

## Article

# Effect of Potassium Application Rates on Sugarcane Yield in Soils with Different Non-Exchangeable Potassium Reserves and Fixation Capacity

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**Abstract:** Reliable fertilizer recommendations should account for factors influencing nutrient supply, including non-exchangeable potassium (K) reserves and fixation capacity, to ensure optimum crop yields. The combined effects of non-exchangeable K reserves and fixation capacity of soils on crop response to K application has not been evaluated. This study evaluated the response of sugarcane yields to K application on two soils with contrasting combinations of non-exchangeable K reserves and fixation capacity. Potassium was applied at 0, 120, and 240 kg K ha<sup>-1</sup> at the commencement of the field trials and after each harvest on an umbric Acrisol, which had low non-exchangeable K reserves and medium K fixation capacity, and a cutanic Acrisol, which had ‘very high’ non-exchangeable K reserves and fixation capacity. Sugarcane stalk and sucrose yield, leaf, and exchangeable K were measured for each season. In the umbric Acrisol, a lower sucrose yield was measured in the 240 kg K ha<sup>-1</sup> treatment compared to the control for the plant crop, but this application rate had higher yields for the second ratoon. In contrast, there was no yield response to K application in cutanic Acrisol. This study indicated the importance of non-exchangeable K reserves and fixation capacity when calculating K requirements and conducting field calibration studies.

**Keywords:** slowly available potassium; potassium fixation; *Saccharum officinarum*; potassium requirement factor; sucrose yields; potassium buffering capacity



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## 1. Introduction

Potassium (K) is one of the most important nutrients in crop production because it is critical for the growth, development, and the translocation of sugars [1]. Adequate amounts of K are required for photosynthesis, the translocation of sugars, and starch synthesis [2,3]. In soils deficient of K, an application of the nutrient may improve yields while reducing incidences of crop lodging [4–6]. However, excessive amounts of K in soils can lead to luxury consumption, a reduced uptake of calcium (Ca) and magnesium (Mg), may reduce juice quality for grapes and sugarcane, resulting in economic losses, and may even cause the deterioration of soil structure [7–14]. In an Oxisol and Inceptisol, increasing leaf K corresponded with decreasing leaf Ca and Mg [11]. There are also several reports showing a reduced juice quality with excessive exchangeable K, which compromise sucrose recovery for sugarcane and grape juice pH for wine production [8–10]. In addition, increasing exchangeable K resulted in an increased clay dispersion of a Luvisol and Vertisol [14]. Hence, reliable recommendations based on accurate soil K testing are essential to ensure optimum yields and quality of crops.

The reliability of fertilizer recommendations hinge on the success of soil test calibrations used to obtain soil test thresholds. In calibration studies, the response of various

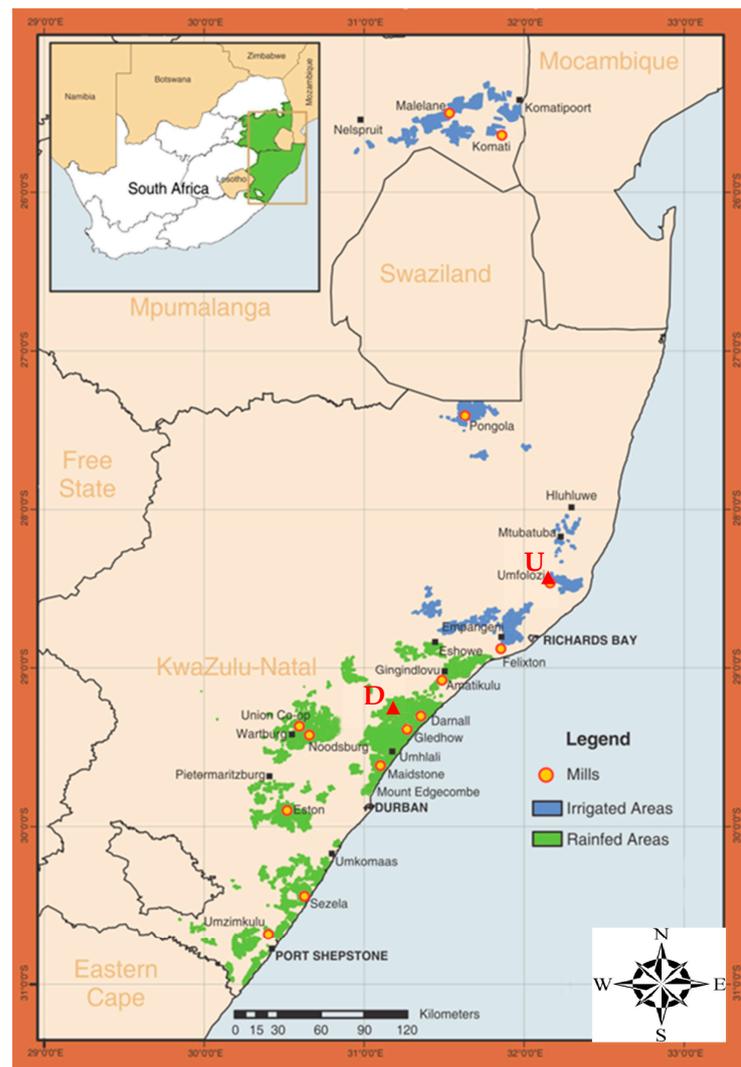
crop parameters is related to both fertilizer application and extractable (exchangeable) K. Soil test threshold is regarded as a soil test value where optimum yields are obtained and there is no response to further K application. The fertilizer requirement is then calculated as the amount of K fertilizer required to raise the soil test to the threshold value. These threshold values are often modified to account for the clay content and base status of the soil since these factors influence the uptake of K by crops [12,15,16]. Because of the lack of response to K application in some soils, approaches that include the supply of K from non-exchangeable reserves and its fixation in the calculation of fertilizer requirement have also been recommended in different parts of the world, and for various crops [17–27]. For example, a reduction in fertilizer requirements by 100, 60, 30, and 0% when the non-exchangeable K reserves are  $>2.5$ ,  $1.5\text{--}2.5$ ,  $0.8\text{--}1.5$ , and  $<0.8$   $\text{cmol}_c\cdot\text{kg}^{-1}$ , respectively, has been recommended for sugarcane [21]. The approach for K fixation, on the other hand, involves multiplying fertilizer requirements by a K retention factor [22–24]. In grasslands, timothy grass (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis*) did not respond to K fertilization in sandy soils with high non-exchangeable K reserves ( $>3$   $\text{cmol}_c\cdot\text{kg}^{-1}$ ) [11]. The same study concluded that the supply from the reserves was a better indicator of K requirements than exchangeable K alone. However, a recent study on an Oxisol and Inceptisol characterized by low exchangeable K (0.14 and 11  $\text{cmol}_c\cdot\text{kg}^{-1}$ ) and low non-exchangeable K reserves (0.22 and 0.70  $\text{cmol}_c\cdot\text{kg}^{-1}$ ) revealed that there was no sugarcane stalk yield response to K application [12]. The sucrose yields in the same study increased with increasing K application only in ratoon 2 for the Oxisol and in the plant crop and ratoon 1 for the Inceptisol. The differences between these soils could be explained by K fixation because both exchangeable and non-exchangeable K reserves were low, but this parameter was not reported. This may point out that crop response to K application may be better understood and predicted by considering the combined effects of non-exchangeable K reserves and the fixation capacity of soils.

There is a dearth of literature that evaluates the combined effects of non-exchangeable K reserves and fixation capacity of soils on crop response to K application. The study that did consider the combined effects of non-exchangeable K reserves and fixation capacity on maize response to K application used Vertosols with comparable levels of non-exchangeable K reserves and fixation capacity [28]. Furthermore, the soils also had high exchangeable K, which would cause a lack of response to K application. It is suggested that crop response to K application may be better evaluated by considering the combined effects of non-exchangeable K reserves and fixation capacity on contrasting soils with low exchangeable K. This study evaluated the response of sugarcane stalk yield and sucrose yields to K application on two soils with contrasting combinations of non-exchangeable K reserves and fixation capacity.

## 2. Materials and Methods

### 2.1. Trial Sites

The response of sugarcane to K fertilization was investigated in field trials at Umfolozi and Doringkop areas in KwaZulu-Natal, South Africa (Figure 1). The Umfolozi site ( $28^{\circ}27'0''$  S,  $32^{\circ}13'0''$  E; 15 m. a.s.l.) is a floodplain and has a mean annual rainfall of  $1033$   $\text{mm annum}^{-1}$ , with most occurring between October and April. The mean minimum daily temperature is  $17.1$   $^{\circ}\text{C}$  and mean maximum daily temperature is  $28.3$   $^{\circ}\text{C}$ . The soil type is a cutanic Acrisol (IUSS Working Group WRB, 2014) [29]. The soil was characterized by very high levels of non-exchangeable K reserves and high K fixation capacity (Table 1).



**Figure 1.** Location of trial sites within the province of KwaZulu-Natal, South Africa. Red triangles with ‘U’ (Umfolozi, cutanic Acrisol) and ‘D’ (Doringkop, umbric Acrisol) indicate the location of each trial site. (Image: W. Mthembu, South African Sugarcane Research Institute).

**Table 1.** Selected soil properties for the cutanic Acrisol and umbric Acrisol.

Determinant		Cutanic Acrisol	Umbric Acrisol
	pH (CaCl <sub>2</sub> )	5.31	4.60
AMBIC (a) extractable cations (cmol <sub>c</sub> -kg <sup>-1</sup> )	K	0.25	0.25
	Ca	10.82	5.14
	Mg	6.50	1.07
	Na	0.30	0.04
	P (mg kg <sup>-1</sup> )	37	64
	Si (mg kg <sup>-1</sup> )	28	18
	Exchangeable Acidity (cmol <sub>c</sub> kg <sup>-1</sup> )	0.01	0.21
	Total cations (b) (cmol <sub>c</sub> kg <sup>-1</sup> )	17.88	6.71
	Reserve-K (mg kg <sup>-1</sup> )	3.84	0.58
	KRF (c) (kg K ha <sup>-1</sup> per unit soil test)	4.44	3.24

**Table 1.** *Cont.*

Determinant	Cutanic Acrisol	Umbric Acrisol
Total organic carbon (%)	0.73	2.45
Clay (%)	35	33

<sup>a</sup> AMBIC = Ammonium bicarbonate. <sup>b</sup> Total cations obtained by summing the quantities of AMBIC extractable Ca, Mg, K, and Na and KCl exchangeable acidity (Al + H). <sup>c</sup> KRF = Potassium requirement factor, indicative of K fixation capacity.

The Doringkop area, which is inland of KwaDukuza (29°13'6" S, 31°14'19" E; 434 m. a.s.l.), has a mean annual rainfall of 998 mm per annum<sup>-1</sup>, mostly occurring between September and March. The mean minimum daily temperature is 14.3 °C and mean maximum daily temperature is 26.7 °C. The soil type is an umbric Acrisol (IUSS Working Group WRB, 2014) [29]. The soil was characterized by low levels of non-exchangeable K reserves and a medium K fixation capacity (Table 1).

## 2.2. Soil Characteristics

Before trial establishment, composite soil samples (25 cores) of the soils were collected from 0 to 20 cm in December 2012 and October 2011, respectively. Samples from each site were air-dried, milled to pass through a 1 mm sieve, and analyzed. Soil pH (CaCl<sub>2</sub>) was measured in a 1:2.5 (soil/solution) ratio and exchangeable acidity (Al + H) was extracted with KCl [30]. Exchangeable K, calcium (Ca), magnesium (Mg), and sodium (Na) were obtained by ammonium bicarbonate (AMBIC) extraction [31] and total cations were obtained by summing the quantities of KCl exchangeable acidity (Al + H) and AMBIC extractable Ca, Mg, K, and Na. Plant available phosphorus (P) was measured using the modified Truog method [32], and plant available silicon (Si) was measured in a CaCl<sub>2</sub> extract [33]. Total carbon was determined by automated (Dumas) dry combustion using a Leco Truspec Analyzer (Leco Corporation, St Joseph, MI, USA). Clay content was measured using the hydrometer method [34]. Non-exchangeable K reserves were determined by boiling 2.5 g of soil in 100 mL of 1.0 M HNO<sub>3</sub> for 30 min [21]. Potassium fixation was estimated using K requirement factor (KRF) adapted from Johnston et al. [24]. This measurement involved adding increasing levels of K to soils and incubating them for six weeks, after which the relationship between exchangeable K and K added was used to result in a measure of K fixation. The characteristics of the two soils are presented in Table 1.

## 2.3. Trial Establishment and Treatments

The trial on the cutanic Acrisol was established during the summer of 2012/2013 on the first ratoon (ratoons are the crops that regrow following harvest of the previous crop) of N23, a South African-bred sugarcane variety. The trial was an exploratory 3N × 3P × 3K unreplicated factorial design with 27 plots each with a surface area of 68.5 m<sup>2</sup> (10 m × 6.85 m) and each plot had five rows with a row spacing of 1.37 m, with the three inside rows being sampled and harvested. This type of design has been recognized as useful in exploratory nutrient response trials [35,36]. In such instances, pseudo-replicates are used for statistical analysis [36]. Since there was no response to P application (application rates of 0, 50, 100 kg P ha<sup>-1</sup> were used) in the current study, P treatments were used as pseudo-replicates for statistical analysis. The K application rates were 0, 120, and 240 kg ha<sup>-1</sup>. The sources of K, N, and P were KCl, limestone ammonium nitrate (LAN, 200 kg N ha<sup>-1</sup>), and double superphosphate, respectively. The treatments were applied at the commencement of the trial and after each harvest as shown in Table 2. The treatments were also accompanied by basal applications of gypsum (200 kg ha<sup>-1</sup>), zinc sulfate (23 kg ha<sup>-1</sup>), copper sulfate (10 kg ha<sup>-1</sup>), solubor (boron, 2.5 kg ha<sup>-1</sup>), and sodium molybdate (0.26 kg ha<sup>-1</sup>) as per schedule (Table 2). There were no interactions between K and N and P treatments for any of the parameters measured, and responses to N and P are not given further consideration in this paper.

**Table 2.** Chronological sequence of activities in the Umfolozi and Doringkop field trials.

Umfolozi (Cutanic Acrisol)		Doringkop (Umbric Acrisol)	
Date	Activity	Date	Activity
December 2012	Plant crop harvested	November 2011	(1) Planting
January 2013	(1) Trial commenced	December 2011	(1) N and K application
April 2013	(2) N, P, and K application	March 2012	(2) Basal applications
November 2013	(3) Basal applications	May 2013	Leaf sampling
December 2013	Leaf sampling	October 2013	(1) Plant crop harvested
March 2014	Flooding interfered first ratoon harvesting	January 2014	(2) Soil sampling for first ratoon
November 2014	N application	September 2014	N and K application
December 2014	Leaf sampling	October 2014	Leaf sampling
January 2015	Second ratoon harvested	March 2015	First ratoon harvested
February 2015	Soil sampling for third ratoon	May 2016	(1) Soil sampling for second ratoon
October 2015	(1) N, P, and K application		(2) N and K application
December 2015	(2) Basal application		Leaf sampling
April 2016	Leaf sampling		(1) Second ratoon harvested
November 2016	Third ratoon harvested		(2) Soil sampling for third ratoon
	(1) Soil sampling for fourth ratoon		
	(2) N, P, and K application		
	Leaf sampling		
	(1) Fourth ratoon harvested		
	(2) Soil sampling for fifth ratoon		

The trial on the umbric Acrisol was established during the summer of 2011 on a plant crop (first crop harvested after planting) of N39, a South African-bred sugarcane variety. The different varieties used between the two trial sites are not expected to cause confounding results because Wood and Schroeder [37] reported that the interaction between variety and K application rates is not significant. The trial had a 3N × 3K factorial design with three replicates and 27 plots of 45 m<sup>2</sup> each (9 m × 5 m), and each plot had five rows with a row spacing of 1.0 m, with the three inside rows being sampled and harvested. Potassium was applied as KCl at the rates of 0, 120, and 240 kg K ha<sup>-1</sup>. The treatments were applied at the commencement of the trial and after each harvest as shown in Table 2. As per schedule, the treatments were also accompanied by basal applications of LAN (200 kg N ha<sup>-1</sup>), double superphosphate (50 kg P ha<sup>-1</sup>), gypsum (1000 kg ha<sup>-1</sup>), zinc sulfate (45 kg ha<sup>-1</sup>), copper sulfate (16 kg ha<sup>-1</sup>), solubor (boron, 5 kg ha<sup>-1</sup>), and sodium molybdate (0.64 kg ha<sup>-1</sup>).

#### 2.4. Soil and Leaf Sampling

Soil samples were collected from the 0–20 cm depth at each site after each of three (3) harvests. Composite samples from each plot were dried (35 to 40 °C) and milled to pass through a 1 mm sieve before analysis. Exchangeable K was extracted with the AMBIC extractant [31] and K in the extract was analyzed using inductively coupled plasma (ICP-OES, VARIAN ICP 720-ES).

Sugarcane leaf samples were collected at each trial site for each cropping cycle when the crop was between 3 and 8 months old. Leaf sampling was undertaken for three ratoon crops on the cutanic Acrisol and on the umbric Acrisol for the plant and two ratoon crops. The third leaf (top visible dewlap) was sampled in each case and 30 leaves were collected from each plot. The tops and bottoms of the leaves were chopped off, leaving roughly 20–30 cm of the central portion of the leaf blade. The midrib was stripped out and discarded. The leaf samples were dried, ground, and analyzed for K using X-ray fluorescence (XRF: Rigaku (Tokyo, Japan), ZSX Primus II).

### 2.5. Harvesting

Four harvests were taken on the cutanic Acrisol and three on the umbric Acrisol. Sugarcane was burnt 12 h before it was harvested manually. All leaf material was removed and the stalks were weighed using a balance mounted on a vehicle to determine sugarcane yield. Harvested stalks were sent to the South African Sugarcane Research Institute (SASRI)'s mill room where sucrose contents were measured using near infrared (NIR) spectroscopy. Yield data could not be obtained for the first harvest on the cutanic Acrisol because of flooding of the field following heavy rainfall (Table 2).

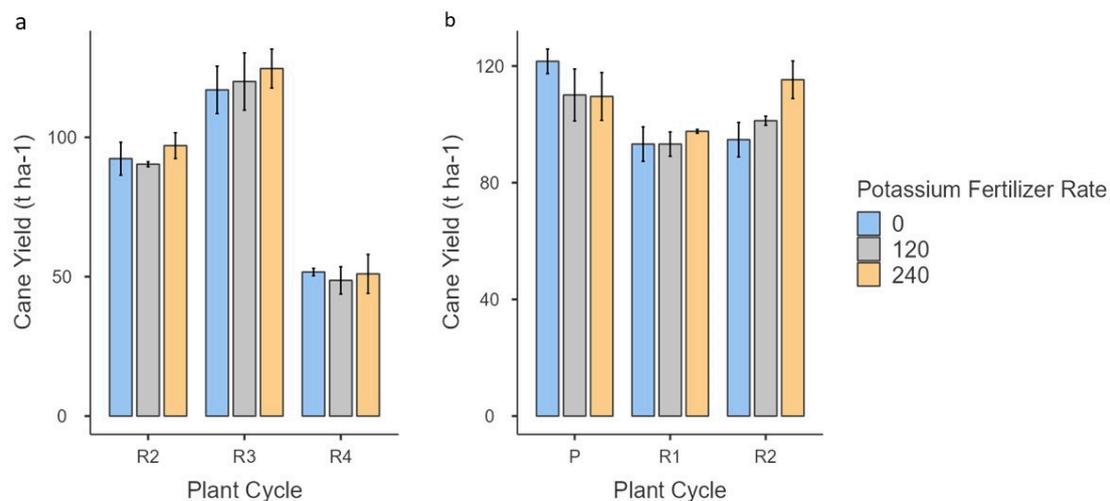
The amount of K removed ( $\text{kg ha}^{-1}$ ) by the crop was estimated by multiplying sugarcane stalk yields ( $\text{t ha}^{-1}$ ) by 1.5 according to the value reported by the International Plant Nutrition Institute [38]. This assumes that 1.5 kg K is removed per ton of cane harvested.

### 2.6. Statistical Analysis

Sugarcane stalk and sucrose yields, leaf K, and exchangeable K, were analyzed using analysis of variance (ANOVA; jamovi version 2.3) for each soil. Where treatments showed significant effects, means were separated using Fisher's protected least significant difference (LSD) test at  $p < 0.05$ .

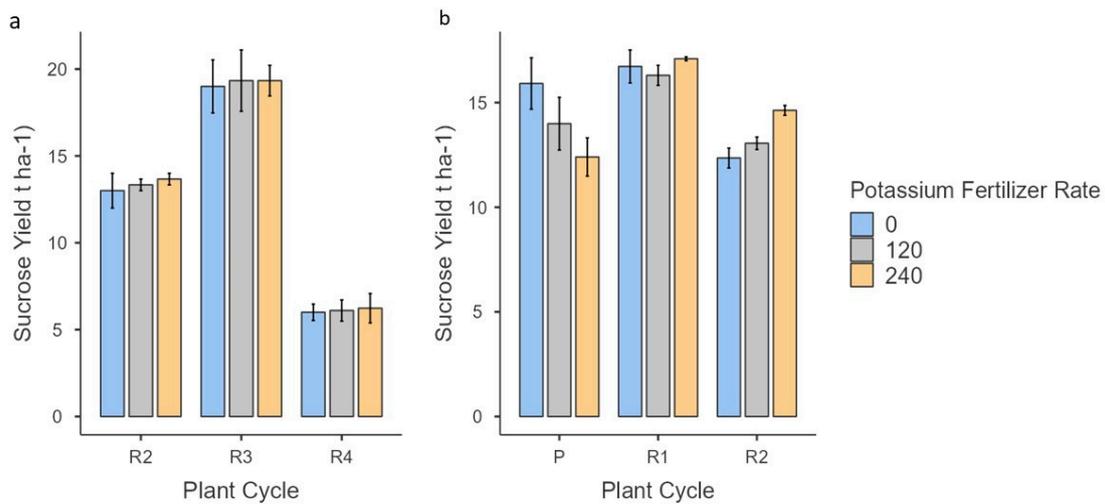
## 3. Results

There was no cane stalk yield response to K application on the cutanic Acrisol for all the ratoon crops (Figure 2a). On the umbric Acrisol, cane yield at the  $240 \text{ kg ha}^{-1}$  application rate was higher compared to the control for the second ratoon (Figure 2b).



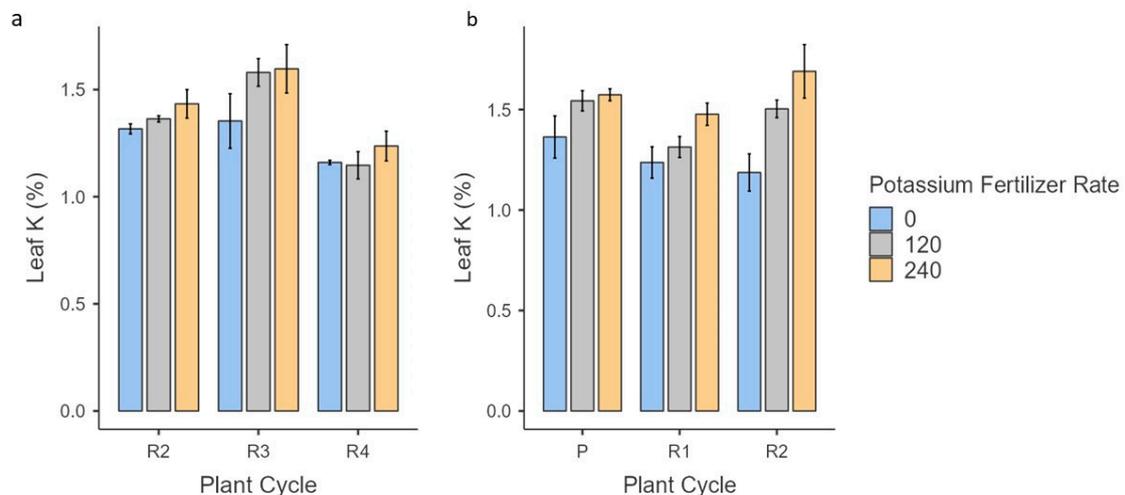
**Figure 2.** Response of sugarcane stalk yield to applied potassium (K) for (a) second ratoon (R2), third ratoon (R3), and fourth ratoon (R4) on the cutanic Acrisol and (b) plant crop (P), first ratoon (R1), and second ratoon (R2) on the umbric Acrisol.

In terms of sucrose yield, there was no response to K application for any of the ratoon crops ( $p > 0.05$ ) on the cutanic Acrisol (Figure 3a). Similarly, on the umbric Acrisol, sucrose yield was not affected by K treatments for the first ratoon crop (Figure 3b). However, sucrose yield was lower in the  $240 \text{ kg K ha}^{-1}$  treatment compared to the control on the plant crop, whereas in the second ratoon crop, sucrose yield was higher at this high K application rate, compared to the control.



**Figure 3.** Response of sucrose yield to applied potassium (K) for (a) second ratoon (R2), third ratoon (R3), and fourth ratoon (R4) grown on cutanic Acrisol and (b) plant crop (P), first ratoon (R1), and second ratoon (R2) on umbric Acrisol.

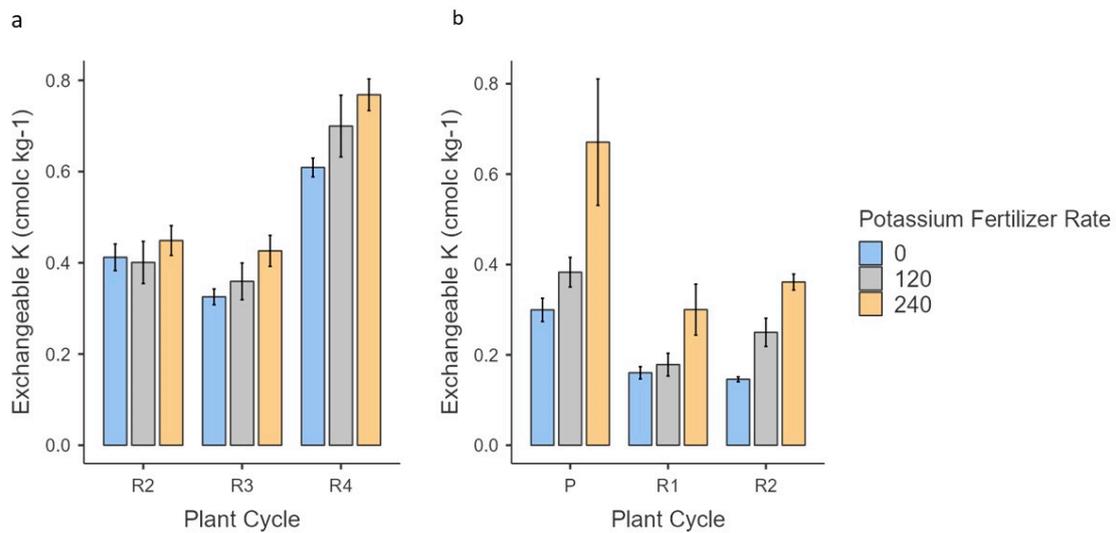
Although third leaf K values increased with the amount of K applied on the cutanic Acrisol, the increase was not significant for any of the crops, with the exception of the second ratoon, where 120 and 240 kg ha<sup>-1</sup> had higher leaf K concentrations (Figure 4a). On the umbric Acrisol, on the other hand, leaf K in the 240 kg K ha<sup>-1</sup> treatment was significantly higher than the control for the first and second ratoon (Figure 4b). In both soils, leaf K concentrations at all K treatment levels and harvests were above the SASRI recommended threshold value of 1.05%.



**Figure 4.** Response of leaf potassium (K) to applied K for (a) second ratoon (R2), third ratoon (R3), and fourth ratoon (R4) grown on the cutanic Acrisol and (b) plant crop (P), first ratoon (R1), and second ratoon (R2) on the umbric Acrisol.

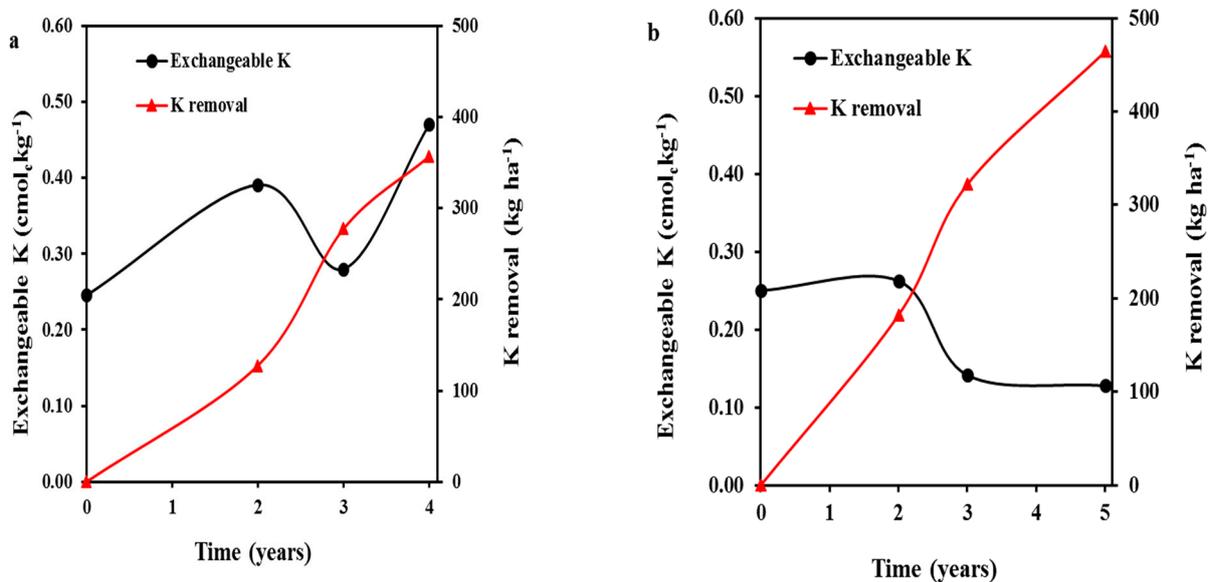
The response of exchangeable K measured in soils after harvest was different despite these two soils having the same initial values at the commencement of the study. In the cutanic Acrisol, exchangeable K measured after the harvest of the fourth ratoon was higher in the 240 kg K ha<sup>-1</sup> treatment compared to the control (Figure 5a). In this soil, exchangeable K after harvest did not drop below the initial value for all three application rates. In the umbric Acrisol, on the other hand, exchangeable K measured after the harvest of the plant crop and second ratoon increased significantly ( $p < 0.05$ ) with increasing applications rates (Figure 5b). Exchangeable K after harvest of the plant crop was higher

than at the commencement of the trial for the 240 K kg ha<sup>-1</sup> application rate. There was also a trend where exchangeable K decreased with successive cropping in the control treatment.



**Figure 5.** Relationships between applied potassium (K) and exchangeable K after harvest of (a) second ratoon (R2), third ratoon (R3), and fourth ratoon (R4) on the cutanic Acrisol and after harvest of (b) plant crop (P), first ratoon (R1), and second ratoon (R2) on the umbric Acrisol.

Changes in exchangeable K with successive cropping in the control treatment were compared against cumulative K removal and showed an upward trend on the cutanic Acrisol despite the continual removal of K by the crop in the four-year duration (Figure 6a). In contrast, there was a downward trend in exchangeable K with an increasing cumulative K removal by the crop in the control of the umbric Acrisol (Figure 6b).



**Figure 6.** Changes in topsoil exchangeable potassium (K) with time and cumulative K removals by the sugarcane crop from zero (untreated) K treatments of the (a) cutanic Acrisol and (b) umbric Acrisol.

#### 4. Discussion

Sugarcane stalk and sucrose yield, leaf, and exchangeable K responses to fertilizer applications on the umbric Acrisol are characteristic of soils with low non-exchangeable K reserves and fixation capacity, which are well-suited for the use of only exchangeable K

when calculating fertilizer requirements. The characteristic response to fertilizer application when these soils are deficient of K is an increase in leaf concentration (leaf K), biomass (cane stalk) and sucrose yields, and the depletion of exchangeable K after harvest. However, the characteristic responses if they have sufficient or surplus levels can be divided into two, depending on whether there is an excessive uptake of K. Where there is no excessive uptake of K, then there will be an increase in leaf concentration, no response of cane and sucrose yields, and a depletion in exchangeable K, reflecting removal by the crop. In the case of an excessive uptake of K, then the response will be an increase in leaf concentration, decline in K and sucrose yields, and a depletion in exchangeable K, reflecting removal by the crop. Admittedly, leaf concentrations will increase despite levels of exchangeable K in the soil, but they should be compared against critical leaf thresholds. Three critical sugarcane leaf K concentrations are reported in the literature. The first is the threshold below which the crop will be deficient in K (1.05%), the second is the level beyond which yield response to K is unlikely (1.25%), and lastly at 1.5%, above which luxury consumption is considered to occur causing decline in crop yield [15,39].

The sucrose yield for the plant crop in the 240 kg K ha<sup>-1</sup> treatment indicates that initial exchangeable K levels were sufficient and K application may have caused luxury consumption and the corresponding decline in yield. This was also consistent with the leaf K concentration, which was above 1.5% for the 240 kg K ha<sup>-1</sup> treatment. However, exchangeable K in the control treatment was not depleted, pointing to its replenishment from other reserves. The reserves may have been non-exchangeable in nature, which could explain the rapid depletion after harvesting the first and second ratoons. It was after the depletion of these reserves that the positive response to K application was observed on cane and sucrose yields. Similar findings were reported where there was a delayed response to K application associated with the depletion of K reserves in control treatments [15,40]. These results may also indicate that the set criteria for non-exchangeable K reserves is conservative, allowing for those crops with extensive K removal [21,27].

In the cutanic Acrisol, sugarcane stalk and sucrose yield, leaf, and exchangeable K response to fertilizer application showed a different trend, and this highlights why both non-exchangeable K reserves and fixation capacity should be considered when calculating fertilizer recommendations. The expected result is that the response of sugarcane stalk and sucrose yield, leaf and exchangeable K to fertilizer application, on the account of non-exchangeable alone, would not be significant [11,20]. Although the response of sugarcane stalk and sucrose yield and leaf K was consistent with the expected results, there was a deviation in exchangeable K response after the second ratoon, which could have been caused by K fixation. On the other hand, exchangeable K response to fertilization, on the account of fixation capacity alone, would be proportional to the amount added through the fertilizer [41]. Nevertheless, the exchangeable K response deviated from this expected result for the second and third ratoons, possibly due to the release of K from non-exchangeable reserves. The response of exchangeable K to fertilizer application monitored after three harvests may provide some insights into the role of non-exchangeable K reserves and fixation capacity in regulating K uptake and, consequently, plant growth and yields.

The lack of exchangeable K responses to fertilizer applications on the cutanic Acrisol after harvest of the second and third ratoons could be caused by three factors or their combination. Firstly, it could be that the amount of K removed by the crop was equal to the amount added through the fertilizer. Secondly, in the control treatment, K could have been released from the non-exchangeable reserves and preventing the depletion of exchangeable K. Lastly, in 120 and 240 kg K ha<sup>-1</sup> treatments, added K could have been fixed by soils, which would lower the extent at which exchangeable K increases. Since there was no stalk and sucrose yield response to fertilizer application, it is unlikely that the lack of the response of exchangeable K was caused by K removal being equal to the amount added. Exchangeable K in the study increased in the control of the cutanic Acrisol over the years, despite K removal, and is most likely explained by the release of non-exchangeable K reserves [42]. However, the application of 240 kg K ha<sup>-1</sup> increased

exchangeable K after the harvest of the fourth ratoon and indicates that an additional factor is at play. It is possible that the first and second applications of fertilizer reduced K fixation capacity, resulting in a higher exchangeable K in the 240 kg K ha<sup>-1</sup> treatment with the third additions, which is consistent with findings from several studies [43–45]. It is proposed then that the combination of high non-exchangeable K reserves and fixation capacity of the cutanic Acrisol served as buffers for soil K availability and regulated exchangeable K concentrations.

The responses of the two soils used in this study, which presented the same initial levels of exchangeable K, have implications on designing future calibration studies. The lack of response in the soil with very high levels of non-exchangeable K reserves makes it unsuitable for calibration studies. Based on this, only 10 out of 14 combinations of non-exchangeable K reserves and fixation capacity identified by Elephant et al. [27] can be used in calibration studies, because the other soils will be non-responsive. In addition, considering that the criteria set by Haysom [21] may be conservative, it is necessary to evaluate the responsiveness of soils with low to medium levels of non-exchangeable K reserves.

## 5. Conclusions

This study demonstrated that non-exchangeable K reserves and fixation capacity influence the response of sugarcane stalk and sucrose yield to K fertilizer application, and these were linked to leaf and exchangeable K. Successive cropping with sugarcane depleted exchangeable K on a soil low in non-exchangeable K reserves, which led to responses in yield to applied K. However, on soils with high reserves, there was no depletion of exchangeable K nor was there a yield response to K application. In addition, K application increased exchangeable K on the soil with a low fixation capacity, while the soil with a high fixation capacity maintained steady levels of exchangeable K, presumably until fixation sites were saturated. This study indicated the importance of including modifications based on levels of non-exchangeable K reserves and fixation capacity when calculating K requirements and when conducting field calibration studies. It also provided some evaluation of published criteria for very high non-exchangeable K reserves, and also suggest that the criteria for low reserves is possibly conservative. Finally, results from this study also indicated that non-exchangeable K reserves and fixation capacity provides a measure of K buffering capacity, which regulates exchangeable K concentrations and K uptake by the crop, both of which need to be considered when designing calibration studies.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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