following operations (a brief scheme is given in Figure 3):

- (I) Conventional soil tillage system (CT): This is the standard system for sugarcane cultivation in Brazil. In this tillage system, the lime was broadcast over the entire area and incorporated at 0.3-0.4 m using single application of a heavy offset disc harrow, a subsoiler, and a leveling disc harrow.
- (II) Deep strip-tillage system (DT): In this system, the lime was broadcast over the entire area and deeply incorporated with a furrower only at the planting rows.

The furrower had a rotary hoe with a working depth of 0.3 to 0.4 m plus a subsoiling rod with a working depth of 0.7 to 0.8 m. This equipment builds furrows with a width of 1.2 m.

- (III) Modified deep strip-tillage system (MDT): This system used the same equipment as in DT. Located on its top, there is a lime storage compartment linked to the subsoiling rod. The subsoiling rod has a pair of channels (openings) located at depths of approximately 0.4 and 0.6 m that allow it to distribute part of the lime into the planting furrows. The term “modified” indicates that the lime was broadcast in localized bands for further incorporation by the furrower; approximately $\frac{3}{4}$ was distributed on the soil surface in bands, and $\frac{1}{4}$ was distributed in the soil profile through the double channels behind the subsoiling rod. The rate decreased with depth due to the lower corrected volume since the application occurred concentrated in bands.

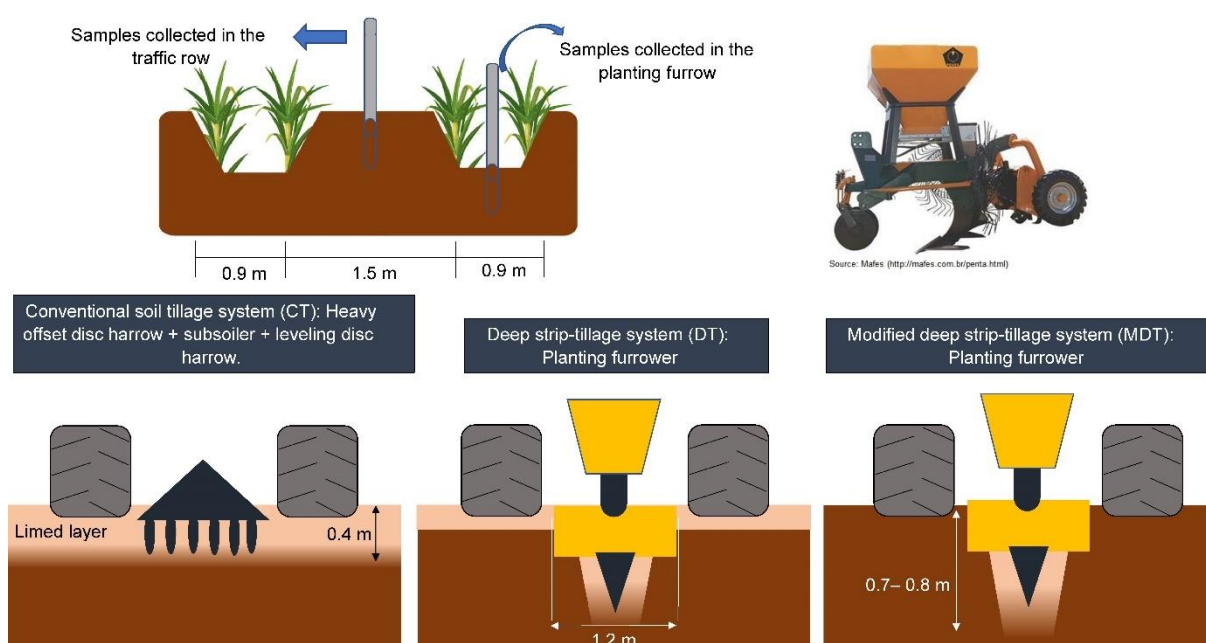


Figure 3. Schematic illustration of the soil tillage systems, agricultural equipment and sugarcane plants disposition.

The sugarcane varieties CTC 20 (Macatuba) and CTC 11 (Piraju) were both mechanically planted immediately after liming at a distribution of 18 viable buds m^{-1} and a depth of approximately 0.3-0.4 m and cultivated with a double-combined row

spacing of 1.50×0.90 m under a controlled traffic system. The experimental plots had an area of 240 m^2 , with dimensions of 20 m in length and 12 m in width, and each plot contained 5 double rows. During sugarcane establishment, 500 kg ha^{-1} of NPK fertilizer 06-28-24 (Macatuba) or 600 kg ha^{-1} of NPK fertilizer 10-25-25 (Piraju), plus 40 kg ha^{-1} of S (pastilles of elementary sulfur) was applied in the bottom of the planting furrow. Also, 200 kg ha^{-1} of fertilizer containing micronutrients (Zn, 10%; B, 1.8%; Mo, 0.12%; Cu, 0.6% and Mn, 1.2%) were applied in both areas 40 days after planting. For the ratoons, topdressing applications were performed as NPK fertilizer 18-07-28 and 20-05-28 at rates of 650 and 600 kg ha^{-1} , respectively, for Macatuba and Pirajú, plus 40 kg ha^{-1} of S (pastilles of elementary sulfur) in both sites. Other standard management practices were performed according to sugarcane needs.

2.2.3 Soil chemical analysis

Immediately after each sugarcane harvest, soil samples at depths of 0.0 to 1.00 m, stratified every 0.2 m, were collected by using a two-inch tubular sampler from the planting furrow located between the double sugarcane rows and from the traffic machinery row. Soil chemical analysis was performed on air-dried soil samples passed through a 10 mesh (2-mm) sieve according to Raij et al. (2001), including pH (0.01 M CaCl_2 solution); exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), which were extracted by ion-exchange resin and determined by atomic absorption spectroscopy (AAS); exchangeable potassium (K^+), which was extracted by ion-exchange resin and determined by flame photometry; and exchangeable Al (Al_{ex}) and potential acidity ($(\text{P}_{\text{ac}}; \text{H} + \text{Al})$), which were extracted by 1 mol L^{-1} KCl solution and 1 mol L^{-1} calcium acetate solution, respectively, and determined by titration with ammonium hydroxide (0.025 mol L^{-1}). The percentages of base saturation (BS) and aluminum saturation (AS) were used to express the soil acidity amendment potential of the treatments according to equations 1 and 2:

$$\text{Base saturation (BS\%)} = (\text{BS} / \text{CEC}_p) \times 100 \quad (1)$$

where BS is the sum of the basic cations ($\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+$) and CEC_p is the potential cation exchange capacity of the soil ($\text{CEC}_p = (\text{BS} + (\text{Al} + \text{H}))$);

$$\text{Aluminum saturation (AS\%)} = (\text{Al}^{3+} / \text{CEC}_e) \times 100 \quad (2)$$

where Al^{3+} is exchangeable Al and CEC_e is the effective cation exchange capacity of the soil ($CEC_e = BS + Al^{3+}$).

2.2.4 Leaf diagnosis

During the period of full vegetative growth of sugarcane, 10 leaves of +1 or TVDs (top visible dewlap leaves) were collected from the two central rows according to the leaf numbering system (Bataglia et al., 1983). The leaf midrib was discarded, and the middle third of the leaf blade was dried in an oven with forced-air circulation at 60 °C until a constant mass was obtained (Spironello et al., 1996). The dried leaves were then milled, and leaf nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and boron (B) concentrations were determined (Malavolta et al., 1997).

2.2.5 Sugarcane stalk and sugar yields

Before non-burning harvests (Macatuba: plant cane, October 2016; first ratoon, October 2017; second ratoon, October 2018; and third ratoon, September 2019; Piraju: plant cane, December 2016; first ratoon, December 2017; second ratoon, December 2018; and third ratoon, November 2019), the stalk and sugar yields ($Mg\ ha^{-1}$) were determined. To determine the stalk yield, stalks were collected in four sequential meters in two central rows of each plot, topped at apical bud height, defoliated, and weighed using a digital scale. The values were extrapolated to hectares. The cleaned stalks from the Macatuba and Pirajú sites were subsequently sent to the Middle Tietê Sugarcane Planters Association (ASCANA) Laboratory in Lençóis Paulista, SP, Brazil, and to the Raízen Ipaussú Sugar Refining Mill Laboratory in Ipaussú, SP, Brazil, respectively, for processing. The apparent percentage of sucrose (sucrose concentration) and total recoverable sugar (TRS; kg of sugar per Mg of stalk) were determined according to the methodology defined in the Sucrose Content-Based Sugarcane Payment System for technological assessments (Fernandes, 2011; Tanimoto, 1964). The sugar yield ($Mg\ ha^{-1}$) was indirectly estimated by equation 3:

$$\text{Sugar yield (Mg ha}^{-1}\text{)} = (\text{TRS (kg Mg}^{-1}\text{)} \times \text{Stalk yield (Mg ha}^{-1}\text{)} / 1000 \quad (3)$$

2.2.6 Statistical analysis

Data were subjected to analysis of variance (ANOVA). In cases of significant differences, the t-test according to the least significant difference (LSD) was used to compare chemical soil attributes separately for each soil depth, leaf analysis, sugarcane technological parameters and yields of stalk and sugar for each growing season. All tests used a 0.1 level of probability.

2.3 RESULTS

2.3.1 Soil chemical analysis in Macatuba, SP

2.3.1.1 pH values

The pH in the planting furrow was higher in all limed treatments than the standard treatment, regardless of soil depth and growing season, except at 0.8-1.00 m in third ratoon (Fig. 4a, b, c and d; Table S1). MDT exhibited the best performance in correcting soil pH in plant cane in the uppermost surface layer (0.0-0.2 m), followed by CT and DT, and at 0.2 to 0.4 m in first ratoon. From 0.2 to 0.8 m, there was no significant difference in soil pH between MDT and CT in plant cane, and at 0.8 to 1.0 m, the effects of liming did not differ among the treatments regardless of the growing season. Nevertheless, a residual effect of liming was observed, as the pH values were significantly higher in these treatments than in the standard treatment (Fig. 4a, b, c and d).

An acidity scale was used according to the soil fertility recommendation bulletin of São Paulo State (Rajj et al., 1997) to classify the range of acidity across the soil profile. The soil pH values were classified as “strongly and extremely acid” in the standard treatment for all growing seasons. “Slightly acid” pH values were observed only under MDT and CT in the uppermost surface layer in plant cane and first ratoon. “Moderately acid” applied to all limed treatments up to 0.4 m in plant cane and first and third ratoon.

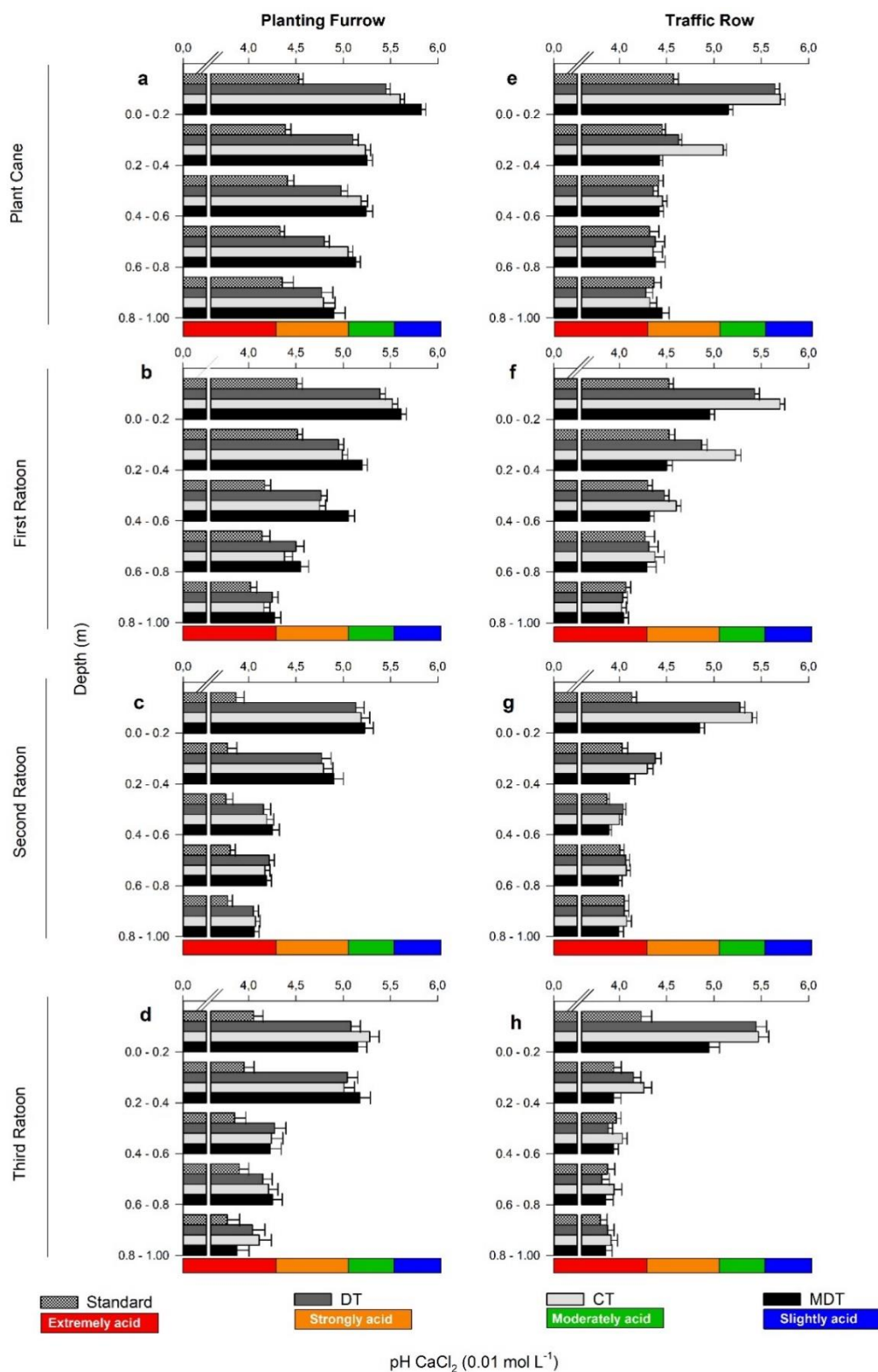


Fig 4. Soil pH (CaCl_2) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Macatuba, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale (Raj et al., 1997).

At depths of 0.4 to 1.00, all limed treatments were “strongly and extremely acid”, except in plant cane under MDT and CT and in first ratoon under MDT (Fig. 4a, b, c and d).

In general, the effects of liming on soil pH in the traffic row were significant at depths of up to 0.4 m in plant cane and up to 0.6 for the subsequent ratoons, with higher pH values under CT and DT (Fig. 4e, f, g and h; Table S1). The pH values up to 0.2 m were classified as “slightly acid” under CT and DT in plant cane and under CT in first ratoon. The pH values under MDT were classified as “moderately acid” up to 0.2 m in plant cane. The pH under CT was also “moderately acid” from 0.2 to 0.4 m in plant cane and first ratoon. In deeper soil layers and subsequent growing seasons, all treatments were within the “strongly and extremely acid” range (Fig. 4e, f, g and h).

2.3.1.2 Exchangeable Ca and Mg (Ca^{2+} and Mg^{2+})

In the planting furrow, all limed treatments increased Ca^{2+} compared with the standard treatment, regardless of soil depth and growing season, except from 0.6 to 1.00 m in third ratoon (Fig. 5a, b, c, and d; Table S1). Among the limed treatments, Ca^{2+} was highest under MDT throughout the soil profile in plant cane, up to 0.6 m in first and second ratoon, and up to 0.4 m in third ratoon. In addition, Ca^{2+} was higher under CSTS than DT up to 0.8 m in plant cane and up to 0.4 m in first and second ratoon. The residual effect of liming on Ca^{2+} concentration was observed up to 0.6 m in the last growing season (Fig. 5a, b, c, and d).

The effect of liming on Ca^{2+} was less pronounced in the traffic row and occurred mainly up to 0.4 m under CT and DT and up to 0.6 m under CT only. Nevertheless, a residual effect of liming was observed through the last growing season. The Ca^{2+} concentration was higher under MDT than in the standard treatment only up to 0.2 m, indicating that liming had no effect in the traffic row (Fig. 5e, f, g and h; Table S1).

Regarding Mg^{2+} in the planting furrow, concentrations were higher in the limed treatments than the standard treatment at all soil depths in plant cane, up to 0.8 m in first and second ratoon, and up to 0.6 m in third ratoon (Fig. 6a, b, c, and d; Table S1).

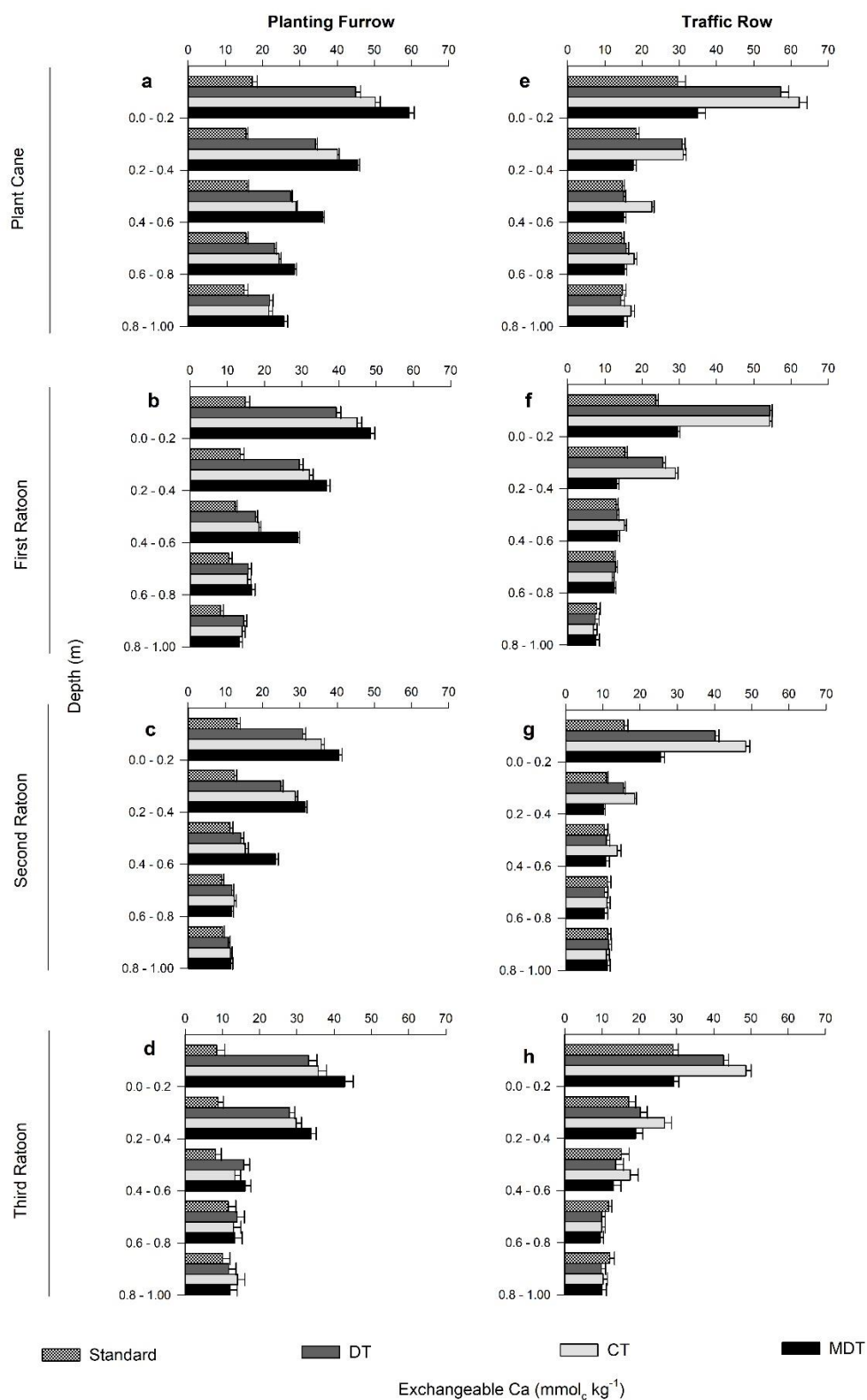


Fig 5. Concentration of exchangeable Ca (Ca^{2+}) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Macatuba, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

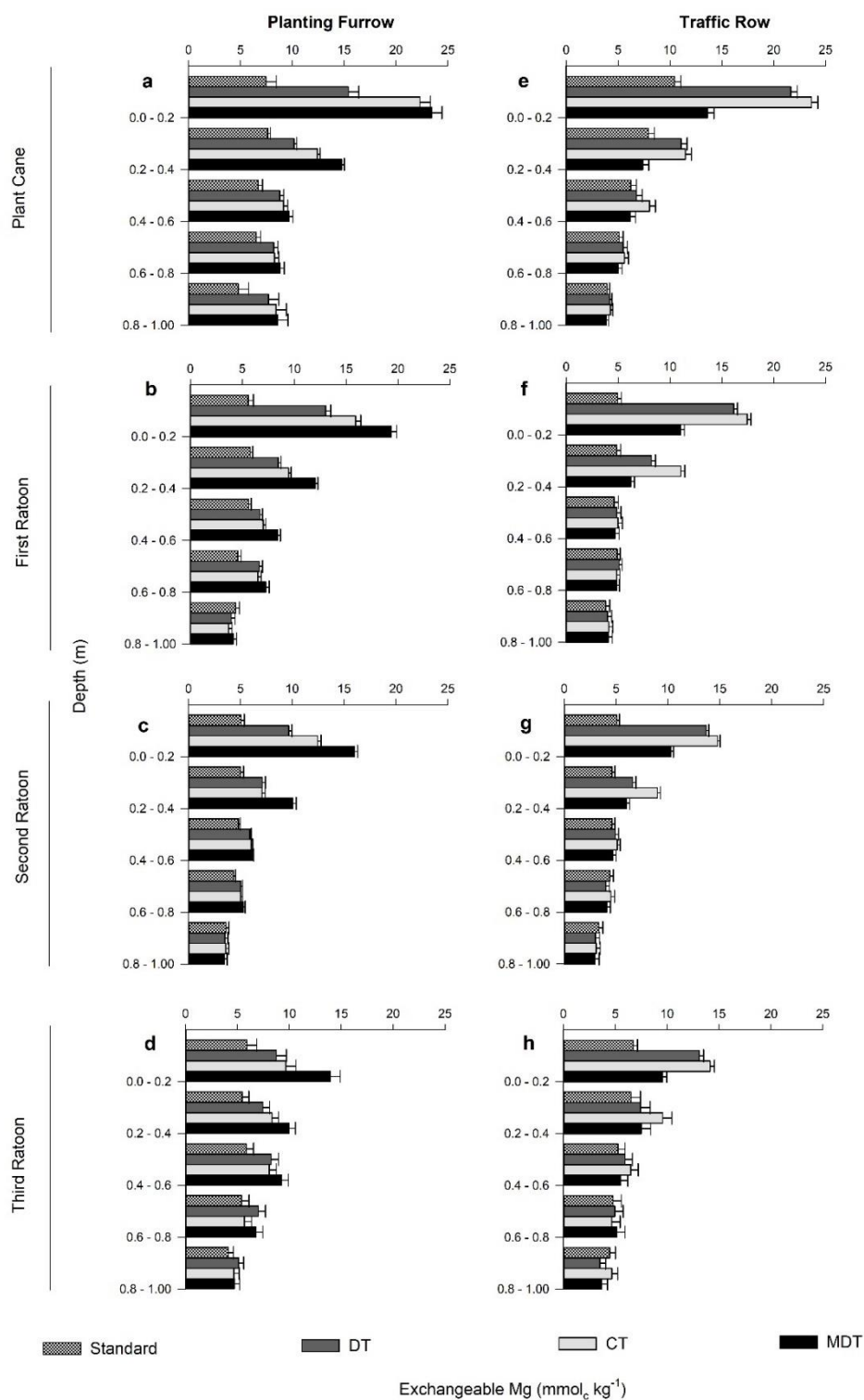


Fig 6. Concentration of exchangeable Mg (Mg^{2+}) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Macatuba, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

Significant differences in Mg^{2+} concentrations between the limed treatments were observed mainly up to 0.4 m. Similar to Ca^{2+} , Mg^{2+} was highest under MDT. Mg^{2+} was higher under CT than DT up to 0.4 m in plant cane and first ratoon and up to 0.2 m in second ratoon (Fig. 6a, b, c, and d).

No evidence of changes in Mg^{2+} concentrations due to liming were observed in the traffic row at depths greater than 0.4 m, except in plant cane, where significant differences were found up to 0.6 m. In general, Mg^{2+} was highest under CT, followed by DT and MDT, in all growing seasons (Fig. 6e, f, g and h; Table S1).

2.3.1.3 Base and aluminum saturation

The BS results clearly showed that MDT was most efficient in improving soil fertility parameters in the planting furrow. The limed treatments exhibited better performance than the standard treatment regardless of soil depth and growing season. BS values were highest under MDT at all depths in plant cane, up to 0.8 m in first ratoon, and up to 0.6 m in second and third ratoon. CT performed better than DT at all depths in plant cane and up to 0.4 m in first and second ratoon. At other depths or growing seasons, BS did not differ significantly between CT and DT. In addition, there were no significant differences among the limed treatments from 0.8 to 1.00 m in first ratoon and from 0.6 to 1.00 m in second and third ratoon (Fig. 7a, b, c and d; Table S1).

For sugarcane, the soil fertility recommendation bulletin of São Paulo State suggests an adequate BS of 60% (Spironello et al., 1996). In plant cane and first ratoon, all limed treatments reached BS above 60% in the first layer (0.0-0.2 m) and values very close to 60% in the second layer (0.2-0.4 m). Under MDT, BS values above 60% were observed up to 0.8 m in plant cane, up to 0.4 m in first ratoon, and up to 0.2 m in second and third ratoon (Fig. 7a, b, c and d).

In the traffic row, the trends of BS were similar to those for Ca^{2+} and Mg^{2+} . CT and DT were more efficient than MDT, which in turn was higher than the standard treatment only from 0.0 to 0.2 m, except in second and third ratoon. BS did not differ significantly from 0.6 m among the growing seasons and from 0.4 m in third ratoon. CT and DT reached BS values above 60% in the uppermost layer

(0.0-0.2 m) in all growing seasons, whereas MDT reached 60% only in plant cane (Fig. 7e, f, g and h; Table S1).

The limed treatments also showed high efficiency in correcting soil acidity by decreasing AS. In general, AS in the planting furrow was significantly lower in the limed treatments than the standard treatment regardless of soil depth and growing season, except from 0.6 to 1.00 m in third ratoon. AS was undetectable or low in all limed treatments up to 0.4 m in all growing seasons. From 0.4 to 0.8 m, AS was lowest in MDT, followed by CT and DT; from 0.8 to 1.00 m, AS was not significantly different among the limed treatments, except in plant cane (Fig. 8a, b, c, and d; Table S1).

In the traffic row, CT and DT were most effective in reducing AS at 0.0 to 0.4 m in all growing seasons and up to 0.8 m in plant cane. Up to 0.8 m, AS was lower in the limed treatments than in the standard treatment, except in third ratoon, where a difference was observed only up to 0.4 m. There were no significant differences in AS between the treatments at 0.8 to 1.00 m (Fig. 8e, f, g, and h; Table S1).

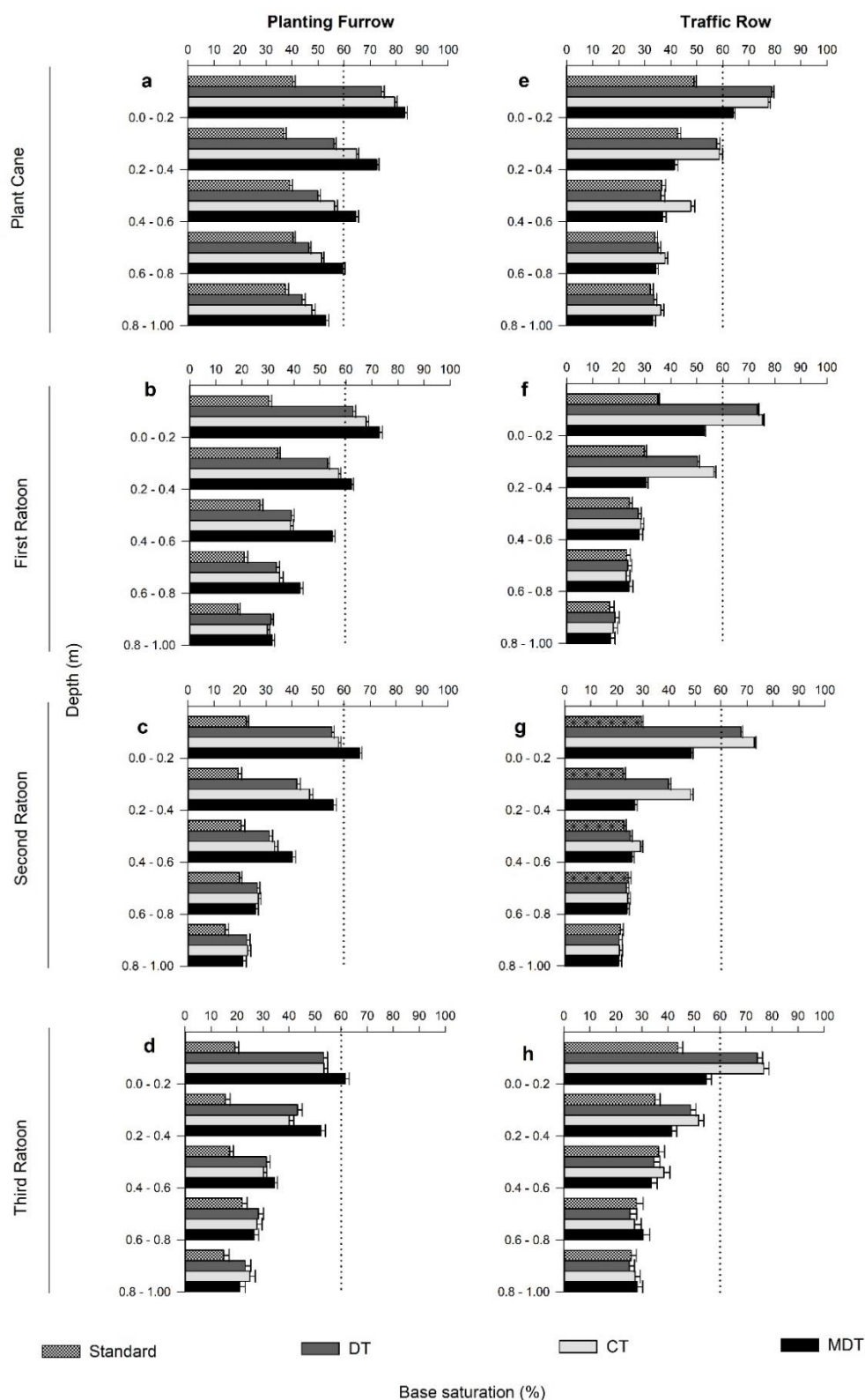


Fig 7. Base saturation (BS) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Macatuba, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$. Dotted line represents adequate BS value of 60% (Spironello et al., 1996).

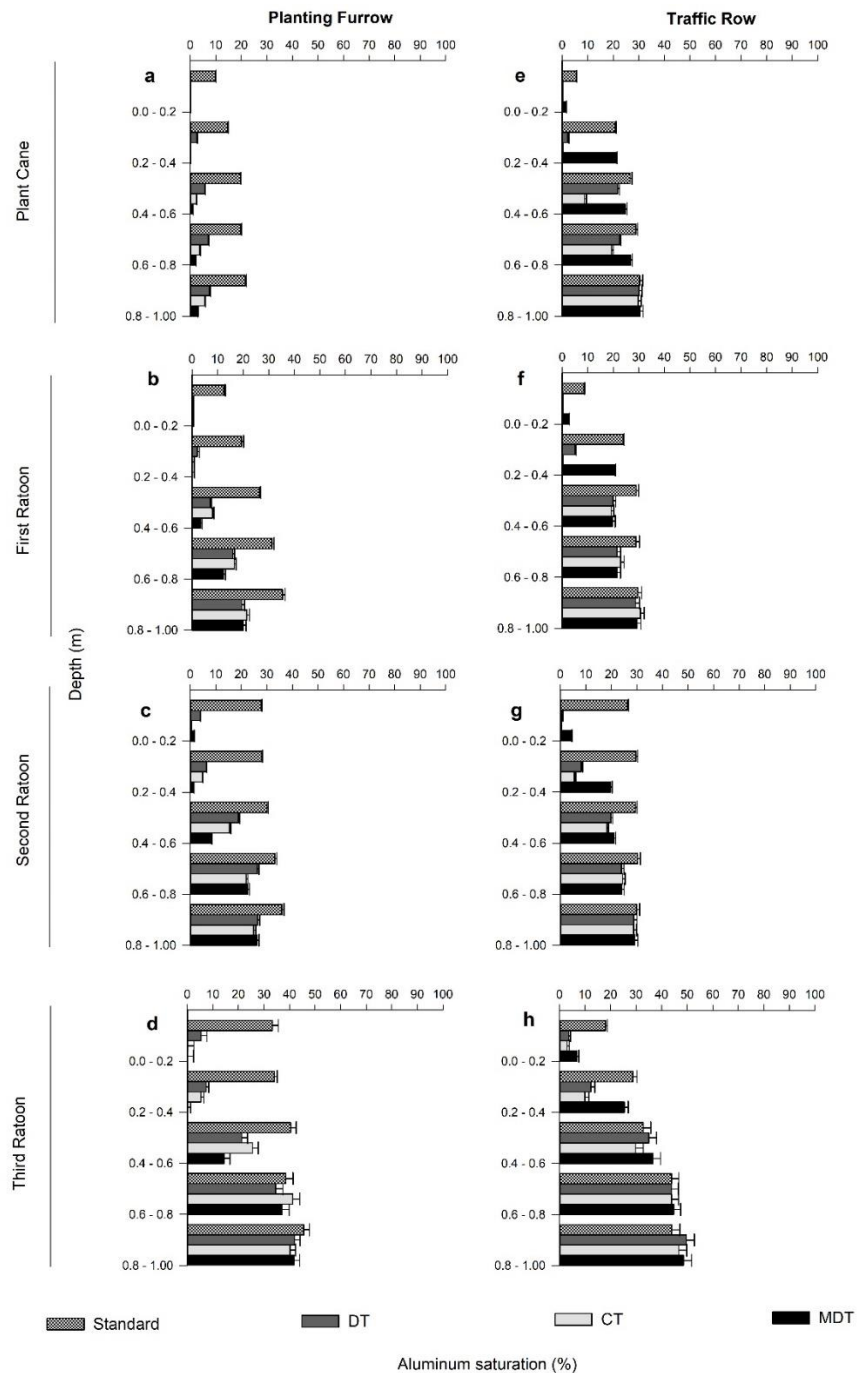


Fig 8. Aluminum saturation (AS) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Macatuba, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$

2.3.2 Soil chemical analysis in Pirajú, SP

2.3.2.1 pH values

In the planting furrow, pH was significantly higher in the limed treatments than in the standard treatment up to 0.6 m in plant cane and first ratoon and up to 0.2 m in second and third ratoon. Among the limed treatments, pH was highest under MDT up to 0.2 m in plant cane and first ratoon, followed by CT and DT. In second and third ratoon, pH remained highest under MDT, and no differences were observed between CT and DT. At 0.2 to 0.4 m, no effect of the limed treatments was observed in plant cane and first ratoon, whereas for second and third ratoon, pH did not differ significantly between MDT and CT and was higher than under DT. There was no difference in pH between the limed treatments from 0.4 to 0.6 m, and no significant effects of liming were observed from 0.6 to 1.00 m in all growing seasons (Fig. 9a, b, c and d; Table S2).

The soil pH was classified as “moderately acid” only in the first layer (0.0-0.2 m) in all limed treatments and growing seasons, whereas in the deeper layers, all treatments were within “strongly and extremely acid” for all growing seasons (Fig. 9a, b, c and d).

In the traffic row, pH did not differ between CT and DT up to 0.4 m in plant cane and up to 0.2 m in first ratoon. pH was higher under MDT than in the standard treatment only up to 0.2 m in all growing seasons. No significant effects of liming were observed from 0.4 to 1.00 m in plant cane and first ratoon and from 0.2 to 1.00 m in second and third ratoon (Fig. 9e, f, g, and h; Table S2). Under CT and DT, the pH values were classified as “slightly acid” at 0.0-0.2 m in plant cane and first ratoon. “Moderately acid” pH values were observed under MDT in plant cane and DT in second and third ratoon up to 0.2 m. In the deeper layers, all treatments were within “strongly and extremely acid” for all growing seasons (Fig. 9e, f, g, and h).

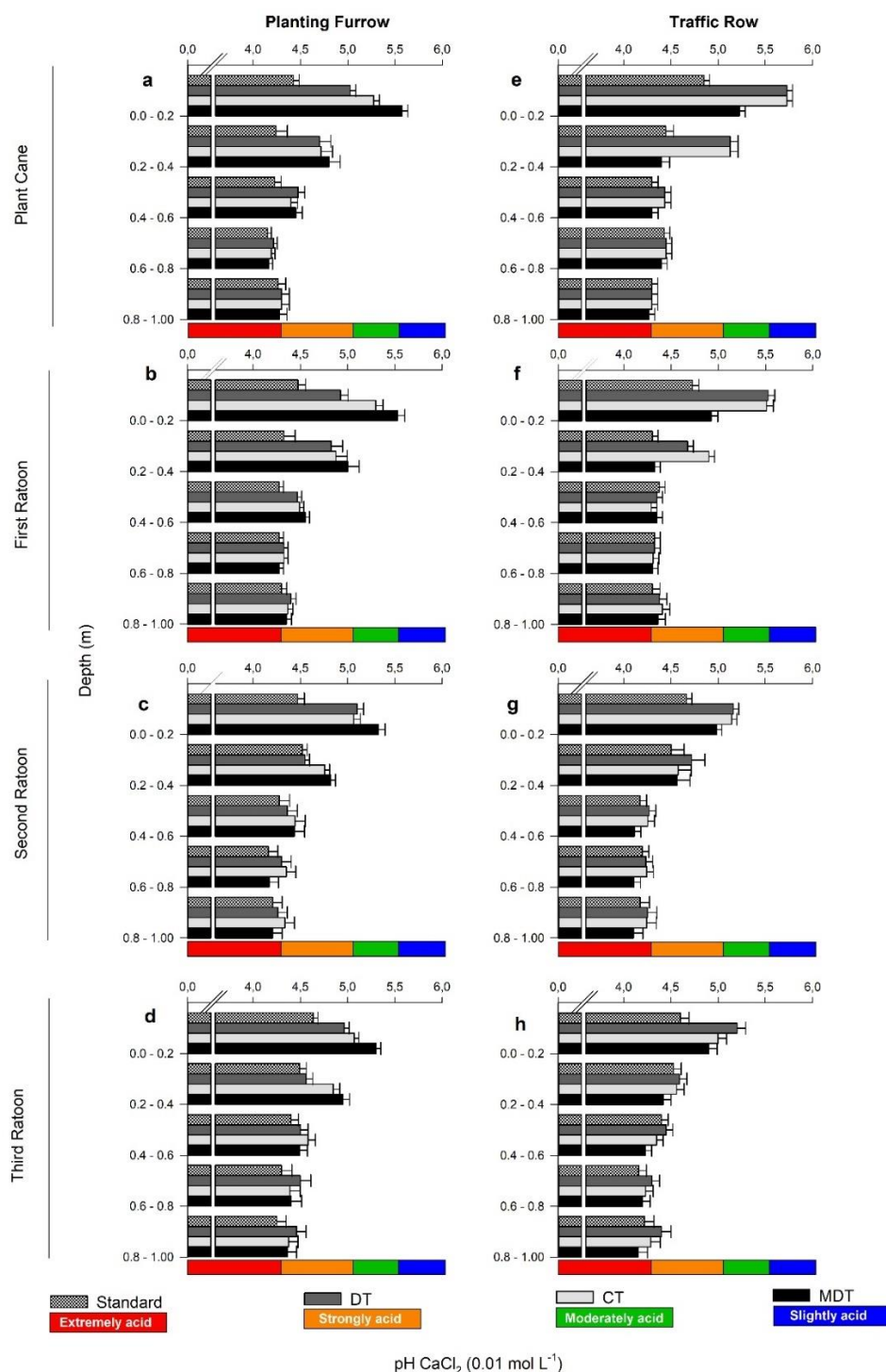


Fig 9. Soil pH (CaCl_2) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Piraju, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$. Colored acidic scale (Raij et al., 1997).

2.3.2.2 Exchangeable Ca and Mg (Ca^{2+} and Mg^{2+})

The concentration of Ca^{2+} in the planting furrow showed the same trend in all growing seasons up to 0.6 m, except from 0.4 to 0.6 m in second and third ratoon. MDT was most efficient in increasing Ca^{2+} up to 0.6 m in plant cane and first ratoon and up to 0.4 m in second and third ratoon, followed by CT and DT. From 0.6 to 1.00 m in plant cane and first ratoon, Ca^{2+} did not differ significantly among the limed treatments. In second and third ratoon, no significant effects were observed from 0.4 to 1.00 m (Fig. 10a, b, c, and d; Table S2).

In the traffic row, DT provided the highest concentrations of Ca^{2+} in the first layer, regardless of the growing season, followed by CT and MDT. In the second layer, Ca^{2+} did not differ between DT and CT in all growing seasons except in third ratoon, in which Ca^{2+} was highest under CT. Regardless of growing season, there were no significant differences in Ca^{2+} among the treatments from 0.4 to 1.00 m (Fig. 10e, f, g, and h; Table S2).

In the planting furrow, the concentrations of Mg^{2+} were influenced by the limed treatments up to 1.00 m in plant cane and first ratoon, up to 0.6 m in second ratoon, and up to 0.2 m in third ratoon. Mg^{2+} did not differ between MDT and CT up to 0.2 m in plant cane, up to 0.4 m in second ratoon, and up to 0.6 m in third ratoon. However, from 0.2 to 0.6 m in plant cane and up to 0.4 m in first ratoon, Mg^{2+} was highest under MDT, followed by CT and DT. In plant cane and first ratoon, Mg^{2+} did not differ between CT and DT at 0.2 to 0.6 m. In third ratoon, Mg^{2+} was higher under DT than in the standard treatment only up to 0.2 m (Fig. 11a, b, c, and d; Table S2).

In the traffic row, significant differences in Mg^{2+} concentrations among the treatments were observed only up to 0.4 m. Mg^{2+} was highest under DT, followed by CT, up to 0.2 m in plant cane and first ratoon. From 0.2 to 0.4 m, Mg^{2+} was significantly higher under CT than DT in plant cane and first ratoon. In second and third ratoon, Mg^{2+} was similar between DT and CT and higher than under MDT. Up to 0.4 m, all limed treatments increased Mg^{2+} compared with the standard treatment, except from 0.2 to 0.4 in second and third ratoon, where MDT and the standard treatment did not differ significantly (Fig. 11e, f, g, and h; Table S2).

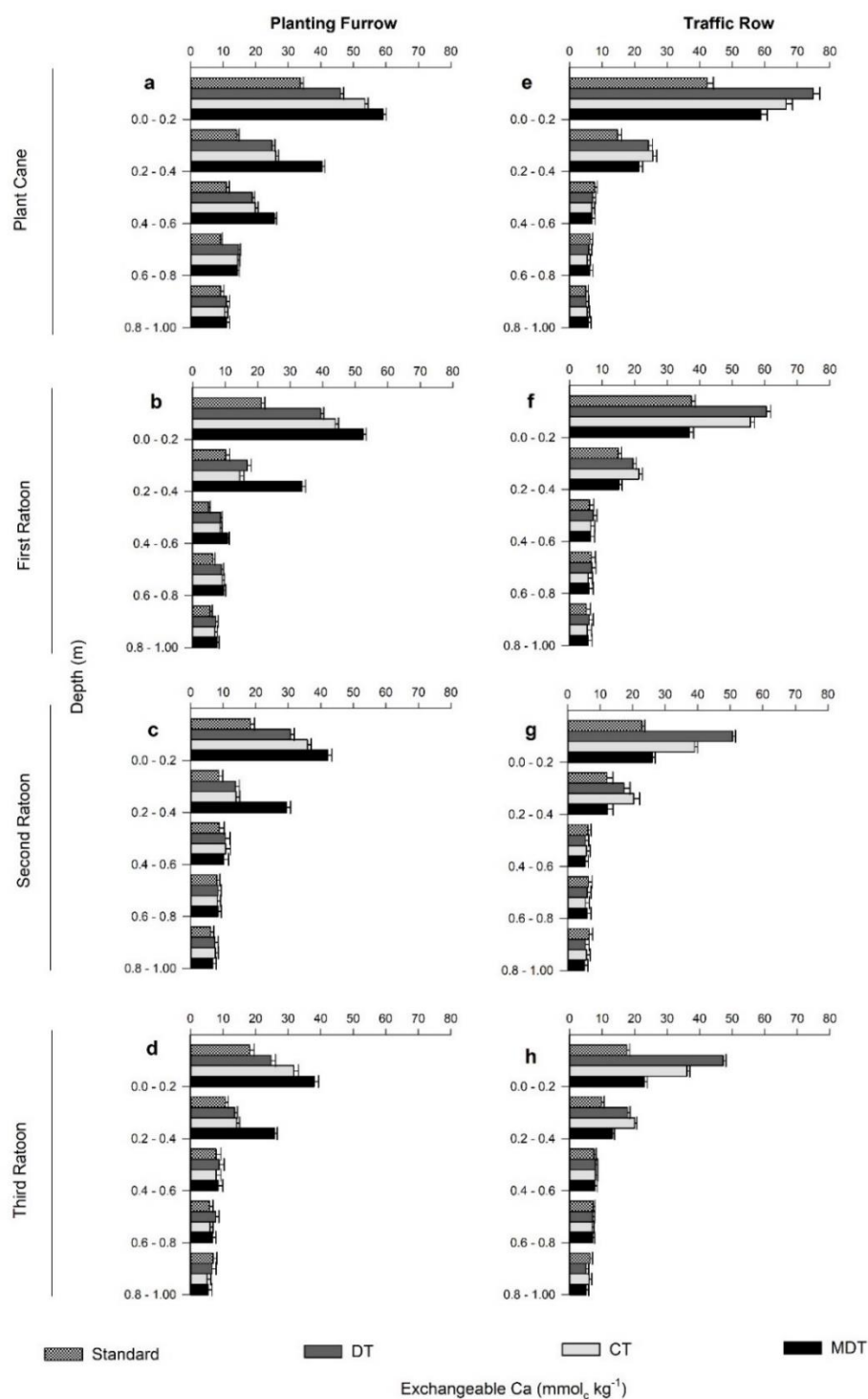


Fig 10. Concentration of exchangeable Ca (Ca^{2+}) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Piraju, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

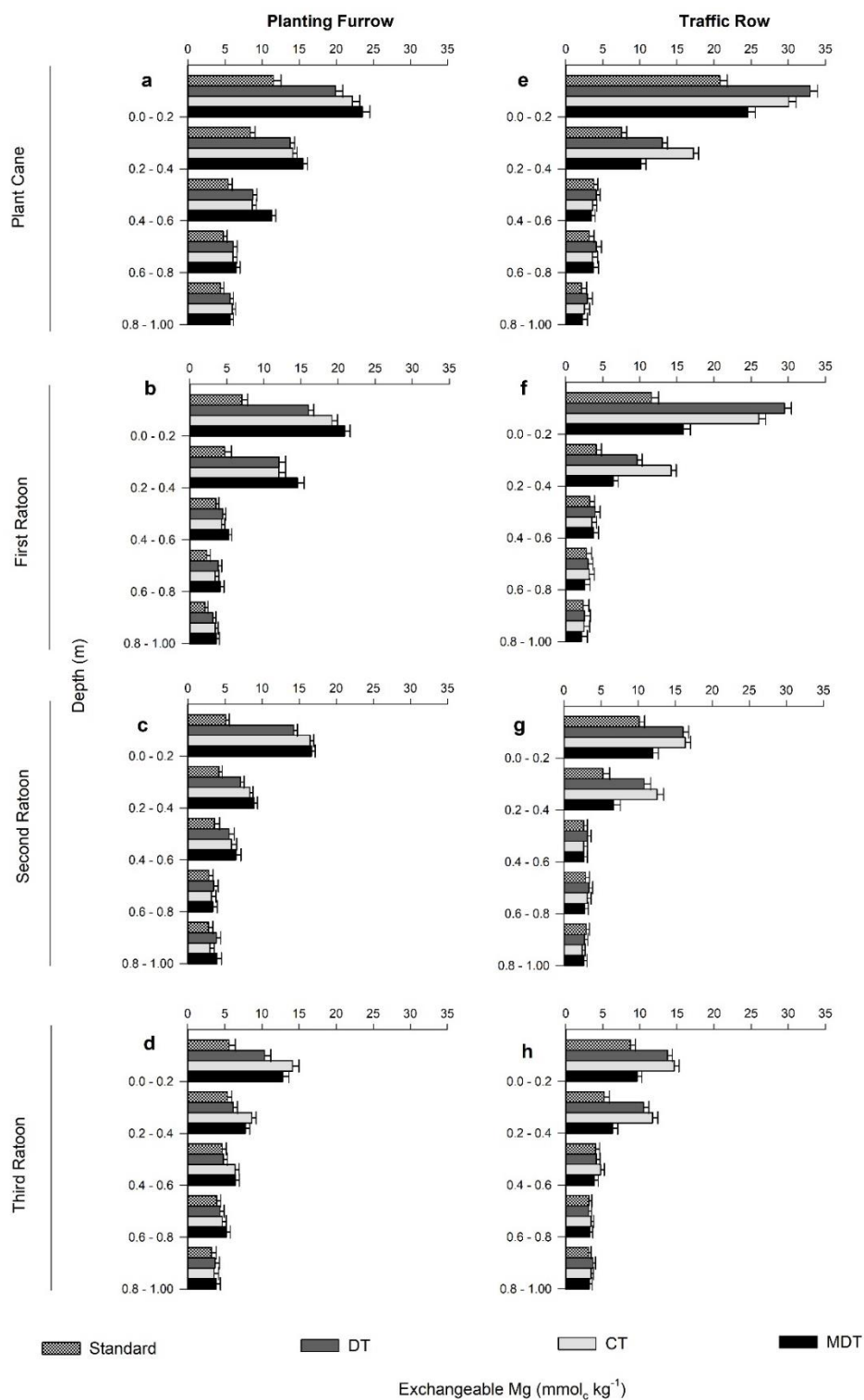


Fig 11. Concentration of exchangeable Mg (Mg^{2+}) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Piraju, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

2.3.2.3 Base and aluminum saturation

In the planting furrow, BS values were generally higher in the limed treatments than in the standard treatment, except from 0.6 to 1.00 m in second and third ratoon, where the treatments did not differ significantly. BS was highest under MDT up to 0.6 m in plant cane and from 0.2 to 0.4 m in the subsequent seasons. Up to 0.2 m in both ratoons, BS did not differ between CT and MDT. BS was superior under CT compared with DT only in the surface layer (0.0-0.2 m) in all growing seasons. In the deeper layers (0.6-1.00 m in plant cane, 0.4-1.00 m in first ratoon, and 0.4-0.6 m in second and third ratoon), no significant differences in BS were observed among the limed treatments (Fig. 12 a, b, c, and d; Table S2). Under MDT, BS reached higher than 60% in the first layer (0.0-0.2 m) regardless of growing season, except third ratoon. BS also reached above 60% under CT up to 0.2 m in first and second ratoon. In the second layer (0.2-0.4 m), BS was above 50% under MDT in plant cane, but none of the treatments reached 60%, despite applying 2× LRR (Fig. 12 a, b, c, and d).

In the traffic row, BS differed significantly among the treatments only in the uppermost surface layers (0.0-0.2 and 0.2-0.4 m). In plant cane and first and third ratoon, BS was highest under DT up to 0.2 m, followed by CT and MDT, and from 0.2 to 0.4 m, BS was highest under CT, followed by DT and MDT. At both depths, BS was higher in all limed treatments than in the standard treatment, regardless of growing season. In second ratoon, BS did not differ between CT and DT and was higher than under MDT and the standard treatment (Fig. 12e, f, g, and h; Table S2). In all limed treatments, BS reached higher than 60% up to 0.2 m in plant cane. In the uppermost layer (0.0-0.2 m), BS reached 60% in all growing seasons only under DT; BS was higher than 60% under CT in all but third ratoon (Fig. 12e, f, g, and h).

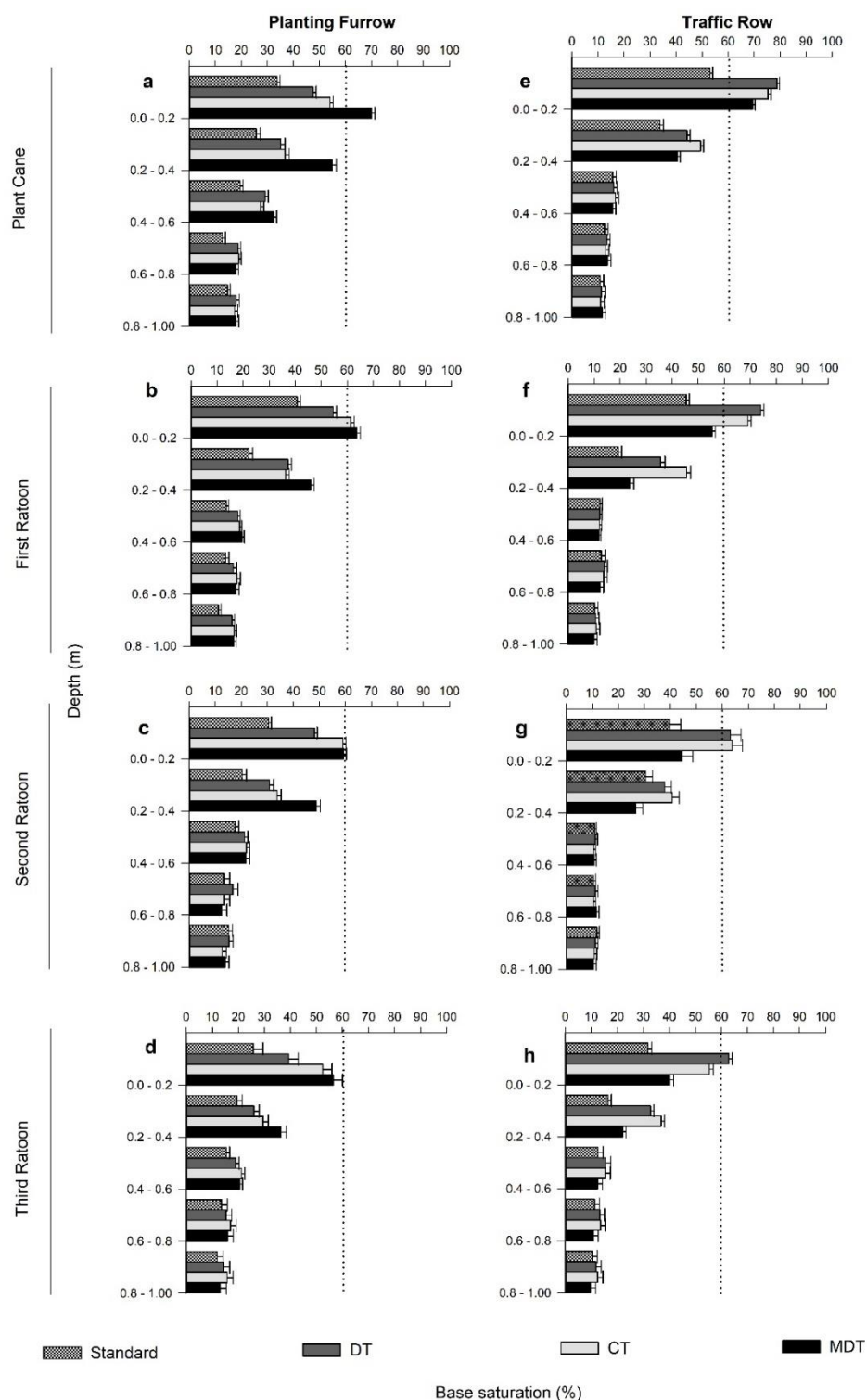


Fig 12. Base saturation (BS) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Piraju, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$. Dotted line represents adequate BS value of 60% (Spironello et al., 1996).

With respect to AS in the planting furrow, efficiency of lime application was clearly evident regardless of the tillage system. MDT and CT showed the same efficiency in correcting Al^{3+} up to 0.2 m in all growing seasons and up to 0.4 m in plant cane, followed by DT. In both ratoon seasons, MDT was more effective up to 0.4 m, followed by CT and DT. In the third layer (0.4-0.6 m), MDT again showed the best results in plant cane, but in the subsequent ratoon seasons, no differences were observed among the limed treatments. AS did not differ significantly among the treatments from 0.6 to 1.00 m in second and third ratoon (Fig. 13a, b, c, and d; Table S2).

In the traffic row, AS differed significantly among the treatments only in the uppermost surface layers (0.0-0.2 and 0.2-0.4 m). In the first layer (0.0-0.2 m), lime application was effective in correcting Al^{3+} in all tillage systems and growing seasons. The same pattern was observed in the second layer (0.2-0.4 m) in all growing seasons except third ratoon, and CT showed the best response, followed by DT. There was no significant difference in AS between MDT and the standard treatment from 0.2 to 0.4 m, regardless of growing season, except in third ratoon (Fig. 13e, f, g, and h; Table S2).

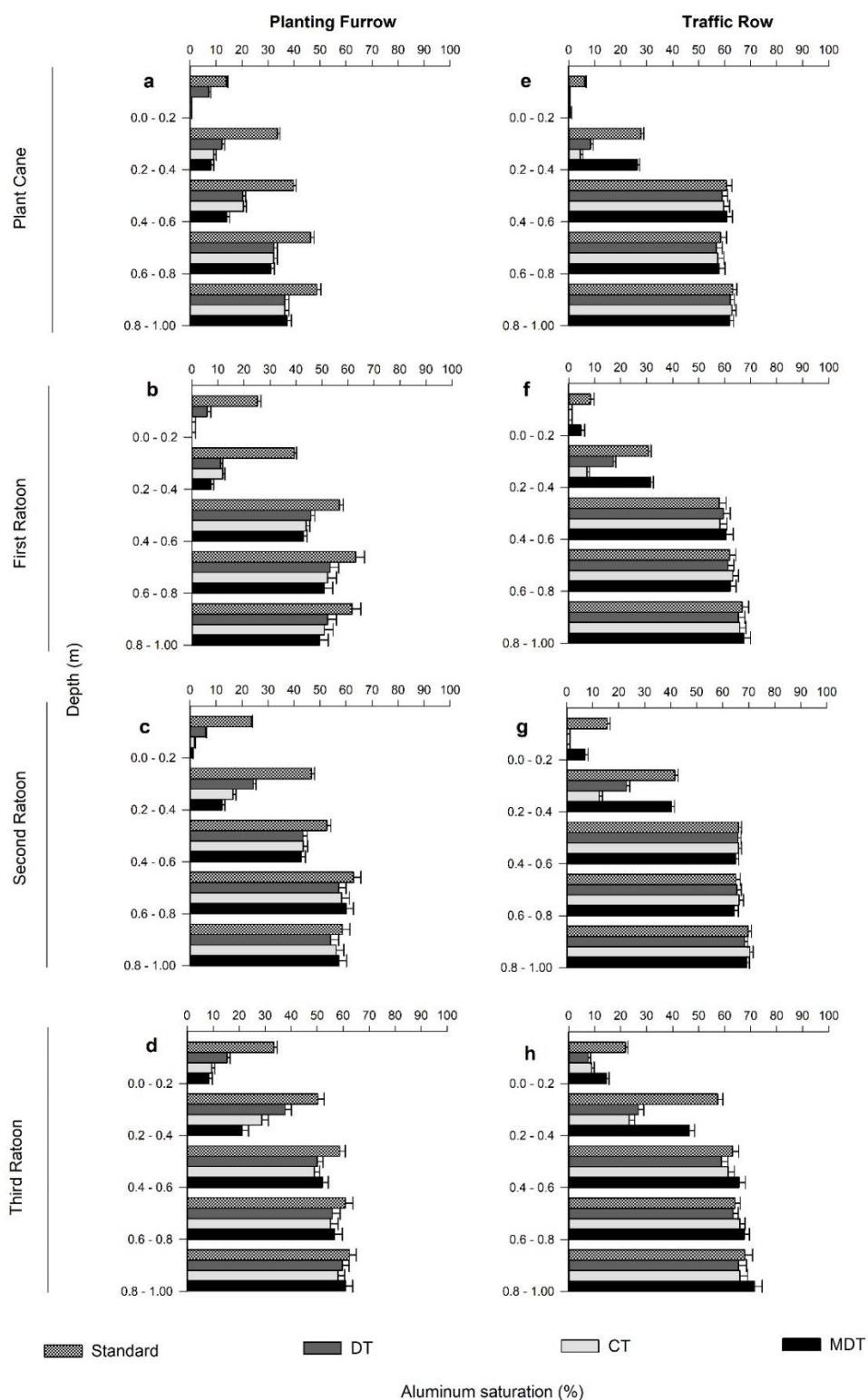


Fig 13. Aluminum saturation (AS) across the soil profile under different soil tillage systems on planting furrow (a, b, c, and d) and traffic row (e, f, g and h) after four growing seasons in Piraju, SP (Plant cane, a and e; First ratoon, b and f; Second ratoon, c and g; Third ratoon, d and h). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

2.3.2.4 Leaf analysis in Macatuba, SP

N, P, K, S, Zn, Mn, and B were not affected by the treatments in all growing seasons. In addition, the levels of all of these elements were in the acceptable range proposed for sugarcane (Spironello et al., 1996) ($18\text{--}25\text{ g kg}^{-1}$ N, $1.5\text{--}3.0\text{ g kg}^{-1}$ P, $10\text{--}16\text{ g kg}^{-1}$ K, $1.5\text{--}3.0\text{ g kg}^{-1}$ S, $10\text{--}50\text{ mg kg}^{-1}$ Zn, $25\text{--}250\text{ mg kg}^{-1}$ Mn and $10\text{--}30\text{ mg kg}^{-1}$ B) (Fig. 14, Table S3).

The leaf Ca concentration differed significantly among the treatments in plant cane and first ratoon (Table S3). In plant cane, leaf Ca was highest under MDT, followed by CT and DT. However, leaf Ca was significantly higher in all of the limed treatments than in the standard treatment. In first ratoon, only MDT differed significantly from the standard treatment (Fig. 14).

The leaf Mg concentration was higher in the limed treatments than in the standard treatment in plant cane; in third ratoon, MDT performed best. Non-significant effects were observed in the other growing seasons (Fig. 14; Table S3).

Effects of the treatments on leaf Fe and Cu concentrations were observed. For Fe, significant differences were observed only in plant cane, while for Cu, significant differences were observed in plant cane, first and second ratoon. In both cases, leaf Fe and Cu concentrations were lower in the limed treatments than in the standard treatment (Fig. 14; Table S3).

Regardless of these differences, the leaf concentrations of Ca, Mg, Fe and Cu were all within the optimum ranges proposed for sugarcane in all growing seasons: $2.0\text{--}8.0\text{ g kg}^{-1}$ Ca, $1.0\text{--}3.0\text{ g kg}^{-1}$ Mg, $40\text{--}250\text{ mg kg}^{-1}$ Fe, and $6.0\text{--}15\text{ mg kg}^{-1}$ Cu (Spironello et al., 1996) (Fig. 14).

2.3.3 Leaf analysis in Pirajú, SP

No effects of the treatments on leaf N, K, Ca, S, Fe, Cu, and B were observed in any of the growing seasons, and all were within the ranges proposed for sugarcane described above (Spironello et al., 1996) (Fig. 14; Table S3).

The leaf concentrations of four elements differed significantly among the treatments. The leaf P concentration was higher under MDT than the other treatments only in third ratoon (Fig. 14; Table S3). In second ratoon, the leaf Mg concentration was higher in the limed treatments than in the standard treatment

(Fig. 14; Table S3). The leaf concentrations of Zn and Mn were higher in the standard treatment than the limed treatments in first ratoon and second ratoon, respectively; no differences in the concentrations of Zn and Mn were observed among the limed treatments. However, the concentrations of all four elements were within the optimal ranges for sugarcane noted above (Spironello et al., 1996) (Fig. 14).

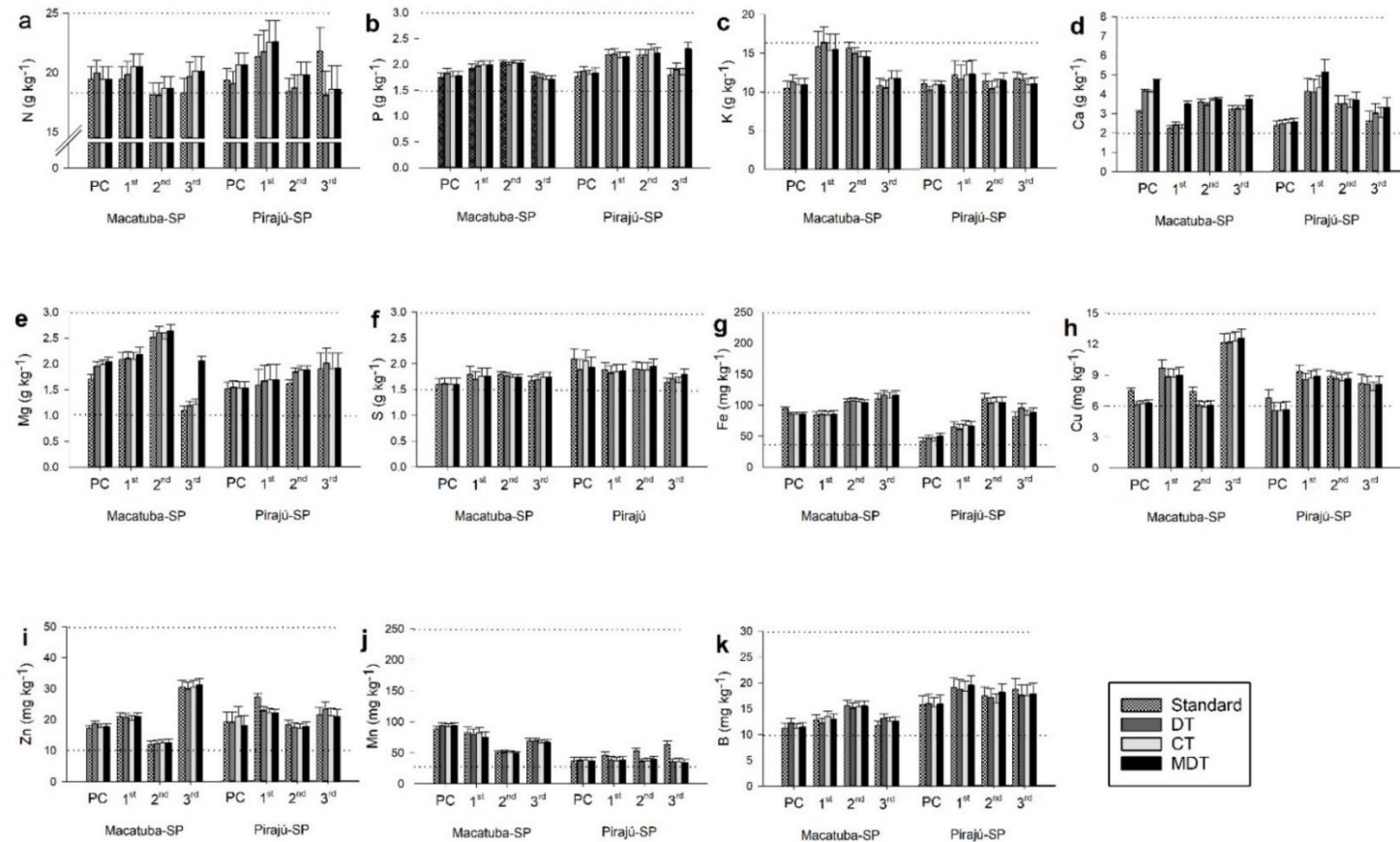


Figure 14. Leaf concentration of elements (a) Nitrogen, (b) Phosphorus (c) Potassium, (d) Calcium, (e) Magnesium, (f) Sulfur, (g) Iron, (h) Copper, (i) Zinc, (j) Manganese and (k) Boron in sugarcane under different soil tillage systems after four growing seasons (Plant cane (PC); first ratoon (1st); second ratoon (2nd); third ratoon (3rd)) in Macatuba, SP and Pirajú, SP. Error bars represent the least significant difference (LSD) $p \leq 0.1$.

2.3.4 Yield assessments in Macatuba, SP

The effects of the treatments on sucrose concentration and TRS were relatively small. In plant cane and first ratoon, no significant effects were observed. In second ratoon, DT better performed than CT and the standard treatment. In the third ratoon, there were no differences among the limed treatments, but all presented higher sucrose concentrations and TRS than the standard treatment (Fig. 15a and b; Table S4).

In plant cane and first ratoon, there were no differences in stalk and sugar yields among the limed treatments, but all exhibited better performance than the standard treatment. The variations in stalk and sugar yields among the treatments were similar in second and third ratoon; the yields were highest under MDT, followed by DT and CT, except sugar yield in second ratoon, which did not differ between MDT and DT (Fig. 15c and d; Table S4).

Summing over all sugarcane growing seasons, stalk yield increased by 29, 35 and 41% under CT, DT and MDT, respectively, compared with the standard treatment, while sugar yield increased by 34, 42 and 47%, respectively. Stalk yield was 9 and 4% higher under MDT compared with CT and DT, respectively, whereas sugar yield was 10 and 4% higher under MDT.

2.3.5 Yield assessments in Piraju, SP

In plant cane, sucrose concentration and TRS were equally influenced by the treatments. These parameters were highest under MDT and did not differ between CT and DT; however, all limed treatments performed better than the standard treatment. In first and second ratoons, no significant differences were observed among the limed treatments, and all presented higher sucrose concentrations and TRS than the standard treatment. In third ratoon, no significant differences were observed among the treatments (Fig. 15e and f; Table S4).

In plant cane, similar variations were observed in stalk and sugar yields. These parameters were highest under MDT and did not differ between CT and DT; all limed treatments performed better than the standard treatment. In first ratoon, there were no significant differences among the limed treatments, and all performed better than the standard treatment. In subsequent ratoons (second

and third), MDT produced the greatest stalk yield, followed by DT and CT, whereas sugar yield did not differ between MDT and DT and was greater than under CT (Fig. 15g and h; Table S4).

Summing over all sugarcane growing seasons, stalk yield increased by 35, 46 and 55% under CT, DT and MDT, respectively, compared with the standard treatment, while sugar yield increased by 44, 57 and 67%. Stalk yield was 15 and 6% higher under MDT compared with CT and DT, respectively, while sugar yield was 16 and 6% higher under MDT.

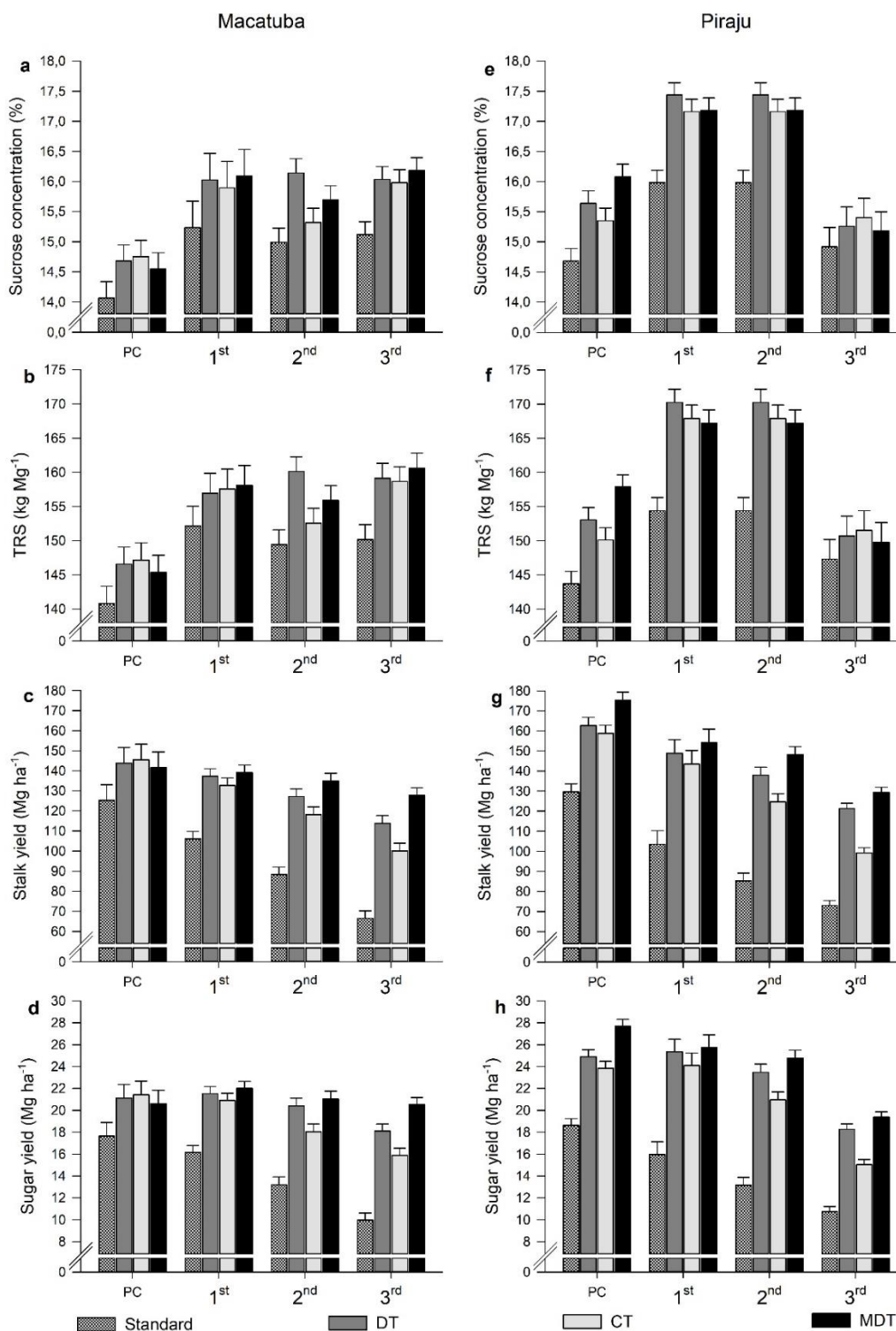


Figure 15. Sucrose concentration (Macatuba, a; Piraju, e), total recoverable sugar (TRS; Macatuba, b; Piraju, f), yield of stalks (Macatuba, c; Piraju, g) and sugar (Macatuba, d; Piraju, h) of sugarcane under different soil tillage systems after four growing seasons (Plant cane (PC); first ratoon (1st); second ratoon (2nd); third ratoon (3rd)). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

2.4 DISCUSSION

2.4.1 Soil chemical analysis

2.4.1.1 pH values

At the Macatuba site, liming markedly increased soil pH in the planting furrow, regardless of the sampled depth, growing season, or tillage system. By comparison, the effect of liming at Pirajú was less pronounced, despite the high lime dose. Nevertheless, these data confirm that liming amendment can improve soil acidity, even when the lime is applied and incorporated up to a depth of approximately 0.4 m.

Soil pH was highest under MDT, indicating higher effectiveness of the reaction with soil. This superior effect may be attributable to a combination of factors, such as the higher equivalent amount applied in bands, better incorporation and improved distribution. A superior residual effect of liming under MDT was observed up to the second ratoon; in subsequent growing seasons, the results were similar among the tillage systems.

By contrast, analysis of soil pH in the traffic row clearly demonstrated a negative effect of the absence of liming in this specific soil strip under MDT, as soil pH was similar to that in the standard treatment. By contrast, since lime was completely incorporated up to a depth of approximately 0.4 m under CT, pronounced chemical alterations of the soil were expected at least up to this depth. Under DT, lime was broadcast over the total area but incorporated only in the planting furrow, which justifies its intermediate performance (lower than CT but higher than MDT) in the traffic row analysis.

In general, the results suggested that regardless of the depth or method of application, the liming reaction occurred around the lime application point. Although lime particles have low solubility, chemical and physical mechanisms of displacement can occur (de Vargas et al., 2019). Soil pH is an important determinant of liming reactivity. The alkalization front, which is determined by the gradient of soil pH values, favors the lime reaction up to a pH range of approximately 4.6 to 5.0 (CaCl_2) (Rheinheimer et al., 2000). At pH values above this range, the liming reaction decreases, and downward or lateral displacement of fine particles to areas of lower pH is favored (Rheinheimer et al., 2018, 2000).

Additionally, physical displacement of lime particles can occur through soil biopores or cracks created by continuous root expansion by ratoons and/or root

mineralization. After plant cane harvest, the original root system dies and becomes non-functional; that is, the root system is renewed completely after each harvest. This process can generate a favorable root distribution as well as large inputs of organic material across the soil profile (Ball-Coelho et al., 1992). In addition to affecting how quickly carbonate reacts, pluvial precipitation and its infiltration are an important vehicle of lime particle displacement (Calegari et al., 2013; Tiritan et al., 2016).

2.4.1.2 Exchangeable Ca and Mg (Ca^{2+} and Mg^{2+})

The effects of liming on Ca^{2+} and Mg^{2+} concentration were similar to those on soil pH, as both ions are constituents of lime and products of lime dissociation (Auler et al., 2019). The higher Ca^{2+} and Mg^{2+} concentrations under MDT are attributable to the higher equivalent amount of lime applied and its incorporation locally in the planting furrow. In addition, a residual effect was observed in the next ratoons in the sugarcane crop cycle. Sugarcane cultivation requires heavy soil tillage at the time of establishment, and liming is typically applied more than once during the cycle. Using a greater lime rate and distributing it locally only in planting furrows across the soil profile proved effective for the long-term supply of Ca and Mg in this study. The concentrations of Ca^{2+} and Mg^{2+} in the traffic rows were in accordance with the form of liming, further supporting the results obtained from soil samples from the planting furrow.

The residual effect of liming on the Ca^{2+} concentration under MDT was observed across the soil profile 18 mo after liming (plant cane) and remained up to a depth of 0.6 m in the ratoons (30, 42, and 54 mo after liming). The decrease in the Ca^{2+} concentration may be due to greater access to deeper layers by the plant roots, facilitating its consumption. The mobility of Ca into phloem is low, which can affect developing roots and means that the Ca required for root growth must be absorbed from the external soil solution in the root apical zone (Marschner, 2012).

The concentrations of Ca and Mg in the subsurface layers were higher in the limed treatments. Subsurface effects of liming have been reported previously for grain crops in no-tillage systems (Alleoni et al., 2010; Antonangelo et al., 2017; da Costa and Crusciol, 2016; de Vargas et al., 2019; Tiritan et al., 2016) and for sugarcane crops with surface liming (Crusciol et al., 2017, 2014; Rossato et al.,

2017). In sugarcane tillage systems, this effect may be due to the transport of fine lime particles downward from the application zone through rainfall or leaching of Ca and Mg paired with inorganic (carbonate, nitrate and sulfate) and organic ligands (organic acids released from mineralization of organic matter) (Antonangelo et al., 2017; Zambrosi et al., 2008). When soil pH is increased by liming, the reaction of HCO_3^- with H^+ becomes more stable, allowing its downward movement along with Ca^{2+} and Mg^{2+} as an ionic pair (Costa and Rosolem, 2007; Crusciol et al., 2011; De Oliveira and Pavan, 1996).

2.4.1.3 Base and aluminum saturation

As BS is mainly determined by the concentrations of Ca^{2+} and Mg^{2+} , the response of BS to the treatments is expected to follow the patterns of these elements. In highly weathered soils, liming is particularly important both for fertilization (providing Ca^{2+} and Mg^{2+}) and increasing the density of negative charges in the soil (Fontes et al., 2001; Sposito, 2008). The soils containing variable charges are pH dependent, and increasing the soil pH above to its point of zero charge (PZC, pH value at which the balance of charges is zero) deprotonates acidic groups (Kosmulski, 2020). Increasing the density of soil negative charges and the concentrations of Ca^{2+} and Mg^{2+} will increase BS values, which in turn benefits root system development (Cury et al., 2014).

As shown in Table 2, Ca equivalents of 2,130 and 1,704 kg ha^{-1} and Mg equivalents of 1,010 and 1,104 kg ha^{-1} were applied in Macatuba and Pirajú, respectively, under CT and DT. By contrast, under MDT, the same rate calculated for the total area was applied in bands in the planting furrow. Since the spacing between rows was 1.5 x 0.9 m (2.4 m total) and the working width of the furrower was 1.2 m, double doses, that is, 4,260 and 3,408 kg ha^{-1} for Ca and 2,020 and 2,208 kg ha^{-1} for Mg, were applied and incorporated under MDT at Macatuba and Pirajú, respectively. Despite these differences in relative amounts between treatments and sites, the concentrations of Ca^{2+} and Mg^{2+} and BS did not differ proportionally.

High buffer capacity and residual effects of liming were observed at both sites. This residual effect is attributable to unreacted lime particles. Acidic soil conditions favor lime reactivity, which decreases with increasing pH and is reestablished when acidity is recovered. The residual effect of liming is important for semi-perennial crops

like sugarcane, which exhibits progressive declines in production related to soil fertility, as sugarcane extracts high amounts of nutrients and requires high levels of nitrogen fertilization (Crusciol et al., 2017; Otto et al., 2020). Such conditions and the exudation of organic acids by roots can contribute to reacidifying the soil (Hinsinger et al., 2003), and therefore the use of high rates of lime or lime with low reactivity may be a strategy for reducing the costs of liming.

Similar effects of liming have been reported previously in studies seeking to alleviate soil acidity before establishing no-tillage for grain crops on degraded pastureland (Auler et al., 2019; Joris et al., 2016; Rheinheimer et al., 2018). Short-term improvements in BS, soil acidity alleviation, and Ca^{2+} and Mg^{2+} concentrations were observed when lime was incorporated, but after a few years, the residual effect was similar to that of surface-applied lime.

In the traffic row, BS higher than 60% were observed only in the uppermost surface layer (0.0-0.2 m) in all limed treatments and growing seasons, except under MDT, in which 60% BS was reached only in plant cane. The effects of liming on BS in the traffic row were more evident in the first layer, as lime was better distributed at this depth. In the ratoon seasons, a residual effect of liming was observed in the surface layers (0.0 to 0.4 m), with a slow decrease in BS, probably because of reduced root system access and nutrient uptake by plants due to the high soil compaction caused by machinery traffic (De Moraes et al., 2019; Marasca et al., 2015).

AS was strongly affected by liming. In Macatuba, the AS values were less than 10% across the soil profile 18 mo after lime application and remained at less than 10% up to 0.6 m and up to 0.4 m in first and second ratoon, respectively. In Piraju, the liming effect was mainly evident up to 0.4 m; the highest concentration of Al^{3+} as well as the highest buffer capacity were observed at this site. Once again, MDT was most effective in reducing AS due to the better lime distribution only in the planting furrow. As expected, in the traffic row, lime efficiency was observed only up to 0.4 m, mainly under CT and DT.

AS reflects how great is the occupation of Al^{3+} ions on soil's negative charges, which decreases when Al^{3+} reacts with lime. When lime is applied in contact with soil moisture, dissociation occurs, resulting in the release of Ca^{2+} and Mg^{2+} into CEC (fertilization process) and hydrolysis of CO_3^{2-} (the accompanying ion) (Fontes et al.,

2001; Sposito, 2008). Carbonate hydrolysis is the process responsible for correcting soil acidity. The donation of hydrogens (H^+) to carbonate by water forms H_2CO_3 and generates hydroxyls (OH^-), which in turn react with excess H^+ in soil solution (active acidity) and H^+ released from Al hydrolysis (exchangeable acidity) (Hiradate, 2004). Thus, an inverse relationship between BS and AS is expected, as observed in the present study.

2.4.2 Plant analysis

Although soil acidity amendment can influence the availability of elements, the vast majority of the analyzed elements did not differ significantly among the treatments. Changes in pH can increase or decrease a nutrient's availability (Souza et al., 2007).

Although the leaf concentration of P under MDT was superior to that in the other treatments in third ratoon, all P leaf concentrations were within the suitable range proposed for sugarcane (Spironello et al., 1996). The difference between MDT and the other treatments may be associated with pH, as soil pH was significantly higher under MDT than the other treatments in third ratoon from 0.0 to 0.2 m. The higher pH may have improved the availability of P in the soil and its uptake by plants, as acidic soil conditions can precipitate P through specific adsorption in ionic form with Al and Fe (de Campos et al., 2018, 2016). Soil pH can also increase the effectiveness of mycorrhizal colonization, which may in turn improves P uptake by plants (Fageria and Baligar, 2008). Therefore, liming is an established strategy for increasing P efficiency and availability in soil (Fageria and Baligar, 2008; Fageria and Barbosa Filho, 2008).

Reduced leaf concentrations of Fe and Cu at Macatuba and Zn and Mn at Pirajú were observed in the limed treatments compared with the standard treatment. The availability of most cationic micronutrients, such as Fe, Cu, Mn, and Zn, is reduced by increasing soil pH due to their precipitation in hydroxide forms by increasing effective CEC (Fageria et al., 2002; Souza et al., 2007), which explains the higher leaf concentrations of these elements in the standard treatment. Although the leaf concentrations of these elements in the present study were within the range proposed for sugarcane (Spironello et al., 1996), further verification of micronutrient

levels over consecutive growing cycles is recommended, particularly under high liming rates.

2.4.3 Yield assessment

Stalk and sugar yields were clearly influenced by the limed treatments compared with the standard treatment, particularly MDT. Although the leaf concentrations of most elements were considered adequate regardless of the treatment, the stalk and sugar yields responded positively to MDT. This result is attributable not only to the higher concentrations of Ca^{2+} and Mg^{2+} throughout the profile but also the better distribution of these elements and the construction of an adequate environment for the root system. Due to the relatively high requirements for Ca^{2+} and Mg^{2+} for cell structure and physiological processes (Taiz and Zeiger, 2017), Costa and Crusciol (2016) concluded that even when an adequate lime rate is broadcast on the soil surface, the distribution of roots in subsurface layers may be severely restricted in acidic soils, emphasizing the importance of adequate distribution of soil acidity amendments.

Ca-pectate and Al-pectate differently cross-link with pectin in cell walls. When Al^{3+} is in excess, Ca^{2+} is largely replaced by Al^{3+} , resulting in modifications of cell wall structure, extensibility and stability (Hepler, 2005). On the other hand, when concentrations of Ca^{2+} and Mg^{2+} are adequate, levels of these ions in the cell membrane surface are rapidly restored, and Al^{3+} activity is strongly inhibited (Rahman et al., 2018).

Some studies have shown a direct relationship between leaf accumulation of sucrose and Mg^{2+} deficiency. The transport of sucrose from leaves (source) to stems and roots (sink) is dependent in part on ATP (active). Because Mg^{2+} is an enzymatic activator of ATPase, Mg^{2+} deficiency will compromise any energy-dependent physiological processes (Cakmak and Kirkby, 2008; Garcia et al., 2020). In addition, Mg^{2+} is a central atom of chlorophyll molecules, and therefore its deficiency will affect photosynthetic processes (Marschner, 2012).

Despite the fundamental role of Mg^{2+} in sucrose distribution, the differences in soil Mg^{2+} concentration among the treatments had little influence on sucrose concentration and TRS. The sugar yield increased with the stalk yield, which, in general, was higher under MDT. This result illustrates the importance of achieving a greater stalk yield, as doing so will also increase the sugar yield.

As discussed above, a residual effect of liming was observed in the traffic rows, especially in the upper surface layers. The concentrations of Ca^{2+} and Mg^{2+} decreased slowly in these rows over successive growing seasons, indicating limited access of the root system due to high soil compaction. Since no lime was applied to this soil strip under MDT and, in general, MDT resulted in superior stalk and sugar yield performance compared with CT and DT, it is reasonable to conclude that localized liming is more efficient and is an important alternative for sugarcane cultivation. Similarly, Martins et al (2021) evaluated the energy consumption and sugarcane yield of deep and conventional tillage systems and concluded the deep strip-tillage had higher stalk yield in addition to smaller fuel consumption.

The longevity of a sugarcane crop is a decisive parameter. All limed treatments presented high average yields far above the national average, particularly MDT. These high average yields reflect a suitable production environment that offers optimum conditions for plant development. In the first two harvests, all limed treatments exhibited similar stalk and sugar yield performance at both sites; however, in the subsequent harvests (second and third ratoon), yield performance was highest under MDT, followed by DT and CT.

Despite the better lime positioning under MDT, high average yield was also observed under DT. As lime was broadcast over the entire area under DT, just like CT, this high average yield appears to reflect an interaction between better chemical and physical conditions achieved by deep tillage. Previous studies have shown that deep strip-tillage can produce a less restricted soil physical environment for root growth compared with conventional tillage, including lower bulk density, higher porosity, and better soil aeration and water availability in subsurface layers, resulting in more abundant root development (Barbosa et al., 2020; Li et al., 2020; Scarpare et al., 2019).

Deep strip-tillage system is an innovative management practice, and rigorous scientific evidence is still lacking in the literature. Further research considering different soils and environments as well as long-term assessments of soil physical and biological conditions are necessary to consolidate this management practice. Robust evidence is important due to the high cost of adopting the machinery required to implement a new tillage system for sugarcane cultivation.

2.5 CONCLUSION

This study aimed to evaluate the effects of different tillage systems on soil fertility and, in turn, sugarcane performance. Attributes such as soil pH and calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were influenced by both liming and tillage system and impacted other analyzed parameters. Modified deep strip-tillage system (MDT) was shown to correct soil acidity most efficiently, mainly due to the positioning of the lime application. Under high aluminum saturation (AS), especially in deeper layers, deep lime placement was more effective, resulting in the best distributions of Ca^{2+} and Mg^{2+} as well as the highest base saturation (BS) and lowest AS compared with the other treatments.

Lime application was more important than tillage system for improving the sucrose concentration and total recoverable sugar (TRS), whereas the tillage system affected the stalk yield and, consequently, the yield of sugar. The average stalk yield was 4.1 and 9.4% higher under MDT than under deep strip-tillage system (DT) and conventional soil tillage system (CT), respectively, at Macatuba, and was 6.3% and 15.3% higher under MDT at Piraju. The average sugar yield was 3.7 and 10.4% higher under MDT than under DT and CT, respectively, at Macatuba, and was 6.1 and 16.3% higher under MDT at Piraju.

Long-term assessments, which are important for semi-perennial crops like sugarcane, showed that the both deep strip-tillage systems were most effective. Although further research considering a wider range of locations is needed, deep strip-tillage systems can be considered an important tool for achieving higher sugarcane crop yields and longevity.

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CHAPTER 3 - EFFECTIVENESS OF DEEP LIME PLACEMENT AND TILLAGE SYSTEMS ON ALUMINUM FRACTIONS AND SOIL CHEMICAL ATTRIBUTES IN SUGARCANE CULTIVATION

Abstract

Combining deep soil tillage systems with lime application is a potential strategy for improving the sugarcane production in acidic soils. The authors evaluated the influence of tillage systems and lime application on sugarcane performance and soil attributes, including acidity. A field study in a clayey-textured Rhodic Hapludox soil was conducted with sugarcane for two growing seasons utilizing a 3 x 2 factorial scheme comprising three soil tillage systems with and without lime: conventional soil tillage system (CT), deep strip-tillage system (DT) and modified deep strip-tillage system (MDT). The soil tillage systems differed in the depth of soil disturbance and/or lime positioning. In addition to sugarcane stalk and sugar yields, pH, potential acidity (Pac), soil organic carbon (SOC), solid-phase and soil-solution calcium (Ca) and magnesium (Mg), the percentage distribution of exchangeable (%Alex) and non-exchangeable aluminum (%Alne) in the solid phase, and total monomeric (%TM-Al) in soil water extracts were analyzed and determined. The positioning of lime by the different tillage systems influenced the distribution of the Al fractions. TM-Al existed exclusively as organic monomeric Al (OM-Al) and showed little influence from treatments. In contrast, the distribution of Alex and Alne were highly influenced by lime and tillage system and varied according to the tillage efficiency of soil amendment. Soil chemical attributes and yield parameters were also influenced by the treatments in both growing seasons, highlighting the residual effect of liming. The soil chemical attributes influenced the Al fractions. Soil pH and exchangeable and soluble calcium (Caex and Cas) and magnesium (Mgex and Mgs) explained the variation of %Alne. Pac correlated with %Alex, whereas SOC explained the variation of %TM-Al. In general, the sucrose concentration, total recoverable sugar and stalk and sugar yields were increased by lime addition in plant cane and by lime addition and tillage systems in second ratoon. The stalk yield was highest in MDT, whereas the sugar yield was highest in both deep tillage systems.

Keywords: Aluminum fractionation; Strip-tillage; Conventional tillage; Furrower; Organic complexed aluminum.

3.1 INTRODUCTION

Sugarcane (*Saccharum* spp.) is grown in an area of 27.68 million hectares globally, producing 2.05 billion tons of stalks with an average yield of 72.69 Mg ha⁻¹ (FAOStat, 2018). Sugarcane is an important plant for CO₂ sequestration and is mainly cultivated to produce sugar and ethanol for clean and renewable energy. Consequently, sugarcane cultivation is directly responsible for generating millions of jobs, with a positive socioeconomic impact (Bordonal et al., 2018). Brazil is the world's largest sugarcane producer, with an estimated stalk production of

approximately 665.1 million tons from 8.6 million hectares in the 2020/2021 growing season (Conab, 2020). Despite this high crop production, the average stalk yield is still relatively low, at approximately 77.92 Mg ha⁻¹ (Conab, 2020).

The low average yield of sugarcane in Brazil is probably attributable to the recent expansion of cultivation to new agricultural areas with low fertility and acidic soils (Bernardo et al., 2019; Bordonal et al., 2018). Brazil has the largest area of acidic soil in any single country (Vitorello et al., 2005), since only Oxisols account for approximately 60% of the country's surface area (Schaefer et al., 2008; von Uexküll and Mutert, 1995). The highly weathered soils under the humid tropical climate of Brazil are affected by free drainage and silica leaching and are mainly composed of 1:1 (Si: Al ratio) clay minerals, such as kaolinite, and iron (Fe) and aluminum (Al) hydrous oxides (Schaefer et al., 2008), whose reactivity is soil pH-dependent (Kosmulski, 2020).

Aluminum is one of the most important pH buffers in acidic soils, which tends to buffer pH in the range of 4.5-5.5 (Abreu Jr. et al., 2003). However, excessive soluble Al is toxic to plants. Aluminum can replace Ca in the Ca-pectate network altering cell wall structure and stability, and cellular membrane extensibility and permeability (Meriño-Gergichevich et al., 2010). These changes can lead to reduced root cell division, expansion, and elongation, resulting in thick and short roots. Accordingly, primary (corruption of ATPase enzyme functioning in the cellular membrane) and secondary (deficiency in active uptake of nutrients) effects can compromise the plant's ability to absorb water and nutrients (Borges et al., 2020; Horst et al., 2010).

The degree of phytotoxicity of Al depends on its chemical speciation, which is highly pH-dependent (Pavan et al., 1982), and is generally determined by Al speciation and fractionation techniques in the soil solution or solid phase (Antonangelo et al., 2017; Brandani et al., 2017; Juo and Kamprath, 1979; Martins et al., 2020; Zambrosi et al., 2007). Soil organic matter (SOM) is an important free Al (Al³⁺) sink, mainly through carboxyl functional groups, which is deprotonated at lower pH values (Alleoni et al., 2010). The intensive soil disturbance on sugarcane establishment can affect SOM aggregate stability and humification, resulting in greater levels of Al³⁺ compared with soils managed by no-tillage. Prohibiting burning

at harvest may preserve SOM, thereby affecting AI dynamics and reducing its negative effect on root growth.

Agricultural lime is widely used to alleviate the problems brought by soil acidity and improve the crop production environment; however, due to its low solubility, its effects are mostly limited to the layer of application (Soratto and Crusciol, 2008; Tiritan et al., 2016). In conventional soil tillage systems, a heavy offset disc harrow, a subsoiler, and a leveling disc harrow are typically used for crop establishment, but lime incorporation is limited to the depth of disturbance, which is approximately 0.4 m. Considering that the sugarcane root system can reach greater depths (Battie Laclau and Laclau, 2009), limiting the incorporation of lime to surface layers is less effective among highly acidic subsurface soils.

One potential strategy to improve sugarcane performance and reduce the soil disturbance in total area is the use of minimum tillage systems. Initially, minimum tillage management was developed to reduce soil physical problems in sugarcane production by controlling machine traffic to preserve the planting furrows, establishing specific traffic rows (Barbosa et al., 2021; Marasca et al., 2015). In this crop management system, a new type of agricultural equipment, called a furrower, is used to build the planting furrows and seedbed to allow the distribution of lime in deeper layers. Briefly, the furrower consists of a rotary hoe that can achieve a depth of approximately 0.3 to 0.4 m plus a double-opening furrow rod with a working depth of approximately 0.7 to 0.8 m. At the top of the furrower, a lime storage compartment linked to the double-opening furrow rod allows the distribution of lime into the planting furrows. Due to limited physical (fine lime particles displacement) and chemical (alkalinization front by lime dissolution products) effects of lime reaction outside the applied zone, proper lime placement may enhance the contact with soil particles, improving the reaction time of lime at the targeted depth (de Vargas et al., 2019).

In sugarcane, the deep strip-tillage system is an innovative management practice, and as such, uncertainties remain. In particular, the effectiveness of combining deep tillage with the deep placement of amendments to control soil acidity is unclear, as most studies have addressed only soil physical properties (Bangita and Rao, 2012; Barbosa et al., 2021; Everton et al., 2016; Li et al., 2020; Lovera et al., 2021; Marasca et al., 2015; Scarpate et al., 2019). Since AI dynamics is pH-

dependent and its phytotoxic effect is related to Al species and the distribution of Al fractions (Brandani et al., 2017; Martins et al., 2020), more specific Al assessments under different soil tillage systems and lime application techniques are necessary. The current study hypothesized that deep strip-tillage improves the potential and efficiency of soil acidity amendments by strategically placing and incorporating lime at a greater depth compared to traditional total surface area application (i.e. broadcast application). To test this hypothesis, sugarcane performance as measured by stalk and sugar yields and soil chemical parameters related to soil acidity were evaluated at the harvest of plant cane (first harvest) and of second ratoon (third harvest) to assess the residual effect of lime across a clayey soil profile.

3.2 MATERIAL AND METHODS

3.2.1 Treatment conditions

The experiment was established in April 2015 at a commercial sugarcane site owned by the Zilor Sugar Mill Group in Macatuba, State of São Paulo, Brazil (22° 29' S and 48° 47' W) (Fig. 1).

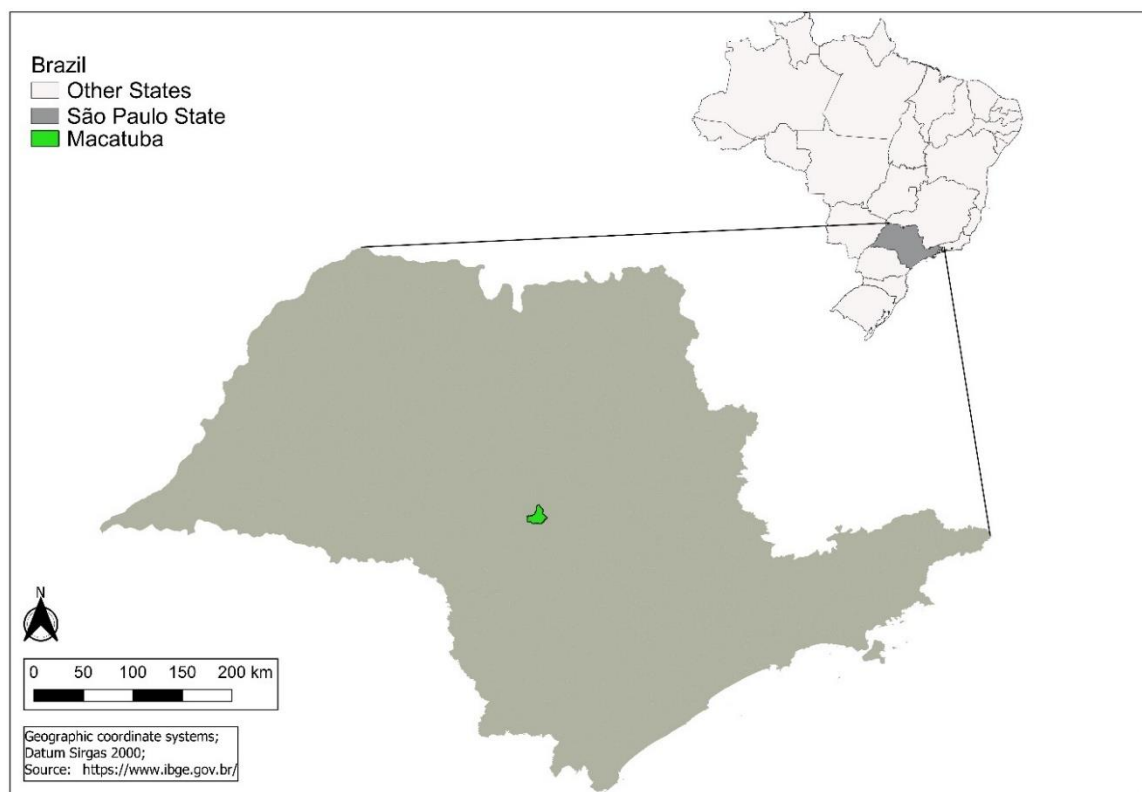


Figure 1. Geographic location of the experimental site.

Two growing seasons were evaluated: the plant cane cycle (first harvest, 18 mo after sugarcane establishment) and the second regrowth cane (ratoon) (third harvest, 42 mo after sugarcane establishment). The climate is classified as Cwa, i.e., predominantly tropical humid with hot summers, according to the Köppen classification. The average rainfall and temperature were collected monthly during the 2015 and 2018 growing seasons. The hydroclimatic balance (mm) was computed (Rolim et al., 1998; Thornthwaite and Mather, 1957) and is shown in Figure 2.

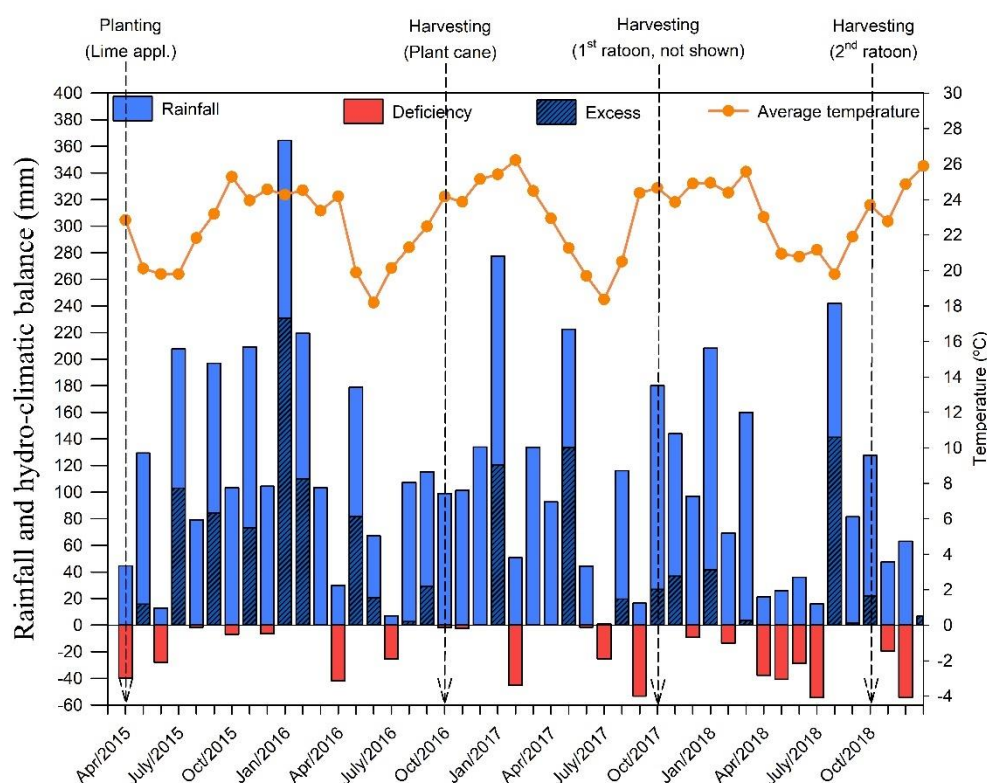


Figure 2. The average of monthly rainfall, temperature and hydro-climatic balance (mm) in the 2015/2018 growing season.

The soil is classified as a clayey-textured Rhodic Hapludox (Soil Survey Staff, 2017). Prior to setting up the experiment, soil chemical (Raij et al., 2001) and texture (Gee and Or, 2002) characterizations were performed using air-dried soil samples collected from depths of 0.0 to 1.00 m in 0.2-m intervals and passed through a 10 mesh (2 mm) sieve (Table 1).

Table 1. Soil chemical attributes and texture characterization prior to the experiment

Attributes	Depth (m)				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.00
pH (CaCl ₂)	4.4	4.0	4.0	3.9	4.0
OC (g kg ⁻¹)	23	15	12	10	10
P _{resin} (mg kg ⁻¹)	12	7	4	3	4
K (mmol _c kg ⁻¹)	2.0	0.8	0.3	0.2	0.7
Ca (mmol _c kg ⁻¹)	19	10	6	7	6
Mg (mmol _c kg ⁻¹)	9	5	3	3	2
S (mg kg ⁻¹)	21	47	36	50	45
Fe (mg kg ⁻¹)	23	15	8	7	7
Cu (mg kg ⁻¹)	3	3.3	2.2	1.8	1.8
Mn (mg kg ⁻¹)	9.7	4.3	3	1.2	2
Zn (mg kg ⁻¹)	1.1	0.5	0.1	0.1	0.1
B (mg kg ⁻¹)	0.2	0.2	0.1	0.1	0.1
Al (mmol _c kg ⁻¹)	5	7	8	7	8
H+Al (mmol _c kg ⁻¹)	52	62	64	70	64
CEC (mmol _c kg ⁻¹)*	82	78	73	80	73
Base saturation (%)**	37	20	13	13	12
Al saturation (%)***	14	30	46	40	48
Clay content (g kg ⁻¹)	358	449	486	469	442
Silt content (g kg ⁻¹)	154	140	116	124	146
Sand content (g kg ⁻¹)	488	410	398	407	412

*Calculated from the equation: CEC (mmol_c kg⁻¹) = Ca²⁺ + Mg²⁺ + K⁺ + (H+Al); ** Base saturation (%) = (Ca²⁺ + Mg²⁺ + K⁺) / (CEC) x 100; ***Al saturation (%) = (Al / (Ca²⁺ + Mg²⁺ + K⁺ + Al³⁺)) x 100.

A randomized block design field study was established with four replicates and a 3 x 2 factorial scheme comprising three soil tillage systems with lime application (10 Mg ha⁻¹ of lime applied immediately before sugarcane establishment) and without lime application (control). The soil tillage systems were as follows:

- (I) Conventional Soil Tillage System (CT): Standard tillage system widely used in sugarcane cultivation. Lime (10 Mg ha⁻¹) was broadcast across the entire area for further incorporation at 0.3-0.4 m using a heavy offset disc harrow, a subsoiler, and a leveling disc harrow.
- (II) Deep Soil Tillage System (DT): Lime (10 Mg ha⁻¹) was broadcast over the entire area and incorporated into a deep strip with a furrower exclusively within planting furrows. The furrower had a rotary hoe with a working depth of 0.3 to 0.4 m to incorporate the lime plus a subsoiling rod with a working depth of 0.7 to 0.8 m. This equipment created planting furrows with a width of 1.2 m.
- (III) Modified Deep Soil Tillage System (MDT): The same equipment used in system (II) was applied. A lime storage compartment linked to the subsoiling

rod is located at the top of the furrower. The subsoiling rod had a pair of channels (openings) located at depths of approximately 0.4 and 0.6 m that distributed part of the lime into the planting furrows. The term “modified” is used because lime was broadcast concentrated in localized -bands for further strip-incorporation by the furrower; approximately $\frac{3}{4}$ (7.5 Mg ha^{-1}) of the lime was distributed in bands on the soil surface, and $\frac{1}{4}$ (2.5 Mg ha^{-1}) was incorporated into the soil profile through the double openings behind the subsoiling rod. Since the lime was applied in concentrated bands, the rate of application decreased with depth due to the lower corrected volume.

A brief scheme is presented in Figure 3.

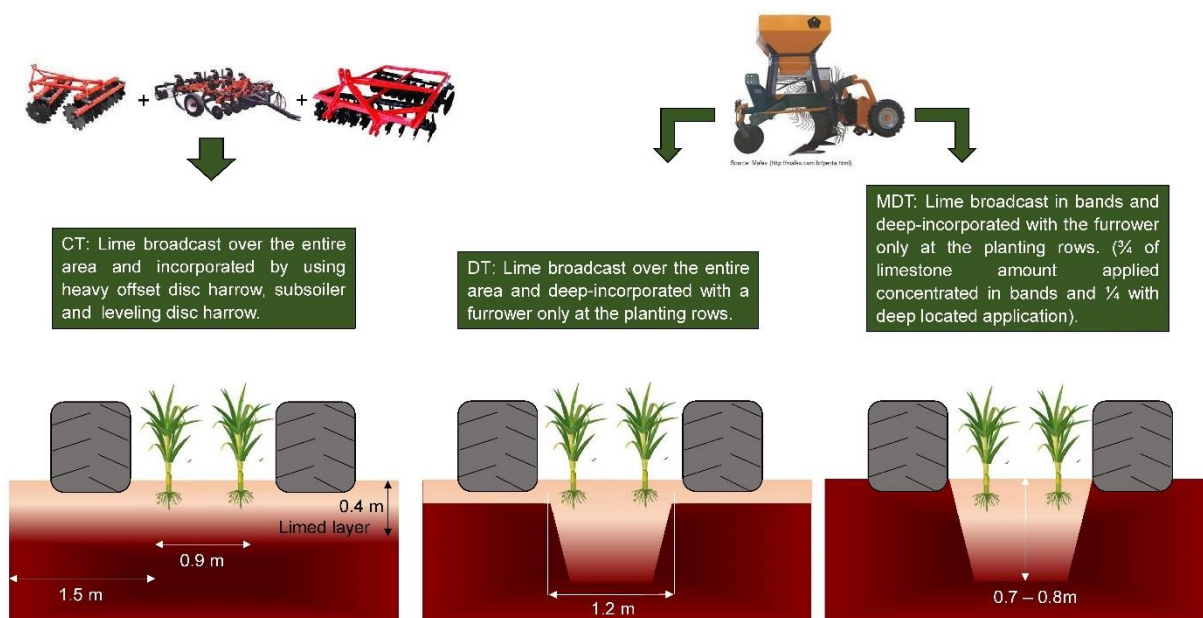


Figure 3. Schematic representation of the study illustrating the soil tillage systems and agricultural equipment.

The recommended lime rate was calculated according to the base cation saturation method (Cantarella et al., 1998a) considering the sum of the uppermost surface layers (0.0 to 0.2 and 0.2 to 0.4 m). “Base cations” are defined here as Na^+ , K^+ , Mg^{2+} , and Ca^{2+} , and used to distinguish from the cations Al^{3+} and H^+ , which are acidic. Al^{3+} is considered an acidic cation because of its ability to hydrolyze in most soils and produce H^+ . For sugarcane, the bulletin recommends a cation saturation goal of 60% (Spironello et al., 1996). The lime application rate was chosen based on a previous calibration study (data not shown) in which four lime rates were tested (no

liming, lime recommended rate (LRR) based on Spironello et al. (1996), 2x LRR and 3x LRR). A rate of 2x LRR (10 Mg ha^{-1}) of a dolomitic calcium and magnesium carbonate (CaO , 30%; MgO , 17%; 95 % of relative efficiency) was used based on the most expressive stalk and sugar yield results.

The sugarcane variety CTC 20 was mechanically planted immediately after lime application at a density of 18 viable buds m^{-1} and a depth of approximately 0.3-0.4 m and cultivated with double-combined row spacing of $1.50 \times 0.90 \text{ m}$ under a controlled traffic system. The experimental plots had an area of 240 m^2 , with a length and width of $20 \times 12 \text{ m}$; each plot comprised 5 double rows. During sugarcane establishment, 500 kg ha^{-1} of an NPK fertilizer 06-28-24 plus 40 kg ha^{-1} of S (pastilles of elementary sulfur) was applied at the bottom of the planting furrow. Also, 200 kg ha^{-1} of fertilizer containing micronutrients (Zn, 10%; B, 1.8%; Mo, 0.12%; Cu, 0.6% and Mn, 1.2%) was applied in fillets for both areas 60 days after planting. For ratoon, topdressing application was performed as NPK fertilizer 18-07-28 at rate of 650 kg ha^{-1} , plus 40 kg ha^{-1} of S (pastilles of elementary sulfur). All other management practices were standard for sugarcane needs.

3.2.2 Soil chemical analysis

Immediately after sugarcane harvest, soil samples from depths of 0.0 to 1.00 m, stratified every 0.2 m, were collected from only the planting furrow located between the double sugarcane rows by using a two-inch tubular sampler. Solid-phase chemical analysis of the soil was performed using air-dried soil samples passed through a 10 mesh (2-mm) sieve according to Raj et al. (2001) and included pH (0.01 M CaCl_2 solution), soil organic carbon (SOC), by the Walkley–Black wet oxidation method; Exchangeable Ca and Mg (Ca_{ex} and Mg_{ex}) were extracted by ion-exchange resin and determined by atomic absorption spectroscopy (AAS). Exchangeable Al (Al_{ex}) extracted by 1 M KCl solution and potential acidity ($(\text{P}_{\text{ac}}; \text{H} + \text{Al})$ extracted with 1 M calcium acetate solution were both determined by titration with ammonium hydroxide (0.025 M).

Non-exchangeable Al (Al_{ne}) plus Al_{ex} was extracted by 0.5 M CuCl_2 (Juo and Kamprath, 1979). Triplicate samples of 2 g of soil were shaken for 2 h ($150 \text{ oscil min}^{-1}$) in 20 mL of 0.5 M CuCl_2 in a 50-mL polyethylene centrifuge tube, centrifuged for 5 min (850 xg), filtered (0.45-micron syringe filter), and analyzed by inductively coupled

plasma-atomic emission spectroscopy (ICP-AES, PerkinElmer Inc., Waltham, MA, USA). Al_{ne} is considered the fraction of Al that interacts with organic complexes of low to medium stability (Brandani et al., 2017; Juo and Kamprath, 1979) and was obtained from the difference between Al-CuCl₂ and Al-KCl.

3.2.3 Soil solution chemical analysis

Soil water extract was obtained by 1:1 aqueous extraction using 30 g of soil and 30 mL of distilled water in a 50-mL polyethylene centrifuge tube. The extract was agitated in a horizontal shaker for 1 h (150 oscil min⁻¹) and centrifuged at 850 xg , followed immediately by filtration using a vacuum system assembly comprised of a magnetic funnel, a 0.45-micron nylon membrane filter (47 mm diameter, 100/Pk), a Büchner flask, and a 50-mL glass test tube to collect the water extract. Samples were extracted in triplicate for each depth. Extracts were analyzed by ICP-AES to determine the Ca and Mg concentrations (Ca_s and Mg_s).

3.2.4 Total monomeric-Al (TM-Al) analysis

Aluminum fractionation in soil water extract was performed according to Barnes (1975) and Driscoll (1984) with modifications (McAvoy et al., 1992). This technique was initially developed for surface water analysis and was adapted for soil solution. In brief, water-soluble Al from a 1:1 aqueous extraction was first immobilized by chelation with 8-hydroxyquinoline (Al-oxinate complex) in solution buffered at pH 8.3 to minimize interference, followed by rapid extraction into the organic solvent methyl isobutyl ketone (MIBK). After extraction, total monomeric Al (TM-Al) was colorimetrically determined by using a Thermo GENESYS™ 10UV UV-Vis spectrophotometer at a wavelength of 395 nm.

All reagents were prepared using water from a nanopure water system (Thermo Scientific™) following the methodology of McAvoy et al. (1992). Specifically, a 1% 8-hydroxyquinoline solution (11.8 mM) was prepared in a 1-L volumetric flask; using a glass funnel, 10 g of 8-hydroxyquinoline was carefully dissolved in 25 mL of glacial acetic acid on a stir plate (slow dissolution) and brought to the final volume with water. To prepare the phenol red indicator solution (phenol sulfone phthalein), a 0.01 M sodium hydroxide (NaOH) solution was prepared by dissolving 0.4 g of NaOH in a 100-mL volumetric flask. Then, in a 250-mL volumetric flask, 28 mL of 0.01 M NaOH

and 0.1 g of phenol red were combined, mixed with a magnetic stirrer, and brought to the final volume with water.

A 10 M NH_4OH solution was prepared in a 1-L volumetric flask by diluting 690 mL of 14.5 M NH_4OH in 310 mL of nanopure water. The pH 8.3 buffer solution was prepared by slowly adding 115 mL of glacial acetic acid in a 1-L volumetric flask containing approximately 250 mL of nanopure water. After cooling, 150 mL of 14.5 M NH_4OH was carefully added, and the pH was adjusted to 8.3 by using 14.5 M NH_4OH and/or glacial acetic acid before bringing the solution to the final volume with water.

The Al stock solution for the calibration curve was prepared by using an ICP grade certified standard ($1,000 \text{ mg L}^{-1}$) and a dilution range of 0 to 1 mg L^{-1} . These standards were used throughout the entire procedure.

The remaining procedures followed McAvoy et al. (1992). An 8.0-mL sample of soil water extract was added to a 15-mL glass test tube. Two to three drops of phenol red indicator plus 1 mL of 1% 8-hydroxyquinoline were added by using a dropper and a pipette dispenser, respectively. The sample was swirled to mix while adding 10 M NH_4OH dropwise until the solution turned red (pH of approximately 8.0). Next, 1 mL of buffer solution (pH 8.3) and 2.0 mL of MIBK were immediately added. A series of dedicated pipette dispensers were set up to avoid delays and contamination.

After the addition of MIBK, the 15-mL glass test tube was capped using a disposable stopper and shaken vigorously for 10 seconds; the aqueous and organic phases were then allowed to separate for 1 min. One milliliter of the MIBK organic phase (floating on the surface) was removed by pipetting and transferred directly to the spectrophotometer cuvette for analysis at a wavelength of 395 nm. The same procedures were used to construct the standard curve using Al stock solution.

3.2.5 Organic (nonlabile) monomeric Al analysis

The organic monomeric Al fraction was determined by passing 60 mL of soil water extract through a column (10-mm-diameter glass burette with a stopcock) containing 9.5 mL of prepared acidic cation-exchange resin (Amberlite IR-120, Sigma Chemical Co., St. Louis, MO) according to Driscoll (1984). This method assumes that organic Al complexes pass through the resin and can be quantified using the procedure described above, whereas inorganic Al is retained on the cation-exchange

column. Inorganic monomeric Al is then quantified by the difference between the total and organic monomeric Al.

To activate ion-exchange resin, an eluent solution containing Na⁺ and H⁺ was prepared by mixing NaCl salt and 1% HCl solution and adjusting the proportions until the eluent resin pH and electrical conductivity (EC) were similar to the pH and EC of the soil solution. This step was necessary to avoid changes in the pH and EC of the samples when passed through the resin (McAvoy et al., 1992).

Considering the high volume of each soil water extract sample (60 mL), the pH and EC of a diluted aliquot were determined using a Thermo Scientific™ Orion Star A211 pH Meter and a SevenCompact™ conductivity meter S230, respectively. Based on the results, custom-made Na⁺ and H⁺ eluent solutions of similar pH and EC of soil water extract samples were used to both prepare the resin (by rinsing and soaking for approximately 24 h before use) and to elute it immediately after passing each sample.

A flow rate of 35 mL min⁻¹ for 9.5 mL of resin was applied and manually controlled (McAvoy et al., 1992). The first ~50 mL of each sample was discarded (enough volume to displace the initial eluent on the column), and the last 10 mL was collected for analysis. After each sample, 60 mL of custom-made Na⁺ and H⁺ eluent specific for the following samples was passed through the exchanger bed prior to the next sample. To avoid Al contamination on resin exchange sites, the resin was discarded daily, after passing approximately 60 to 80 samples through it. The organic fraction was analyzed using the same procedure for total monomeric Al described above.

The Al fractions were summed, and the percentage of each fraction was calculated for each layer in the soil profile according to equations 1, 2, and 3:

$$Al_{ne} (\%) = Al_{ne} / (Al_{ne} + Al_{ex}) \times 100 \quad (1)$$

$$Al_{ex} (\%) = Al_{ex} / (Al_{ne} + Al_{ex}) \times 100 \quad (2)$$

$$TM-Al (\%) = TM-Al / (Al_{ne} + Al_{ex}) \times 100 \quad (3)$$

where Al_{ne} is non-exchangeable Al, Al_{ex} is exchangeable Al and TM-Al is total monomeric Al. The TM-Al was not included in equations 1 and 2 because the water extractable Al (TM-Al) is accessed to the same pool of Al_{ex} and, thus, TM-Al is already part of the exchangeable Al.

3.2.6 Sugarcane stalk and sugar yields

Prior to non-burning harvests (plant cane in October 2016 and second ratoon in October 2018), the stalk and sugar yields (Mg ha^{-1}) were determined. The stalk yield was determined by weighing the stalks in four continuous meters in two central rows of each plot. The stalks were collected, topped at apical bud height, defoliated, and weighed using a digital scale with values extrapolated to hectares. The cleaned stalks were then sent to the Middle Tietê Sugarcane Planters Association (ASCANA) Laboratory in Lençóis Paulista, SP, Brazil, for processing. The apparent percentage of sucrose (sucrose concentration and total recoverable sugar (TRS; (kg of sugar per tons (Mg) of stalk)) were determined according to the methodology defined in the Sucrose Content-Based Sugarcane Payment System for technological assessments (Fernandes, 2011; Tanimoto, 1964). The sugar yield (Mg ha^{-1}) was indirectly estimated by equation 4:

$$\text{Sugar yield (Mg ha}^{-1}\text{)} = (\text{TRS (kg Mg}^{-1}\text{)} \times \text{Stalk yield (Mg ha}^{-1}\text{)}) / 1000 \quad (4)$$

3.2.7 Statistical analysis

Data were subjected to analysis of variance (ANOVA) to evaluate the interaction between soil tillage systems and lime application. For significant differences, the t-test based on the least significant difference (LSD) was used to compare the percentage of each AI fraction and soil chemical attributes separately for each depth across the soil profile and growing seasons by using a probability level of 0.05. For technological attributes and sugarcane yield, a probability level of 0.1 was used. Multivariate analysis in the form of principal component analysis (PCA) was performed by using the statistical software package from Statistica (Statsoft, 2005). To determine the factors in PCA, the Kaiser rule was used, considering eigenvalues >1 or explaining over 85% of the total variance (Kaiser, 1958). Correlations $> |0.70|$ were considered (Manly, 1994).

3.3 RESULTS AND DISCUSSION

Soil samples collected immediately after the growing seasons for plant cane (18 months after lime application) and second ratoon (42 months after lime application) were used for chemical analysis. At all soil depths, the TM-AI in the soil

water extract was mainly present as organic complex, which ranged from 93 to 100% (Table 2). Although the Al_{ex} concentration increased in the subsurface layers, TM-Al, did not follow the same pattern and instead was positively correlated with SOC content, which decreased in the subsurface layers. Similarly, Alleoni et al (2010) found that the most soluble Al in a no-till system in Brazil was organically complexed, mainly associated with high-molecular-weight ligands (fulvic acids). Other analyses of Al species in soil water extract using speciation techniques have also indicated that the largest Al fractions are linked to dissolved organic carbon (DOC) and Al-hydroxide species (Chen et al., 2018; Martins et al., 2020; Miotto et al., 2020), even in deeper layers (Antonangelo et al., 2017; Zambrosi et al., 2008). Thus, in the subsequent discussion, we consider TM-Al as being 100% organically complexed in the soil water extract.

A significant interaction between tillage systems and lime application was observed for %TM-Al at depths from 0.0 to 0.6 m (Table S1) in both growing seasons. The %TM-Al ranged from 0.6 to 7.1% in plant cane and from 1 to 3% in the second ratoon and was higher when lime was applied, regardless of the tillage system, except in the 0.4–0.6 m layer in CT (plant cane). In the two deepest layers (0.6–0.8 and 0.8–1.00 m), %TM-Al was barely detectable, with values close to zero, and there was no effect of lime application in any of the tillage systems and growing seasons (Fig. 4). For the 0.0–0.2 m layer in plant cane, %TM-Al was similar in MDT and CT and lowest in DT. In the 0.2–0.4 and 0.4–0.6 m layers, %TM-Al was highest in CT, followed by DT and MDT (Fig 5). For the second ratoon, %TM-Al was lower in MDT and DT than in CT in the uppermost layers (0.0–0.4 m) but lower in CT at 0.4–0.6 m. In most of the subsurface layers, there were no significant differences in %TM-Al for both growing seasons (Fig. 5).

Significant interaction ($p < 0.01$) between tillage systems and lime application was observed at all soil depths for % Al_{ex} and % Al_{ne} in both growing seasons, except at 0.8–1.00 m in the second ratoon (Table S1). In plant cane, lime application was effective in reducing % Al_{ex} in all soil layers, regardless of the tillage system (Fig. 4). % Al_{ex} was 67 to 86% of total Al in treatments without lime application, regardless of the tillage system, and decreased by 0 to 11% in MDT and 0 to 33% in CT and DT when lime was applied (Fig 4). Considering the second ratoon, the residual effect of

lime application effectively reduced %Al_{ex} up to 0.4 m in CT and DT, and up to 0.8 m in MDT (Fig. 4). In the treatments without lime application, %Al_{ex} was 27 to 38% of total Al, regardless of the tillage system, and was reduced to 4 to 33% in MDT and DT and 13 to 31% in CT when lime was applied.

Table 2. Chemical solid phase and solution attributes through the soil profile as a function lime application after two sugarcane harvests

Depth	Lime	Tillage ²				Plant cane			Second ratoon					
			Al _{ex} ³ mmolc kg ⁻¹	Al _{ne} ⁴ kg ⁻¹	pH H ₂ O	TM- --- mg L ⁻¹ ---	OM- ---	OM/TM ⁷ %	Al _{ex} mmolc kg ⁻¹	Al _{ne} kg ⁻¹	pH H ₂ O	TM- --- mg L ⁻¹ ---	OM- ---	OM/TM %
0.0-0.2	No liming	CT	2.5	1.3	5.2	0.16	0.15	93	7.9	15.0	4.6	0.32	0.32	99
		DT	2.9	0.6	5.2	0.21	0.20	95	8.1	13.8	4.5	0.49	0.50	102
		MDT	2.9	0.5	5.3	0.14	0.14	99	8.1	14.4	4.7	0.24	0.23	93
	2x LRR	CT	0.0	3.0	6.4	0.20	0.19	97	1.3	8.4	6.1	0.22	0.21	96
		DT	0.0	2.3	6.2	0.12	0.12	96	2.0	13.4	5.5	0.23	0.22	94
		MDT	0.0	2.2	6.5	0.15	0.14	97	0.5	11.5	5.9	0.17	0.16	94
0.2-0.4	No liming	CT	4.4	0.7	5.0	0.14	0.14	97	6.6	14.9	4.9	0.17	0.18	106
		DT	4.8	2.3	5.1	0.19	0.20	104	7.0	14.1	4.6	0.28	0.22	99
		MDT	4.9	2.4	5.3	0.13	0.15	115	7.0	14.3	4.6	0.20	0.24	120
	2x LRR	CT	0.0	4.9	5.5	0.18	0.22	125	2.8	9.9	5.4	0.22	0.22	94
		DT	0.8	4.5	5.3	0.39	0.42	111	2.3	12.0	5.1	0.19	0.20	105
		MDT	0.0	4.0	5.3	0.09	0.10	111	0.7	13.3	5.6	0.21	0.20	96
0.4-0.6	No liming	CT	5.2	0.9	5.1	0.06	0.06	107	6.2	16.5	4.7	0.17	0.20	119
		DT	6.2	2.4	4.8	0.05	0.06	116	6.5	16.6	4.7	0.09	0.10	117
		MDT	6.3	2.3	4.9	0.03	0.04	123	6.5	16.6	4.6	0.09	0.10	114
	2x LRR	CT	1.0	5.1	4.9	0.06	0.07	119	4.1	11.5	4.8	0.07	0.07	107
		DT	2.3	4.7	4.9	0.06	0.07	116	4.5	11.9	4.9	0.10	0.11	111
		MDT	0.5	5.9	5.2	0.04	0.04	119	2.9	15.8	4.9	0.11	0.11	109
0.6-0.8	No liming	CT	6.5	2.8	4.8	0.06	0.07	119	6.7	16.2	4.8	0.08	0.11	143
		DT	6.5	2.6	4.7	0.06	0.07	116	6.7	13.6	4.6	0.08	0.13	169
		MDT	6.4	2.8	4.8	0.04	0.04	119	6.6	14.1	4.7	0.05	0.06	125
	2x LRR	CT	2.5	5.6	4.8	0.06	0.10	166	5.3	12.3	4.7	0.07	0.08	117
		DT	2.4	5.7	4.8	0.05	0.08	152	5.2	12.6	4.7	0.07	0.10	145
		MDT	0.8	6.8	5.0	0.03	0.05	184	5.2	14.9	4.8	0.10	0.14	145
0.8-1.0	No liming	CT	6.5	2.8	4.7	0.05	0.05	109	7.1	18.0	4.7	0.08	0.13	164
		DT	6.4	3.1	4.7	0.07	0.11	160	7.1	13.9	4.6	0.08	0.11	148
		MDT	6.4	3.0	4.8	0.03	0.05	151	7.1	14.0	4.7	0.06	0.09	140
	2x LRR	CT	2.5	5.3	4.9	0.06	0.08	147	5.6	10.3	4.8	0.05	0.07	145
		DT	2.5	5.5	4.7	0.05	0.08	146	6.2	12.5	4.7	0.08	0.12	151
		MDT	0.9	8.0	5.0	0.03	0.05	160	5.4	11.4	4.8	0.06	0.09	155

¹Lime application: No liming; 2x LRR two times the lime recommended rate. ²Soil tillage systems: CT, Conventional soil tillage system; DT, Deep strip-tillage system; MDT, Modified deep strip-tillage system. ³Al_{ex}, exchangeable Al (solid phase); ⁴Al_{ne}, non-exchangeable Al (solid phase); ⁵TM-Al, total monomeric Al. ⁶OM-Al, organically adsorbed monomeric Al. ⁷OM/TM, percentage relation between the OM-Al and TM-Al.

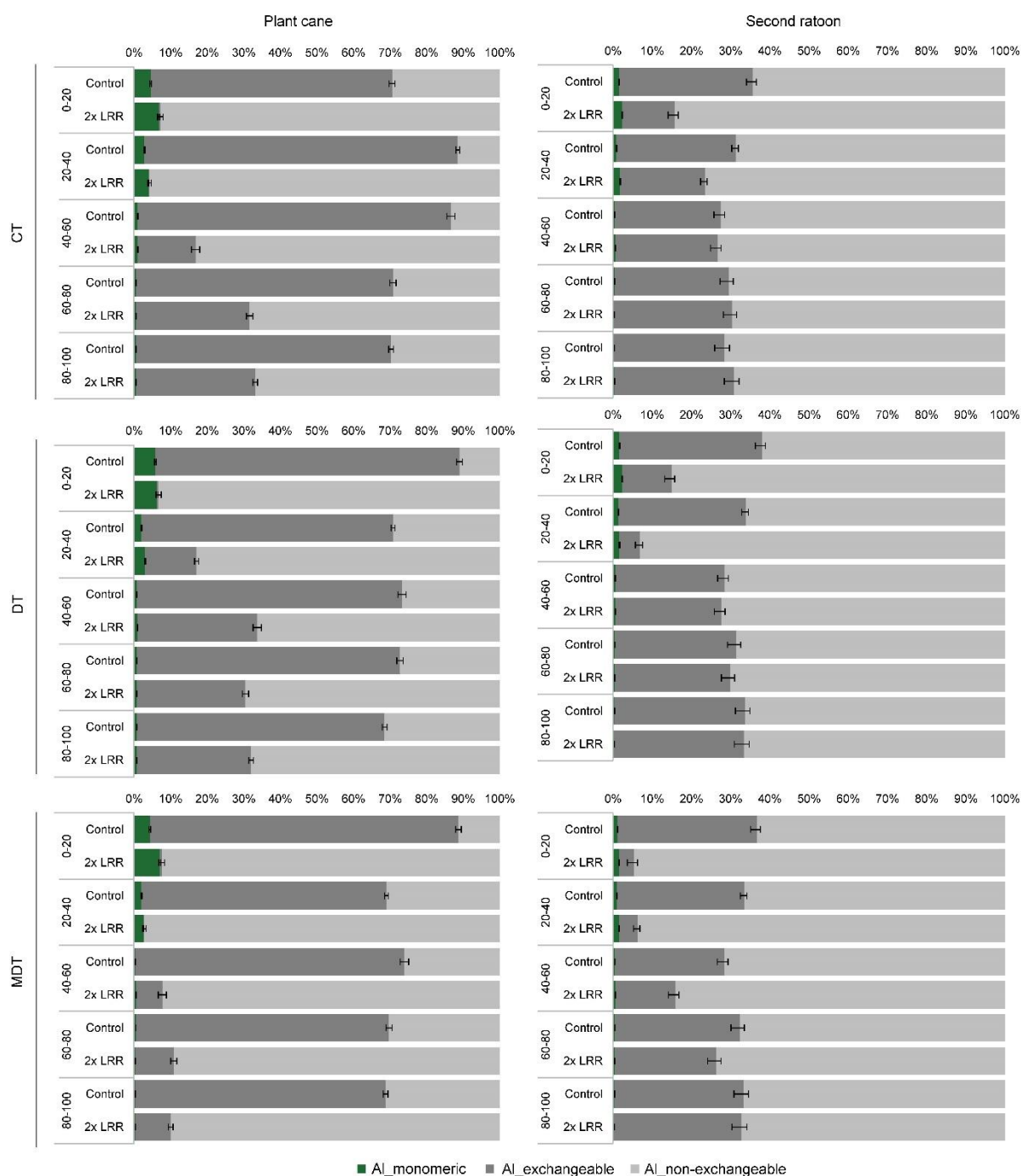


Figure 4. The distribution of aluminum fractions percentage across the soil profile under different soil tillage systems and liming after two harvests (Plant cane and second ratoon). Error bars represent the least significant difference (LSD) $p \leq 0.05$.

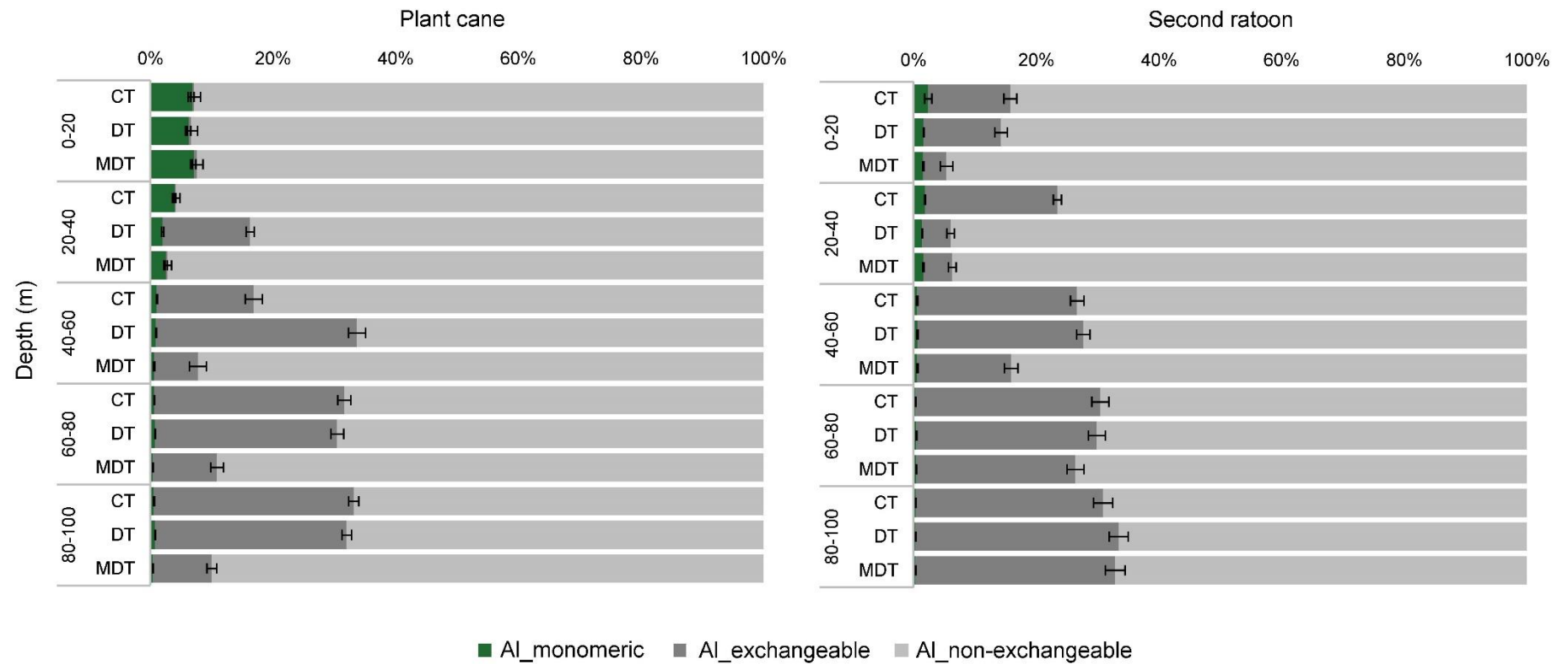


Figure 5. Comparative distribution of aluminum fractions percentage across the soil profile under different soil tillage systems in amended soil. Error bars represent the least significant difference (LSD) $p \leq 0.05$.

When lime was applied, %Al_{ex} sharply decreased. This shift was due mainly to the influence of soil pH on the Al_{ex} fraction, as its availability is strongly affected by pH in highly weathered tropical soils (Pavan et al., 1982). Al³⁺ exhibits a great degree of ionic hydration because of its large negative enthalpy. Due to its moderate to high ionic potential (ratio of charge to ionic radius), which ranges from 0.03 to <0.1, Al³⁺ tends to strongly polarize the water molecules in its hydration shell, coordinating six of them in aqueous solution (Al(H₂O)₆³⁺) (Essington, 2015). In aqueous acidic solutions, to maintain thermodynamic equilibrium dictates that dissociation of protons from the Al³⁺ hydration shell is not favored. However, when pH is increased by lime application, H⁺ activity decreases, and equilibrium is maintained by dissociation of protons from hydration water (Hiradate, 2004). Therefore, during the hydrolysis process, H⁺ de-protonates counteracting the effect of rising pH and behaves as a pH buffer. This de-protonation can occur several times and changes the species of the Al. Essentially, Al³⁺ becomes a hydroxy-Al species (Al(H₂O)₅ (OH)²⁺, Al(H₂O)₄(2OH)⁺ or Al(H₂O)₃(3OH)), which have minor or no toxicity in plants (Li and Johnson, 2016). The concentration of each Al species changes drastically within the pH range (as measured with water) of 4.5 to 6.5 and, above approximately 5.0, the concentration of Al³⁺ is practically null (Antonangelo et al., 2017). Aluminum toxicity in plants is mainly caused by free Al (Al³⁺), which binds more strongly than Ca²⁺ to the Ca-pectate structure of the cell wall and membrane of roots (Voiniciuc et al., 2018). Ca²⁺ plays a fundamental role in cross-linking pectin in the cell wall and membrane, and thus its displacement by Al³⁺ will inevitably alter physical properties such as extensibility, rigidity and permeability (Rahman et al., 2018).

%Al_{ne} was consistently higher under lime application throughout the soil profile, regardless of the tillage system (Fig. 4). In plant cane, %Al_{ne} was 11 to 31% of total Al without lime application, regardless of the tillage system, and increased to 89 to 92% in MDT and to 66 to 95% in CT and DT with lime application, whereas in the second ratoon, %Al_{ne} represented 61 to 72% of total Al in the treatments without lime application, regardless of the tillage system, and increased to 66 to 95% in MDT and 66 to 85% in DT and CT when lime was applied. (Fig. 4). In plant cane, variations in the Al fractions were observed among the tillage systems from 0.2 m. In the second and third layers, %Al_{ne} was highest in MDT, followed by CT. In all layers between 0.4 and 1.0 m, %Al_{ne} was highest in MDT, whereas there were no

differences in %Al_{ne} and %Al_{ex} in the two deepest layers between CT and DT (Fig 5). In the second ratoon, the residual effect of lime application increased %Al_{ne} at depths of up to 0.4 m in DT and CT and up to 0.8 m in MDT. At 0.8–1.00 m, no residual effect of lime application on %Al_{ne} was observed (Fig. 4). Among the tillage systems, MDT was most effective in reducing %Al_{ex} and increasing %Al_{ne} at depths of up to 0.8 m, followed by DT at 0.2–0.4 m only. In deeper soil layers, there were no differences in Al fractions between CT and DT (Fig. 5). Since higher soil pH sensibility of Al_{ex}, the amendment capacity of each tillage controlled the distribution of Al fraction. The better positioning of lime in deeper layers highlighted the influence of MDT in controlling the exchangeable acidity (Al_{ex}), making the proportion of non-exchangeable acidity (%Al_{ne}) more evident. Thus, the difference between the Al_{ex} and Al_{ne} fractions decreased as a function of soil depth, mainly due to the lower SOC content and the greater Al_{ex} concentration. In an evaluation of Al_{ex} and Al_{ne} in a Brazilian Oxisol under lime application, Zambrosi et al. (2007) also observed smaller differences between these fractions in the subsurface layers, which they attributed to lower pH values in these layers, where the lime activity was smaller. Despite the decrease in SOC content in the subsurface layers (0.6–1.0 m), %Al_{ne} still represented approximately 30 and 60% of total Al for plant cane and second ratoon without lime application, respectively, and 60 and 90% with lime application, respectively. As supported by Juo and Kamprath (1979), even in subsurface layers the strong complexing power of Cu²⁺ ions and the low pH of the salt solution (pH value approximately 3) of the extracting solution can release polymerized hydroxy-Al and more soluble Al from the inorganic phase, which explains the high degree of this fraction present despite little SOC. These findings support the notion that every form of Al that is able to donate protons under pH lower than 7.0 is considered reactive and the Al fraction extracted by CuCl₂ is an important estimate of the potentially reactive Al reservoir and the buffer capacity of acidic soils (Juo and Kamprath, 1979; Martins et al., 2020; Zambrosi et al., 2007).

The significance of the effects of the interaction of lime application and tillage system on chemical attributes in the soil solid phase (pH, SOC, P_{ac}, Ca_{ex} and Mg_{ex}) and soil water extract (Ca_s and Mg_s) in plant cane and second ratoon is presented in Table S2. For plant cane, an effect of the interaction between tillage systems and lime application on soil pH was observed only in the uppermost surface layer (0.0–

0.2 m). Lime application increased soil pH regardless of the tillage system, growing season, and soil layers; however, in the first and third layers, pH was higher in MDT than in CT and DT in plant cane and at 0.2-0.4 m in the second ratoon (Fig. 6a and h Table S3 and S4). In general, soil pH increased throughout the soil profile when limed, regardless of the method of application, indicating neutralization reaction beyond the lime application point. Mobility of fine lime particles can occur by chemical and physical mechanisms, such as alkalinization front and downward or lateral displacement by water movement over fine particles through soil biopores or root cracks (de Vargas et al., 2019; dos Santos et al., 2018). Increasing soil pH is particularly important in acidic soils not only because of Al^{3+} precipitation, but also because the availability of the nutrients can be influenced by it. In highly weathered soils, excessively acid pH levels are detrimental to plant nutrient bioavailability, especially phosphorus (Cantarella et al., 1998b; Penn and Camberato, 2019). Regardless of tillage system, improvements in pH were achieved in plant cane throughout the entire soil profile and in the second ratoon up to 0.2 m for all tillage systems and up to 0.4 m for MDT.

In plant cane, SOC content exhibited isolated effects from tillage system and lime application, whereas in the second ratoon an interaction between treatments was observed up to 0.6 m (Table S2). In plant cane there was an interaction between the treatments in the first layer, and SOC content was highest in CT without lime application (Fig. 6b, Table S3). At depths of 0.2–0.6 m, SOC content was higher under lime application. The effect of lime application was observed regardless of soil tillage system at 0.2–0.4 m and was higher in CT at 0.4–0.6 m. There were no significant differences between treatments in SOC in the subsurface layers (Fig. 6b, Table S3). For the second ratoon, in general, SOC content was higher without lime application only in CT. There was no effect of either tillage or lime application on SOC in DT and MDT and no effect of lime application in CT (Fig. 6i, Table S4). Lime application may improve SOC content by increasing the effective cation exchange capacity of soil and by providing Ca and Mg, which can act as cationic bridges between mineral and organic particles to stabilize organo-mineral complexes (Rowley et al., 2018). Increased root growth due to improved soil conditions can provide more organic matter for producing SOC. Conversely, lime application also

increases soil pH, which can increase soil biological activity and SOC mineralization (Keil and Mayer, 2013), thereby reducing SOC content. The use of a rotary hoe in MDT and DT increases contact between the lime and soil particles but may excessively turn over the soil and expose SOC that was protected as organo-mineral complexes (De Mastro et al., 2020; Weng et al., 2018). This exposure may increase access to microorganisms and oxygen and therefore accelerate SOC mineralization compared with conventional tillage systems (Keil and Mayer, 2013; Zhou et al., 2014). Long-term assessments are necessary to draw more accurate conclusions about SOC content in deep strip-tillage system.

Interactions between tillage systems and lime application were observed for P_{ac} , Ca_{ex} and Ca_s at all depths, for Mg_{ex} at 0.0–0.4 m, and for Mg_s at 0.0–0.8 m, in plant cane, and for P_{ac} up to 0.8 m, for Ca_{ex} up to 0.6 m and Ca_s from 0.2 to 1.00 m, for Mg_{ex} at 0.0–0.8 m and Mg_s at 0.0–1.00 m, in the second ratoon (Table S2).

In plant cane, lime application reduced P_{ac} regardless of tillage system up to 0.6 m and at all depths in MDT. Among the limed treatments, P_{ac} at 0.2–0.8 m was lowest in MDT, followed by CT and DT. There were no significant differences between CT and DT in P_{ac} at 0.0–0.2 m and 0.8–1.0 m (Fig. 6c, Table S3). For the second ratoon, P_{ac} was consistently higher without lime application across the entire soil profile regardless of the tillage system. MDT exhibited the best performance in decreasing this variable at depths of up to 0.8 m, except at 0.0–0.2 m and 0.6–0.8 m, where DT or CT showed the same efficiency as MDT, respectively (Fig. 6j, Table S4).

Throughout the soil profile, Ca_{ex} and Ca_s were higher under lime application in plant cane. MDT was consistently the most effective tillage system, with higher Ca_{ex} and Ca_s regardless of soil depth, followed by CT and DT (Fig. 6d and f, Table S3). In the second ratoon, residual effect of lime application was able to increase both Ca_{ex} and Ca_s throughout the soil profile. In general, Ca_{ex} was higher in MDT at depths of up to 0.6 m, followed by CT and DT up to 0.4 m (Fig. 6k, Table S4). In the uppermost surface layer, only an isolated effect of lime application was observed for Ca_s . Ca_s was higher in MDT at 0.2–1.00 m, except at 0.4–0.6 m, where CT produced a similar result (Fig. 6m, Table S4).

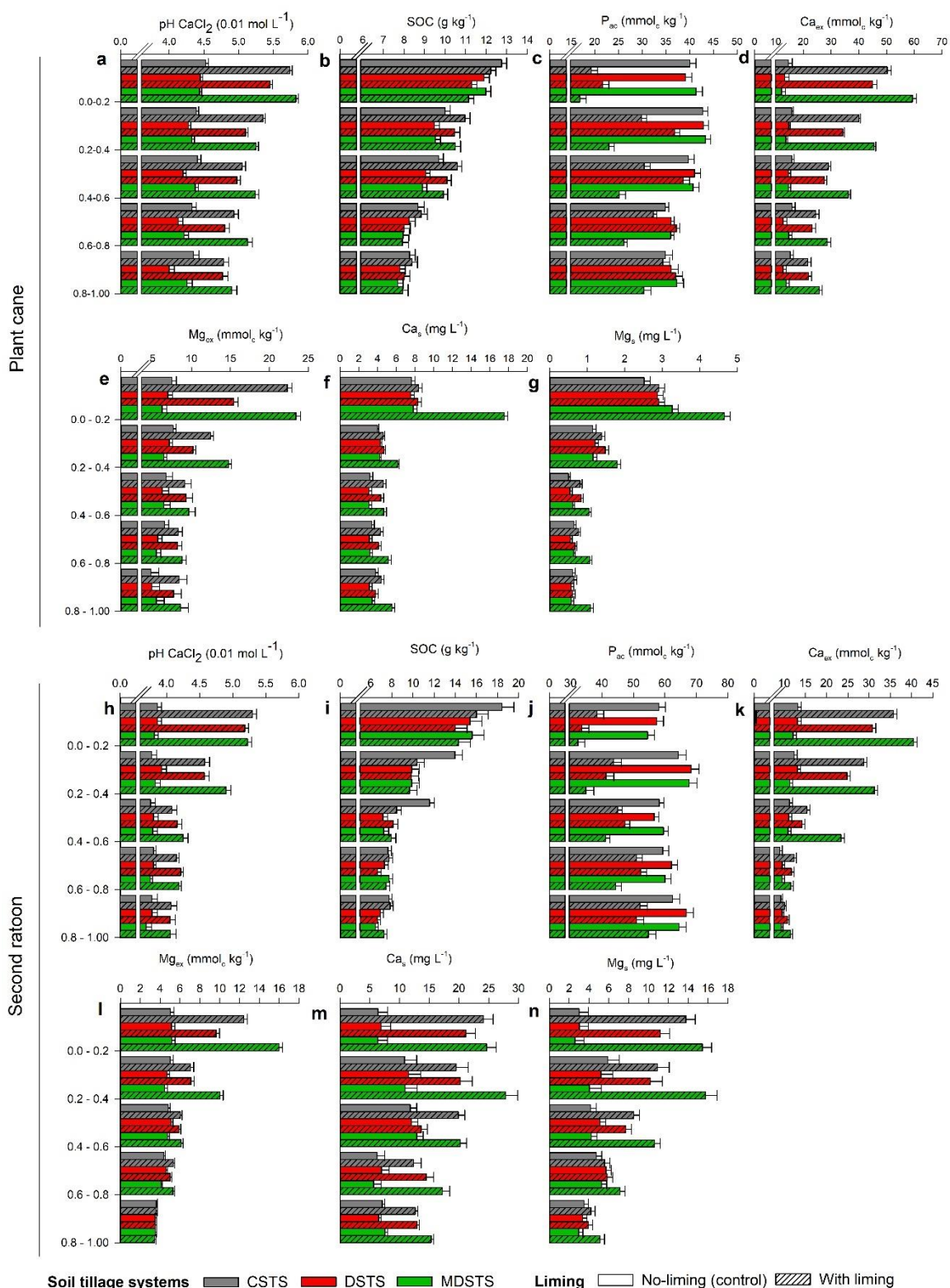


Figure 6. Soil chemical attributes across the soil profile under different soil tillage systems and liming after two harvests (Plant cane and second ratoon). Error bars represent the least significant difference (LSD) $p \leq 0.05$

An isolated effect of lime application was observed for Mg_{ex} and Mg_s at all depths in plant cane. At depths of up to 0.2 m, Mg_{ex} did not differ between MDT and CT and was higher than in DT. At 0.2–0.4 m, Mg_{ex} was significantly higher in MDT than in CT and DT. At 0.4–1.00 m, there was no effect of tillage system on Mg_{ex} . Mg_s was consistently higher in MDT than in CT and DT at all depths (Fig. 6e and g, Table S3). For the second ratoon, Mg_{ex} was highest in MDT under lime application, followed by CT and DT up to 0.4 m. A residual effect of lime application on Mg_{ex} was observed at 0.0–0.8 m, except in DT at 0.4–0.8 m (Fig. 6l, Table S4). Similar to Ca_s , Mg_s was higher in MDT from 0.0 to 0.8 m and did not differ between DT and CT. In the most subsurface layer, an isolated effect of lime application was observed only in MDT (Fig. 6n, Table S4).

According to the amount of lime applied, the equivalents of 2,130 and 1,010 kg ha^{-1} of Ca and Mg, respectively, were applied under CT and DT. Conversely, under MDT, the same dose calculated for the total area was instead applied concentrated in bands with width of 1.2 m, for further incorporation by the furrower. As the spacing between rows was 1.5 x 0.9 m (2.4 m total) it was expected that the double dose was applied and incorporated, that is, 4,260 and 2,020 kg ha^{-1} for Ca and Mg, respectively, under MDT. Despite such differences, the concentrations of Ca^{2+} and Mg^{2+} did not increase proportionally. These results might be expected since acidic soil conditions are necessary for the lime reaction (i.e. lime dissolution and neutralization). However, the residual effect was observed due to unreacted lime particles whose reactivity can be reestablished when acidity is recovered (Rheinheimer et al., 2018). By comparing soil tillage systems, the results clearly demonstrate the capacity of MDT to better distribute lime throughout the soil profile, thanks to the ability of the furrower to reach deeper layers and the application of the lime in concentrated bands covering only the planting furrows.

The percentages of TM-Al, Al_{ex} , and Al_{ne} were also submitted to PCA to identify the soil attributes responsible for explaining their variations, considering the effects of lime application across the soil profile. Since these Al fractions followed similar patterns in the different soil tillage systems, the systems were grouped for analysis. Figure 8 shows the projections for soil chemical attributes (a) and soil depths (b). The eigenvalues ≥ 1 are presented in factor 1 (horizontal axis in Fig. 8a)

and factor 2 (vertical axis in Fig. 8a). Factor 1 explained 67% of the variation (Table 3) in %Al_{ex} and %Al_{ne}. In factor 1, pH, Ca_s, Mg_s, Ca_{ex}, and Mg_{ex} were closely correlated with %Al_{ne} (Table 3, Fig. 8a). By contrast, the attribute P_{ac} in factor 1 was highly correlated with %Al_{ex} ($\geq |0.70|$) (Table 3, Fig. 8a). Factor 2 explained 33% of the variation in %TM-Al and correlated with SOC (Table 3, Fig. 8a). Factor 1 had opposing effects on %Al_{ex} and %Al_{ne}. In the treatments with lime, the decrease in %Al_{ex} was more pronounced since this fraction is highly pH dependent and more sensitive to soil neutralization. According to Juo and Kamprath (1979), the concentration of Al extracted with CuCl₂ is the sum of reactive Al forms that are not exchangeable with KCl, but are susceptible to reaction with lime. Due to the higher-than-recommended lime rate used in this study, the greater Ca and Mg may displace non-exchangeable Al from organic complexes and precipitate it as Al-hydroxyl forms at elevated soil pH under lime application. Thus, when the ratio of Al_{ex} decreases, the ratio of Al_{ne} increases. %Al_{ex} was closely correlated with P_{ac}, as their values increased in deeper layers, where lime activity was lower. Regarding %TM-Al, as discussed above, this fraction was considered 100% organically complexed Al, which explains the positive correlations of %TM-Al with SOC.

Figure 8b presents the correlations of the aluminum fractions with soil depth. Depths of 0.0–0.4 m were considered surface layers, whereas depths of 0.4–1.00 m were considered subsurface layers. Results are grouped as amended surface layers (on the upper left side), amended subsurface layers (on the bottom left side), non-amended surface layers (on the upper right side), and non-amended subsurface layers (on the bottom right side). The samples grouped on the left side were influenced by higher Ca_{ex}, Mg_{ex}, Ca_s, Mg_s, and pH, in addition to SOC. Therefore, they represented lime treatments. Conversely, the samples grouped on the right side were influenced by higher P_{ac}. Therefore, they represented the treatments without lime application.

Table 3. Principal component analysis results for chemical soil solid phase and soil solution attributes

	Eigenvalue	Total Variance %	Cumulative eigenvalues	Cumulative %
1	2.00	66.72	2.00	66.71
2	1.00	33.27	2.99	99.98
3	0.00	0.01	3.00	100.00
	Eigenvectors		Correlations	
Active ²	Factor1	Factor 2	Factor 1	Factor 2
%Al _{ne}	-0.99	-0.07	0.99	-0.07
%Al _{ex}	0.99	0.01	-0.99	0.01
%TM-Al	0.08	0.99	0.08	0.99
	Correlations between soil properties ¹			
Supplementary ³	Factor 1	Factor 2		
pH	-0.93	0.24		
SOC	-0.14	0.70		
Ca _s	-0.84	0.31		
Ca _{ex}	-0.84	0.38		
Mg _s	-0.83	0.31		
Mg _{ex}	-0.76	0.39		
P _{ac}	0.90	-0.02		

¹Correlations $\geq |0.70|$ are significant (Manly, 1994). ²Actives: %Al_{ne}, relation of the non-exchangeable Al in soil solid phase (%); %Al_{ex}, relation of the exchangeable Al in soil solid phase (%) and TM-Al, relation of total monomeric Al in soil solution (%). ³Supplementary: pH (CaCl₂ 0.01 mol L⁻¹); SOC, soil organic carbon (mg kg⁻¹); Ca_s and Mg_s, calcium and magnesium concentration in soil solution (mg L⁻¹); Ca_{ex} and Mg_{ex}, exchangeable calcium and magnesium concentration in soil solid phase (mmol_c kg⁻¹); and P_{ac}, soil potential acidity (mmol_c kg⁻¹).

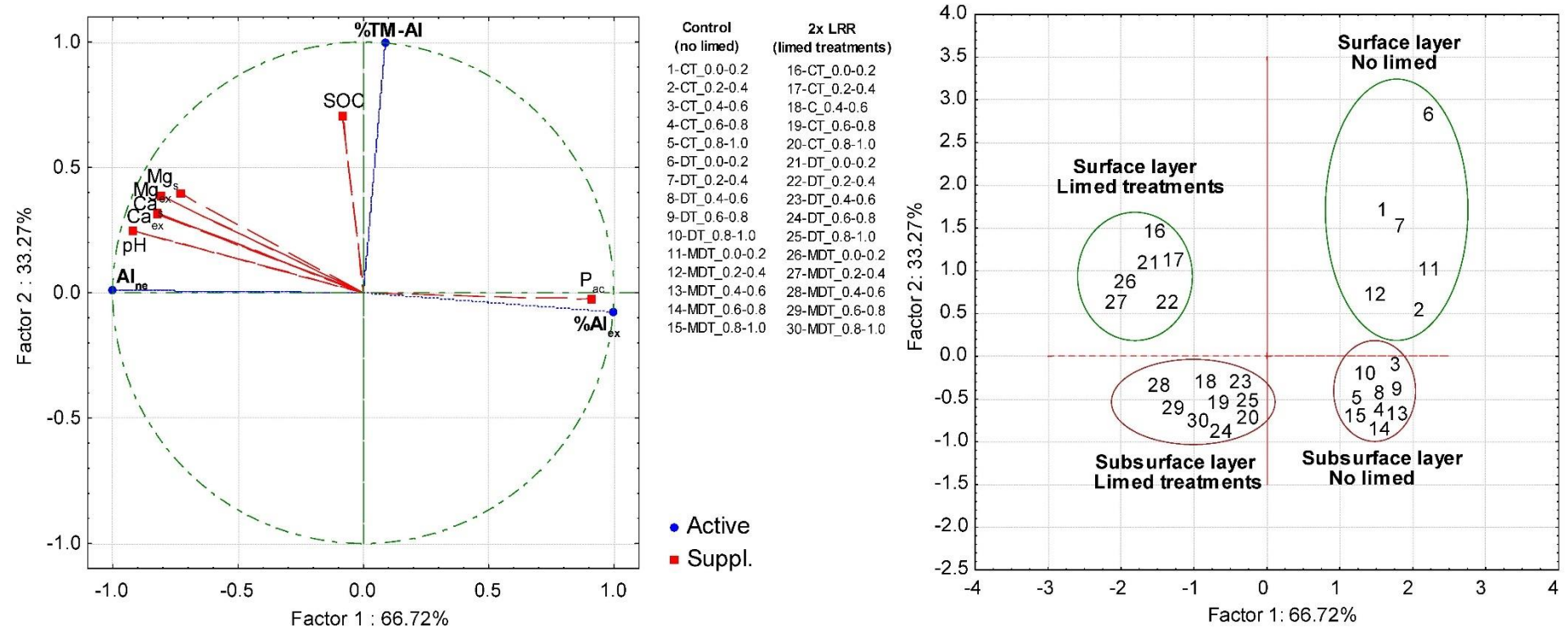


Figure 7. Projection of dataset based on correlations between the aluminum fractions and soil chemical attributes (a) and soil depths (b) subjected to principal component analysis.

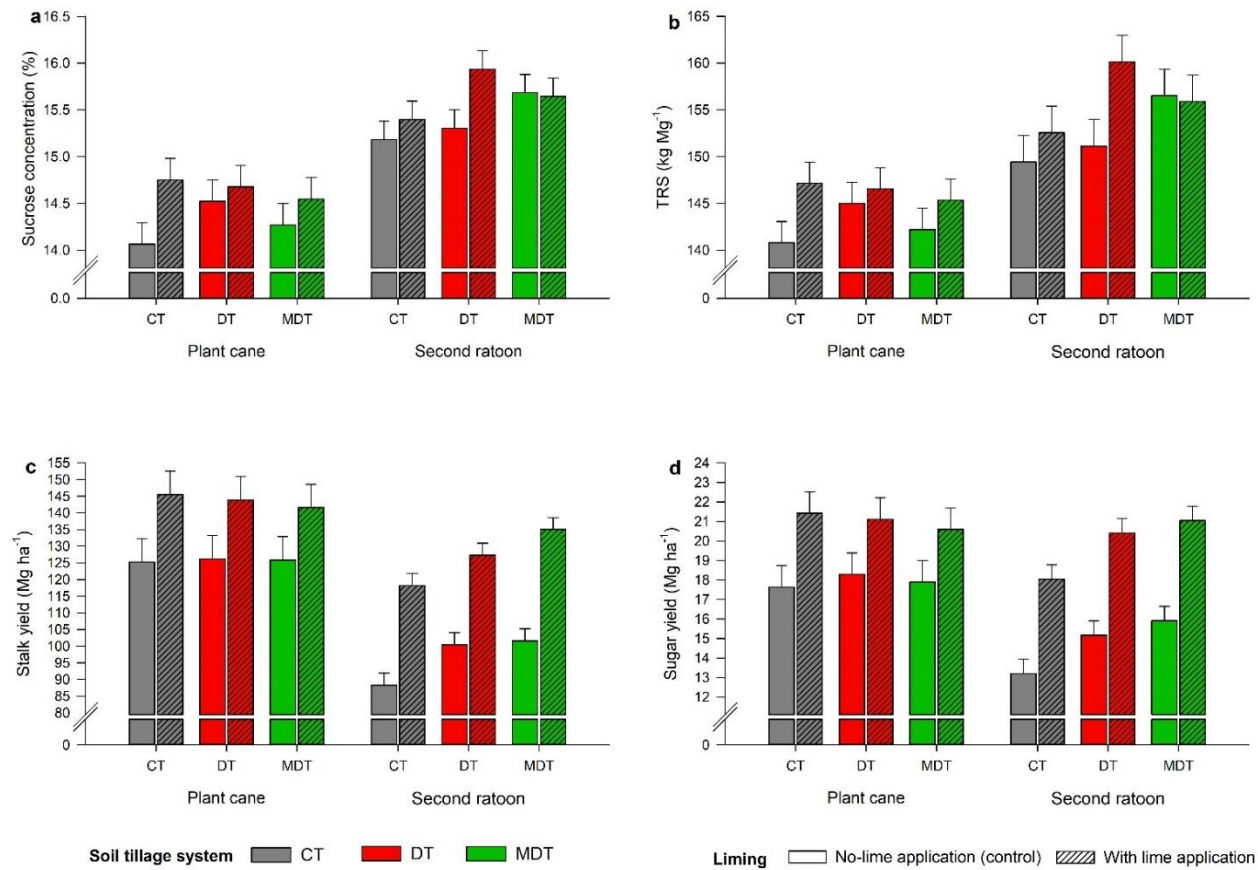


Figure 8. Sucrose concentration (a), total recoverable sugar (TRS) (b), yield of stalk (c) and sugar (d) of sugarcane under different soil tillage systems and liming after two harvests (Plant cane and second ratoon). Error bars represent the least significant difference (LSD) $p \leq 0.1$.

In plant cane, the sucrose concentration and TRS were both affected by lime application (Table S5) only in CT (Fig. 7a and b, Table S4). An isolated effect of lime application was also observed for stalk and sugar yields, regardless of tillage system (Fig. 7c and d, Table S4). For the second ratoon, isolated effects of tillage system and lime application were observed for both technological attributes (Table S5). Sucrose concentration and TRS were both affected by lime application only in DT (Fig. 7a and b, Table S5). Both stalk and sugar yields were increased by lime application, regardless of the tillage system. Among the treatments with lime application, stalk yield was highest in MDT, followed by DT and CT, whereas the sugar yield was significantly higher in MDT and DT (Fig. 7c and d, Table S6).

Due to the high industrial efficiency of the sucrose recovery process, the sucrose concentration measured before sugarcane processing was quite similar to the total recoverable sucrose (TRS), and thus similar results were obtained for these attributes. The yield parameters were influenced by the treatments, especially lime application for plant cane and lime application plus tillage systems for second ratoon. The greater soil disturbance due to tillage favors the mineralization of nutrients from the above- and below-ground residues of earlier plants (Fortes et al., 2013), resulting in high yields in both tillage systems. The performance of both tillage systems was also favored by the adequate soil physical conditions for root development and the high vigor of the cane seedlings at plant cane harvest. However, even for plant cane, the treatments with lime had higher stalk and sugar yields, confirming the strong dependence of crop production on amendments in highly weathered soils.

The yield parameters in the second ratoon also reflected effects of both tillage system and lime application. As discussed above, chemical improvements throughout the soil profile can explain the differences in performance between tillage systems. In this context, MDT better positioned the lime by limiting it to the planting furrow, which effectively increased the concentrations of Ca and Mg and soil pH, in addition to increasing the $Al_{ne} : Al_{ex}$ ratio. The resulting higher base cation saturation and higher $Al_{ne} : Al_{ex}$ ratio throughout the soil profile provided a suitable chemical environment for root development, as suggested by the superior stalk and sugar yields. Considering the sum of both harvests, the yield

was 10.4 and 10.1% higher in MDT than in CT and DT, respectively. Nonetheless, the percentage increases in stalk (23, 19 and 21% respectively for CT, DT and MDT) and sugar (27, 24 and 23% respectively for CT, DT and MDT) yields due to lime application were highest in CT. This effect reflects the sharp decrease in stalk yield between cropping seasons in CT without lime application, which may be attributed to different soil physical conditions, since both deep strip-tillage systems had similar stalk yields in the second ratoon without lime application (approximately 11% higher than CT). Superior root growth induced by better soil physical conditions was reported by Scarpore et al. (2019), who reported lower soil bulk density, higher soil porosity, and, consequently, more abundant root development under deep tillage compared with conventional tillage. Similarly, Barbosa et al. (2020) concluded that deep furrow tillage increases aeration and water availability in subsurface layers. However, long-term assessments are still necessary to justify the use of innovative management practices like deep strip-tillage for perennial or semi-perennial crops such as sugarcane.

3.4 CONCLUSION

The results of this study revealed that aluminum (Al) fractions vary depending on the positioning of lime by the soil tillage system. In general, lime application sharply decreased the fraction of exchangeable Al ($\%Al_{ex}$); non-exchangeable Al ($\%Al_{ne}$) was the main Al fraction regardless of soil depth, tillage system or growing season. Even under high acidity conditions, the total monomeric Al ($\%TM-Al$) was organically complexed in the soil solution.

In general, soil chemical parameters related to soil acidity were affected by lime application and the tillage system, and these effects persisted even 42 months after lime application. The long-term lime residual effect was dependent on the method of application. In this context, the modified deep strip-tillage system (MDT) allowed the lime to efficiently reach deeper layers, reducing the potential acidity (P_{ac}) and increasing exchangeable calcium (Ca), magnesium (Mg), and soil pH, which influenced the yield parameters. Sucrose concentration, total recoverable sugar and stalk and sugar yields were increased by lime

application in plant cane and by lime application and tillage system in second ratoon. The highest stalk yield occurred in MDT, whereas the highest sugar yield was observed in both deep strip-tillage systems.

In this clayey soil, long-term results indicated that the deep strip-tillage systems were highly effective and can be used as an important alternative tillage for better performance in sugarcane crop yields and longevity. Despite being an innovative tillage system in sugarcane, information is still incipient and other studies, mainly in different textured-soils, are still required.

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FINAL CONSIDERATIONS

This study evaluated the effects of different tillage systems and liming rates on soil fertility and sugarcane performance. Firstly, we hypothesized there would be yield responses under increasing lime rates for each tillage systems and impact of liming rates on soil chemical fertility. Then, one specific lime rate was used to compare the performance of each tillage system on soil chemical fertility and yield parameters and, finally, we tested whether aluminum fractions could vary influenced by different tillage systems.

In general, this study showed that the parameter related to on soil chemical fertility varied according to the tillage systems and liming rates and the modified deep soil tillage system showed to be more adequate system. MDT better positioned the lime and the yields parameters were also positively affected.

The results of testing a new tillage management were promising and showed the deep tillage systems can be considered an important tool for achieving higher sugarcane crop yields and longevity. However further long-term research considering a wider range of locations, different classes of soils and soil physical and biological assessments influenced by the deep tillage systems is needed.

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APPENDIX (SUPPLEMENTARY MATERIAL) – CHAPTER 1

Table S1. P values indicating the effect of lime rates for each tillage systems on soil chemical attributes after harvests at each soil depth in Macatuba

Depth (m)	CT ¹					DT ²					MDT ³				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Plant Cane															
pH	<0.001	<0.001	<0.001	<0.001	0.0169	<0.001	<0.001	<0.001	<0.001	0.0294	<0.001	<0.001	<0.001	<0.001	<0.001
Ca ²⁺	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mg ²⁺	<0.001	<0.001	<0.001	0.0035	0.0058	<0.001	<0.001	<0.001	<0.001	0.0164	<0.001	<0.001	<0.001	<0.001	<0.001
BS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
AS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
1 st Ratoon															
pH	<0.001	<0.001	<0.001	<0.001	0.0077	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ca ²⁺	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mg ²⁺	<0.001	<0.001	<0.001	<0.001	0.1649	<0.001	<0.001	<0.001	<0.001	0.2145	<0.001	<0.001	<0.001	<0.001	<0.001
BS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
AS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2 nd Ratoon															
pH	<0.001	<0.001	<0.001	<0.001	0.0075	<0.001	<0.001	0.0027	0.0020	0.0039	<0.001	<0.001	<0.001	<0.001	0.1563
Ca ²⁺	<0.001	<0.001	<0.001	<0.001	0.1337	<0.001	<0.001	<0.001	<0.001	0.1328	<0.001	<0.001	<0.001	<0.001	<0.001
Mg ²⁺	<0.001	<0.001	<0.001	<0.001	0.1998	<0.001	<0.001	0.0073	0.1936	0.5221	<0.001	<0.001	<0.001	<0.001	0.2143
BS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
AS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0016	<0.001	<0.001	<0.001	<0.001	<0.001
3 rd Ratoon															
pH	<0.001	<0.001	0.0016	0.2554	0.1562	<0.001	<0.001	0.0453	0.1322	0.3265	<0.001	<0.001	<0.001	0.1656	0.6834
Ca ²⁺	<0.001	<0.001	<0.001	0.8918	0.3787	<0.001	<0.001	<0.001	0.6584	0.2958	<0.001	<0.001	<0.001	0.1055	0.7650
Mg ²⁺	<0.001	<0.001	0.0356	0.0300	0.1595	<0.001	0.0011	0.0333	0.4363	0.2333	<0.001	<0.001	<0.001	0.1298	0.5264
BS	<0.001	<0.001	<0.001	0.1033	0.1505	<0.001	<0.001	<0.001	0.2965	0.3256	<0.001	<0.001	<0.001	<0.001	0.1887
AS	<0.001	<0.001	<0.001	0.1589	0.1362	<0.001	<0.001	<0.001	0.1864	0.4387	<0.001	<0.001	<0.001	0.1860	0.5648

¹ Conventional soil tillage system; ² Deep strip-tillage system; ³ Modified deep strip-tillage system; no significative $p \geq 0.1$.

Table S2. P values indicating the effect of lime rates for each tillage systems on sugarcane leaf diagnosis in Macatuba and Piraju

Elements	N	P	K	Ca	Mg	S	Fe	Cu	Zn	Mn	B
CT						Plant Cane					
Macatuba	0.5455	0.1235	0.1963	<0.001	<0.001	0.9055	0.0216	0.0025	0.9165	0.8086	0.5631
Piraju	0.8953	0.1812	0.9419	0.8214	0.8804	0.8247	0.5127	0.6107	0.6982	0.3544	0.2128
DT											
Macatuba	0.8799	0.4622	0.3402	0.0119	0.0112	0.3736	0.4226	0.6079	0.5340	0.4651	0.2383
Piraju	0.1482	0.1893	0.7340	0.8875	0.1479	0.1552	0.9712	0.9676	0.5714	0.8666	0.9597
MDT											
Macatuba	0.5918	0.1995	0.1838	<0.001	0.0341	0.5427	0.6774	0.1327	0.6874	0.1418	0.1663
Piraju	0.4548	0.5633	0.3231	0.6580	0.2190	0.1810	0.8764	0.5212	0.3033	0.1217	0.2847
						1 st Ratoon					
CT											
Macatuba	0.6589	0.5135	0.8918	0.6705	0.4961	0.4127	0.2991	0.3665	0.4055	0.6903	0.2146
Piraju	0.2559	0.3208	0.8711	0.3799	0.3566	0.1339	0.2565	0.2110	0.1103	0.1214	0.4148
DT											
Macatuba	0.6739	0.2214	0.1174	0.2380	0.3550	0.8919	0.1854	0.1233	0.9267	0.6460	0.4008
Piraju	0.6810	0.2577	0.7366	0.4463	0.5540	0.6310	0.8895	0.9045	0.1821	0.1874	0.1578
MDT											
Macatuba	0.4865	<0.001	0.1385	0.0024	0.8187	0.3868	0.7427	0.2126	0.0372	0.7377	0.5889
Piraju	0.9957	0.9804	0.4100	0.7528	0.6445	0.9358	0.8042	0.1084	0.8164	0.2318	0.4158
						2 nd Ratoon					
CT											
Macatuba	0.8744	0.3078	0.1987	0.8224	0.0388	0.9097	0.3054	0.0452	0.1443	0.8453	0.1417
Piraju	0.4987	0.6102	0.4470	0.2914	<0.001	0.4716	0.9930	0.7145	0.1195	<0.001	0.1798
DT											
Macatuba	0.8094	0.4810	0.1885	0.0102	0.0435	0.1765	<0.001	0.1243	0.6447	0.2302	0.3813
Piraju	0.5851	0.7881	0.2382	0.0025	0.3363	0.5851	0.4469	0.7044	0.1315	0.1107	0.3724
MDT											
Macatuba	0.1601	0.1083	0.2389	0.9502	0.5695	0.2787	0.7064	0.6976	0.6484	0.4276	0.5696
Piraju	0.8869	0.6192	0.3425	0.0199	0.3316	0.4122	0.6579	0.3189	0.1185	0.1624	0.1223
						3 rd Ratoon					
CT											
Macatuba	0.7159	0.5993	0.7243	0.0072	<0.001	0.9651	0.3608	0.6801	0.2626	0.1465	0.8700
Piraju	0.7279	0.8170	0.8612	0.4172	0.2599	0.3661	0.7695	0.3087	0.5062	<0.001	0.8503
DT											
Macatuba	0.2433	0.1380	0.2342	0.0174	0.0359	0.9007	0.5612	0.5508	0.4877	0.3085	0.2758
Piraju	0.1646	0.7683	0.8937	0.4573	0.0230	0.8749	0.2264	0.5450	0.5551	<0.001	0.4494
MDT											
Macatuba	0.7656	0.8131	0.2213	0.0045	0.0024	0.9384	0.9373	0.9230	0.2231	0.2862	0.5026
Piraju	0.4698	0.4068	0.5079	0.1001	0.4970	0.7199	0.9905	0.7829	0.8128	<0.001	0.9184

no significative $p \geq 0.1$.

Table S3. P values indicating the effect of lime rates for each tillage systems on sugarcane technological and yield parameters in Macatuba and Piraju

Yield parameters	Macatuba			Piraju		
	CT ¹	DT ²	MDT ³	CT	DT	MDT
	Plant cane					
Sucrose	0.1710	0.8884	0.1627	0.1052	0.0400	0.0062
TRS ⁴	0.1619	0.9132	0.1380	0.040	0.0065	0.0067
Stalk yield	0.0153	0.0684	0.0697	0.0023	<0.001	<0.001
Sugar yield	0.0104	0.0625	0.0178	0.001	<0.001	<0.001
	1st Ratoon					
Sucrose	0.0365	0.4709	0.3589	0.0069	0.0325	0.0011
TRS	0.0451	0.3942	0.4626	0.0020	0.0452	<0.001
Stalk yield	<0.001	0.0083	<0.001	<0.001	<0.001	<0.001
Sugar yield	<0.001	0.0075	<0.001	<0.001	<0.001	<0.001
	2nd Ratoon					
Sucrose	0.1580	0.1559	0.4948	0.0069	0.0439	<0.001
TRS	0.1204	0.1822	0.5077	0.0020	0.0486	<0.001
Stalk yield	<0.001	<0.001	0.0067	<0.001	<0.001	<0.001
Sugar yield	<0.001	<0.001	0.0093	<0.001	<0.001	<0.001
	3rd Ratoon					
Sucrose	0.0223	0.0115	<0.001	0.4281	0.5083	0.7108
TRS	0.0162	0.0100	<0.001	0.5924	0.4402	0.8260
Stalk yield	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sugar yield	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

¹ Conventional soil tillage system; ² Deep strip-tillage system; ³ Modified deep strip-tillage system; ⁴Total recoverable sugar; no significative p≥0.1.

Table S4. P values indicating the effect of lime rates for each tillage systems on soil chemical attributes after harvests at each soil depth in Piraju

Depth (m)	CT1					DT2					MDT3				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Plant Cane															
pH	<0.001	<0.001	<0.001	0.8436	0.8727	<0.001	<0.001	0.1031	0.2282	0.1255	<0.001	<0.001	<0.001	0.2514	0.8142
Ca ²⁺	<0.001	<0.001	<0.001	<0.001	0.1145	<0.001	<0.001	<0.001	0.3707	0.2797	<0.001	<0.001	<0.001	<0.001	<0.001
Mg ²⁺	<0.001	<0.001	<0.001	<0.001	0.7834	<0.001	<0.001	<0.001	<0.001	0.0213	<0.001	<0.001	<0.001	<0.001	<0.001
BS	<0.001	<0.001	<0.001	<0.001	0.0154	<0.001	<0.001	<0.001	0.6310	0.1503	<0.001	<0.001	<0.001	<0.001	<0.001
AS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.1021	0.7044	<0.001	<0.001	<0.001	<0.001	<0.001
1 st Ratoon															
pH	<0.001	<0.001	<0.001	0.8017	0.7222	<0.001	<0.001	<0.001	0.6434	0.5493	<0.001	<0.001	0.0129	0.5085	0.7082
Ca ²⁺	<0.001	0.0021	0.9910	0.9898	0.5157	<0.001	<0.001	<0.001	0.2215	0.1181	<0.001	<0.001	<0.001	0.1468	0.5177
Mg ²⁺	<0.001	<0.001	0.0134	0.6915	0.7515	<0.001	0.0023	<0.001	0.0176	0.3457	<0.001	<0.001	0.0162	<0.001	0.1002
BS	<0.001	<0.001	<0.001	0.6238	0.3769	<0.001	<0.001	<0.001	0.4022	0.4363	<0.001	<0.001	<0.001	0.0127	0.0032
AS	<0.001	<0.001	0.0067	0.5463	0.6115	<0.001	<0.001	0.0042	0.2760	0.2038	<0.001	<0.001	<0.001	<0.001	0.2332
2 nd Ratoon															
pH	<0.001	0.0256	0.0063	0.8436	0.3217	0.0139	0.0170	0.0035	0.1807	0.2427	<0.001	<0.001	<0.001	0.1084	0.1046
Ca ²⁺	<0.001	<0.001	0.2506	0.1066	0.7099	<0.001	<0.001	<0.001	0.2003	0.6072	<0.001	<0.001	0.7834	0.1637	0.4108
Mg ²⁺	<0.001	<0.001	0.0419	0.3795	0.2455	<0.001	<0.001	0.1649	0.1953	0.6434	<0.001	<0.001	0.0438	0.0015	0.1877
BS	<0.001	<0.001	0.0014	0.1035	0.1706	<0.001	<0.001	<0.001	0.8072	0.1516	<0.001	0.0158	<0.001	0.0238	0.0354
AS	<0.001	<0.001	<0.001	0.1843	0.5832	<0.001	<0.001	<0.001	0.2865	0.1916	<0.001	<0.001	<0.001	<0.001	0.3394
3 rd Ratoon															
pH	<0.001	<0.001	0.0254	0.6867	0.2404	<0.001	<0.001	0.0320	0.2194	0.1135	<0.001	<0.001	0.0499	0.2231	0.3313
Ca ²⁺	<0.001	<0.001	0.1580	0.5626	0.1517	<0.001	<0.001	<0.001	0.1229	0.3437	<0.001	<0.001	0.8247	0.1138	0.6915
Mg ²⁺	<0.001	0.0037	0.1595	0.9514	0.9271	<0.001	<0.001	0.2882	0.9048	0.3272	<0.001	<0.001	<0.001	0.1889	0.1194
BS	<0.001	<0.001	<0.001	0.1615	0.9238	<0.001	<0.001	<0.001	0.2404	0.3120	<0.001	<0.001	<0.001	0.3923	0.3214
AS	<0.001	<0.001	<0.001	0.2811	0.1413	<0.001	<0.001	<0.001	0.4363	0.5455	<0.001	<0.001	<0.001	0.0020	0.2041

1 Conventional soil tillage system; 2 Deep strip-tillage system; 3 Modified deep strip-tillage system; no significant p≥0.1.

APPENDIX (SUPPLEMENTARY MATERIAL) – CHAPTER 2

Table S1. P values indicating effect of different soil tillage systems and lime placement on soil chemical attributes across the profile in Macatuba

Soil attributes	Planting Furrow					Traffic Row				
	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.00	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.00
Plant Cane										
pH	< 0.001	< 0.001	< 0.001	< 0.001	0.0059	< 0.001	< 0.001	0.1711	0.9171	0.2574
Ca ²⁺	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.0089	0.1968
Mg ²⁺	< 0.001	< 0.001	< 0.001	0.0031	< 0.001	< 0.001	< 0.001	0.0073	0.2610	0.2413
BS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.0216	0.0142
AS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.3621
1 st Ratoon										
pH	< 0.001	< 0.001	< 0.001	0.0103	0.0485	< 0.001	< 0.001	< 0.001	0.1561	0.7970
Ca ²⁺	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.1711	0.4521
Mg ²⁺	< 0.001	< 0.001	< 0.001	< 0.001	0.3076	< 0.001	< 0.001	0.2145	0.3214	0.1985
BS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.1296	0.1537
AS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.2416
2 nd Ratoon										
pH	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.2995	0.8247
Ca ²⁺	< 0.001	< 0.001	< 0.001	0.0017	0.0045	< 0.001	< 0.001	< 0.001	0.3267	0.9514
Mg ²⁺	< 0.001	< 0.001	< 0.001	0.0304	0.1436	< 0.001	< 0.001	0.3624	0.1936	0.4363
BS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.2684	0.7046
AS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.2690
3 rd Ratoon										
pH	< 0.001	< 0.001	0.0308	0.0236	0.1505	< 0.001	0.0082	0.2264	0.5207	0.2710
Ca ²⁺	< 0.001	< 0.001	< 0.001	0.7569	0.2360	< 0.001	< 0.001	0.1859	0.6544	0.9201
Mg ²⁺	< 0.001	< 0.001	0.0019	0.1877	0.2072	< 0.001	< 0.0496	0.2975	0.9488	0.1542
BS	< 0.001	< 0.001	< 0.001	0.0426	0.2351	< 0.001	< 0.001	0.3677	0.2101	0.8572
AS	< 0.001	< 0.001	< 0.001	0.1485	0.1835	< 0.001	< 0.001	0.2075	0.9852	0.4068

no significative $p \geq 0.1$.

Table S2. P values indicating effect of different soil tillage systems and lime placement on soil chemical attributes across the profile in Piraju

Soil attributes	Planting Furrow					Traffic Row				
	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.00	0.0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.00
Plant Cane										
pH	< 0.001	0.0063	0.0308	0.4975	0.9801	< 0.001	< 0.001	0.2661	0.2280	0.2307
Ca ²⁺	< 0.001	< 0.001	< 0.001	< 0.001	0.0045	< 0.001	< 0.001	0.1320	0.4410	0.1116
Mg ²⁺	< 0.001	< 0.001	< 0.001	0.0024	< 0.001	< 0.001	< 0.001	0.1276	0.3187	0.1855
BS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.1154	0.3325	0.1652
AS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	-	< 0.001	0.1658	0.2370	0.2116
1 st Ratoon										
pH	< 0.001	< 0.001	< 0.001	0.5934	0.4047	< 0.001	< 0.001	0.2307	0.8804	0.2450
Ca ²⁺	< 0.001	< 0.001	< 0.001	< 0.001	0.0091	< 0.001	< 0.001	0.1100	0.2019	0.3176
Mg ²⁺	< 0.001	< 0.001	0.0388	< 0.001	< 0.001	< 0.001	< 0.001	0.1652	0.1855	0.2231
BS	< 0.001	< 0.001	< 0.001	0.0489	< 0.001	< 0.001	< 0.001	0.5214	0.9745	0.1789
AS	< 0.001	< 0.001	< 0.001	0.009	0.0059	-	< 0.001	0.4127	0.2536	0.1425
2 nd Ratoon										
pH	0.0088	0.0145	0.8800	0.1854	0.3109	< 0.001	0.2328	0.1158	0.3440	0.1237
Ca ²⁺	< 0.001	< 0.001	0.5664	0.2635	0.2345	< 0.001	0.0426	0.1550	0.3360	0.1450
Mg ²⁺	< 0.001	< 0.001	< 0.001	0.1662	0.1896	< 0.001	< 0.001	0.1328	0.1482	0.4363
BS	< 0.001	< 0.001	< 0.001	0.2450	0.1854	0.0109	0.0024	0.2635	0.4015	0.2490
AS	< 0.001	< 0.001	< 0.001	0.1153	0.3235	< 0.001	< 0.001	0.2351	0.2410	0.4421
3 rd Ratoon										
pH	< 0.001	< 0.001	0.1556	0.4197	0.3641	0.0011	0.1773	0.1454	0.1457	0.3860
Ca ²⁺	< 0.001	< 0.001	0.2987	0.1194	0.2389	< 0.001	0.0426	0.7611	0.7970	0.1482
Mg ²⁺	< 0.001	0.0026	0.0435	0.1606	0.5157	< 0.001	< 0.001	0.1460	0.8727	0.4363
BS	< 0.001	< 0.001	< 0.001	0.1440	0.3149	< 0.001	< 0.001	0.1247	0.1560	0.2355
AS	< 0.001	< 0.001	< 0.001	0.2388	0.1789	< 0.001	< 0.001	0.1646	0.1155	0.2435

no significant $p \geq 0.1$.

Table S3. P values indicating effect of different soil tillage systems and lime placement on sugarcane leaf diagnosis in Macatuba and Piraju

Elements	N	P	K	Ca	Mg	S	Fe	Cu	Zn	Mn	B
						Plant Cane					
Macatuba	0.8474	0.3070	0.5442	< 0.001	0.0034	0.8279	0.0069	< 0.001	0.2971	0.2430	0.4588
Piraju	0.1646	0.4441	0.2097	0.9974	0.9182	0.9265	0.2444	0.1813	0.6804	0.9962	0.9647
						1 st Ratoon					
Macatuba	0.4580	0.1993	0.7286	< 0.001	0.8270	0.7300	0.9693	0.0043	0.4930	0.1566	0.4021
Piraju	0.7001	0.8223	0.9587	0.2119	0.9689	0.8835	0.7398	0.4749	<0.001	0.1920	0.8942
						2 nd Ratoon					
Macatuba	0.1830	0.6451	0.1161	0.1183	0.2608	0.1942	0.7762	0.0185	0.9043	0.7636	0.9203
Piraju	0.9462	0.5600	0.4221	0.7604	0.0343	0.5748	0.6637	0.8165	0.7659	0.0023	0.5402
						3 rd Ratoon					
Macatuba	0.2594	0.2772	0.4530	0.1645	< 0.001	0.7361	0.2300	0.9063	0.8872	0.8059	0.2190
Piraju	0.1419	<0.001	0.7707	0.1452	0.8890	0.1678	0.1461	0.4694	0.9883	<0.001	0.7940

no significative $p \geq 0.1$.

Table S4. P values indicating effect of different soil tillage systems and lime placement on sugarcane technological and yield parameters in Macatuba and Piraju

	Sucrose %	TRS kg Mg ⁻¹	Stalk yield Mg ha ⁻¹	Sugar yield Mg ha ⁻¹
			Plant Cane	
Macatuba	0.1400	0.1550	0.0685	0.0792
Piraju	0.0016	<0.001	<0.001	<0.001
			1 st Ratoon	
Macatuba	0.3050	0.2561	<0.001	<0.001
Piraju	<0.001	<0.001	<0.001	<0.001
			2 nd Ratoon	
Macatuba	0.0090	0.0067	<0.001	<0.001
Piraju	<0.001	<0.001	<0.001	<0.001
			3 rd Ratoon	
Macatuba	0.0062	0.0057	<0.001	<0.001
Piraju	0.5362	0.5586	<0.001	<0.001

no significative p≥0.1.

APPENDIX (SUPPLEMENTARY MATERIAL) – CHAPTER 3

Table S1. P values indicating potential effect of lime application and tillage systems on aluminum fractions after harvests of plant cane and second ratoon, within each soil depth

Soil depth (cm)	Total Monomeric-Al (%)					Al-Exchangeable (%)					Al-Non-Exchangeable (%)				
	0-20	20-40	40-60	60-80	80-100	0-20	20-40	40-60	60-80	80-100	0-20	20-40	40-60	60-80	80-100
Plant Cane															
Tillage (T)	0.1270	<0.001*	<0.001*	0.2430	0.1245	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Lime (L)	<0.001*	0.1658	0.0023*	0.1623	0.2453	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
T x L	<0.001*	<0.001*	0.0372*	0.5234	0.1214	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
CV%	5.19	6.51	12.05	7.31	5.94	2.70	2.04	3.10	2.42	1.84	5.66	4.09	3.52	4.04	3.05
Second Ratoon															
Tillage (T)	<0.001*	0.0179*	0.0021*	0.5654	0.1425	<0.001*	<0.001*	<0.001*	0.0484*	0.1511	<0.001	<0.001	<0.001*	0.0436*	0.1227
Lime (L)	<0.001*	<0.001*	0.2534	0.4568	0.1382	<0.001*	<0.001*	<0.001*	<0.001*	0.2760	<0.001	<0.001	<0.001*	<0.001*	0.2227
T x L	<0.001*	<0.001*	<0.001*	0.2145	0.5436	<0.001*	<0.001*	<0.001*	<0.001*	0.1145	<0.001	<0.001	<0.001*	<0.001*	0.1549
CV%	1.8	6.50	11.85	12.31	11.39	4.97	2.99	4.7	5.03	5.13	6.57	4.11	5.32	8.50	3.93

*Significant $p \leq 0.05$.

Table S2. P values indicating potential interactions and effect of lime application and tillage systems on soil chemical attributes (solid phase and solution) after harvests of plant cane and second ratoon at each soil depth

<i>P</i> value ¹	Plant cane						Second ratoon							
	pH CaCl ₂	SOC g kg ⁻¹	P _{ac} -----	Ca _{ex} mmol _c kg ⁻¹	Mg _{ex} -----	Ca _s --- mg L ⁻¹ ---	Mg _s ---	pH CaCl ₂	SOC g kg ⁻¹	P _{ac} -----	Ca _{ex} mmol _c kg ⁻¹	Mg _{ex} -----	Ca _s --- mg L ⁻¹ ---	Mg _s ---
0.0-0.2														
Tillage (T)	0.0027*	<0.001*	0.1254	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.5478	<0.001*	<0.001*	0.2351	0.0328*
Lime (L)	<0.001*	0.0225*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.0278*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
T x L	<0.001*	0.0077*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.1345	0.0018*	<0.001*	<0.001*	<0.001*	0.4571	<0.001*
CV%	1.19	2.83	5.09	5.93	5.16	2.53	7.20	2.10	11.06	4.51	6.41	11.71	13.11	13.12
0.2-0.4														
Tillage (T)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.5142	<0.001*	0.0270*	0.0178*	0.1289
Lime (L)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
T x L	<0.001*	0.4123	<0.001*	<0.001*	<0.001*	<0.001*	0.0421*	<0.001*	<0.001*	<0.001*	<0.001*	0.0111*	0.0103*	0.0049*
CV%	1.07	3.13	4.52	8.42	6.77	4.68	11.12	2.97	7.58	4.38	6.01	8.45	11.20	15.60
0.4-0.6														
Tillage (T)	<0.001*	<0.001*	<0.001*	<0.001*	0.1987	<0.001*	<0.001*	0.1965	<0.001*	<0.001*	<0.001*	<0.001*	0.0109*	0.1253
Lime (L)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.5621	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
T x L	0.3245	0.1243	<0.001*	<0.001*	0.1432	0.0134*	0.0045*	0.3612	<0.001*	<0.001*	<0.001*	<0.001*	0.0208*	<0.001*
CV%	1.40	3.00	4.09	7.86	15.20	5.43	10.20	3.07	7.19	2.87	8.05	6.86	11.90	14.41
0.6-0.8														
Tillage (T)	0.2365	0.6325	<0.001*	<0.001*	0.3214	<0.001*	<0.001*	0.3256	0.2436	<0.001*	0.1236	<0.001*	0.0044*	0.0987
Lime (L)	<0.001*	0.2145	<0.001*	<0.001*	<0.001*	<0.001*	0.6358	<0.001*	0.1298	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
T x L	0.6532	0.1325	<0.001*	0.0130*	0.3256	<0.001*	<0.001*	0.5432	0.6542	<0.001*	0.3653	<0.001*	<0.001*	<0.001*
CV%	1.86	5.94	2.64	7.80	11.49	3.60	7.63	1.65	8.01	3.44	7.66	6.37	8.60	11.27
0.8-1.00														
Tillage (T)	0.1368	0.5268	0.0202*	0.0180*	0.1698	<0.001*	<0.001*	0.2147	0.5436	0.5214	0.2563	<0.001*	0.0048*	0.3251
Lime (L)	<0.001*	0.6398	0.0332*	<0.001*	<0.001*	<0.001*	0.2163	<0.001*	0.3245	<0.001*	<0.001*	0.0169*	<0.001*	<0.001*
T x L	0.8792	0.1453	<0.001*	0.0481*	0.1145	<0.001*	0.4532	0.7136	0.2145	0.4136	0.3251	0.2145	0.0309*	0.0114*
CV%	3.13	5.90	4.80	7.83	13.16	10.06	7.67	3.97	7.89	5.42	8.61	11.23	6.22	18.85

*Significant $p \leq 0.05$.

Table S3. Soil chemical attributes (solid phase and solution) and comparison between tillage systems and lime application rates among each soil depth. Soils sampled after plant cane harvest

	pH CaCl ₂		SOC g kg ⁻¹		P _{ac}		Ca _{ex} mmol _c kg ⁻¹		Mg _{ex}		Ca _s mg L ⁻¹		Mg _s	
	Control ¹	2x LRR ²	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR
Tillage														
0.0-0.2														
CT ³	4.6 aB	5.6 bA	12.8 aA	12.2 aB	40 aA	19.3 aB	17.1 aB	50.3 bA	7.5 aB	22.4 aA	7.64 aB	8.38 bA	2.90 aB	3.47 bA
DT ⁴	4.5 aB	5.5 bA	11.9 bA	11.3 bB	39 aA	21.6 aB	13.8 aB	45.3 cA	7.0 aB	15.4 bA	7.55 aB	8.32 bA	2.87 aB	3.39 bA
MDT ⁵	4.4 aB	5.9 aA	12.0 bA	11.2 bB	41 aA	16.9 bB	12.9 aB	59.4 aA	6.8 aB	23.4 aA	7.83 aB	17.55 aA	3.26 aB	4.65 aA
LSD	0.1102		0.5081		2.6741		2.9042		1.2391		0.7316		0.3997	
0.2-0.4														
CT	4.4 aB	5.2 bA	-	-	42.7 aA	30.0 bB	15.3 aB	40.5 bA	7.6 aB	12.4 bA	3.99 aB	4.60 bA	1.14 aB	1.38 bA
DT	4.3 aB	5.1 bA	-	-	42.9 aA	37.0 aB	14.7 aB	34.2 cA	7.2 aB	10.2 cA	4.30 aB	4.70 bA	1.21 aB	1.48 bA
MDT	4.3 aB	5.4 aA	-	-	43.3 aA	23.0 cB	13.7 aB	45.6 aA	6.6 aB	14.8 aA	4.24 aB	6.17 aA	1.16 aB	1.73 aA
LSD	0.0778		-	-	2.1413		1.1183		1.1114		0.3055		0.1854	
0.4-0.6														
CT	-	-	-	-	39.7 aA	30.3 bB	16.1 aB	28.9 bA	-	-	3.19 aB	4.60 bA	0.50 aB	0.81 bA
DT	-	-	-	-	41.0 aA	38.2 aB	15.5 aB	27.6 bA	-	-	3.16 aB	4.35 bA	0.54 aB	0.83 bA
MDT	-	-	-	-	40.6 aA	25.3 cB	14.7 aB	36.2 aA	-	-	3.09 aB	4.65 aA	0.61 aB	1.05 aA
LSD	-	-	-	-	2.5138		1.6777		-	-	0.4314		0.1462	
0.6-0.8														
CT	-	-	-	-	34.8 aA	32.3 bA	15.2 aB	24.4 bA	-	-	3.38 aB	4.33 bA	0.65 aB	0.77 bA
DT	-	-	-	-	36.0 aA	37.3 aA	13.9 aB	23.3 bA	-	-	3.15 aB	4.11 bA	0.55 aB	0.67 bA
MDT	-	-	-	-	35.9 aA	26.3 cB	14.7 aB	28.8 aA	-	-	3.17 aB	4.65 aA	0.64 aB	1.07 aA
LSD	-	-	-	-	0.9834		2.4487		-	-	0.2460		0.1077	
0.8-1.00														
CT	-	-	-	-	34.9 aA	34.3 aA	15.0 aB	21.7 bA	-	-	3.80 aB	4.41 bA	-	-
DT	-	-	-	-	36.1 aA	36.9 aA	13.2 aB	21.9 bA	-	-	3.13 aB	3.80 bA	-	-
MDT	-	-	-	-	37.2 aA	31.1 bB	14.1 aB	25.9 aA	-	-	3.41aB	5.53 aA	-	-
LSD	-	-	-	-	2.9837		2.6178		-	-	0.7096		-	-

¹ No lime application; ² Two times the lime recommended rate; ³ Conventional soil tillage system; ⁴ Deep strip-tillage system; ⁵ Modified deep strip-tillage system. Lime recommended rate according to (Spironello et al., 1996). Lowercase letters compare lime application rates, whereas uppercase letters compare tillage systems.

Table S4. Soil chemical attributes (solid phase and solution) and comparison between tillage systems and lime application rates among each soil depth. Soils sampled after harvest of second ratoon

	pH CaCl ₂		SOC g kg ⁻¹		P _{ac}		Ca _{ex} mmol _c kg ⁻¹		Mg _{ex}		Ca _s mg L ⁻¹		Mg _s	
	Control ¹	2x LRR ²	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR	Control	2x LRR
Tillage														
0.0-0.2														
CT ³	-	-	18.3 aA	16.0 aB	58.3 aA	38.3 aB	13.2 aB	35.8 bA	5.1 aB	12.5 bA	-	-	3.02 aB	13.77 aA
DT ⁴	-	-	15.4 bA	15.0 aA	57.1 aA	32.3 bB	13.2 aB	30.7 cA	5.0 aB	9.7 cA	-	-	3.01 aB	11.20 bA
MDT ⁵	-	-	15.6 bA	14.3 aA	54.4 aA	33.6 bB	12.1 aB	40.5 aA	5.0 aB	16.0 aA	-	-	2.57 aB	15.43 aA
LSD	-	-	2.2221		4.4273		1.6012		0.6930		-	-	1.8762	
0.2-0.4														
CT	3.8 aB	4.1 cA	14.0 aA	10.3 aB	64.2 aA	43.6 aB	12.4 aB	28.8 bA	5.4 aB	7.1 bA	10.83 aB	22.32 bA	5.86 aB	10.87 bA
DT	3.8 aB	4.6 bA	9.9 bA	9.8 aA	68.0 aA	41.3 aB	12.7 aB	24.5 cA	4.7 aB	7.2 bA	11.50 aB	20.18 bA	5.21 aB	10.18 bA
MDT	3.6 aB	4.9 aA	9.8 bA	9.9 aA	67.6 aA	34.6 bB	11.4 aB	31.3 aA	4.5 aB	10.1 aA	10.92 aB	27.82 aA	4.02 aB	15.73 aA
LSD	0.1532		1.3961		5.0664		1.4625		0.6258		4.0856		2.3876	
0.4-0.6														
CT	-	-	11.6 aA	8.3 aB	58.2 aA	45.0 aB	11.3 aB	15.4 bA	4.8 aB	6.0 aA	11.78 aB	19.89 aA	4.14 aB	8.51 bA
DT	-	-	7.3 bA	8.0 aA	56.6 aA	47.3 aB	11.0 aB	14.2 bA	5.1 aA	5.5 bA	11.98 aA	13.61 bA	5.11 aB	7.70 bA
MDT	-	-	7.0 bA	8.0 aA	59.5 aA	41.1 bB	10.9 aB	23.2 aA	4.8 aB	6.1 aA	12.89 aB	20.18 aA	4.23 aB	10.60 aA
LSD	-	-	1.5461		3.0802		1.4386		0.3819		3.2596		1.1737	
0.6-0.8														
CT	-	-	-	-	62.3 aA	50.9 bB	-	-	4.5 aB	5.0 aA	6.23 aB	12.34 bA	4.74 aA	5.57 bA
DT	-	-	-	-	66.8 aA	52.3 aB	-	-	4.6 aA	5.1 aA	7.00 aB	12.46 bA	5.70 aA	5.85 bA
MDT	-	-	-	-	64.4 aA	44.3 bB	-	-	4.1 bB	5.3 aA	5.65 aB	17.16 aA	5.20 aB	7.11 aA
LSD	-	-	-	-	3.7684		-	-	0.3180		1.5884		1.0703	
0.8-1.00														
CT	-	-	-	-	-	-	-	-	-	-	7.10 aB	12.62 bA	3.49 aA	4.19 aA
DT	-	-	-	-	-	-	-	-	-	-	6.48 aB	12.91 bA	3.35 aA	3.92 aA
MDT	-	-	-	-	-	-	-	-	-	-	7.56 aB	15.29 aA	2.97 aB	5.12 aA
LSD	-	-	-	-	-	-	-	-	-	-	0.8132		0.8746	

¹ No lime application; ² Two times the lime recommended rate; ³ Conventional soil tillage system; ⁴ Deep strip-tillage system; ⁵ Modified deep strip-tillage system. Lime recommended rate according to (Spironello et al., 1996). Lowercase letters compare lime application rates, whereas uppercase letters compare tillage systems.

Table S5. P values indicating the effect of lime application and tillage systems on technological attributes and sugarcane yield of plant cane and second ratoon

<i>P</i> value ¹	Sucrose concentration %	TRS kg Mg ⁻¹	Stalk yield Mg ha ⁻¹	Sugar yield
		Plant cane		
Tillage (T)	0.4939	0.5288	0.9627	0.8642
Lime (L)	0.0223*	0.0208*	0.0015*	<0.001*
T x L	0.3446	0.4768	0.9230	0.7996
CV%	2.54	2.51	8.38	9.04
		Second ratoon		
Tillage (T)	0.0578*	0.0407*	<0.001*	<0.001*
Lime (L)	0.0456*	0.0500*	<0.001*	<0.001*
T x L	0.1197	0.1507	0.4807	0.9407
CV%	3.01	2.97	5.23	6.86

*Significant $p \leq 0.1$.

Table S6. Effect of lime application and tillage systems on technological attributes and sugarcane yield of plant cane and second ratoon

Tillage	Sucrose concentration		TRS		Stalk yield		Sugar yield	
	%		kg Mg ⁻¹		Mg ha ⁻¹			
	Control ¹	2x LRR ²	Control	2x LRR	Control	2x LRR	Control	2x LRR
Plant cane								
CT ³	14.1 aB	14.8 aA	140.8 aB	147.2 aA	125.3 aB	145.5 aA	17.6 aB	21.4 aA
DT ⁴	14.5 aA	14.7 aA	145.0 aA	146.6 aA	126.2 aB	143.9 aA	18.3 aB	21.1 aA
MDT ⁵	14.3 aA	14.5 aA	142.2 aA	145.4 aA	125.9 aB	141.6 aA	17.9 aB	20.6 aA
LSD	0.4568		4.5075		14.0141		2.1851	
Second ratoon								
CT	15.0 bA	15.3 bA	149.4 bA	152.6 bA	88.5 bB	118.2 cA	13.2 bB	18.0 bA
DT	15.2 abA	16.1 aB	151.1 abB	160.1 aA	100.4 aB	127.3 bA	15.2 aB	20.4 aA
MDT	15.8 aA	15.7abA	156.5 aA	155.9 abA	101.6 aB	135.0 aA	15.9 aB	21.0 aA
LSD	0.5804		5.6985		7.2575		1.4723	

¹ No lime application; ² Two times the lime recommended rate; ³ Conventional soil tillage system; ⁴ Deep strip-tillage system; ⁵ Modified deep strip-tillage system. Lime recommended rate according to (Spironello et al., 1996). Lowercase letters compare the results in the lines, whereas uppercase letters compare the results in the columns.