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Abiotic and biotic factors affecting sugarcane yield in Gihofi Industrial plantations, Burundi

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Although it is produced at only one location, Gihofi, cane sugar is a strategic product for Burundi. However, data from recent decades have shown that expanding plantations has not been accompanied by an increase in yields. In order to determine the limiting factors of sugarcane yield, data on soil, pests, diseases and management practices were collected from 65 representative plots. Soil analysis was carried out at the Laboratoire d'Analyse du Sol et des Produits Agroalimentaires (LASPA) of the Institut des Sciences Agronomiques du Burundi (ISABU) using wet analytical method. The limiting factors found were related to agricultural practices (Weeds > Stem borer caterpillar severity > Compactness) and physicochemical factors. The results have shown that all diagnosed plots were deficient in phosphorus (<50 ppm) and zinc (<20 mg kg^{-1}), 95.92% were moderately to highly deficient in carbon (<3% C), 59.18% were deficient in nitrogen (<0.2%N), 40.83% of plots were deficient in potassium (<0.5 cmolc kg^{-1}), 44.90% in calcium (<4 cmol kg^{-1}) and 46.94% in magnesium (<0.5 cmol kg^{-1}). However, the five most important physicochemical factors that most limiting sugarcane yield were: Ca/Mg>Fe>P>CEC>Ca. To overcome these challenges, standards have been developed for the application of each deficient element.

Key words: Limiting curves, limiting factors, physicochemical factors ,productivity, standards.

INTRODUCTION

Grown in tropical and subtropical regions, sugarcane (*Saccharum officinarum*) is globally important, providing over 70% of the world's sugar consumption (Sentíes-Herrera et al., 2017; Yadav et al., 2020). As well as

providing food, sugarcane is being promoted for its many uses, including animal feed and as an energy source to replace fossil fuels (McKay et al., 2016; Sentíes-Herrera et al., 2017). In Burundi, sugar is used by households and the food industry. The Gihofi area is the only industrial sugarcane production zone, with annual production of around 20,000 tonnes (Moso Sugar Company [SOSUMO], 2022), enough to cover 60% of national sugar needs (BRB, 2020).

However, sugarcane yields and sugar production in the country are falling sharply (SOSUMO, 2017). Causes of such trend are numerous. Soil quality and soil organisms are negatively affected by certain sugarcane management practices (Chi et al.. 2020). Removal of sugarcane straw/ from fields reduces nitrogen cycling and depletes carbon stocks (Sousa Junior et al.. 2018). These soils become poor in organic matter and unproductive, limiting soil life and the biological activity of soil microorganisms, which would nevertheless improve the physico-chemical properties of the soil, while ensuring the production and efficient use of the nutrients needed by plants (Indoria et al., 2018). From the above, the agricultural production function of soils is closely linked to changes in soil physicochemical and biological properties, which in turn are functions of organic status (quality and quantity) (Benouadah, 2022). Soil organic carbon stocks and macroelement availability can therefore be influenced by the presence and management of sugarcane residues (Behiels et al., 2023). In addition, the reduction in the rate of water infiltration into the soil and the loss of water and soil through erosion are detrimental consequences of the lack of surface cover in the fields after the cane has been harvested (Valim et al., 2016).

Other inappropriate farming practices, such as long-term monoculture without crop rotation, excessive tillage, and post-harvest burning of waste, are all factors that degrade soil quality and reduce cane yields (Tabriz et al., 2022).

Furthermore, soil acidification, reduction of C/N ratio, hydrolysable alkaline nitrogen, total sulfur, organic matter, soil fungal and bacterial life, and disease dissemination are often associated with monocultural practices and hinder the sustainability of improved sugarcane production (Pang et al., 2021; Tayyab et al., 2021).

Fertilisation has a major impact on soil microbial communities, which play a central role in soil biogeochemical cycling and ecological processes (Li et al., 2017). Sustainable agriculture depends on the effectiveness of fertilisers, which in turn is determined by soil microbial communities (Liu et al., 2022). Organic fertilisation is one of the best ways to improve and restore soil, using crop residues and animal manure as soil improvers to encourage soil microbial life and activity (Tayyab et al., 2018). Sugarcane straw recycling provides a range of ecosystem services including erosion control, nutrient recycling, soil biodiversity, water storage, carbon sequestration, and weed control (Carvalho et al., 2019;

Carvalho et al., 2017; and could be a promising complement to mineral fertiliser for sustainable agriculture (Poultney, 2021). In water-stressed conditions, switching from a burnt cane harvesting system to a mulch system improves yields while increasing sugar content (De Aquino et al., 2018). Specifically, while leaving straw on the soil surface increases sugarcane yields, leaving it completely unmulched reduces yields by 37% under water stress conditions (De Aquino et al., 2017). When straw is used, 80% of the nitrogen, 55% of the potassium, and 33% of the phosphorus contained in the above-ground parts of the sugar cane come from the straw left on the ground (CIRAD, 2020). Inadequate weed management is also a major handicap to plant productivity, as it competes for the nutrients, light, and water the cane needs, thereby reducing yields in a relatively short time (Khaliq et al., 2020; Moreau et al., 2020) and can cause yield losses of 27-36% (Correia, 2016).

Climate change and variability increase the vulnerability of the agricultural sector by affecting changing water regimes, and agricultural production is one of the most sensitive sectors to climate change (Lemi, 2019). As a tropical and subtropical crop, sugarcane production is adversely affected by extreme fluctuations in temperature and rainfall due to climate change (Ali et al., 2021; Namdev et al., 2023). Thus, weed growth, pest behaviour and the spread of disease from one region to another are greatly influenced by climate variability (Msomba et al., 2024). Climate variability also disrupts sugarcane metabolism, growth, and production (Mokhena et al., 2016). Under these conditions, the sugar industry often suffers from the proliferation of diseases and pests that attack sugarcane, leading to reduced yields in terms of quantity and quality and, consequently, financial losses (Militante et al.. 2019; Elsharif and Abu-Naser. 2019).

Moreover, because of its high biomass production, sugar cane exports large quantities of nutrients, which accumulate in the plant and lead to soil depletion (Cheng et al.. 2016). As sugarcane yields are affected by both nutrient deficiency and excess (Bhatt, 2020), better fertilisation must be based on the quantification of inputs, considering the general state of soil fertility, soil structure, and agro-climatic conditions (Bhatt, 2020; Cheng et al., 2016; X. Zhang et al., 2020). This approach requires regular monitoring of the biotic and abiotic parameters that can affect yield. In Burundi, very little work has been done in this area to date. It is therefore important to have up-to-date results on the factors limiting sugarcane productivity in Gihofi's industrial plantations and to propose ways of correcting them.

This study aims to analyze the biotic and abiotic factors that limit sugarcane yield in the industrial plantations of Gihofi, managed by SOSUMO, given that no other study has been carried out since the introduction of sugarcane in 1986 in Burundi. Understanding these limiting factors will allow corrections to be made to increase cane yields
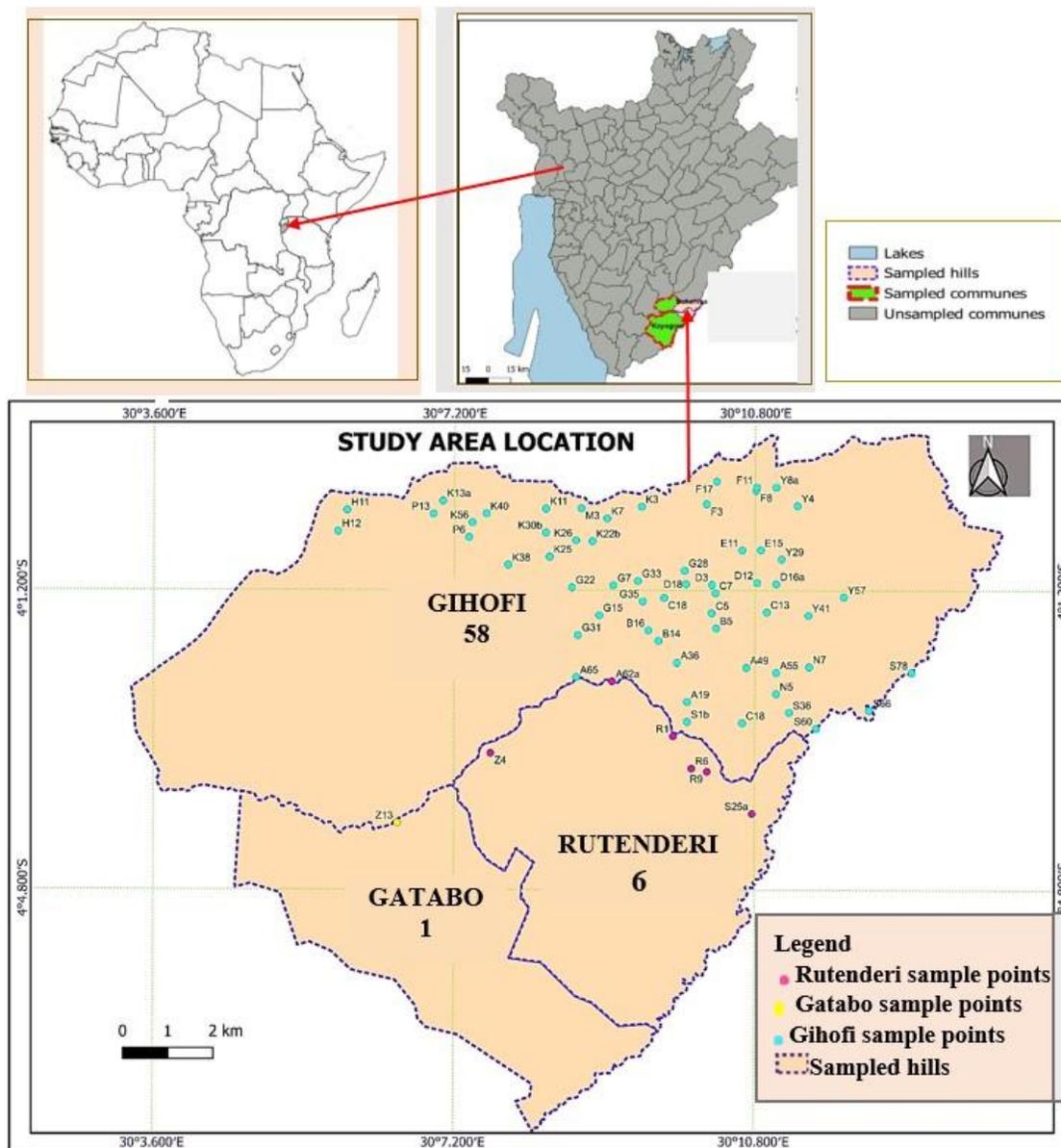
Figure 1. Map sampling location.
source: Author.

and sugar production, both in terms of quantity and quality.

MATERIALS AND METHODS

Site description

The study was carried out on SOSUMO plantations located in the Moso natural region in the Bukemba commune of Rutana province and the Kayogoro commune of Makamba province in south-eastern Burundi (Figure 1). With an altitude ranging from 1171 to 1260 m, this region receives an average annual rainfall of 1175 mm, while average monthly temperatures vary between 21 and 22°C, with minimums of up to 14°C and maximums of 28°C (MPDRN, 2006; Nzigidahera et al., 2008). The SOSUMO estate covers a total area of 5,800 ha, of which 3,880 ha (66.9%) are used to grow sugarcane.

Data collection and laboratory analysis

Representative plots were selected from the SOSUMO plantations. A total of 65 plots were selected, representing 20% of the sugarcane plots. These plots represented the diversity observed in the plantations in terms of location, yields and soil characteristics.

A total of 65 soil profiles corresponding to 65 representative plots were excavated and described. Describing these profiles made it possible to identify soil types according to the INEAC (Institut

National pour l'Etude Agronomique du Congo Belge) classification used in Burundi (Frankart and Sottiaux, 1972).

To determine the physico-chemical characteristics of the soil, samples were taken to a depth of 30 cm. Sampling points were selected in the two diagonals of the plot, with 20 points being sampled by auger. For each plot, a composite sample was taken by mixing the 20 samples and collecting 500 g of soil for laboratory analysis. Analyses were carried out at the LASPA (Laboratoire d'Analyse du Sol et des Produits Agro-alimentaires) of the ISABU (Institut des Sciences Agronomiques du Burundi). LASPA is an accredited SOAC, N°ES23010. The granulometry was determined using LASPA's internal method which, after destroying the organic matter, eliminates the clays by sedimentation, separates the sands and silts by filtration and determines the different sand fractions by sieving, while the silts are determined by decantation and filtration.

Wet method analysis was used and parameters analysed were water pH, organic carbon (Org C), total N, plant available P, exchangeable Ca, exchangeable Mg, exchangeable K, cation exchange capacity (CEC) total S, Zn, Copper and total Iron. Wet pH was determined using a pH meter in a 1:5 soil-water suspension; method certified according to ISO 10390 (N. E. 10390. 202. ISO, 2021). Organic C was determined using the method developed by the Centre d'Expertise du Québec (M.A.405-C .1.1) (Ma, 2023), which consists of sulphochromic oxidation and volumetric dosing. CEC and exchangeable cations were determined by the Metson method. Exchangeable cations were determined by extracting exchangeable by percolation with 1 M ammonium acetate at pH 7 and determination by atomic absorption spectrometry (AAS/flame); certified method NF X 31-108, and CEC was determined by the ammonium acetate method; certified method NF X 31-130 (CIRAD, 2017). Total nitrogen was determined by the modified Kjeldahl method and volumetric dosing; certified method ISO 11261 (N. 11261 ISO, 1995). Plant available phosphorus was determined by the modified Olsen-Dabin method, consisting of extraction with NaHCO$_3$ and determination by UV spectrophotometry; method certified by ISO 11263 (N. 11263 ISO, 1994).

Disease and pest severity were measured on 10 clumps selected diagonally. The severity was determined for each stem in the clump and the average of all the stems was taken as the average for the clump. The compactness of the B horizon was measured at the centre of the plot using a penetrometer. The percentage of weeds was obtained by estimating the percentage covered on a square meter, repeated 5 times in 5 randomly chosen locations in the plot in the direction of the diagonal, and the average constituted the data for the plot (Marnotte et al., 2018).

Determination of the limiting factor for sugarcane yield

The relationships between cane yield and soil characteristics, on one hand, and management and biotic factors, on the other, have been developed using usable cane yield in megagram per hectare (Mg kg^{-1}). The method used is that of determining boundary curves, which has previously been used to describe relationships between two biological variables (Webb, 1972). A Spearman test was used to determine the correlations between various factors and yield. Relationships were sought for factors with a significant Spearman test (p ≤ 0.05) or those that showed the existence of a functional relationship for the limit points (Fermont et al., 2009; Shatar and Mcbratney, 2004; Wairegi et al., 2010; D. Zhang et al., 2019; D. Zhang et al., 2020). Three models were used: (i) the logistic function for increasing functions with storage

$$YI = \frac{Ymax}{((1 + (Kexp(-R.x_n))}$$

(1)

where YI: the cane yield; Ymax: the maximum cane yield obtained;

x$_n$: the nth independent variable; K and R: coefficients. The target yield in this study is 121.03 Mg. ha^{-1} of usable cane ha^{-1}, that is 95% of the maximum achievable yield of 127.4 Mg. ha^{-1}

(ii) For factors with a negative or no significant correlation with yield, a quadratic or (iii) linear model was fitted to the limit points.

$$YI = ax^2 + bx + c$$

(2)

$$YI = ax + b$$

(3)

After determining the coefficients of the equations for the different soil or management parameters, the cane yield was calculated for each plot using the functions developed from the limit curve. For each plot, there are as many yield values calculated as there are factors taken into account. Ymin (minimum yield) was then determined by taking into account the cane yields calculated with all the factors.

$$Ymin = Min(Y_{x1}.Y_{x2}. ... Y_{xn})$$

(4)

with YX$_n$: yield calculated with factor x$_n$. This is the yield predicted by von Liebig's minimum law (Shatar and Mcbratney, 2004). The factor corresponding to this minimum yield was identified as the limiting factor.

RESULTS

Soil types

The soil survey of all SOSUMO sugarcane plantations showed that SOSUMO plantations located in swamps and valleys were dominated by humic regogley and typical regogley (Figure 2). The dominant soils on the hills and slopes were typical ferralsols and silty ferrisols.

Relationship between abiotic and biotic factors and yield

Table 1 shows the mean, standard deviation, minimum, and maximum values of sugarcane management parameters and physicochemical values obtained by wet and dry analysis methods. Factors associated with management practices were weed percentage (MH), penetration/penetrometer resistance (PN) and stem boring caterpillar severity (SCF), with mean and max values of (25.48; 100%) for MH, (6.34; 10.30 cm) for PN and (206.12; 1800 stem boring caterpillars) for SCF. The physico-chemical parameters had mean and maximum values of (6.09; 7.33) for pH$_{H2O}$, (2.24; 4.76 %) for organic carbon (C org), (0.20; 0. 39 %) for nitrogen (N), (10.93; 34.80 mg kg^{-1}) for phosphorus (P), (20.14; 30.40 cmolc kg^{-1}) for cation exchange capacity (CEC), (0.04; 0.10 mg kg^{-1}) for sulphur (S), (4. 99 ; 12.37 cmolc kg^{-1}) for calcium (Ca), (0.58; 1.11 cmolc kg^{-1}) for magnesium (Mg), (0.66; 1.49 cmolc kg^{-1}) for potassium (K), (3.22; 9.40 mg kg^{-1}) for zinc (Zn), (7.89; 12. 60 mg kg^{-1}) for copper (Cu), (84.57; 121.60 g kg^{-1}) for iron (Fe), (8.39

Table 1. Values of minimum, maximum, mean, and standard deviation of management practices and physicochemical parameters.

| Variable	Parameter	Min	Max	Mean	Standard deviation
	MH (%)	0.00	100.00	25.48	22.13
Parameters related to management practices	PN (cm)	0.70	10.30	6.34	2.26
	SCF (Number)	0.00	1800.00	206.12	351.43
	Soil pH$_{H20}$	4.69	7.33	6.09	0.58
	Organic C (%)	0.98	4.76	2.24	0.71
	N (%)	0.09	0.39	0.20	0.06
	P (mg kg^{-1})	1.40	34.80	10.93	8.27
	CEC (cmolc kg^{-1})	8.40	30.40	20.14	6.59
	S (mg kg^{-1})	0.01	0.10	0.04	0.02
	Ca (cmolc kg^{-1})	0.94	12.37	4.99	2.80
Physicochemical parameters	Mg (cmolc kg^{-1})	0.18	1.11	0.58	0.26
	K (cmolc kg^{-1})	0.03	1.49	0.66	0.36
	Ca/Mg	1.65	17.61	8.39	2.48
	Mg/K	0.17	21.70	1.57	3.03
	(Ca+Mg)/K	1.13	31.92	10.91	7.29
	Zinc (mg kg^{-1})	0.30	9.40	3.22	1.71
	Copper (mg kg^{-1})	3.80	12.60	7.89	2.16
	Iron (g kg^{-1})	23.50	121.60	84.57	25.77

Source: Author.
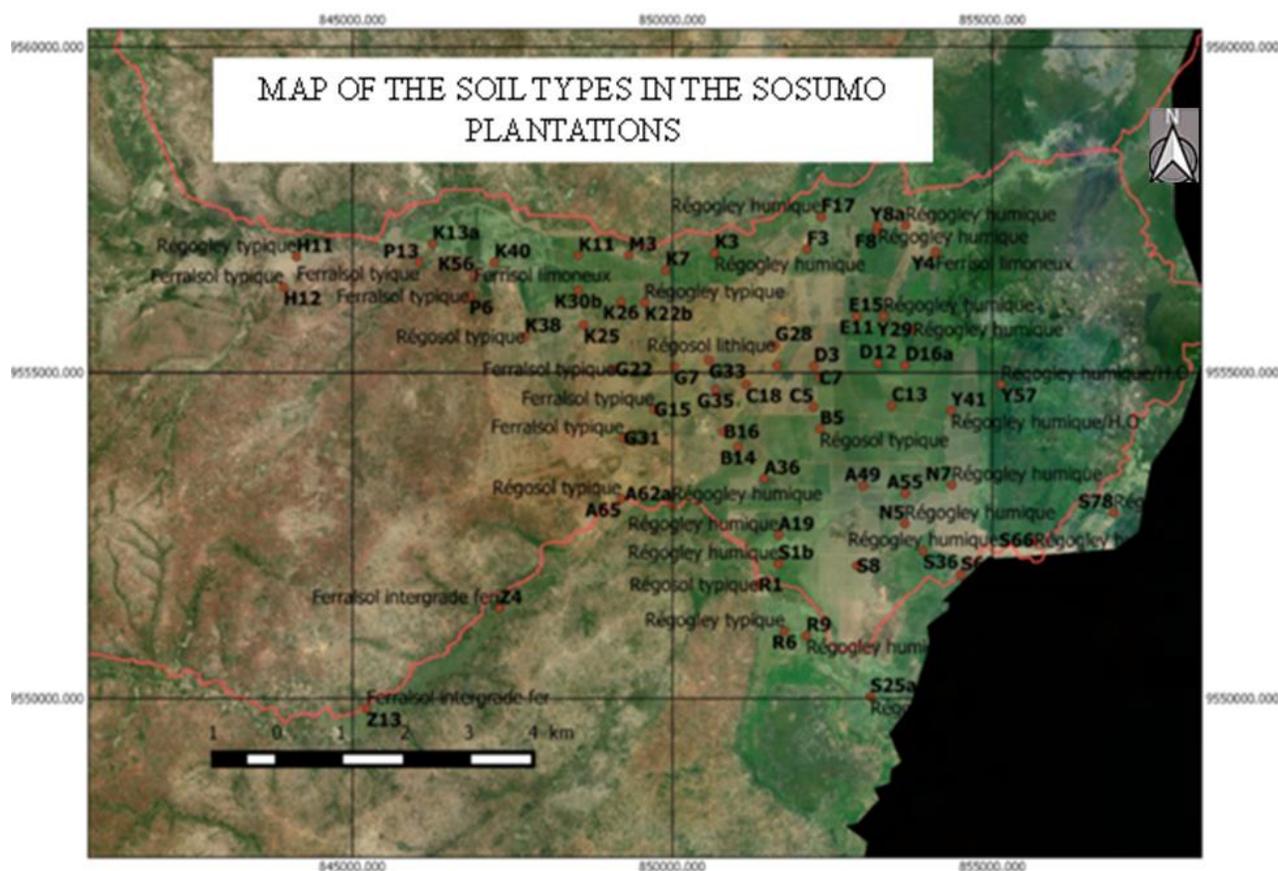
Figure 2. Sampled plot locations and soil types by plot.
source: Author.

Table 2. Analysis of yield as a function of physicochemical and management practices parameters.

Variable	Parameter	Yied	P
Parameters related to management practices	MH (%)	-0.489	0.003**
	PN (cm)	0.115	0.286
	SCF(Number)	-0.004	0.873
Physicochemical parameters	Soil pH$_{H2O}$	0.133	0.85
	C org (%)	0.133	0.402
	N (%)	0.349	0.014*
	P(mg kg^{-1})	-0.131	0.344
	CEC (cmolc kg^{-1})	0.397	0.001**
	S (mg kg^{-1})	0.075	0.942
	Ca (cmolc kg^{-1})	0.335	0.004**
	Mg (cmolc kg^{-1})	0.332	0.013*
	K (cmolc kg^{-1})	-0.034	0.463
	Ca/Mg	0.250	0.015*
	Mg/K	0.200	0.645
	(Ca+Mg)/K	0.219	0.981

Source: Author.

;17.61) for the Ca/Mg ratio, (1.57 ;21.70) for the Mg/K ratio and (10.91 ;31.92) for the (Ca+Mg)/K ratio.

The correlations between cane yield, management and biotic factors on one hand and physicochemical parameters on the other are shown in Table 2. The management factors and physicochemical parameters that showed significant correlations (p ≤0.05) according to Spearman's test were weeds (MH: r= -0.489, p = 0. 003), nitrogen (N: r= 0.349, p= 0.014), cation exchange capacity (CEC: r= 0.397, p = 0.001), calcium (Ca: r= 0.335, p=0.004), magnesium (Mg: r= 0.332, p= 0.013) and Ca/ Mg ratio (r= 0.250, p= 0.015).

Linear, polynomial, and logistic relationships between sugarcane yield, management parameters, and physicochemical parameters are as shown in Figure 3.

Ranking of limiting factors

The factors limiting usable cane yield in order of importance of the percentage of plots affected were compactness with 15% of plots affected, followed by CEC (14%), S (11%), Ca, the ratio (Ca+Mg)/K, Cu and Fe each affecting 8% of plots, pH, weeds and stem-boring caterpillars each affecting 6% of plots, P 5%, K 3%, N and the Ca/Mg ratio 1% of plots (Figure 4).

Limiting factors with the lowest average usable cane yield were the Ca/Mg ratio with a minimum average yield of 26.4 Mg ha^{-1}, followed by Fe (34 Mg ha^{-1}), P (52.8 Mg ha^{-1}), CEC (62.9 Mg ha^{-1}), Ca (64.4 Mg ha^{-1}), weeds (65. 9 Mg ha^{-1}), K (68 Mg ha^{-1}), S (72.9 Mg ha^{-1}), ratio (Ca+Mg)/K (74.3 Mg ha^{-1}), pH (79.3 Mg ha^{-1}), stem-boring caterpillar severity (80 Mg ha^{-1}), N (81.8 Mg ha^{-1}),

Cu (85.5 Mg ha^{-1}) and compactness with an average minimum yield of 93.8 Mg ha^{-1} (Figure 5).

Explained and unexplained yield gaps

The maximum observed machinable cane yield used was 127.38 Mg ha^{-1}. The coefficient of determination of the linear regression between the minimum predicted yield and the actual observed yield R^2 is 0.42 (Figure 6). Note that Ymax=127.38 Mg ha^{-1} and the diagonal represents the function (Y=X). For each point above the diagonal, the difference (Ymax-Ymin) shows the explained yield and is indicated by the arrow above Ymin (minimum predicted yield), while the arrow below Ymin shows the difference in unexplained yield (Ymin-Y observed).

Proposed standards for interpreting soil analyses and sugarcane management factors

Table 3 show the different equations used and the proposed interpretation standards for the physicochemical factors obtained and for the cultivation practices. The limiting physicochemical factors identified are limiting if they are outside the norms obtained after solving the equations for each element. From the above, organic carbon becomes limiting when it is less than 2%, nitrogen when it is less than 0.2%, cation exchange capacity concentration less than 21.6 cmolc kg^{-1}, calcium concentration less than 5.1 cmolc kg^{-1}, magnesium concentration less than 0.6 cmolc kg^{-1}, potassium concentration less than 0.6 cmolc kg-1, Ca/Mg ratio less
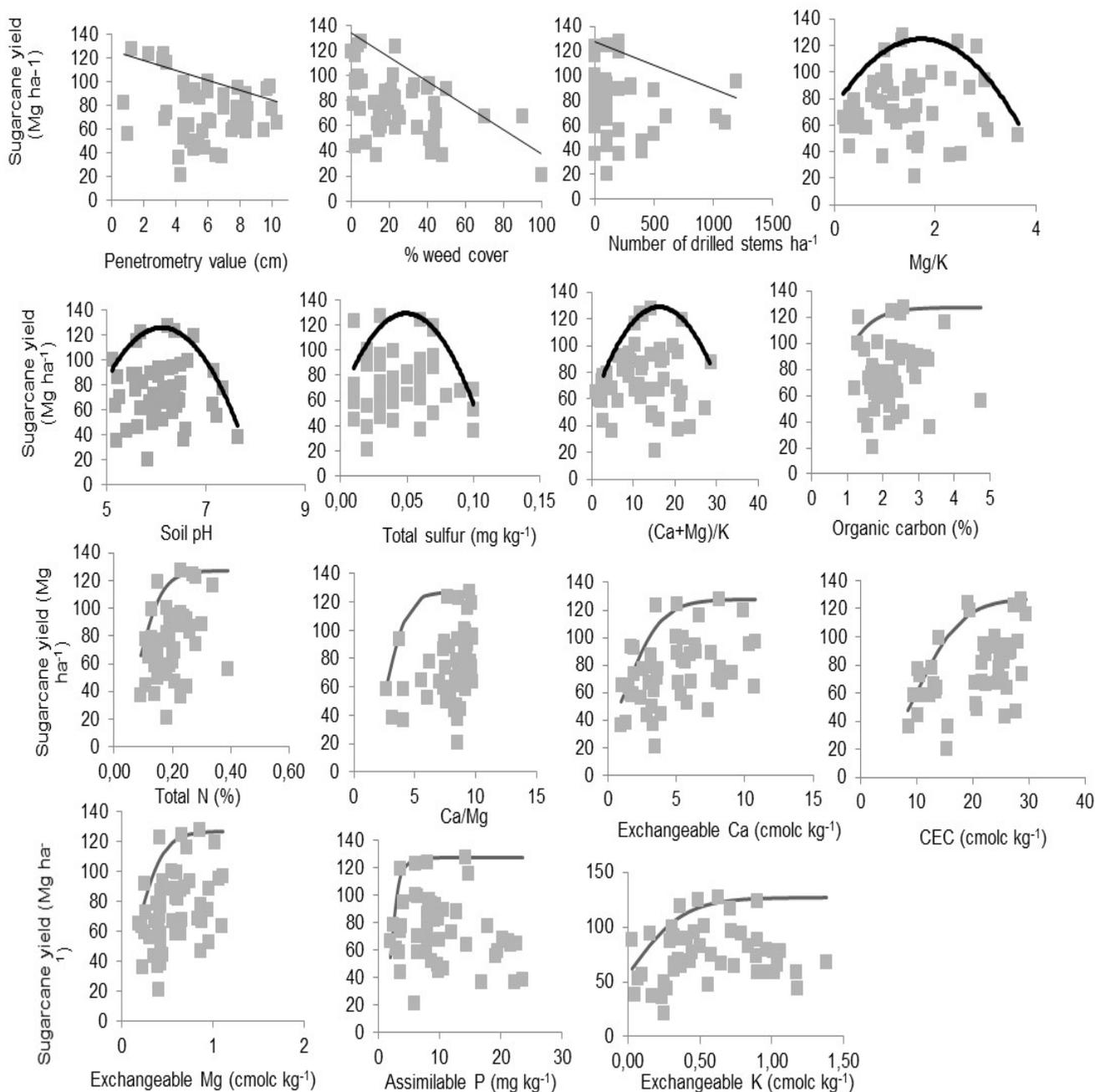
Figure 3. Relationships between yield, management parameters, and soil physicochemical parameters.
Source: Author.

than 5.2 and plant available phosphorus less than 4.2 mg kg^{-1}. In addition, the pH becomes a limiting factor if it is less than 5.7 or greater than 6.5, the Mg/K ratio if it is less than 1.3 or greater than 2.2, the (Ca+Mg)/K ratio if it is less than 10.9 or greater than 21.5 and, finally, sulphur becomes a limiting factor if it is less than 0.03 or greater than 0.1.

As for the cultivation practices, the same table shows that weeds are limiting factors for % of soil weed occupancy greater than 13, the penetrometry value for values greater than 1.3 cm and the severity of stem-boring caterpillars for values greater than 171.   The standards proposed for SOSUMO plantations are higher than those found in the literature for organic C, N, CEC, Ca and K, while they are lower than those found in the literature for Mg, available P and S. The standards
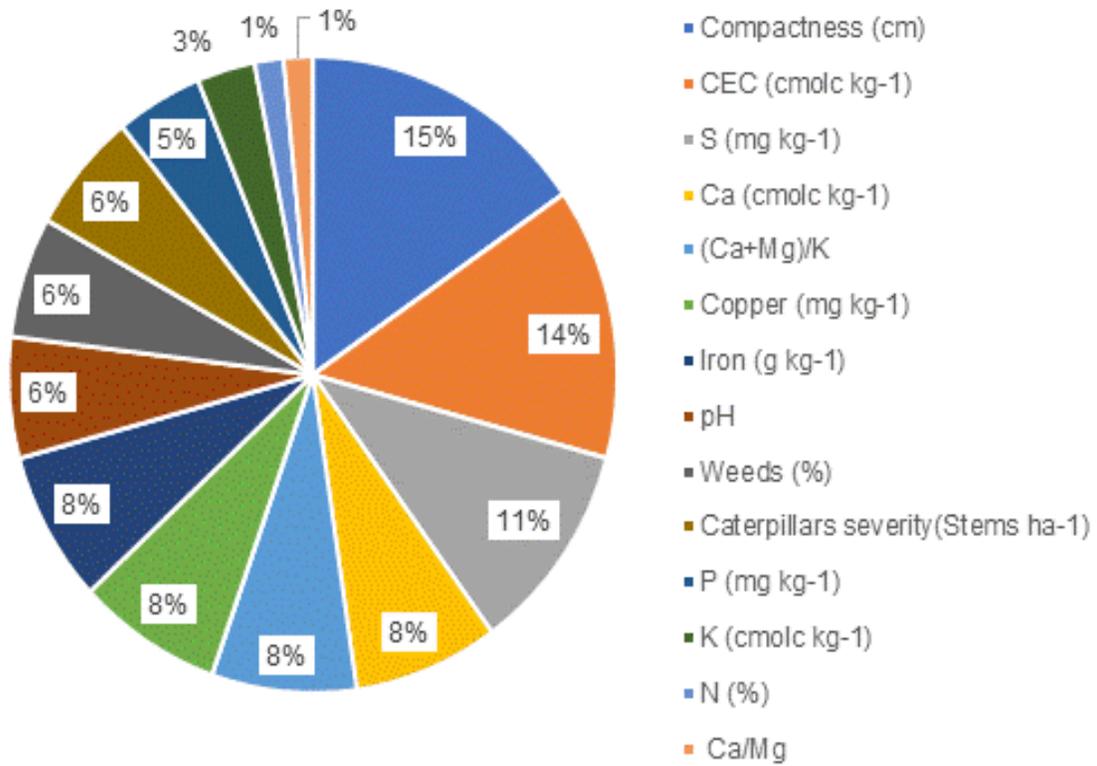
Figure 4. Limiting factor hierarchy.
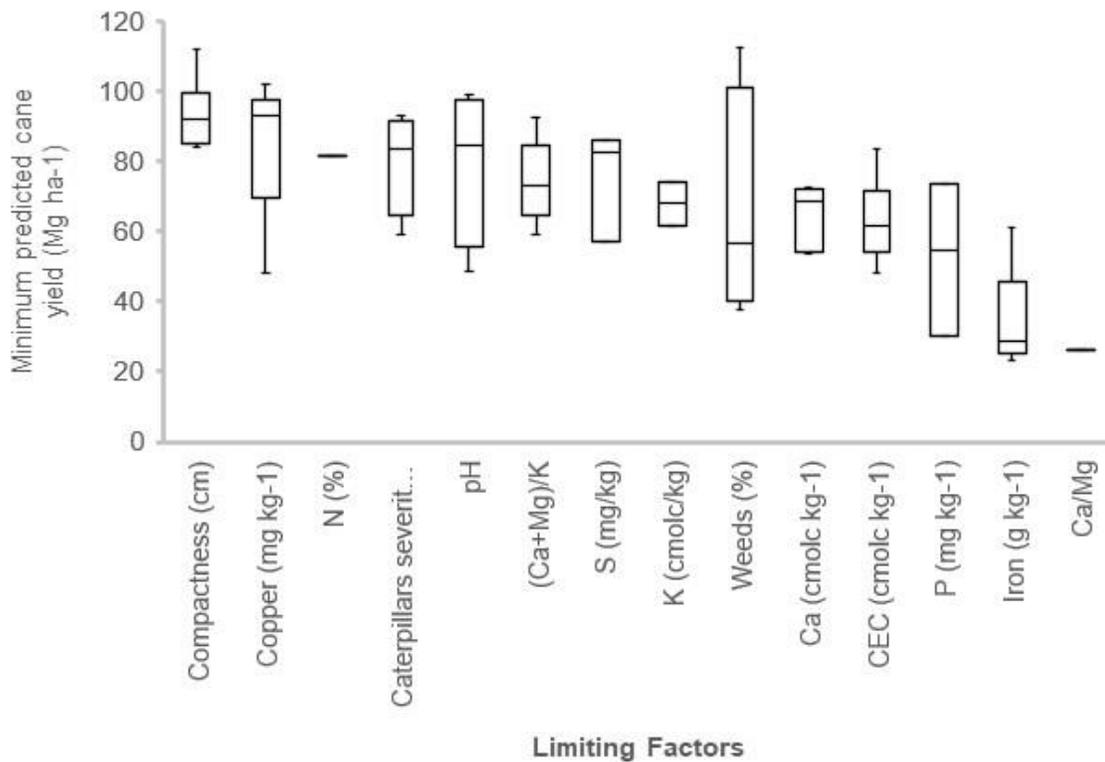Source: Author.

Figure 5. Hierarchy of limiting factors related to predicted average minimum yield.
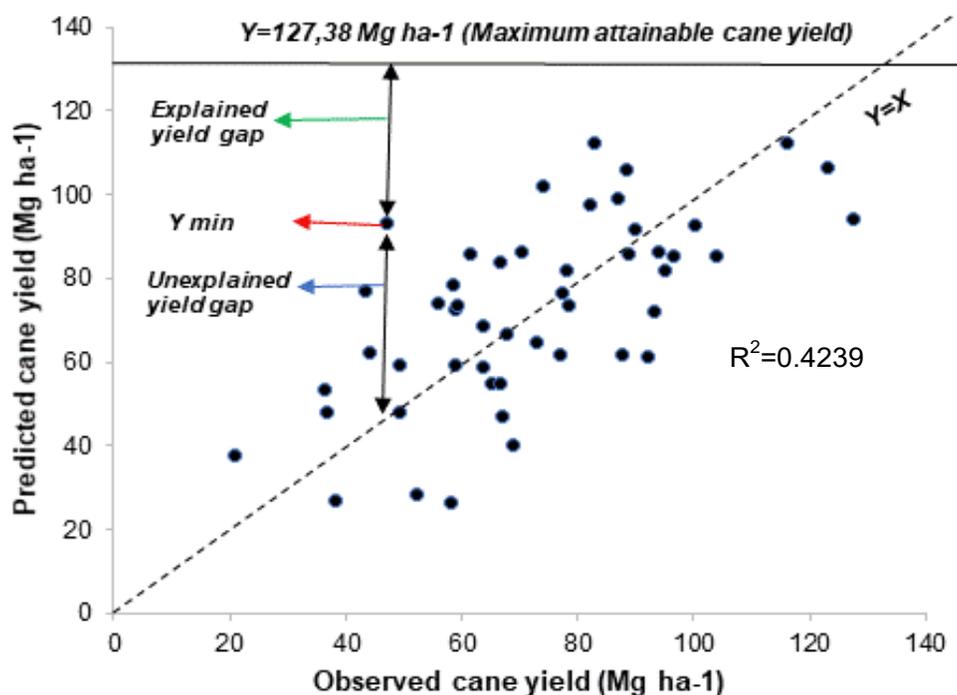Source: Author.

Figure 6. Relationship between observed machinable cane yield and predicted minimum yield.
Source: Author.

Table 3. Proposed formulae and standards for soil physicochemical factors and cultivation practices.

Factor	Formula	Standard	Literature Standard	Author
Physico-chemical factors				
Organic C (%)	$121 = \dfrac{127.38}{((1 + (2.88\exp(-2.02x))}$	≥ 2	>0.15	[1]
N (%)	$121 = \dfrac{127.38}{((1 + (9.26\exp(-25.56x))}$	≥ 0.2	>0.15	[1]
CEC (cmolc kg^{-1})	$121 = \dfrac{127.38}{((1 + (14.24\exp(-0.26x))}$	≥ 21.5	>10	[1]
Ca (cmolc kg^{-1})	$121 = \dfrac{127.38}{((1 + (2.87\exp(-0.78x))}$	≥ 5.1	>4.5	[1]
Mg (cmolc kg^{-1})	$121 = \dfrac{127.38}{((1 + (3.46\exp(-7.24x))}$	≥ 0.6	>2.2	[1]
K (cmolc kg^{-1})	$121 = \dfrac{127.38}{((1 + (1.26\exp(-5.63x))}$	≥ 0.6	>0.4	[1]
Ca/ Mg	$121 = \dfrac{127.38}{((1 + (27.6\exp(-1.2x))}$	≥ 5.2	-	

Table 3. Cont'd

P assimilable (mg kg⁻¹)	$121 = \dfrac{127.38}{((1 + (25.6\exp(-1.48x)))}$	≥ 4.2	> 80	[1]
pH$_{eau}$	$121 = -33x^2 + 408.7x - 1121$	5.7-6.5	>5.50	[1]
Mg/K	$121 = -17.16x^2 + 59.33x + 73.53$	1.3-2.2	-	
(Ca+Mg)/K	$121 = -0.284x^2 + 9.217x + 54.16$	10.9-21.5	-	
S (mg kg⁻¹)	$121 = -27917x^2 + 2748x + 61.66$	0.03-0.07	>15	[2]
Farming practice				
Weeds (%)	$121 = -0.959x + 133.6$	≤ 13	-	
Penetrometer value (compactness) (cm)	$121 = -4.145x + 126.4$	≤ 1.3	-	
Stem boring caterpillar severity	$121 = -0.038x + 127.5$	≤ 171 Stems drilled ha⁻¹	-	

[1]Standards established by Fillols and Chabalier (2006) ; [2] Standards established by Schroeder et al. (2007).
Source: Author.

established for pH are close to those found in the literature, since the values found are in the same order of magnitude.

DISCUSSION

Effect of soil physicochemical parameters on sugarcane yield

pH

Quantitative assessment of soil physicochemical parameters is essential to reduce yield variation (Khechba et al., 2021). The results of the analyses (Table 1) showed that the local soils were very acidic to neutral (Tessens and Gourdin, 1993; Kaboneka et al., 2020). From the above, the results obtained showed that 2.04% of the SOSUMO plots diagnosed were very acidic (pH<5), 16.33% strongly acidic (5<pH<5.5), 28.57% moderately acidic (5.6<pH<6) and 53.06% weakly acidic to neutral (6.1<pH<7.5).

In Burundi, more than a quarter of cultivated soils are acidic, with a pH below 5, and very few soils have an optimal pH and it is not easy to find basic soils (Nduwimana et al., 2013). Recent studies have shown that 61% of the soils in the eastern depressions are very highly acidic or highly acidic (IFDC, 2022). However, even though the SOSUMO plantations are located in the eastern depressions, the results show that only 18.37% of the soils are very acidic to acidic (pH<5.5). Therefore,

local acidity is not a major problem in the study area. This may be because more than 80% of SOSUMO's sugarcane plantations are located in low-lying areas with high organic matter content, and acidity problems are more prevalent in hilly plantations, which are often eroded, and the study was conducted in a small part of the eastern depression with fewer hills.

On one hand, this acidification is thought to be due to the excessive use of acidifying mineral fertilisers, which are sources of nitrogen, phosphorus, and potassium in plantations (Konkobo et al., 2018), and on the other hand, low levels of organic matter, which can lead to rapid soil degradation (Amonmide et al., 2019). Moreover, in the part of the soil with high acidity, there is a risk of aluminium toxicity and excess of Cu, Fe, Zn, Co, and Mn, as well as deficiencies of Ca, K, N, Mg, Mo, P, and S, leading to nutrient imbalance and limited plant development, resulting in yield losses (Kouadio et al., 2018; Landon, 1991; Rajeshwar et al., 2018).

Adequate liming of acid soils can raise pH to 6.6-7.5, allowing plants to use nutrients efficiently. Conservation agriculture practices that leave straw on fields can help combat soil degradation and nutrient loss while maintaining good soil characteristics, improving soil fertility and increasing sugarcane yield quantity and quality (Arcoverde et al., 2023; Cherubin et al., 2021).

Primary macro-elements

To grow better and ensure the quantity and quality of

crop yields, macronutrients must be present in sufficient quantities as they are the main essential nutrients required by the plant (Konkobo et al., 2018). However, using the interpretation standards established by Tessens and Gourdin (1993), 95.92% were moderately to highly deficient in organic carbon (<3% C), all the plots diagnosed (100%) had a low availability phosphorus (< 50 mg kg^{-1}), 59.18% of the plots have a low level of nitrogen (<0.2%), 8.16% of the diagnosed plots were poor in potassium (<0.2 cmolc kg-1) and 32.65% of the plots had average values (0.2-0.5 cmolc kg^{-1}).

As soil organic carbon, 95.92% were moderately to highly deficient in organic carbon (<3% C). However, soil organic carbon plays an essential role in soil fertility and soil health. Soils with low organic carbon levels lead to biological degradation (reduction in fauna) and physico-chemical degradation (structure, porosity, aeration, soil retention, nutrient recycling and availability). The low levels of organic carbon observed in SOSUMO area can be attributed to the high temperatures in the Moso region, which accelerate the mineralisation of organic matter. The results confirm those of previous studies, which found that in Burundi, organic carbon levels are low at low altitudes (Imbo region) and in the eastern depressions (Moso region) as a result of rapid mineralisation of organic matter under the influence of temperature (IFDC, 2022). Land management and use affect soil organic carbon and nutrient availability to plants. In the top 20 cm of soil, straw burial significantly increases soil organic carbon, soil available nitrogen, phosphorus and potassium, and total soil nitrogen, phosphorus and potassium (Huang et al., 2021). Soil organic carbon, and therefore soil biological, physical and chemical functions, could be restored by burying organic matter, compost or crop residues.

The results show that all the plots diagnosed (100%) had a low availability phosphorus (< 50 mg kg^{-1}). Indeed, the results from the study area complement those of previous studies, which found that almost all Burundian soils (85%) are poor in assimilable phosphorus (Nduwimana et al., 2013). The unavailability of phosphorus is thought to be related to soil texture, acidity, low organic matter content, inadequate P inputs and losses through erosion (Niyungeko et al., 2023). In tropical environments, in addition to the export of P by sugar cane (from 30 to over 100 kg P ha^{-1} per year), most tropical soils have an exceptional capacity to retainphosphate ions, which limits the agricultural production potential, despite the high levels in this region of the world (COMIFER, 2023). Cultivation practices that promote adequate phosphorus inputs in mineral form according to the needs of the environment, liming and the application of organic matter (farmyard manure, compost) or crop residues could be a way to overcome phosphorus deficiencies.Through its decomposition products, organic matter can influence the availability and forms of phosphorus in the soil by acting on the soil pH to keep it within the range of 6.5-7.5, which is the optimum pH for phosphorus uptake by plants (Dahane and Abid, 2022).

As far as nitrogen is concerned, the results obtained show that 59.18% of the plots have a low level (<0.2%), while 40.82% of the plots have an average level of nitrogen (0.2 to 0.5%). Our results confirm those of recent studies showing that Burundian soils have low or average levels of nitrogen (IFDC, 2022). Although nitrogen is the main nutrient required by plants, it is the most commonly deficient nutrient in agriculture, and the low levels observed are due to volatilisation losses as ammonia (NH_3) or leaching losses as nitrate (NO_3) (Poultney, 2021), emissions of nitrous oxides (N_2O), nitrous gases (NO and NO_2), nitrous gases (N_2), nitrogen bound to organic matter by water and wind erosion (Pal et al., 2020), and harvest crop exports. In sugarcane cultivation, burning practice and excessive removal of straw from fields at harvest leads to depletion of soil organic matter and reduction of carbon stocks, which play a role in nutrient recycling (Carvalho et al., 2019; Gmach et al., 2021; Morais et al., 2020; Tenelli et al., 2021), reducing total and available soil nitrogen (Huang et al., 2021) and also affects physical conditions, soil health, biodiversity and sugarcane yield (Gmach et al., 2019; Melo et al., 2020). Using mineral nitrogen fertilisers that the crop actually needs, as well as using organic matter and/or recycling sugarcane crop residues, are recommended to address local nitrogen deficiencies. In fact, nitrogen fertilisation of sugarcane needs to be controlled to avoid degradation of sugarcane quality, as excessive nitrogen inputs reduce fibre content (Kumar et al., 2020). Furthermore, adding organic matter to the soil and recycling crop residues helps to control erosion, increase and maintain soil organic matter levels (Guedegbe et al., 2020) , providing ecosystem services and improving soil health through the release of elements beyond fertiliser (Sarkar et al.. 2020).

For exchangeable potassium, 8.16% of the diagnosed plots were poor in potassium (<0.2 cmolc kg-1), 32.65% of the plots had average values (0.2 to 0.5 cmolc kg^{-1}), while 59.18% of the plots had sufficient amounts (>0.5 cmolc kg^{-1}). Although potassium is not a major problem on most of the plots in the SOSUMO plantations, it is important to maintain soil fertility in terms of potassium on all plots, because if nothing is done, pronounced deficiencies may occur in the near future. The study carried out in 2013 showed that the majority of Burundian soils have optimal potassium levels, with the exception of a few localities in the communes of Vyanda, Bururi, Songa, Giheta, Bisoro and Gihogazi (Nduwimana et al., 2013). Recent studies have shown that more than half of the soils in Burundi are poor in potassium and that only 25 to 30 per cent of the soils in the Imbo and northern depressions are rich in potassium (IFDC, 2022). These results show that soil potassium levels have deteriorated significantly in 9 years. In sugarcane plantations, potassium deficiency disrupts the metabolism of the

plant, adversely affecting its growth and development and consequently reducing the yield of usable sugarcane (Jaiswal et al., 2020). It is therefore important to maintain the potassium fertility of the soils of the eastern depressions in general, and of the SOSUMO plantations in particular, at an optimum level by providing sufficient amounts of potassium in mineral or organo-mineral form, or by adding organic matter (manure, compost or biomass).

Secondary macro-elements

Based on the standards established by Jones 1972 and adapted by (Landon, 1991), 6.12% of the plots diagnosed had high calcium levels (>10 cmolc kg^{-1}), 48.98% had average levels (4-10 cmolc kg^{-1}) and 44.90% were deficient (<4 cmolc kg^{-1}) in this element. For magnesium, 46.94% of the plots were deficient (<0.5 cmolc kg^{-1}) and 53.06% of the plots had average magnesium levels (0.5 to 1.5 cmolc kg^{-1}). Almost half of the plots were deficient in sulphur. Ca and Mg are closely linked and their supply requires special attention to maintain the Ca/Mg ratio at an optimal level (3-4). This can lead to serious nutrient imbalances. In tropical areas, in addition to potassium, calcium, magnesium and sulphur are the main factors limiting sugarcane production and yield, while also affecting juice quality (Bhatt et al., 2021). In Burundi, unlike the other two elements (Ca and Mg), sulphur is very little considered in plant fertilisation, although it is an important secondary nutrient that plays a role in the primary metabolism and growth of the plant, while also providing the plant with antioxidant and abiotic stress resistance functions (Ranjendra and Janardhan, 2020; Zenda et al., 2021). To improve agricultural production and the quality of local sugar cane in calcium-deficient conditions, calcium amendments are one of the possible solutions to raise the pH to the optimum (6.5-7.5) and facilitate better nutrient uptake. The same applies to magnesium deficient soils, where magnesium amendments are recommended to maintain a balanced Ca/Mg ratio.

In the case of sulphur, mineral sulphur must be added to compensate for the deficiencies observed and care must be taken to ensure that only what the plant really needs is applied. In all cases, organic matter is essential to deal with secondary mineral deficiencies.

Oligoelements

Although oligoelements are nutrients that plants need in small amounts, their deficiency can cause physiological disorders. Using the standards established by Jones 1972 and adapted by (Landon, 1991), 2.04% of the plots were deficient in copper, while 97.96% of the plots were adequate and all plots were deficient in zinc (<20 mg kg^{-1}). An imbalance of micronutrients in the soil affects the efficient use of nutrients by plants, disrupts the environment and agro-ecological systems, and consequently reduces agricultural production (Majeed et al., 2022).

Zinc is an essential element for sugarcane growth and tillering, and any deficiency of this element results in a reduction in yield and in the production cycle of regrowth (Silva et al., 2022). As well as its nutritive role, zinc is important for plant defence and reduces the severity of diseases; therefore, any lack of zinc makes the plant susceptible to disease, while excess zinc slows plant growth due to toxicity (Bastakoti, 2023). Application of zinc sulphate ($ZnSO_4$) with optimum NPK fertiliser supply improves sugarcane production and sucrose content (Majeed et al., 2022).

As for Iron, 85% of the plots surveyed had adequate iron levels, and these ferralitic soils have a high capacity to fix phosphorus (Solvar et al., 2021). In acid soils, iron becomes soluble and unavailable to plants; the presence of iron oxides and hydroxides inhibits phosphorus uptake by forming insoluble phosphates (Esther, 2019; Tahraoui, 2024).

Impact of management practices on sugarcane yields

Weeds

The results show that 65.3% of the plots diagnosed had a weed cover of more than 15%. Based on the standards established in this study (Table 3a), weeds pose an immediate threat to the SOSUMO plantations. A major factor in the loss of sugarcane productivity is weed infestation (Verçosa et al., 2022). Under these conditions, weeds cause a variety of nuisances, resulting in reduced yields because they compete with sugarcane for the nutrients it needs, as well as for water and moisture, further reducing its production (De et al., 2016; Jayanthi et al., 2023). As sugarcane is a slow-growing crop, competition from weeds occurs early in the growth cycle and ineffective management during critical growth periods can result in yield losses of up to 10 to 70% (Rathika et al., 2023). Growth retardation and yield losses depend on the type of weed species and the duration of infestation (Bassey et al., 2023). To improve management practices for better sugarcane production in the tropics, weed control is essential as weeds are themain pests in the sector (Mansuy et al., 2019). Manual and mechanical weeding is used to reduce weed pressure in sugarcane fields.

Given that there are large areas and localities that are inaccessible to tractors during the rainy season, it is recommended to use selective herbicides, avoiding excessive use which could pollute the environment.

Pests

Stalk-boring caterpillars, which cause losses in quantity

and quality, are among the biotic constraints on sugarcane recorded in the study area. The pests observed on young sugarcane regrowth were borer caterpillars (*Eldana saccharina*) and fall armyworm (CLA), Spodoptera frugiperda. The total incidence varies between 0.01 and 0.02%.

Damage caused by *E. saccharina* includes galleries with holes in the stem, while CLA causes irregular holes in the leaves, particularly in the whorl. The incidence of both pests was low, around 0.02%. Severe infestations of *E. saccharina* lead to the death of young shoots. Large infestations of sugarcane by stalk-boring caterpillars cause significant production losses (Rutherford et al.. 2019). Majumder (2020) points out that these insects can cause yield losses of 15-20% in addition to reducing product quality (Mishra et al., 2023). Chemical and mechanical control measures should be considered to reduce the level of infestation as soon as these pests appear. Good agricultural practices (weed control, disease, and pest management) can increase sugarcane yields by an average of 23.1 to 29.2% (Khaoma et al., 2022).

Compactness

When herbicides are not available, SOSUMO uses machines to remove weeds from plantations. The same applies to the loading and transport of sugar cane at harvest time. The results show that penetrometry ranges from 0.70 to 10.30 cm (Table 1) and that 15% of the plots are affected by compaction (Figure 4), although it does not significantly affect sugarcane yield (Figure 5). The use of these heavy machines leads to physical soil degradation through compaction and reduced soil porosity (Lokossou et al.. 2018), resulting in high bulk density and resistance to soil penetration (Esteban et al.. 2019). Compaction thus affects the physical fertility of the soil (storage and supply of water and nutrients) and leads to changes in the plant physiology of sugarcane, which in the long term can reduce its productivity in terms of quantity and quality, especially in fine-textured soils (silty clay) (Geneti, 2021). This leads to a lack of aeration and a reduction in the water-holding capacity of the soil, resulting in chemical and biological disturbances that lead to soil degradation and lower yields (Mebarki. 2022). Swinford and Boevey (1984) found that compaction reduced sugarcane yields by 24-47% and sucrose yields by 29 to 48% (Van and Stranack, 2021). Unfortunately, the use of tractors is unavoidable in the agricultural intensification system. A possible solution to improve compacted soils is no-tilling/direct seeding of sugarcane or mechanical chiseling (Awe et al., 2023).

Limiting factors identified by limit curves

In the diagnosed plots, the limiting factors and their proportions vary from plot to plot (Figure 4). The limiting factors that affect the most plots are not necessarily those that reduce sugarcane yield the most (Figure 5). Exponential, logistic, and linear relationships allowed us to determine the standards at which these factors become limiting and differ according to the method of analysis used (Table 3).

Based on established standards (Fillols and Chabalier, 2006; Schroeder et al., 2007), limiting factors in sugarcane production for the wet method are higher than those reported in the literature for organic C, N, CEC, Ca, K, and pH_{eau}; while the standards established are lower than those reported in the literature for Mg, plant available P and S. In addition, the standards established for the dry method are within the range of the standards set by the SoilCare laboratory for the following parameters: organic C, N, CEC and Fe. However, the standards set are outside the SoilCare standards for Ca, Mg, K, Zn, total P, Cu, and pH_{kcl}.

In fact, any input that does not provide a concentration of these elements within the range defined by the standards will not enable the predicted yield of 121 t ha-1 to be achieved, while any input that exceeds the defined standards will lead to luxury consumption and risks of toxicity without increasing yield. For the same limiting factors, the standards established using the dry method are higher than those established using the wet method.

Conclusion

The soil analyses carried out in the SOSUMO sugar cane plantations have made it possible to identify the soil types, the current state of soil fertility, and the various factors limiting sugarcane production in the area. Thus, the factors that most limit and negatively influence the yield of usable cane are related, on one hand, to agricultural practices (weeds, stem-boring caterpillars, compactness) and, on the other, to physical and chemical factors.

Control of weeds and stem-boring caterpillars is essential to improve yields, otherwise there can be huge losses. Another major handicap is the compaction caused by tractors when weeding, loading, and transporting the crop. This distorts the soil structure. Unfortunately, there is currently no solution in sight to alleviate this problem, since the intensification of agriculture and the expansion of plantations (around 4,000 ha of sugar cane), as well as the distance to be covered to transport the sugar cane to the factory, are all factors that require the use of tractors.

As far as the physicochemical factors are concerned, moderate to neutral acidity was found in most of the plots, which is not an obstacle at the moment, except for a few plots with a pH below 5.5, which will have to be monitored regularly to raise the pH by liming. All the plots are deficient in phosphorus, an essential element for the life and production of any plant. Deficiencies in other

macro-elements (N, K, S, Ca, Mg), and trace elements (Zn, B) were also found in some of the plots. Soil fertility management, with the use of suitable organic mineral inputs to replace missing elements, is essential to increase and ensure sustainable sugar cane production. In addition, it is essential to keep the cane stalks in the fields in order to increase the level of organic matter in the soil, which is essential for the development of biological activity in the soil, and to improve the physical and chemical conditions of the soil, such as porosity, moisture and temperature.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Ali S, Zubair M, Hussain S (2021). The combined effect of climatic factors and technical advancement on yield of sugarcane by using ARDL approach: evidence from Pakistan. Environmental Science and Pollution Research 28(29):39787-39804. https://doi.org/10.1007/s11356-021-13313-x

Amonmide I, Dagbenonbakin G, Agbangba CE, Akponikpe P (2019). Contribution à l'évaluation du niveau de fertilité des sols dans les systèmes de culture à base du coton au Bénin. International Journal of Biological and Chemical Sciences 13(3):1846-1860. https://doi.org/10.4314/ijbcs.v13i3.52

Arcoverde SNS, Kurihara CH, Staut LA, Tomazi M, Pires AMM, Silva CJda (2023). Soil fertility, nutritional status, and sugarcane yield under two systems of soil management, levels of remaining straw and chiseling of ratoons. Revista Brasileira de Ciencia Do Solo 47:1-21. https://doi.org/10.36783/18069657rbcs20220138

Awe GO, Fontanela E, Reichert JM (2023). Degree of compaction, aeration, and soil water retention indices of a sugarcane field without soil disturbance after initial tillage. Canadian Journal of Soil Science 103(3):578-591. https://doi.org/10.1139/cjss-2022-0066

Bassey MS, Shittu EA, Lawan ZM, Eze JN (2023). Evaluation of Sugarcane Hybrid Clones on Weed Dynamics, Sugar Quality and Plant Crop Productivity At Badeggi, Nigeria. Badeggi Journal of Agricultural Research and Environment 5(2):1-13. https://doi.org/10.35849/bjare202302/94/001

Bastakoti S (2023). Role of zinc in management of plant diseases: A review. Cogent Food and Agriculture 9(1):1-13. https://doi.org/10.1080/23311932.2023.2194483

Behiels Z, Burban A, Cassin C, Alexandre G, Amand G, Margaux G, Marianna G, Antonine L, Clémence M, Enzo P (2023). Synthèse bibliographique sur les modalités de gestion de la paille de la canne à sucre (Saccharum Officinarum) et leurs effets sur le continuum sol-plante-atmosphère pp. 1-67. Available at: https://agritrop.cirad.fr/607145/1/Synth%C3%A8se_bibliographique_MJE_TROPI.pdf

Benouadah S (2022). Caractérisation physicochimique d'une jachère dans une zone céréalière semi-aride en vue d'orienter sa gestion et d'améliorer sa productivité agricole (région de Sébain, Tiaret). Mémoire de Master Juin 2020.

Bhatt R (2020). Resources Management for Sustainable Sugarcane Production. Resources Use Efficiency in Agriculture. pp. 647-693. https://doi.org/10.1007/978-981-15-6953-1

Bhatt R, Singh P, Ali OM, Abdel Latef AAH, Laing AM, Hossain A (2021). Polyhalite positively influences the growth, yield and quality of sugarcane (Saccharum officinarum l.) in potassium and calcium-deficient soils in the semi-arid tropics. Sustainability (Switzerland) 13(19):10689. https://doi.org/10.3390/su131910689

Banque de la Republique du Burundi (BRB) (2020). Rapport annuel de la Banque de la république du Burundi. Available at: https://www.brb.bi/rapports_annuels

Carvalho JLN, Nogueirol RC, Menandro LMS, Bordonal RDO, Borges CD, Cantarella H, Franco HCJ (2017). Agronomic and environmental implications of sugarcane straw removal : a major review. Gcb Bioenergy 9(7):1181-1195. https://doi.org/10.1111/gcbb.12410

Carvalho JLN, Menandro LMS, de Castro SGQ, Cherubin MR, Bordonal R de O, Barbosa LC, Gonzaga LC, Tenelli S, Franco HCJ, Kolln OT, Castioni GAF (2019). Multilocation Straw Removal Effects on Sugarcane Yield in South-Central Brazil. Bioenergy Research 12(4):813-829. https://doi.org/10.1007/s12155-019-10007-8

Cheng YL, Lee CY, Huang YL, Buckner CA, Lafrenie RM, Dénommée JA, Caswell JM, Want DA, Gan GG, Leong YC, Bee PC, Chin E, Teh AKH, Picco S, Villegas L, Tonelli F, Merlo M, Rigau J, Diaz D, Mathijssen RHJ (2016). Liveness detection in biometrics. In Advenced BiometricTechnologies. IntechOpen 11(tourism):13. Available at: https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

Cherubin MR Bordonal RO, Castioni GA, Guimarães, EM, Lisboa IP, Moraes LAA, Menandro LMS, Tenelli S, Cerri CEP, Karlen DL, Carvalho JLN (2021). Soil health response to sugarcane straw removal in Brazil. Industrial Crops and Products 163(February). https://doi.org/10.1016/j.indcrop.2021.113315

Chi L, Huerta-Lwanga E, Álvarez-Solís D, Kú-Quej VM, Mendoza-Vega J (2020). Abundance and diversity of soil macroinvertebrates in sugarcane (Saccharum spp.) plantations under organic and chemical fertilization in Belize TT-Abundancia y diversidad de macroinvertebrados de suelo en el cultivo de caña de azúcar (Saccharum spp.) b. Acta Zoológica Mexicana 36:1-19. https://doi.org/10.21829/azm.2020.3611106

Centre de coopération Internationale en Recherche pour le Développement (CIRAD) (2017). Catalogue des analyses courantes : Analyses de sols et supports de cultures. P 16. Available at: https://us-analyses.cirad.fr/content/download/4892/35058/version/1/file/Catalogue_analyses_courantes_15-09-2017.pdf

Centre de coopération Internationale en Recherche pour le Développement (CIRAD) (2020). L'agriculture au coeur de l'économie circulaire pp. 1-20. Available at: https://agritrop.cirad.fr/595980/1/Agronews_2020_hors_s%C3%A9rie.pdf

Comité Française d'Etude et de Développement de la Fertilisation Raisonnée (COMIFER) (2023). De la fertilisation raisonnée et de l'analyse. Programme and résumés pp. 44-45. Available at: https://comifer.asso.fr

Correia NM (2016). Controle químico de espécies de corda-de-viola em áreas de cana soca crua colhida nas épocas seca e semiúmida. Planta Daninha 34(2):333-343. https://doi.org/10.1590/S0100-83582016340200015

Dahane A, Abid I (2022). Etude de l'effet de la matière organique sur certaines propriétés des sols de la wilaya de Bordj Bou Arreridj. (Doctoral dissertation). pp. 1-38. Available at: ttps://dspace.univ-bba.dz/server/api/core/bitstreams/930882f9-c6be-44df-bb84-b51b9e137333/content

De A, Nuisibilite LA, Bleuet DU, Colza D'hiver EN, Alrustom B, Guillemin JP, Darmency H (2016). AFPP-23e Conférence du COLUMA: journées internationales sur la lutte contre les mauvaises herbes, Dijon-6-8 Décembre 2016. Available at: https://www.cabdirect.org/cabdirect/FullTextPDF/2017/20173254442.pdf

De Aquino G S, Medina CDC, Cunha ACB, Kussaba DAO, Dos Santos JH, Carvalho J B, Moreira A (2017). Development and production of sugarcane under different levels straw after four years of cultivation. Semina:Ciencias Agrarias 38(5):2957-2966. https://doi.org/10.5433/1679-0359.2017v38n5p2957

De Aquino GS, Medina CD, Silvestre DA, Gomes EC, Cunha ACB, Kussaba DAO, Almeida LF, Shahab M, Santiago AD (2018). Straw removal of sugarcane from soil and its impacts on yield and industrial quality ratoons. Scientia Agricola 75(6):526-529. https://doi.org/10.1590/1678-992x-2017-0093

Elsharif AA, Abu-Naser SS (2019). An Expert System for Diagnosing Sugarcane Diseases. International Journal of Academic Engineering Research 3(3):19-27.

Esther MM (2019). Understanding Soil Phosphorus. International

Journal of Plant and Soil Science 31(2):1-18. https://doi.org/10.9734/ijpss/2019/v31i230208

Esteban DAA, de Souza ZM, Tormena CA, Lovera LH, de Souza Lima E, de Oliveira IN, de Paula Ribeiro N (2019). Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. Soil and Tillage Research 187:60-71.

Fermont AM, van Asten PJA, Tittonell P, van Wijk MT, Giller KE (2009). Closing the cassava yield gap: An analysis from smallholder farms in East Africa. Field Crops Research 112(1):24-36. https://doi.org/10.1016/j.fcr.2009.01.009

Fillols E, Chabalier P (2006). Le guide de la fertilisation de la canne à sucre à La Réunion. Co-Éd. Cirad and CTICS pp. 29-41.

Frankart R, Sottiaux G (1972). Carte des sols et de la végétation du Congo, du Rwanda et du Burundi. Institut National Pour l'étude Agronomique Du Congo, Brussels pp. 1-87.

Geneti D (2021). Effect of Soil Compaction on Growth, Yield and Quality of Sugarcane (Saccharum Officinarum L.) Crop and It is Management: A Review. Journal of Environment and Earth Science 11(5):17-25. https://doi.org/10.7176/jees/11-5-02

Gmach MR, Kaiser K, Cherubin MR, Cerri CEP, Lisboa IP, Vasconcelos ALS, Siqueira-Neto M (2021). Soil dissolved organic carbon responses to sugarcane straw removal. Soil Use and Management 37(1):126-137. https://doi.org/10.1111/sum.12663

Gmach MR, Scarpare FV, Cherubin MR, Lisboa IP, Belarmino dos Santos AK, Pellegrino Cerri CE, Cerri CC (2019). Sugarcane straw removal effects on soil water storage and drainage in southeastern Brazil. Journal of Soil and Water Conservation 74(5):466-476. https://doi.org/10.2489/jswc.74.5.466

Guedegbe GG, Moriaque AT, Vigninou T, Hetcheli F (2020). Evaluation du niveau de fertilité et d'aptitude des sols aux cultures du maïs, de l'ananas, de L'arachide et du soja dans la commune de Tori-bossito au sud-Bénin. Revue Scientifique MIRD 7(7):382-399.

Huang T, Yang N, Lu C, Qin X, Siddique KHM (2021). Soil organic carbon, total nitrogen, available nutrients, and yield under different straw returning methods. Soil and Tillage Research 214(August):105171. https://doi.org/10.1016/j.still.2021.105171

International Fertilizer Development Centre (IFDC) (2022). Cartographie de la fertilité des sols du Burundi: Edition pp. 1-180. Available at: https://isabu.bi/wp-content/uploads/2023/03/Cartographie-de-la-fertilite-du-sol-au-Burundi2022.pdf

Indoria AK, Sharma KL, Reddy KS, Srinivasarao C, Srinivas K, Balloli SS, Osman M, Pratibha G, Raju NS (2018). Alternative sources of soil organic amendments for sustaining soil health and crop productivity in India – impacts, potential availability , constraints and future strategies. Current Science 115(11):2052-2062

ISO N 11261 (1995). Qualité du sol - Dosage de l'azote total- Méthode de Kjeldahl modifiée pp. 1-4. Available at: . https://cdn.standards.iteh.ai/samples/19239/57a1f0c458bf438c87f5ca4cbe110e11/ISO-11261-1995.pdf

ISO N 11263 (1994). Qualité du sol-Dosage du phosphore-Dosage spectrométrique du phosphore soluble dans une solution d'hydrogénocarbonate de sodium pp. 1-6. Available at: https://cdn.standards.iteh.ai/samples/19241/a107fe0f9ce540d68a248389d66fab25/ISO-11263-1994.pdf

ISO NE 10390. 202 (2021). Sols, biodéchets traités et boues-Détermination du pH 1(I):2-5. Available at: https://cdn.standards.iteh.ai/samples/75243/296acb762c5c47c0ab72d2dc309ffea1/ISO-10390-2021.pdf

Jayanthi M, Mareeswaran P, Vijay Prabha V, Charan MS (2023). Case Study on Production and Marketing Constraints of Sugarcane Farmers in Southern Tamil Nadu, India. Asian Journal of Agricultural Extension, Economics and Sociology 41(10):289-293. https://doi.org/10.9734/ajaees/2023/v41i102170

Kaboneka S, Ndayishimiye J, Hakizimana S, Ndagijimana E (2020). Analyse des phyto-indicateurs de la fertilité des sols en communes Mabanda et Vugizo. Revue de l'Université Du Burundi: Série-Sciences Exactes et Naturelles 2(29):1-12. Available at: https://ub.edu.bi/JUB

Khaliq A, Ahmad HB, Nadeem MA, Mehmood A, Ahmad N, Yasin M, Sher R ul (2020). Valuation of Weed Control Methods by using Inter Row Rotary Weeder in Sugarcane Crop. Indian Journal of Agricultural Research 54(5):666670.

https://doi.org/10.18805/IJARe.A-549

Khaoma J, Korir J, Okaka F (2022). Influence of field practice on sugarcane production in Webuye East Sub-County in Bungoma County, Kenya. East African Journal of Humanities and Social Sciences 1(1):21-36.

Khechba K, Laamrani A, Dhiba D, Misbah K, Chehbouni A (2021). Monitoring and analyzing yield gap in africa through soil attribute best management using remote sensing approaches: A review. Remote Sensing 13(22):1-19. https://doi.org/10.3390/rs13224602

Konkobo J, Somé YSC, IDANI TF (2018). Evaluation de l'état de dégradation de la fertilité chimique des sols dans la commune rurale de Kouka (Burkina Faso). Archives of Anesthesiology and Critical Care 4(4):527-534.

Kouadio ENG, Koffi EK, Messoum GF, Brou KND B (2018). Diagnostic de l ' Etat de Fertilité des Sols Sous Culture Cotonnière Dans les Principaux Bassins de Production de Côte d ' Ivoire. European Scientific Journal 14(33):221-238. https://doi.org/10.19044/esj.2018.v14n33p221

Kumar S, Meena RS, Jhariya MK (2020). Resources Use Efficiency in Agriculture. Resources Use Efficiency in Agriculture (Issue September 2020). https://doi.org/10.1007/978-981-15-6953-1

Landon JR (1991). Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics.

Lemi T (2019). Effects of Climate Change Variability on Agricultural Productivity. International Journal of Environmental Sciences and Natural Resources 17(1). https://doi.org/10.19080/ijesnr.2019.17.555953

Li F, Chen L, Zhang J, Yin J, Huang S (2017). Bacterial community structure after long-term organic and inorganic fertilization reveals important associations between soil nutrients and specific taxa involved in nutrient transformations. Frontiers in Microbiology 8(2):187. https://doi.org/10.3389/fmicb.2017.00187

Liu Q, Pang Z, Yang Z, Nyumah F, Hu C, Lin W, Yuan Z (2022). Bio-fertilizer Affects Structural Dynamics, Function, and Network Patterns of the Sugarcane Rhizospheric Microbiota. Microbial Ecology 84(4):1195-1211. https://doi.org/10.1007/s00248-021-01932-3

Lokossou RS, Akouehou GS, Avononmon ML, Matilo AO (2018). Modes de gestion des terres dans la zone tampon de la réserve de biosphère de la Pendjari. Journal of Applied Biosciences 124(1):12433. https://doi.org/10.4314/jab.v124i1.5

Ma C (2023). Méthode d'analyse MA. 405–C 1.1 (révision 4) : Détermination du carbone organique total dans les solides: dosage par titrage. Available at: https://www.ceaeq.gouv.qc.ca/methodes/pdf/methode-analyse-405-carbone-dosage-titrage.pdf

Majeed A, Rashid I, Niaz A, Ditta A, Sameen A, Al-Huqail AA, Siddiqui MH (2022). Balanced Use of Zn, Cu, Fe, and B Improves the Yield and Sucrose Contents of Sugarcane Juice Cultivated in Sandy Clay Loam Soil. Agronomy 12(3):696. https://doi.org/10.3390/agronomy12030696

Mansuy A, Marnotte P, Martin J, Roux E, Chouteau R, Wilt M, Soubadou G (2019). CanécoH : mise au point de leviers pour une Canne àsucre économe en Herbicide à La Réunion. Innovations Agronomiques 76(2019):103-119.

Marnotte P, Baillif S, Esther J, Marion D (2018). Suivi des mauvaises herbes: levée et phénologie. Mieux les connaitre pour mieux les maitriser. L'Etang-Salé-2017 et pp. 1-63.

McKay B, Sauer S, Richardson B, Herre R (2016). The political economy of sugarcane flexing: initial insights from Brazil, Southern Africa and Cambodia. Journal of Peasant Studies 43(1):195-223. https://doi.org/10.1080/03066150.2014.992016

Mebarki MN (2022). Analyse du comportement physico-mécaniques des sols compactés et non compactés sous l'action de deux techniques culturales et conséquences sur le développement des céréales (Doctoral dissertation). Ecole Normale Supérieure d'Agronomie, Université, Algérie

Melo PLA, Cherubin MR, Gomes TCA, Lisboa IP, Satiro LS, Cerri CEP, Siqueira-Neto, M (2020). Straw removal effects on sugarcane root system and stalk yield. Agronomy 10(7):1048. https://doi.org/10.3390/AGRONOMY10071048

Militante SV, Gerardo BD, Medina RP (2019). Sugarcane Disease Recognition using Deep Learning. Paper presented at: 2019 IEEE

Eurasia Conference on IOT, Communication and Engineering (ECICE); october 2019; Yunlin, Taiwan pp. 575-578. https://doi.org/10.1109/ECICE47484.2019.8942690

Mishra AK, Kurre D, Mishra SK, Tiwari (2023). Major Insect Pests of Sugarcane (Saccharum officinarum) Crop and Their Integrated Management Approaches. Just Agriculture 4(3):160-166. Available at: https://justagriculture.in/files/newsletter/2023/december/25.%20Major%20Insect%20Pests%20of%20Sugarcane%20(Saccharum%20officinarum)%20Crop%20and%20Their%20Integrated%20Management%20Approaches.pdf

Mokhena T, Mochane M, Tshwafo M, Linganiso L, Thekisoe O, Songca, S (2016). Sugarcane bagasse and cellulose polymer composites. Sugarcane-technology and Research pp. 225-240.

Morais MC, Siqueira-Neto M, Guerra HP, Satiro LS, Soltangheisi A, Cerri C EP, Feigl B J, Cherubin MR (2020). Trade-offs between sugarcane straw removal and soil organic matter in Brazil. Sustainability (Switzerland) 12(22):1-13. https://doi.org/10.3390/su12229363

Moreau D, Perthame L, Colbach N (2020). La compétition pour les ressources entre plantes : des clés pour choisir les cultures et variétés pour contrôler les adventices. Innovations Agronomiques 81(2021):19-32. https://doi.org/10.15454/qrwv-7344

Ministère de la Planification du Développement et de la Reconstruction Nationale (MPDRN) (2006). Monographie de la commune bukemba. pp. 1-70.

Msomba BH, Ndaki PM, Joseph CO (2024). Sugarcane sustainability in a changing climate: a systematic review on pests, diseases, and adaptive strategies. Frontiers in Agronomy 6(8):1423233. https://doi.org/10.3389/fagro.2024.1423233

Namdev VK, Khan AI, Madanlal VS (2023). Impact of climate change on sugarcane production and its mitigation. International Journal of Progressive Research in Engineering Management and Science 3:389-396. https://doi.org/10.58257/IJPREMS32389

Nduwimana O, Nzohabonayo Z, Hicintuka C, Nibasumba M (2013). Cartographie de La Fertilité des sols du Burundi Et des besoins des principales cultures vivrières en éléments nutritifs. pp. 1-30 Available at: http://www.archives.biodiv.be/burundi/chm-burundais/pfinstitut/institut-des-sciences-agronomiques-du-burundi-isabu/projets-et-realisations/programme-programme-de-recherche-amenagement-et-ecologie/1er-partie_fertilite-des-sols-du-burundi/download/fr/1/1%C3%A9r%20partie_f%C3%A9rtilit%C3%A9%20des%20sols%20du%20Burundi.pdf?action=view

Niyungeko C, Marie-chantal, N, Sindayihebura A (2023). Evaluation des propriétés physicochimiques liées à la disponibilité du phosphore des différents types de sols du Burundi pp. 1-12. Available at: https://www.researchgate.net/publication/370680805_Evaluation_des_proprietes_physicochimiques_liees_a_la_disponibilite_du_phosphore_des_differents_types_de_sols_du_Burundi/link/645d1b26434e26474fdda631/download?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uIn19

Nzigidahera B, Njebarikanuye A, Kakunze AC, Misago A (2008). Etude préliminaire d'identification des milieux naturels à mettre en défens dans la dépression de Kumoso. pp. 1-33. Available at: http://www.archives.biodiv.be/burundi/implementation/questions-transectorielles/aires-protegees/plans-de-gestion-et-etudes-d-identification/rapport_final.pdf

Pal A, Adhikary R, Barman S, Maitra S (2020). Nitrogen transformation and losses in soil: A cost-effective review study for farmer. International Journal of Chemical Studies 8(3):2623-2626. https://doi.org/10.22271/chemi.2020.v8.i3al.9609

Pang Z, Tayyab M, Kong C, Liu Q, Liu Y, Hu C, Huang J, Weng P, Islam W, Lin W (2021). Continuous Sugarcane Planting Negatively Impacts Soil Microbial Community Structure, Soil Fertility, and Sugarcane Agronomic Parameters. Microorganisms 9(10):2008.

Poultney D (2021). The effect of organic fertiliser application on nitrogen biogeochemical cycle of sugarcane crops in Réunion Island. Doctoral dissertation , Université de la Réunion pp. 1-203.

Rajeshwar MMC, Vidyasagar GECH, Balaguruvaiah D (2018). Soil constraints and management in relation to the distribution of available macro and micronutrients in sugarcane growing soil profiles of semi arid tropical region of Telangana. Journal of Pharmacognosy and Phytochemistry 7(3):260-270.

Ranjendra S, Janardhan G (2020). Analysis of Chemical Properties of Soil under Sugarcane Crop : A Case Study of Khandala , Shrirampur, Ahmednagar District, Maharashtra State, India. Journal of Environment and Ecology Management 68(30):6522-6547.

Rathika S, Ramesh T, Jagadeesan R (2023). Weed management in sugarcane : A review Weed management in sugarcane : A review. The Pharma Innovation Journal 12(6):3883-3887.

Rutherford RS, McFarlane S, Memela N, Snyman S (2021). Harnessing the Sugarcane Microbiome for Improved Resistance To the Stalk Borer *Eldana Saccharina* Walker (Lepidoptera: Pyralidae).Preprint, April 2021. ResearchGate pp 1-5. Available at:https://www.researchgate.net/publication/350544937_Harnessing_the_sugarcane_microbiome_for_improved_resistance_to_the_stalk_borer_Eldana_saccharina_Walker_Lepidoptera_Pyralidae

Sarkar S, Skalicky M, Hossain A, Brestic M, Saha S, Garai S, Ray K, Brahmachari K (2020). Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability (Switzerland) 12(23):1-24. https://doi.org/10.3390/su12239808

Schroeder BL, Panitz J, Wood A, Moody P, Salter B (2007). Soil-Specific Nutrient Management Guidelines for Sugarcane Production in the Bundaberg District. BSES Technical Publication TE07004.

Sentíes-Herrera HE, Trejo-Téllez LI, Gómez-Merino FC (2017). The Mexican sugarcane production system: History, current status and new trends. In Sugarcane: Production Systems, Uses and Economic Importance (Issue January).

Shatar TM, Mcbratney AB (2004). Boundary-line analysis of field-scale yield response to soil properties. Journal of Agricultural Science *142*(5):553-560. https://doi.org/10.1017/S0021859604004642

Jaiswal VP, Shukla SK, Sharma L, Singh I, Pathak AD, Nagargade M, Masto E (2021). Potassium influencing physiological parameters, photosynthesis and sugarcane yield in subtropical India. Sugar Tech 23(2):343-359.

Silva Mde A, Germino GH, de Holanda LA, Oliveira L C, Santos HL, Sartori MMP (2022). Sugarcane Productivity as a Function of Zinc Dose and Application Method. Agriculture (Switzerland) 12(11):1-12. https://doi.org/10.3390/agriculture12111843

Solvar F, Desfontaines L, Sierra J (2021). Détermination du phosphore biodisponible dans les sols ferrallitiques de Guadeloupe. https://hal.inrae.fr/hal-03200445v1

Société Sucrière du Moso (SOSUMO) (2017). Rapport annuel-Exercice 2016-2017 (Vol. 01, Issue 257). Available at: https://www.sosumo-burundi.com/images/Rapport_annuel_2016-2017.pdf

Société Sucrière du Moso (SOSUMO) (2022). Rapport de la SOSUMO.

Sousa Junior JGdA, Cherubin MR, Oliveira BG, Cerri CEP, Cerri CC, Feigl BJ (2018). Three-Year Soil Carbon and Nitrogen Responses to Sugarcane Straw Management. Bioenergy Research 11(2):249-261. https://doi.org/10.1007/s12155-017-9892-x

Swinford JM, Boevey TMC (1984). The effects of soil compaction due to infield transport on ratoon cane yields and soil physical characteristics. https://www.cabidigitallibrary.org/doi/full/10.5555/19840326254

Tabriz SS, Kader MA, Rokonuzzaman M, Hossen MS, Awal MA (2022). Prospects and challenges of conservation agriculture in Bangladesh for sustainable sugarcane cultivation Prospects and challenges of conservation agriculture. Environment, Development and Sustainability 23(11):15667-15694. https://doi.org/10.1007/s10668-021-01330-2

Tahraoui S (2024). Contribution à l ' optimisation de la fertilisation phospho -azotée en sol salé et calcaire. Doctoral dissertation, UNIVERSITE MOHAMED KHIDER-BISKRA Available at: http://thesis.univ-biskra.dz/6538/1/th%C3%A8se%20Tahraoui%20souaad%20%282%29.pdf

Tayyab M, Islam W, Arafat Y, Pang Z, Zhang C, Lin Y, Waqas M, Lin S, Lin W, Zhang H (2018). Effect of sugarcane straw and goat manure on soil nutrient transformation and bacterial communities. Sustainability 10(7):1-21. https://doi.org/10.3390/su10072361

Tayyab M, Yang Z, Zhang C, Islam W, Lin W, Zhang H (2021). Sugarcane monoculture drives microbial community composition, activity and abundance of agricultural-related microorganisms. Environmental Science and Pollution Research 28(35):48080-48096.

Tenelli S, Bordonal RO, Cherubin MR, Cerri CEP, Carvalho JLN (2021). Multilocation changes in soil carbon stocks from sugarcane straw removal for bioenergy production in Brazil. GCB Bioenergy *13*(7):1099-1111. https://doi.org/10.1111/gcbb.12832

Valim WC, Panachuki E, Pavei DS, Sobrinho TA, Almeida WS (2016). Effect of sugarcane waste in the control of interrill erosion. Semina: Ciencias Agrarias 37(3):1155-1164. https://doi.org/10.5433/1679-0359.2016v37n3p1155

Van Antwerpen R, Stranack AR (2021). Soil conservation practices used in the South African Sugarcane Industry over the last 80 years – A Review Proc S Afr Sug Technol Ass (2021)93:172-186. Available at: https://cabidigitallibrary.org

Verçosa JPS, Dos Santos Silva FH, Almeida Araujo F, Toujaguez la Rosa Massahud R, Da Silva Pereira FR, Rocha de Carvalho Almeida HR, De Barros Braga M, Costa Falcão Tavares A (2022). Early detection of weed in sugarcane using convolutional neural network. International Journal for Innovation Education and Research 10(11):210-226. https://doi.org/10.31686/ijier.vol10.iss11.4004

Wairegi LWI, van Asten PJA, Tenywa MM, Bekunda MA (2010). Abiotic constraints override biotic constraints in East African highland banana systems. Field Crops Research 117(1):146-153. https://doi.org/10.1016/j.fcr.2010.02.010

Webb RA (1972). Use of the Boundary Line in the analysis of biological data. Journal of Horticultural Science 47(3):309-319. https://doi.org/10.1080/00221589.1972.11514472

Yadav S, Jackson P, Wei X, Ross EM, Aitken K, Deomano E, Atkin F, Hayes B J, Voss-Fels KP (2020). Accelerating genetic gain in sugarcane breeding using genomic selection. Agronomy 10(4):1-21. https://doi.org/10.3390/agronomy10040585

Zenda T, Liu S, Dong A, Duan H (2021). Revisiting sulfur_The once neglected nutrient: It's roles in plant growth, metabolism, stress tolerance and crop production. Agriculture 11(7):626. https://doi.org/10.3390/agriculture11070626

Zhang D, Wang C Li X, Yang X, Zhao L, Xia S (2019). Correlation of production constraints with the yield gap of apple cropping systems in Luochuan County, China. Journal of Integrative Agriculture 18(8):1714-1725. https://doi.org/10.1016/S2095-3119(18)62098-2

Zhang D, Wang C, Li X (2019). Yield gap and production constraints of mango (Mangifera indica) cropping systems in Tianyang County, China. Journal of Integrative Agriculture 18(8):1726-1736. https://doi.org/10.1016/S2095-3119(18)62099-4

Zhang X, Davidson EA, Zou T, Lassaletta L, Quan Z, Li T, Zhang W (2020). Quantifying Nutrient Budgets for Sustainable Nutrient Management. Global Biogeochemical Cycles 34(3):1-25. https://doi.org/10.1029/2018GB006060