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Potassium fertilisation strategies for rotational grain-legume crops — implications for the subsequent sugarcane crop

NV Halpin[1], MJ Bell[2], WE Rehbein[1] and PW Moody[3]

[1]*Queensland Department of Agriculture and Fisheries, Bundaberg, Qld 4670;* Neil.Halpin@daf.qld.gov.au
[2]*University of Queensland, Gatton, Qld 4343*
[3]*Queensland Department of Environment and Science, Dutton Park, Qld 4102*

Abstract Sugarcane is regarded as a luxury accumulator of potassium (K). Soil testing at plough-out of older ratoons prior to establishing grain-legume crops (soybean and peanuts) sometimes highlights low soil reserves of the element. Agronomists have been seeking guidance on fertilization strategies to maximize break-crop grain yields in sugarcane soils that have depleted K levels. A replicated field trial was established to determine the effect of a range of K fertilizer additions on the productivity of a soybean and then a peanut crop in a long fallow from sugarcane. The residual value of the K supplied in the legume phase was also assessed in the subsequent sugarcane crop. Despite the additions of K from 0 to 250 kg K/ha in 50 kg increments there was no productivity response in either legume crop. The subsequent plant-cane crop (Q208$^{\phi}$) also demonstrated no productivity response to K fertilizer that was applied to the soil prior to the establishment of the soybean crop. Analysis of plant-cane K concentrations showed no difference in K returned to the site as trash. However, there were significant differences in the quantities of K exported off-farm in millable stalk. The lack of fertilizer K responses, despite low soil-test K concentrations at the end of the sugarcane crop cycle, suggest considerable uncertainty in the interpretation of current soil-testing strategies remains. However, it is unsustainable to mine soil nutrients. Growers have two options; either to supply enough K to meet expected legume crop removal or alternatively recognize that if K is over-supplied to the legume phase, then there is the opportunity to 'discount' that in the plant-cane fertilization strategy.

Key words Potassium, grain legume rotations, farming systems

INTRODUCTION

Grain-legume rotations are one of the key pillars of a more sustainable sugar-based farming systems on the Queensland coast. Leguminous crop rotations improve the productivity of the subsequent sugarcane crop (Garside *et al.* 1999) and reduce populations of plant-parasitic nematodes (Stirling *et al.* 2001). The legume crop residues enable nitrogen (N) fertiliser to be reduced for the plant-cane crop (Bell *et al.* 2003; Schroeder *et al.* 2007) and provide soil cover that significantly reduces soil erosion (Nachimuthu *et al.* 2017). Legume break crops are a strategic component to reduce the impact of yield decline, which is defined as the loss in the productive capacity of soils under long-term monoculture (Garside *et al.* 1997).

Grain-legume production has become an integral part of the farming system in the southern canelands with approximately 1,000 ha and 1,500 ha of peanuts and soybeans, respectively, grown annually. The Grains Research and Development Corporation (GRDC) has recognised this by investing in project activities in the region to increase the profitability of grain production in this coastal environment.

Soil sampling prior to the establishment of a legume crop at the end of the sugarcane cropping phase typically highlights several issues. Soils are often acidic, low in nitrate N (NO_3^-N) and exchangeable potassium (K_{exch});

micro-nutrients can also be at low levels. Sugarcane is regarded as a luxury accumulator of K and this is consistent with the depleted K status of the soil at the end of the cane cycle.

Potassium is an essential element for plant growth. It plays a major role in ionic balance in the plant, increases plant vigour and disease resistance, influences water movement in the plant and is essential to the formation and transport of starches, sugars and oils (Incitec 1991). Potassium plays an important role in stomatal regulation and efficiency of water use.

Growers and their advisors want to maximise productivity of legumes and there has been limited field-trial experimentation to provide K-fertiliser recommendations. Current commercial practice is to ensure that productivity of legumes is not limited by K availability, with K fertiliser typically applied at rates of 50 kg K/ha and 120 kg K/ha for soybean and peanuts, respectively. To improve industry confidence in these strategies, we established a field trial with a range of rates of K addition in the Bundaberg region after the conclusion of a sugarcane crop cycle. The productivity of successive annual crops of soybean and peanut was assessed over an 18-month break from sugarcane cropping. A new sugarcane crop cycle was then established, and the residual value of fertilizer K applied prior to the fallow legume crops was monitored in the plant and first-ratoon crops.

MATERIALS AND METHODS

The site was located at Kalkie 6.5 km SE of Bundaberg (24°54’01.48”S 152°23’21.85”E) on a Yellow Dermosol soil (Isbell 1996). Soil sampling was undertaken just prior to harvest of the third-ratoon crop of Q188$^{\Phi}$ in July 2008 to determine the nutritional status of the site, with key soil characteristics shown in Table 1.

Table 1. Selected soil chemical characteristics from samples collected just prior to harvest of the final ratoon in the prior crop cycle.

Parameter	Depth		
	0–10 cm	10–20 cm	20–40 cm
pH (1:5 water)	5.5	5.7	5.9
Organic carbon (%)	1.4	1.1	0.87
NO_3–N (mg/kg)	1	1	1
Sulfate S (mg/kg)	15	21	15
P – BSES (mg/kg)	96	100	79
P – Colwell (mg/kg)	63	27	45
PBI	67	71	63
Exch K cmol(+)/kg	0.13	0.1	0.07
Exch Ca cmol(+)/kg	1.8	2	1.9
Exch Mg cmol(+)/kg	0.55	0.44	0.44
Exch Al cmol(+)/kg	0.3	0.17	0.11
Exch Na cmol(+)/kg	0.04	0.04	0.06
Cation-exchange capacity (cmol(+)/kg)	2.82	2.75	2.57
DTPA Cu (mg/kg)	1.6	1.5	1.4
DTPA Zn (mg/kg)	1.7	1.5	1.1
DTPA Mn (mg/kg)	2.7	2.6	1.1
DTPA Fe (mg/kg)	240	190	150

Fine agricultural lime was applied at 3.3 t/ha on 28 August 2008 to correct acidity prior to land preparation. The cane stool was destroyed by two passes of a rotary hoe and sub-soil compaction was alleviated with a deep-ripping operation. Muriate of potash (50% K) was applied to the soil surface at six rates: 0, 50, 100, 150, 200 and 250 kg K/ha, in plots that were six soybean rows (three 1.83 m beds) wide by 20 m long. These treatments were replicated four times. The K was applied on 14 November and incorporated into the top 10–15 cm of the soil profile and a slight bed was formed.

Soybean cultivar Fraser was planted on 26 November 2008 using ‘Flexicoil’ single-disc openers and a ‘Janke’ twin-inclined plate planter. Seed was sown to establish 325,000 plants/ha. Group H inoculant was delivered onto the seed and into opened furrows via peat water injection at a rate of 140 L water/ha. Irrigation was supplied to the trial via an overhead low-pressure boom and was scheduled via tensiometers once a moisture potential of 40–50 Cbar was reached. Weeds were controlled via herbicides (Blazer® and Spinnaker®) at registered rates and insects were controlled once thresholds were reached, using industry best practice.

Crop growth at maximum biomass was determined by destructively sampling a 3.66 m^2 plot area. Maximum biomass sampling occurred on 16 March 2009 when the crop was at R6.5 growth stage (http://weedsoft.unl.edu/documents/GrowthStagesModule/Soybean/R8.htm). Samples were placed in a hessian bag then dried at 60°C until constant dry weight was attained. Weights were recorded and samples mulched through a garden-type mulcher to facilitate more uniform sub-sampling. The sub-samples were ground to <2 mm and analysed for K concentration using plant element nitric microwave digest ICP (Rayment and Higginson 1992).

Once the crop reached full maturity (R8) it was desiccated with Reglone® at 2.5 L/ha + Hasten crop oil at 1 L/100 L 4 days prior to harvest. Grain yield was determined using a KEW plot thresher, harvesting 8 m of the centre two rows of each plot. The grain from each plot was bagged and placed in a dehydrator at 32°C for 12 hr followed by a further 72 hr with no additional heating. Prior to weighing, samples were cleaned to remove extraneous material.

Following the unexpected lack of soybean growth response to applied K, soil in the control (0K applied) plots was re-sampled in 10 cm increments to 40 cm after soybean harvest, air-dried, passed through a 2 mm sieve and sent for analysis. The soil K status was assessed using both the standard soil exchangeable K test (extraction with NH_4Cl at pH7) and extraction with sodium tetra-phenol-boron (TBK), as Moody *et al.* (2007) had shown that the TB-K test may indicate additional reserves of slowly available K that could contribute to crop K acquisition.

A winter field pea crop was sown and harvested for grain, but the productivity data from that phase was not captured. The beds were renovated in late spring after the field pea harvest using a pass with a rotary hoe and beds were reformed.

Peanut cultivar Holt was sown on 26 November 2009 into the same plots without any additional fertiliser. The peanuts were sown at a rate to establish 120,000 plants/ha using the same planter and inoculant delivery system as described for the soybean crop. Natural gypsum was applied in-crop prior to flowering to ensure adequate soil calcium status. Irrigation application and scheduling for the peanut crop phase was similar to that used for the soybean crop. The protectant fungicide chlorthalonil 720 g/L was applied at 1.8L/ha on a 10–14-day schedule to prevent foliar diseases, with sprays commencing 4 weeks post planting and continuing until crop maturity. The crop reached physiological maturity on 4 May 2010, when maximum biomass (including pods) was determined by destructive sampling a 1.8 m^2 quadrat. The samples were placed in a labelled hessian bag, taken back to the laboratory and washed to remove soil, then placed into a 'tobacco barn' dehydrator at 60°C until a constant dry weigh was attained. The samples were weighed, mulched with a garden mulcher, then ground to <2 mm using a 'Christie' beater mill. Samples from the 0K, 100K and 250K were analysed for K concentration using plant-element nitric-microwave digest ICP.

The crop was harvested on 5 June 2010, 183 days after planting. A yield quadrat of 12.81 m^2 was marked out of each plot. The crop was field dried for 9 days after it was dug. The yield samples were then threshed using a stationary thresher, with the pods collected in labelled hessian bags that were placed into a tobacco barn for air-drying. The samples were put over a KEW peanut cleaner to remove soil and extraneous matter, after which the sample weight was recorded. A 1,000 g sub-sample was hulled and hand-shelled to remove loose peanut shell. The kernels were placed over a series of sieves to determine treatment impact on grade/quality.

The percentage of each grade was determined by dividing the weight of each grade (in grams) by the original 1,000 g sample. Shell percentage was determined by the difference of the sum of all the grades from the original 1,000 g sample. The nut-in-shell samples from the 0K, 100K and 250K plots were ground using a kitchen blender, passed through a 2 mm sieve, and were analysed for K concentration using plant-element nitric-microwave digest ICP.

The site remained fallow until planted to sugarcane cultivar Q208$^{\Phi}$ on 23 August 2010, using a billet planter and fertilised with DAP at a rate that supplied 26 kg N/ha and 28 kg P/ha; no other fertiliser was applied. The 0K, 100K and 250K plots were soil sampled in 10-cm increments to a depth of 40 cm, air-dried and passed through a 2 mm sieve prior to being sent for analysis for extractable cations using the NH_4Cl pH7 ICP technique prior to planting the cane crop.

Treatment effects on plant cane yield were determined in October 2011 by hand harvesting 10 m of row of the centre row of the plots, with stalks counted, total biomass recorded, sub-samples partitioned into trash and millable stalk and commercial cane sugar (CCS) determined on a six-stalk sample sent to Sugar Research

Australia for CCS determination by NIR. A sub-sample of millable stalk and trash (consisting of dry trash, green leaf and cabbage) was mulched, weighed wet and dried at 60˚C as described by (Liu and Kingston 1993). Treatment effects on crop-K uptake and partitioning between millable stalk and trash were determined using plant-element nitric-microwave digest ICP for samples from the 0K, 100K and 250K treatments. Nutrient uptake was calculated as the product of the dry weight of harvested biomass and the element concentration for each component.

The ratoon crop was fertilised with urea to provide 140 kg N/ha and the final yield of the first-ratoon crop was determined from the 0K, 100K and 250K treatments in the same way as described above. Nutrient concentrations were not determined on these crop samples.

Data were analysed using Genstat (release 16.1, VSN International) as a general design. Pair-wise testing of means was conducted at P = 0.05 using Fischer's Protected LSD.

RESULTS AND DISCUSSION

Dynamics of soil-K fertility during the experiment

On the basis of the current soil-test guidelines for legume crops, the site chemical assessment (Table 1) suggest applications of 30 kg K/ha and 20 kg K/ha to maximise the yield potential of soybean and peanuts, respectively, while the application of agricultural lime was to achieve a target pH of between 6.0 and 6.5 in the cultivated layer (0–20 cm).

The effect of fertilizer application rates on soil K status was not assessed until the end of the 18-month fallow period (i.e. after the soybean, field pea and peanut crops), with data for selected K application rates shown in Table 2. There were significant increases in available K in the 20–30 cm and 30–40 cm soil layers, and trends for similar effects in the layers above that were consistent with increasing rates of K application. Interestingly, while K fertilizer was only incorporated in the top 20 cm, there is clear evidence of movement of fertilizer K into deeper profile layers, especially at the 250K application rate. This potential to leach K in sandy soils with limited ability to retain cations (i.e. low cation exchange capacity) is well known (Rosolem *et al.* 2010) and is still evident despite K accumulation by the three successive legume crops and removal of K in harvested produce (discussed later).

Table 2. Soil potassium status at cane planting in the top 40 cm for selected rates of K applied 18 months previously*.

Treatment	Exchangeable K (cmol(+)/kg				Profile exchangeable K to 40 cm (kgK/ha)
	0–10cm	10–20cm	20–30cm	30–40cm	
0K	0.18	0.13	0.08 ^{b}	0.04 ^{b}	240 ^{b}
100K	0.29	0.19	0.12 ^{ab}	0.07 ^{b}	373 ^{b}
250K	0.28	0.23	0.15 ^{a}	0.12 ^{a}	446 ^{a}
P Value	0.069	0.054	0.021	0.008	0.024
LSD (P=0.05)	ns	ns	0.05	0.04	134

*Data within columns followed by the same superscript are not significantly different at P=0.05.

Interestingly, there is considerable similarity in the profile K content of the soil that received no K fertilizer determined at the end of the previous sugarcane cycle (shown in Table 1), in samples collected after the initial soybean crop harvest, and again at the time of planting of the next cane cycle 18 months later (Figure 1). The data suggest that there was even a slight increase (not significant) in the quantity of exchangeable K in the top 40 cm of the soil profile over the fallow, despite the effects of three successive legume crops and no K-fertilizer application; effects were most evident in the top 20 cm of the soil profile. The quantity of exchangeable K in the top 40 cm of the profile was initially 220 kg K/ha, 260 kg K/ha after the initial soybean crop harvest and 260–270 kg K/ha after peanut harvest and immediately prior to cane planting.

The enrichment of the surface soil layers is consistent with the relatively low K harvest indices in harvested product (i.e. the ratio of K removed in grain: total above ground K accumulated in crop biomass) of most crops harvested for grain, and, hence, the return of significant amounts of K in crop residues to the topsoil layers.

However, the lack of any obvious profile K depletion after the legume fallow crops was unexpected but may relate to the return and subsequent release of unaccounted K in the trash and stools from the previous cane crop cycle. The initial site characterisation samples were collected before cane harvest, and so the K in tops and trash and stools would not have been included, resulting in an under-estimate of the starting K availability. The potential quantum of K returned in tops and trash for the plant cane crop at the end of this experiment are presented below and provide an indication of the size of any potential errors in starting K estimation.

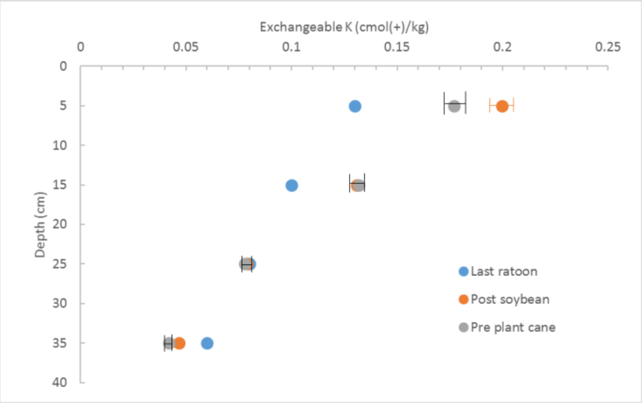

Figure 1. Distribution of exchangeable K [cmol(+)/kg] in the top 40 cm of the soil profile at harvest if the final ratoon and beginning of the fallow, after harvest of the initial soybean crop and then after peanut crop harvest and prior to planting the next cane crop. The error bars in the second and third samplings represent standard errors of the means for each depth layer.

After the initial soybean crop, soil samples were collected from the replicate plots of the unfertilized treatment to determine if there may have been additional reserves of plant-available K that were not being accounted for in the exchangeable K extract. The profile was sampled to 50 cm, in 10-cm depth increments, and the amounts of (potentially) available K determined in a TB-K extraction were compared to those from the exchangeable K method, with data shown in Figure 2. Data show that across all profile depths, the TB-K extract indicated the profile bioavailable K may have been as much as 41% higher than the measurement of exchangeable K would suggest. As indicated in Moody and Bell (2006), the bioavailability of the additional K extracted in the TB-K extraction can vary with soil type, so the utility of this as a more accurate estimate of soil K status in coastal farming systems needs further exploration.

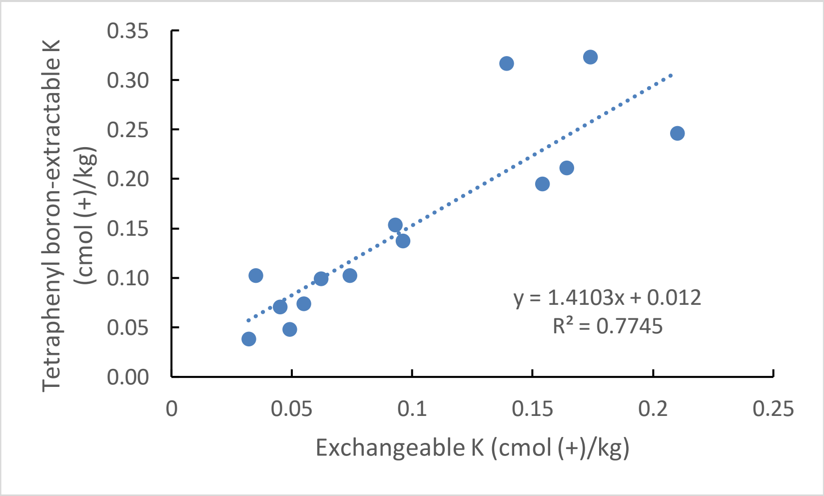

Figure 2. Correlation between bioavailable K estimates determined using an NH_4Cl extraction (exchangeable K) or a tetraphenyl boron extraction (TB-K) determined on soils from the unfertilized Control profile layers.

Biomass and yield responses to applied K during the experiment

Biomass production and harvestable yield were determined for the soybean, peanut and plant-cane crops across the treatment range over three successive years, while yields from selected K rates were determined in the first-ratoon sugarcane crop as a final assessment of residual effects of applied K (Table 3). Despite the low starting soil K status, the wide range of rates of applied K and the demonstrated impact on available K status within the cultivated layer (Table 2), effects on biomass production or harvested yield were never statistically significant. The closest any crop came to generating a positive response was in biomass production during the peanut crop, where there was >30% more biomass in the 250K treatment, compared to the unfertilized control (0K). However, this did not result in any additional pod yield.

Table 3. Effects of applied K rate on above ground (including pods in the peanut crop) dry biomass production (t/ha) and harvested crop yield (t/ha of soybean grain, peanut pods or millable stalk cane yields) over a sequence of four years after the initial fertilizer K treatment application at Bundaberg. (ns = not significant).

Treatment	Soybean		Peanut		Plant cane		First-ratoon cane	
	Biomass	Grain	Biomass	Pods	Biomass	Cane	Biomass	Cane
0K	9.4	4.29	9.25	3.43	34.5	86.7	na	73.6
50K	9.9	4.35	na	4.36	34.2	89.1	na	na
100K	9.8	3.90	11.05	3.50	35.4	92.5	na	71.4
150K	10.3	4.18	na	3.80	35.6	90.6	na	na
200K	10.4	4.42	na	3.78	35.8	94.5	na	na
250K	9.9	4.00	12.44	4.13	35.9	92.4	na	79.0
LSD (P=0.05)	ns	ns	ns	ns	ns	ns		ns

Effects of K rate on crop quality parameters (shell-out and grades in the peanut crop, and CCS in the sugarcane crops) were generally small and only occasionally statistically significant. In the peanut crop, application of K at any rate resulted in a small but significant increase in the percentage of the pod yield that was shell (29.9% shell with K applied, versus 27.8% shell without K). This was accompanied by a 5% decrease in the proportion of the kernels classified as Jumbos, Grade 1 and Grade 2 (the higher value components) and a concomitant increase in the lower grade Manufacturing and Oil grade kernels. The importance of elevated K relative to calcium (Ca) in the pod zone of peanuts is well recognized but is usually countered by topdressing of soluble Ca sources, such as gypsum, during the peanut crop.

There was no effect of K rate on CCS in the plant-cane crop (average of 15.5%), but there was a suggestion of elevated CCS in response to residual K in the 1R, with CCS of 18.1% in the unfertilized control and 18.9% in both the 100K and 250K treatments.

Crop accumulation of soil and fertilizer K, and K removal at harvest

Whilst effects of K fertilizer application on biomass production or crop yield were minimal (Table 3), there were significant increases in K uptake in crop biomass in response to K rate (Figure 3). The smallest effects were in the soybean crop, which also accumulated the greatest K uptake in the unfertilized (control) treatments.

These differences in K uptake were due almost exclusively to differences in K concentration measured in crop biomass in all crop species, with these increases typically accompanied by slight but significant decreases in tissue concentrations of Mg in all crops, and also by decreases in tissue Ca concentration in the peanut crop. Leaf samples collected from the plant cane crop in March 2011 showed similar effects of K rate on tissue K concentration (increasing from 1.28% in the Control treatment, to 1.45%K and 1.51%K in the 100K and 250K treatments, respectively), but effects on other cation concentrations were not significant.

The cation interactions are indicative of the limited capacity of these sandy soils to buffer cation concentrations in the soil solution, which increases the chances of unforeseen negative impacts of high rates of addition of nutrients in K fertilizer applications, or potentially in response to other soil ameliorants such as lime (Ca) or dolomite (Ca and Mg).

Unlike total crop biomass, there was no increase in grain or peanut pod K concentration in response to K application rate or indeed crop K uptake (data not shown). This is a common observation in other K research being undertaken on the Ferrosol soils at Kingaroy (MJ Bell, unpublished data), with the result that the proportion of crop K leaving the field in harvested produce declines with increasing K rate/availability. Therefore, the large increase in crop-K uptake recorded for all crops in Figure 3 resulted in increasing redistribution of K from across the active root zone into top soil layers as crop residues were returned to the soil surface and K is leached out with rainfall or irrigation. Whilst not readily evident in the exchangeable K data shown in Table 1 (due to the incorporation of residues with tillage and the low cation-exchange capacity of this soil type), it is a major factor contributing to the surface stratification of available K in soils with a greater clay content and cation-exchange capacity.

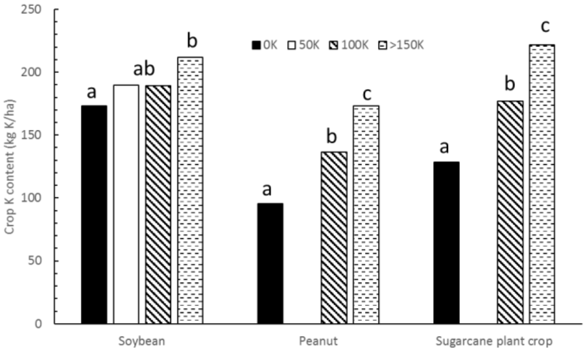

Figure 3. Effects of K fertilizer application on K accumulation in above ground biomass in the soybean, peanut and plant cane crops at Bundaberg. As there were no significant differences in crop K uptake for K rates of 150 kg K/ha or greater in the soybean crop, values are shown as means across these treatments for that crop. Different letters denote statistically significant differences ($P<0.05$) between K rates within each crop species.

In contrast to the legume break crops, however, the distribution of K between harvested (cane) and unharvested (trash and tops) plant parts changed in the opposite direction due to an increasing proportion of crop K accumulation in the millable stalk with increasing crop K uptake (Figure 4). Increasing crop K accumulation in the plant crop had no significant impact on either the amount of trash or the concentration of K in it (1.06%K, on average). However, increasing concentrations of K in millable stalk with increasing K rate (from 0.22%K in the unfertilized Control to 0.37% and 0.52%K in the 100K and 250K treatments, respectively) resulted in the proportion of crop K leaving the field in harvested produce increasing from 50% to 61% and 68% for the higher rates of K application. This type of response is clearly undesirable from both a sugar-quality perspective (higher stalk K concentrations result in higher ash contents and poorer sugar crystal quality) (Calcino *et al.* 2018) and a K-use efficiency perspective (i.e. more K leaving the field without any productivity benefit).

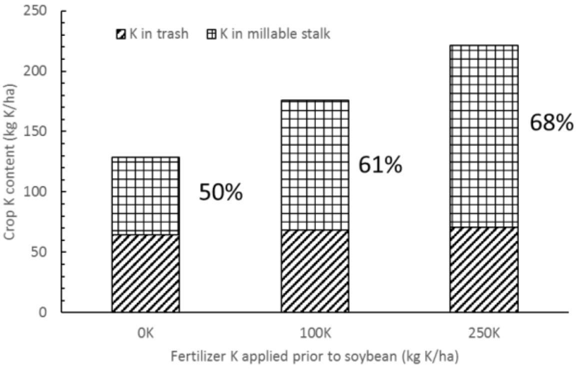

Figure 4. Impact of residual effects of K rates applied during the sugarcane fallow on partitioning of crop K between millable stalk and trash (leaf and cabbage) fractions of the crop biomass in the Q208$^{\phi}$ plant-cane crop. The percentage of crop K leaving the field in harvested cane is indicated for each treatment**.**

CONCLUSIONS

The results from this one experiment highlight several important issues that relate to management of K fertility across a diversified sugarcane-cropping system. Foremost is the highlighted uncertainty in interpreting the critical soil-test K concentration below which fertilizer-K responses would be expected in legume break crops. There are suggestions from this study that fertilizer-K recommendations for these crops may be unnecessarily high, but there will need to be more research undertaken before better guidance can be provided. Confounding effects of soil type, K mineralogy, presence of soil K pools with differing availability and different depths of root activity from season to season will all complicate soil sampling and soil-test interpretation.

From the perspective of sustainable soil management, it is clearly not possible to continue to deplete soil-K reserves, and fertilizer-K applications will be needed. However, given the differences in crop response in terms of quality (peanut grades determining crop value, and ash content in sugar) and the fate of luxury K uptake (either recycled via legume residues or removed in harvested cane), careful consideration needs to be given to the rate and frequency of fertilizer-K applications. In lighter textured soils such as the one in our study, data suggest that lower rates applied more frequently, possibly to balance crop-K removal, may be the most successful strategy. The contribution of any residual K from fallow crops (either in soil or returned in residues) will need to be considered as part of any subsequent K recommendations for the sugarcane crop cycle.

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