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Macronutrient accumulation and partitioning in sugarcane biomass grown in the Burdekin region

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Abstract Developing an understanding of how nutrients accumulate and partition in sugarcane is important for fine-tuning fertiliser recommendations to improve nutrient-use efficiency in a profitable, productive and ecologically sustainable farming system. The commercial sugarcane varieties Q253$^{\phi}$, Q208$^{\phi}$ and KQ228$^{\phi}$, which are grown in the Burdekin, were sampled several times throughout the growing season to study the accumulation of the macronutrients nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg) in above- and below-ground biomass. In sugarcane, the accumulation of macronutrients in above-ground biomass peaked by 270 days after planting (DAP). The concentration of these nutrients was monitored from 200 to 365 DAP and showed a general decline in all components from 200 DAP onwards. Sugarcane exhibited three distinct phases of growth, the first being a lag phase, followed by a period of rapid development, and a final phase of sucrose accumulation. A positive relationship between stalk dry matter yield and macronutrient accumulation in above-ground biomass was identified. Below-ground biomass which included roots and stool of Q208 was monitored at 200 and 365 DAP. The concentration of all macronutrients except N remained unchanged or declined over this period. In contrast, N concentration during this period increased significantly. Surface trash biomass for Q253, Q208 and KQ228 was sampled at 365 DAP with macronutrient accumulation compared across the three varieties. Due to the free-trashing characteristics of Q208 it produced considerably more surface trash compared to Q253 and KQ228, consequently this variety accumulated considerably more macronutrients in surface trash. These data provide insights into the key periods of macronutrient uptake and their partitioning in above- and below-ground biomass during sugarcane development.

Key words Macronutrient accumulation, concentration, biomass, crop components

INTRODUCTION

There have been few studies in Australia to gain an insight into the accumulation of macronutrients in above- and below-ground biomass (roots and stool) in sugarcane. Studies by Wood *et al*. (1996) investigated the uptake and accumulation of nitrogen (N) and a review by Bell *et al*. (2014) summarised available nitrogen data. However, there is little information about the accumulation and partitioning of phosphorous (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg) in current commercial varieties.

Industry guidelines recommend balanced plant nutrition for maximising crop yield potential. N is required in large quantities and is essential for photosynthesis and plant growth, but when available in excess it can negatively impact commercial cane sugar (CCS) (Kingston 2014). P plays a crucial role in cell division and the growth of root systems, tillers, and shoots (Kingston 2014) and is required in significantly smaller quantities than N.

Of all the macronutrients, K is required in the greatest quantity due to its role in regulating osmotic potential in plant cells, which is essential for photosynthesis. S, Ca and Mg are considered secondary macronutrients that play important roles. S is essential for the formation of proteins, whilst Ca is essential for cell walls and plays a

key role in nitrogen metabolism. Mg is involved in numerous physiological and biochemical process, including a crucial role in the chlorophyll molecule (Kingston 2014).

The objective of my study was to gain an insight into the accumulation and partitioning of macronutrients in three commercial varieties grown in the Burdekin region of Australia.

METHODS

Experimental design, management practices and sampling methods are briefly presented here. Full details were provided by Connellan and Deutschenbaur (2016).

The study was conducted on a Sugar Research Australia farm located in the Lower Burdekin region of Queensland (19°30'S, 147°17'E). Three varieties, Q208$^{(f)}$, Q253$^{(f)}$ and KQ228$^{(f)}$, were grown as plant crops over the 2014-2015 season. A split-plot design was established with six rows by 10 m in each replicate. In total, there were 48 plots in this trial. Sulphate of potash was used to apply 88 and 39 kg/ha of K and S, respectively, to all plots as a side dressing banded into the soil. Irrigation water was applied to all plots via furrows with water supplied from bores. No nitrogen fertiliser was applied to the three main plots (variety) due to significant quantities of mineral N found in the top 60 cm of the soil profile with an average of 95 kg N/ha across the three main plots. An additional 68 kg N/ha was applied over the season via nitrate in the irrigation water.

At the end of the tillering stage (approximately 130 days after planting (DAP)), a 3 m length of row from each main-plot was harvested and tillers counted and weighed. A sub-sample was dried at 60°C to determine dry matter accumulation (t/ha). Sub-samples were ground and analysed using Kjeldahl digestion to determine total N and P concentration. K, S, Ca and Mg concentration was determined using a microwave digestion method using nitric acid and hydrogen peroxide. The accumulation (kg/ha) of macronutrients was calculated by multiplying their concentration by the estimated biomass dry weight per hectare.

At 200, 270 and 365 DAP, the sampling was repeated as described above. At 365 DAP surface trash from the sampling area was also collected. Fresh weight of each plant component, stalk, leaf, cabbage (area around the growing point), attached dead leaf and surface trash, was determined, and a subsample dried and analysed as described above. The accumulation of macronutrients on an area basis in each plant component was calculated by multiplying the macronutrient concentration of each component by the biomass of the respective component. Net above-ground accumulation of macronutrients was calculated as the sum of the accumulation of each macronutrient in the individual components.

Below-ground biomass sampling took place at 200 and 365 DAP in the Q208 plots. Sampling was undertaken in areas where above-ground biomass was harvested during the same period. Roots and stool were excavated, and a subsample was taken, dried and analysed for macronutrients as described above. Macronutrient accumulation (kg/ha) was calculated by multiplying the concentration of each macronutrient by the below-ground biomass.

RESULTS

Above-ground biomass and macronutrient accumulation

The accumulation of above-ground biomass for three varieties can be broken up into three distinct phases and described by a sigmoidal pattern (Leite *et al.* 2016, Wanderley *et al.* 2021). The initial growth phase (~0-130 DAP) was relatively slow due to the development of below-ground biomass and tiller production and is referred to as a lag phase. At this stage above-ground biomass amounted to approximately 9% of the total biomass accumulated. The second phase (~130-270 DAP) was a period of rapid crop development and constituted approximately 95% of the final biomass accumulation. It is referred to as stalk elongation. The final phase (~270-365 DAP), which is often described as a period of sucrose accumulation, accounted for a 5% increase in biomass (Figure 1).

The accumulation of N, P, K, S, Ca and Mg for Q253, Q208 and KQ228 can be described by typical non-linear models for the period of the trial and followed a similar pattern to above-ground biomass accumulation in all cases.

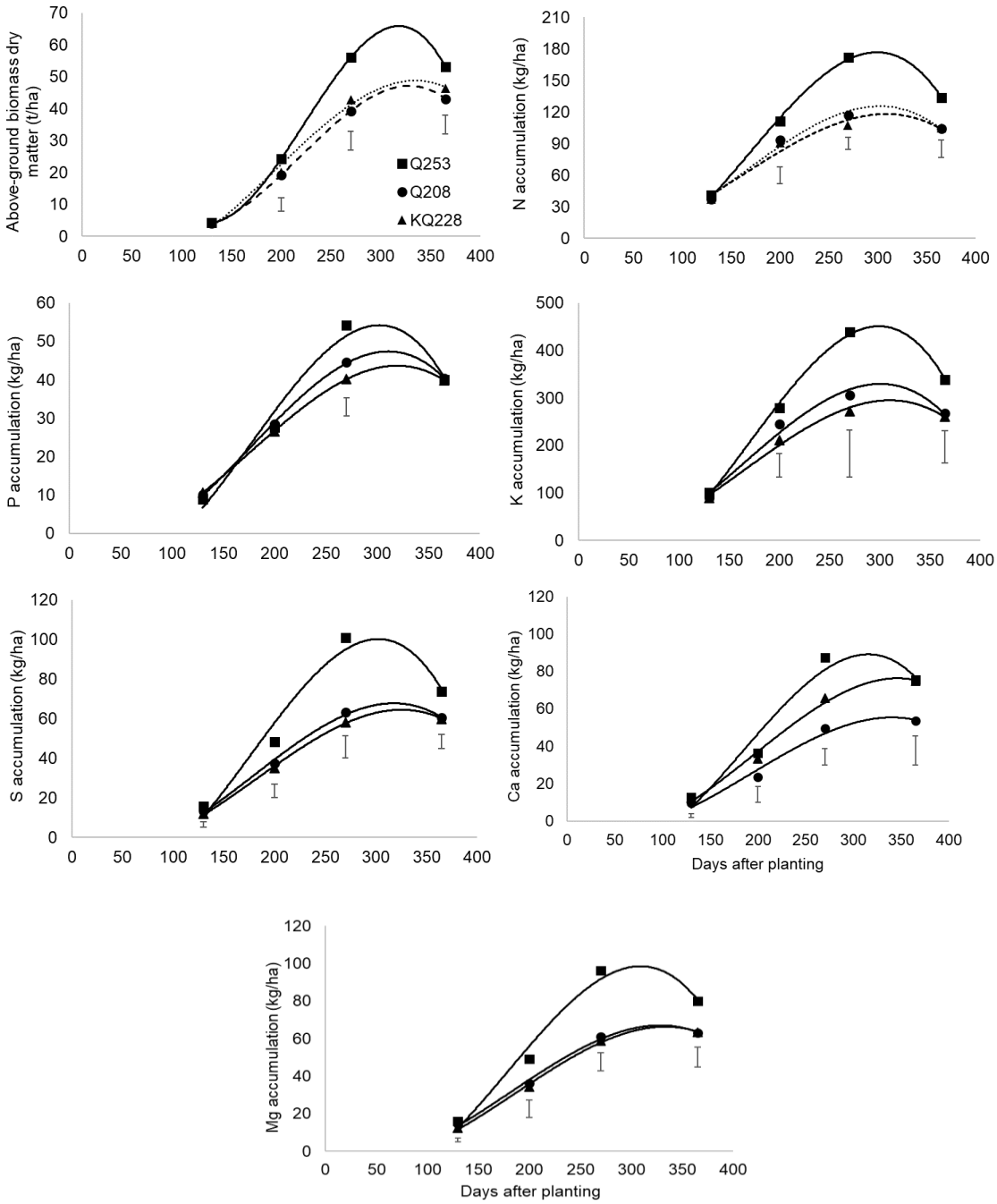

Figure 1. Crop above-ground biomass dry matter and N, P, K, S, Ca & Mg accumulation in relation to DAP for three varieties. Vertical bars show the least significant differences of means (P=0.05) between the three varieties.

In the first 130 DAP, N accumulation amounted to 30% of total above-ground N accumulated, P 22%, K 28%, S 19%, Ca 18% and Mg 21%. Accumulation of macronutrients increased dramatically from 130 DAP until 270 DAP (following biomass accumulation) and by 270 DAP N, P, K, S and Mg accumulation peaked, reaching 100%. The accumulation of Ca followed a slightly different pattern with KQ228 continuing to accumulate until harvest, whilst Q253 and Q208 appeared to reach 100% of total Ca accumulation by 270 DAP.

Of the three varieties, Q253 accumulated significantly more N, K, S and Mg than Q208 and KQ228 from 200 days onwards, mirroring biomass accumulation. In contrast, although Q253 appeared to have accumulated significantly more P at 270 DAP, by 365 DAP there was no significant difference among varieties.

Concentration of macronutrients in plant components

The concentration of macronutrients in plant components were monitored from 200 DAP onwards, little variation between varieties was observed and data presented are mean concentrations of three varieties with standard error (Figure 2).

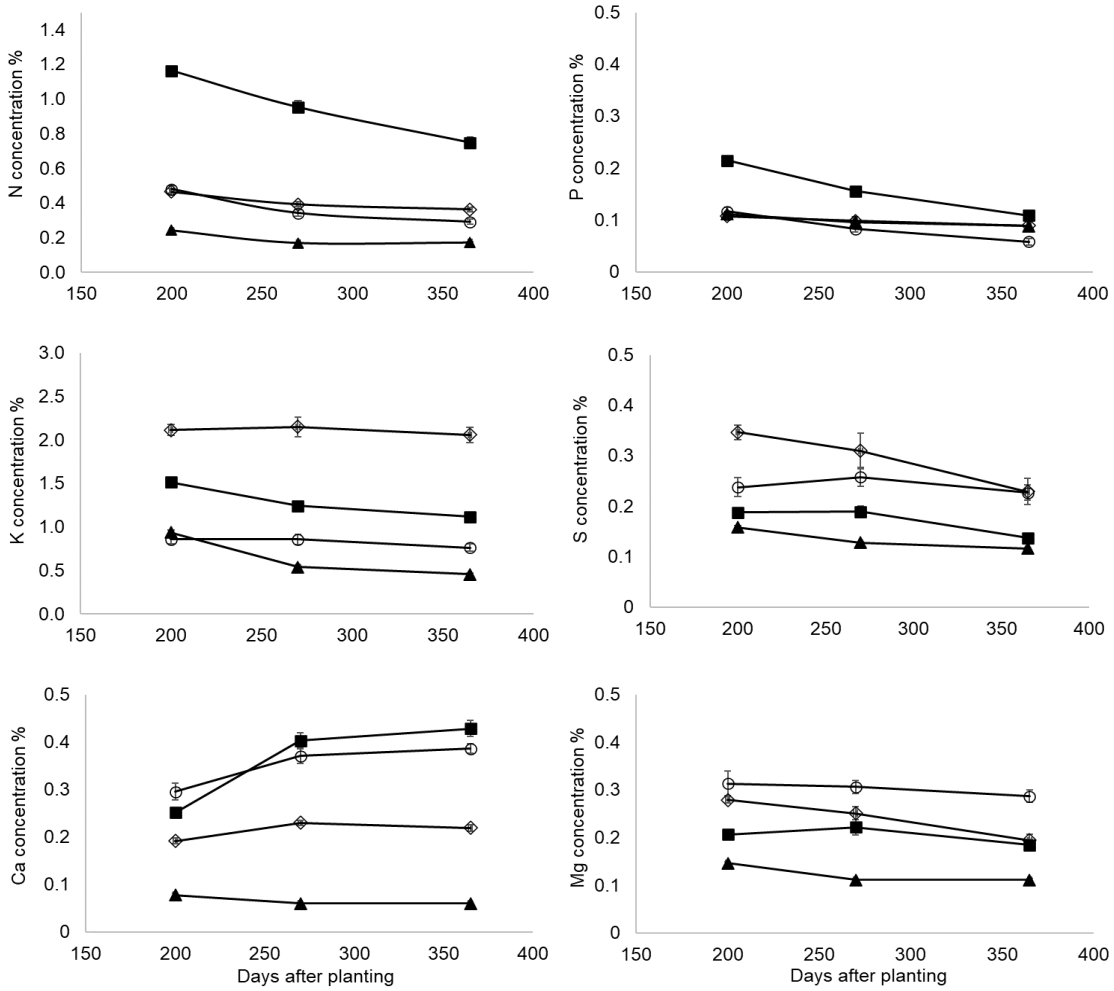

Figure 2. Mean macronutrient concentrations in plant components for three varieties in relation to DAP (vertical line indicates standard error). Plant components included leaf (■), stalk (▲), cabbage (◊) and attached dead leaf (○).

The concentration of N was highest in leaf, followed by cabbage, attached dead leaf, and then stalk. N concentration in leaves declined considerably from 1.16% at 130 DAP to 0.75% at 365 DAP and in stalks from 0.24% at 130 DAP to 0.17% at 365 DAP. Concentrations of N in attached dead leaf and cabbage declined only slightly.

Phosphorus concentration was highest in leaf, followed by cabbage then stalk and lowest in attached dead leaf. Concentration in leaves declined considerably, from 0.21% at 130 DAP to 0.11% at 365 DAP, whilst in stalk, cabbage and attached dead leaf, they declined only slightly.

Concentration of K was highest in cabbage, followed by leaf, attached dead leaf and lowest in stalk. K concentrations appeared to decline in leaf from 1.52% at 200 DAP to 1.1% at 365 DAP and stalk 0.94% at 200 DAP to 0.46% at 365 DAP, but cabbage and attached dead leaf concentrations showed little variation.

S concentrations were highest in cabbage, followed by attached dead leaf, then leaf and lowest in stalk. Concentrations in leaf and stalk were similar and appeared to decline only slightly in leaf from 0.19% at 200 DAP to 0.12% at 365 DAP, and stalk 0.16% at 200 DAP to 0.12% at 365 DAP, but attached dead leaf showed little variation.

The concentration of Ca was highest in leaf, followed closely by attached dead leaf, then cabbage and lowest in stalk. In contrast to other macronutrients, Ca levels in leaf and attached dead leaf increased considerably (0.25% to 0.43% and 0.30% to 0.39%, respectively) from 200 DAP to 365 DAP. Concentration levels also appeared to increase in cabbage, although this was minor. Contrary to other components, concentration of Ca in stalk appeared to decline slightly from 0.08% at 200 DAP to 0.06% at 365 DAP.

Mg concentration was highest in attached dead leaf, followed by cabbage, then leaf and lowest in stalk. Generally, concentrations of each component declined slightly over the monitoring period. Leaf concentrations declined from 0.21% at 200 DAP to 0.19% at 365 DAP and in stalk from 0.15% at 200 DAP to 0.11% at 365 DAP.

In general, concentration of macronutrients in stalk were lower compared to all other above-ground components, the exception being P concentrations in attached dead leaf at 365 DAP.

Accumulation and partitioning of dry matter and macronutrients

Dry matter accumulation peaked in millable stalk at 365 DAP for all three varieties. Leaf and cabbage accumulation varied little between 200 and 365 DAP. However, attached dead leaf plateaued by 270 DAP for Q253 and Q208, and increased in KQ228. The variation in attached dead leaf accumulation among varieties is due to their trashing characteristics. The partitioning of the three primary macronutrients N, P and K in components followed a similar pattern to dry matter accumulation (Figure 3).

The accumulation of N followed a similar pattern to dry matter accumulation. Stalk N accumulation was higher than other components, primarily due to its high biomass dry matter content. Leaf N accumulation was similar to stalk due to its high N concentration. Although N concentration in leaf declined from 200 to 365 DAP, accumulated leaf N remained greater than all other components except stalk. Cabbage and attached dead leaf N accumulation tended to mirror dry matter accumulation over the monitoring period.

Like N, the majority of P accumulated in stalk, followed by leaf, attached dead leaf and then cabbage. Concentration of P in all components was low and resulted in less accumulated P compared to all other macronutrients. Leaf P declined from 200 DAP onwards and was reflected in accumulated totals. There was minor variation in P concentration in stalk and cabbage, consequently accumulation in these components tended to follow the pattern of biomass dry matter accumulation.

The accumulation of K was significantly higher than all other macronutrients due to its high concentration in all components. K accumulation, like N and P, was greatest in stalk followed by leaf, attached dead leaf and then cabbage. In stalk and leaf, K accumulation tended to decline slightly from 270 DAP onwards due to a decline in K concentration in these components. However, cabbage and attached dead leaf K concentration remained similar during the monitoring period with changes in K accumulation driven by dry matter accumulation.

The secondary macronutrients S, Ca and Mg accumulated in lower quantities compared to N and K (Figure 4). Generally, S accumulation showed a similar pattern to biomass accumulation. A small decline in S concentration in each component was evident from 200 DAP onwards, which resulted in a slight decline in accumulation totals in each component. The majority of S accumulated in the stalk, followed by attached dead leaf, then leaf and finally cabbage.

Unlike other macronutrients, Ca concentration in leaf and attached dead leaf increased significantly from 200 DAP onwards whilst stalk and cabbage Ca concentrations remained unchanged (Figure 2). This resulted in leaf and attached dead leaf accumulating similar quantities of Ca to stalk. KQ228, classified as a ‘Tight’ trashing variety (Sugar Research Australia 2022), accumulated more Ca in attached dead leaves compared to stalk.

The accumulation of Mg showed similar trends to biomass accumulation with stalk accumulating more Mg than all other components due to greater biomass dry matter accumulation. Attached dead leaf had the highest Mg concentration of all components and, consequently, accumulated considerably more Mg than leaf and cabbage.

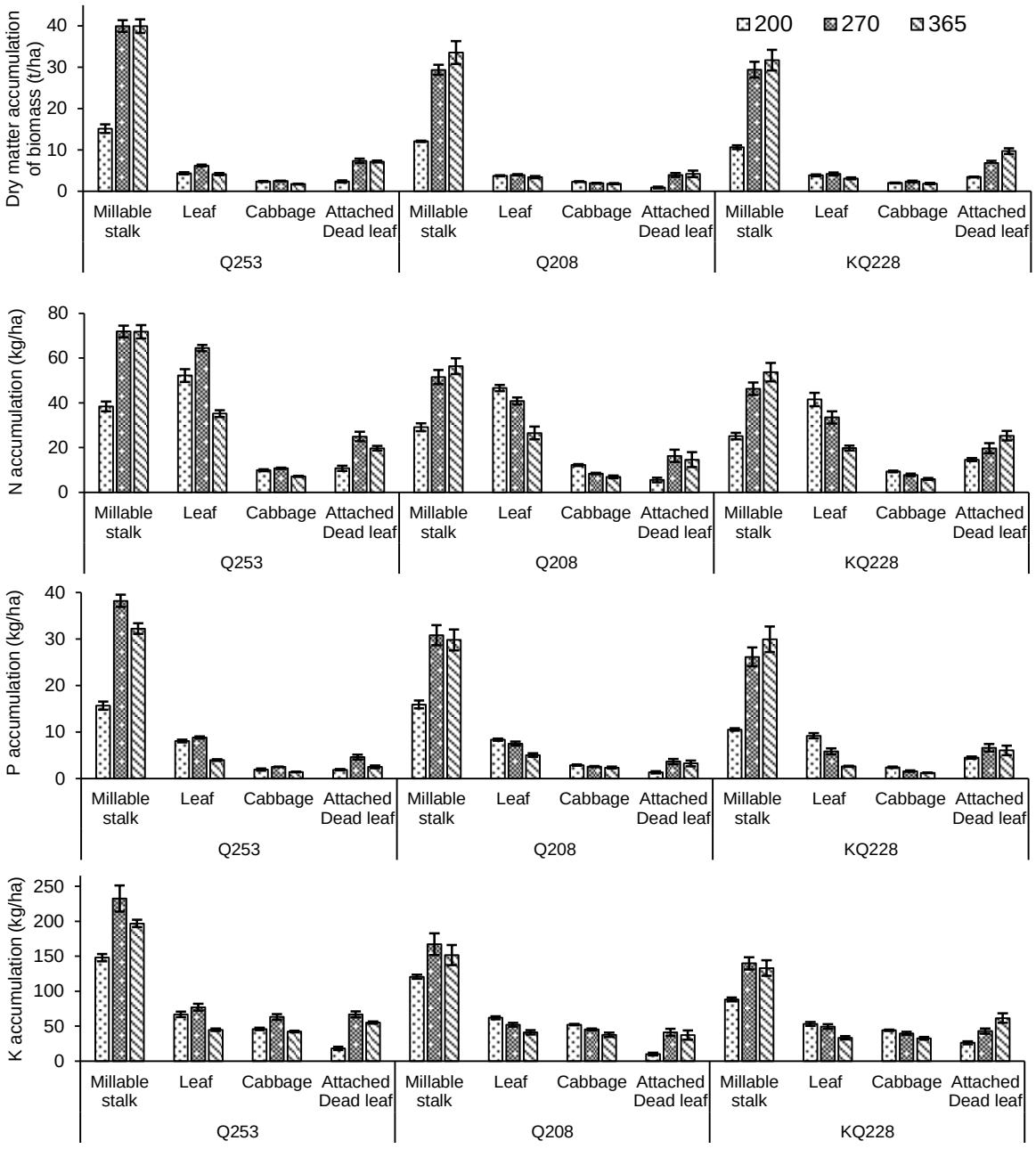

Figure 3. Dry matter accumulation of biomass, and N, P, and K accumulation and partitioning in crop components for three commercial varieties, Q253, Q208 and KQ228, in relation to DAP (vertical line indicates standard error).

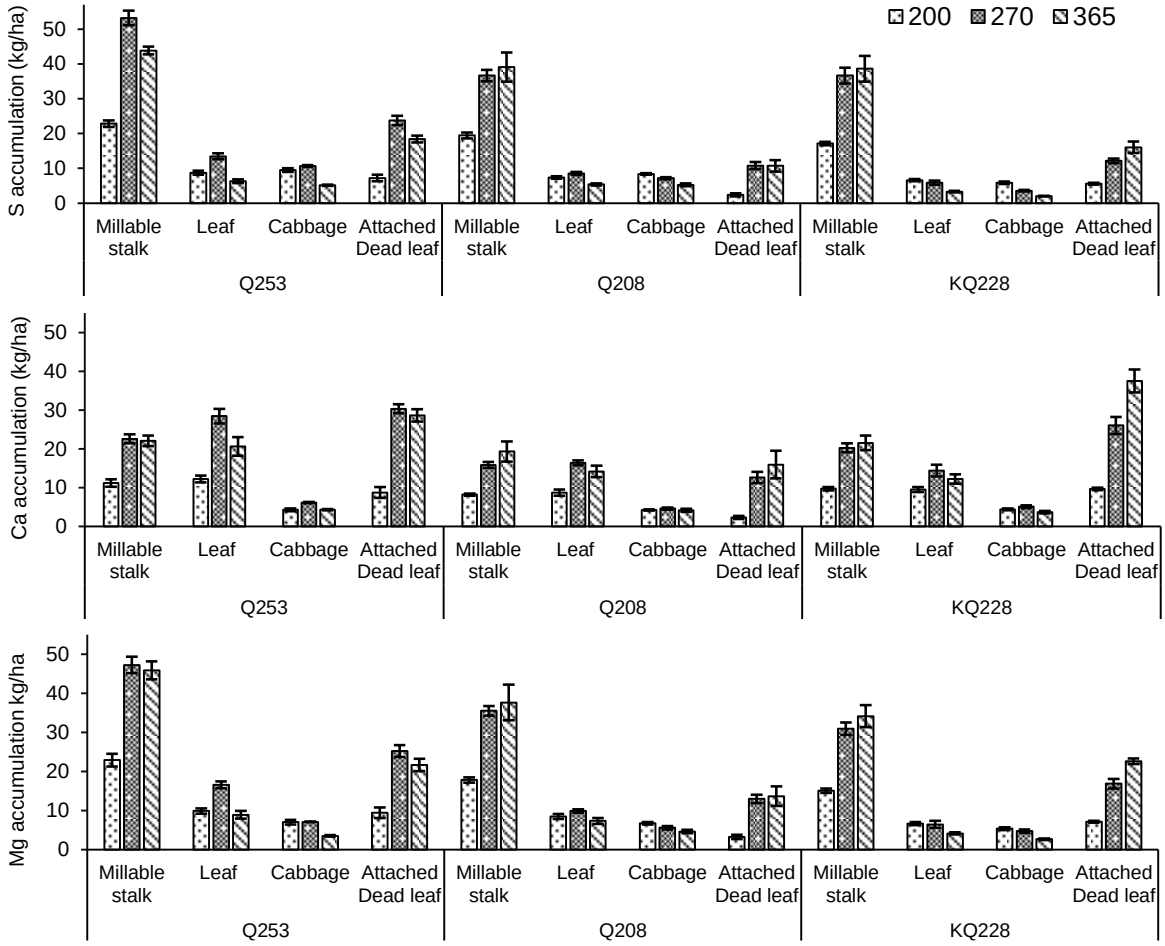

Figure 4. Accumulation of S, Ca, and Mg and partitioning in crop components for three commercial varieties, Q253, Q208, and KQ228, in relation to DAP (vertical line indicates standard error).

Relationship of yield to stalk macronutrient accumulation

Stalk dry matter yield and stalk macronutrient accumulation were determined from hand-cut biomass samples collected from Q253, Q208 and KQ228 at 200, 270 and 365 DAP, based on the assumption that macronutrient content would be close to maximum. Mean stalk dry matter yields were plotted against stalk macronutrient content for the three varieties with linear regression models fitted for each (Figure 5).

The analysis showed a significant relationship between stalk dry matter yield and stalk macronutrient accumulation. For instance, a stalk yield of 30 t/ha dry matter (approx. 100 t/ha fresh matter) exported to the mill would have accumulated 53 kg of N, 28 kg of P, 160 kg of K, 37 kg of S, 18 kg of Ca and 34 kg of Mg per hectare.

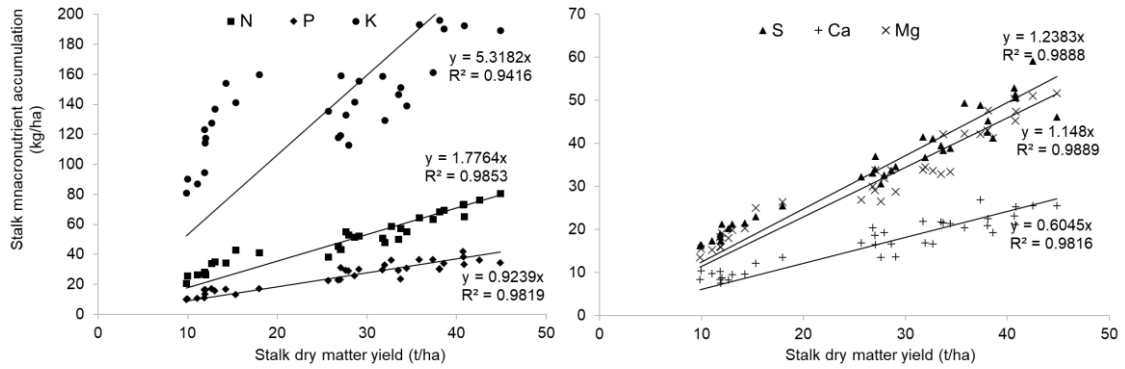

Figure 5. Relationship between stalk macronutrient accumulation and stalk dry matter yield for three commercial varieties, Q253, Q208, and KQ228, from 200 to 365 DAP.

Relationship of yield to above-ground biomass macronutrient accumulation

The relationship between stalk dry matter yield and above-ground biomass macronutrient accumulation was also assessed. Mean stalk dry matter yields were plotted against above-ground biomass macronutrient accumulation for the three varieties with linear regression models fitted for each (Figure 6).

The analysis demonstrated a relationship between stalk dry matter yield and above-ground biomass macronutrient accumulation. For instance, a stalk yield of 30 t/ha dw (approx. 100 t/ha fw) prior to harvest would have accumulated 117 kg of N, 40 kg of P, 297 kg of K, 65 kg of S, 63 kg of Ca and 66 kg of Mg per hectare.

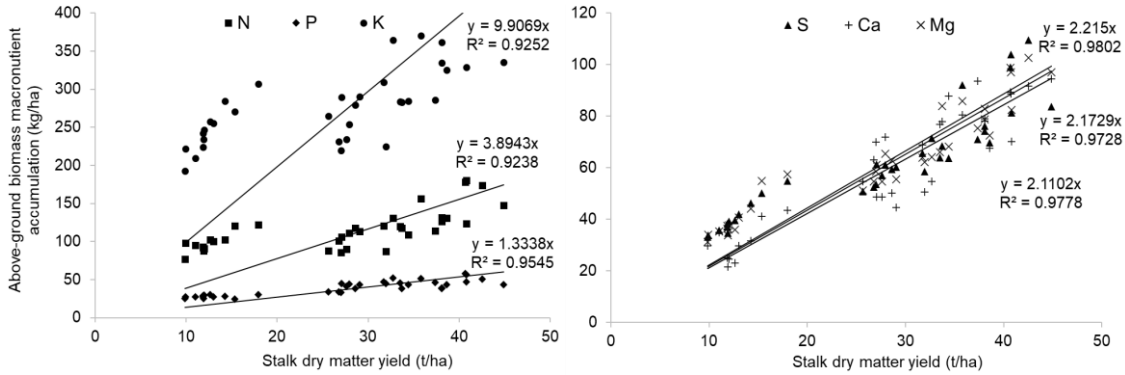

Figure 6. Relationship between above-ground macronutrient accumulation and stalk dry matter yield for three commercial varieties, Q253, Q208, and KQ228, from 200 to 365 DAP.

Below-ground biomass macronutrient accumulation

Below-ground biomass samples were collected from Q208 plots at 200 and 365 DAP. At 200 DAP dry matter weight was 3.6 ± 0.33 t/ha and by 365 DAP 4.3 ± 0.07 t/ha (Connellan and Deutschenbaur 2016). Concentrations of macronutrients in below-ground biomass were monitored during this period (Figure 7).

Macronutrient accumulation in below-ground biomass is shown in Figure 8. N accumulation increased from 200 DAP onwards due to an increased below-ground biomass weight, along with an increase in N concentration (0.29% at 200 DAP to 0.36% at 365 DAP). Concentration of Ca did not appear to change (~0.21%) over the monitoring period, but Ca content increased with increased biomass dry weight. The concentration of P declined

slightly (0.10% at 200 DAP to 0.08% at 365 DAP), but, due to the increase in biomass dry weigh, P content remained constant. K, S and Mg contents declined over the monitoring period due to lower macronutrient concentrations.

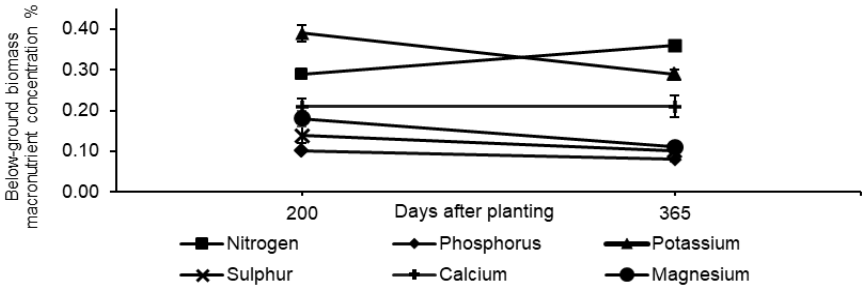

Figure 7. Mean macronutrient concentrations in below-ground biomass for Q208 at 200 and 365 DAP (vertical line indicates standard error).

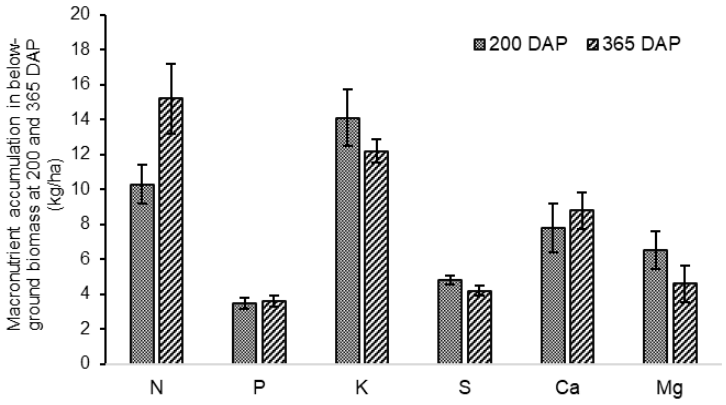

Figure 8. Macronutrient accumulation in below-ground biomass for Q208 at 200 and 365 DAP (vertical line indicates standard error).

Surface trash biomass and macronutrient accumulation

Surface trash biomass collected at 365 DAP varied according to variety. Q208 had considerably more surface trash than Q253 and KQ228 (Figure 9).

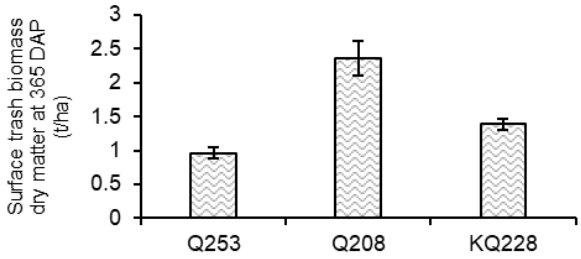

Figure 9. Mean surface trash biomass dry matter for three varieties, Q253, Q208, and KQ228, at 365 DAP (vertical line indicates standard error).

Mean macronutrient concentration was calculated for the three varieties (Table 1). Concentration of N was higher in surface trash compared to attached dead leaf (Connellan and Deutschenbaur 2016), but P, K, S, Ca and Mg concentration of surface trash was similar to the respective macronutrient concentration in attached dead leaf.

Table 1. Mean and standard error of surface trash macronutrient concentration for Q253, Q208 and KQ228 at 365 DAP.

Macronutrient	Concentration %		
	Q253	Q208	KQ228
N	0.52 ± 0.02	0.45 ± 0.03	0.51 ± 0.04
P	0.08 ± 0.01	0.09 ± 0.01	0.13 ± 0.01
K	0.49 ± 0.03	0.85 ± 0.08	0.43 ± 0.04
S	0.23 ± 0.01	0.25 ± 0.01	0.17 ± 0.01
Ca	0.44 ± 0.02	0.35 ± 0.01	0.43 ± 0.01
Mg	0.29 ± 0.01	0.32 ± 0.01	0.24 ± 0.01

Accumulation of macronutrients in surface trash varied among varieties. Q208 accumulated more macronutrients in trash than did Q253 or KQ228 (Figure 10). This is due to the trashing characteristics of Q208 with significantly more trash deposited onto the soil surface compared to the other varieties. The concentration of macronutrients in surface trash varied little among varieties and had a minor impact on macronutrient accumulation.

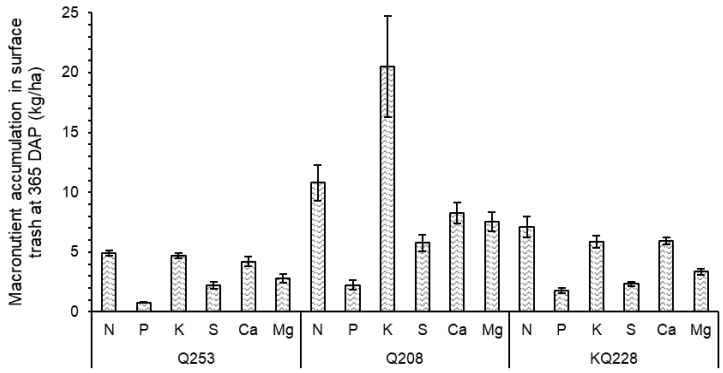

Figure 10. Surface trash macronutrient accumulation for three varieties, Q253, Q208, and KQ228, at 365 DAP (vertical line indicates standard error).

Proportion of macronutrients in plant components

The proportion of macronutrients in plant components was calculated for Q208 at 365 DAP and included above- and below-ground biomass (Figure 11). In all cases the greatest proportion of each macronutrient was in stalk. Although stalk macronutrient concentration were low compared to other plant components, the significantly larger biomass of stalk resulted is higher proportions of accumulated macronutrients.

The proportion of Ca in plant components varied compared to other macronutrients. Ca concentration in stalk was low compared to leaf and attached dead leaf. Concentration in leaf and attached dead leaf increased from 200 DAP, resulting in the majority of Ca residing in these plant components, which is contrary to other macronutrients.

Following stalk, leaf had the highest proportion of N, P and K, but attached dead leaf had a higher proportion of S, Ca, and Mg in comparison to all other components except stalk.

The proportion of macronutrients in below-ground biomass was low compared to the above-ground biomass due to the small quantity of the below-ground dry matter in comparison to above-ground dry matter. Connellan and Deutschenbaur (2016) reported that below-ground biomass was approximately 5% of above-ground biomass.

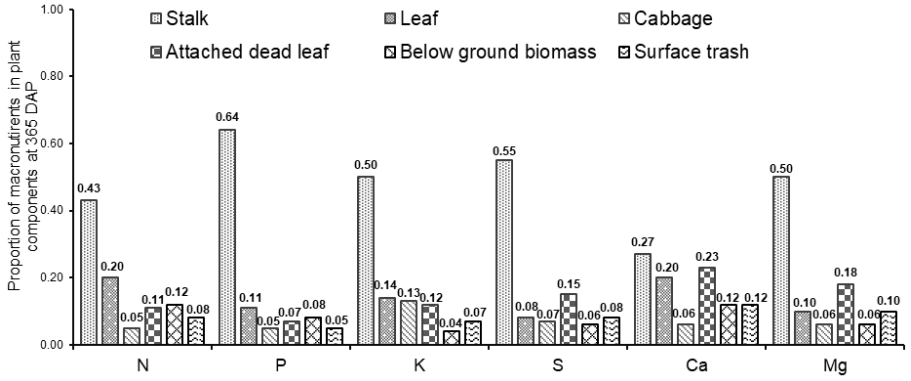

Figure 11. Proportion of macronutrients in each plant component for Q208 at 365 DAP.

DISCUSSION

Previous work showed that maximum sugarcane N uptake occurred between 7-10 months (Bell *et al*. 2015; Connellan and Deutschenbaur 2016) following planting or ratooning. However, there is limited information about the accumulation of other macronutrients such as P, K, S, Ca and Mg in sugarcane grown in Australia.

The first 130 days of development of the three varieties can be described as slow, due to the establishment of roots and tillers. By the end of the first phase of crop development (~130 DAP), on average only 9% of the total crop above-ground biomass had been established. Leite *et al*. (2016) reported a similar finding of 10% of total crop above-ground biomass established during this period. At this stage, biomass contained 30% of total crop N, 22% of P, 28% of K, 19% of S, 18% of Ca and 21% of Mg. By the end of the second phase of crop development (~270 DAP), 95% of total above-ground biomass had accumulated and contained 100% of the accumulated N, P, K, S and Mg. Leite *et al.* (2016) reported ~75% of the final above-ground biomass had been accumulated by the end of this period. Ca accumulation in Q253 and Q208 had also reached 100%, but KQ228 continued to accumulate Ca until 365 DAP. By the end of the third phase of development, often referred to as sucrose accumulation, the remaining 5% of biomass had accumulated. Wanderely *et al.* (2021) and Leite *et al*. (2016) both described similar phases of crop biomass development.

Minor variation in macronutrient concentration was observed among varieties and, consequently, results presented were means of the three varieties. Generally, macronutrient concentrations declined or varied little over the monitoring period in all components. The only exception was Ca concentration in KQ228 which increased from 200 DAP onwards in leaf, cabbage and attached dead leaf. Ca concentrations in stalk varied little over this period. At 270 DAP there were considerable differences in Ca accumulation among varieties. However, by 365 DAP no significant difference was identified between Q253 and KQ228, even though there were significant differences in biomass accumulation. This finding may be attributed to the trashing characteristics of KQ228 which is classified at 'Tight' whilst Q253 is classified as 'Free-Average' (Sugar Research Australia 2022). From 200 DAP onwards, Q208 accumulated significantly less Ca than the other two varieties, which is due to this variety's characteristic of readily dropping attached dead leaves.

The accumulation of macronutrients in leaf, stalk, cabbage and attached dead leaf, tended to follow a similar pattern to dry matter accumulation, but macronutrient concentration in crop components also impacted macronutrient accumulation. In all cases, the majority of macronutrients were found in stalk due to the high proportion of total plant dry matter accumulated in this component.

To understand the relationship between dry matter accumulation and macronutrient accumulation, stalk dry matter yield was plotted again stalk macronutrient content and against above-ground biomass macronutrient accumulation. In both cases, linear regression models were fitted for all macronutrients, demonstrating that stalk and above-ground biomass macronutrient accumulation was positively related to stalk biomass. Leite *et al.* (2016) demonstrated a similar positive relationship between yield and above-ground macronutrient accumulation for N, P, and K.

Below-ground biomass samples showed the concentration of all macronutrients except N declined or varied little over the monitoring period. Connellan and Deutschenbaur (2016) reported that N concentrations increased over this period. Although data were limited, by 365 DAP below-ground biomass of Q208 constituted approximately 9% of the total plant biomass, contained 8% of total plant N, 5% of P, 7% of K, 8 % of S, 12% of Ca and 10% of Mg.

Surface trash biomass samples were collected at 365 DAP from Q253, Q208 and KQ228, the quantity of surface trash deposited varied due to the trashing characteristics of each variety, which in turn impacted the quantity of macronutrients deposited on the soil surface prior to harvest. The concentration of all macronutrients in surface trash except N were similar to those found in attached dead leaf. Connellan and Deutschenbaur (2016) reported that N concentration in surface trash was higher than attached dead leaf which was possibly due to microbial breakdown or trash absorbing nitrates from irrigation water.

Plant-cane macronutrient accumulation averaged in above-ground biomass at 365 DAP can be described in absolute terms in descending order as K>N>Mg≥Ca≥S>P, which is similar to findings described by Mariano *et. al*. (2016) and Silva *et.al* (2017), although in these cases the order of Mg, Ca and S varied slightly.

CONCLUSIONS

My study showed the accumulation of macronutrients in sugarcane followed dry matter accumulation; however, macronutrient accumulation was also influenced by nutrient concentration at the time of sampling. Generally, from 200 DAP onwards concentration of macronutrients declined in crop components, but this was not the case for Ca.

Dry matter yield and above-ground macronutrient accumulation was positively correlated and demonstrated that dry matter accumulation was the primary driver of macronutrient accumulation in the three varieties included in this study.

Of the three varieties, Q253 accumulated more N, K, S and Mg than Q208 and KQ228 from 200 DAP onwards, primarily due to greater biomass accumulation. In contrast there was no differences among varieties in P accumulation at 365 DAP.

Below-ground biomass of Q208 at 365 DAP constituted 9% of total plant biomass. All macronutrients except N showed either little change or declined in concentration from 200 DAP onwards. In general, there was little change in macronutrient accumulation over the monitoring period. However, more research is required to gain a clearer understanding of the accumulation of below-ground biomass and macronutrients in commercial varieties.

The accumulation of surface trash biomass was influenced by trashing characteristics of varieties, which in turn impacted the quantity of accumulated macronutrients deposited onto the soil surface over the various stages of crop development. The concentration of macronutrients (except N) in surface trash was similar to attached dead leaf at 365 DAP.

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