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Modelling nitrogen uptake by sugarcane crops to inform synchrony of N supply from controlled release fertiliser

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Abstract: Sugarcane is a dominant cropping system in the tropics and sub-tropics of Australia. High nitrogen (N) input to support sugarcane productivity has, however, been associated with low N use efficiency due to N losses. Controlled release fertilisers (CRF) have gained interest for their potential to reduce N losses through better synchronisation of N release with crop N demand.

There is almost no experimental data on N release from CRF specific to conditions experienced in sugarcane soils and the limited data on N uptake patterns typically come from short-term experiments under specific conditions. So, a systematic analysis of N uptake patterns, as a function of soil, crop and management factors as well as considering the effect of seasonal climate variability, is needed in order to inform the required synchrony.

As a first step, this paper presents an analysis of N uptake patterns of sugarcane crops in response to varying seasonal climate conditions by extending field observation data using APSIM modelling. The objectives of the analysis were to characterise the seasonal variability in N uptake patterns and to explore what this may mean for the design of CRF release patterns for Australian sugarcane systems.

The analysis was based on past simulations by Keating et al. (1999) of a number of experimental datasets on sugarcane growth and yield. Ten datasets containing both biomass and biomass N measurements for plant or ratoon crops from one growing season were selected. The datasets came from five different locations to capture the key climatic differences within the Australian sugarcane growing region. Selected single year datasets and simulations from Keating et al. (1999) were extrapolated using historical climate data (1958-2013) and scenario modelling. Management rules were used to mimic actual management in the one year trials, but defined in more general terms to allow extrapolation to 55 additional seasons. Above-ground biomass and biomass N accumulation were simulated to characterise the system's productivity and N accumulation in response to seasonal climate variability. In addition, total N uptake, which includes N accumulated in below-ground roots, was predicted. The simulated N uptake patterns were then compared with a three-stage, conceptual release pattern commonly attributed to polymer coated fertilisers.

Preliminary results show that large variations were found in observed (experimental) above-ground biomass and biomass N accumulation. Both, however, showed some consistency during the early growing period across sites although patterns for plant and ratoon crops were different. The APSIM simulated time-course of above-ground biomass either using original management from the experimental trial or general rule-based management, agreed well with the observations across all the selected datasets conducted under high N and water input conditions. During the early growing stages of sugarcane, simulated N accumulation in above-ground biomass also closely followed the measurements, providing support for the extrapolation to other seasons through simulation. For each dataset there was considerable variability in predicted total N uptake across the 56 seasons. During the early stages of growth (100 - 150 days after planting or ratooning), however, the simulated variation in above-ground biomass, N accumulation and total N uptake were quite small and as a consequence the simulated N uptake pattern was quite well defined and relatively insensitive to seasonal climatic differences. In terms of CRF design, these simulation results provide an early indication of the required release patterns, the length of a potential delay in release and subsequent release rate, if N from CRF is targeted at the rapid N uptake stage and early N requirements can be met from other sources (initial soil N, N in planting mix or N mineralisation).

The simulation based systems approach enabled the quantification of N uptake patterns of sugar systems in response to soil, crop and management factors as well as seasonal climate variability. The simulated variability in uptake patterns and responses to seasonal climate were caused by a combination of factors including crop class (plant or ratoon), crop age, genotype as well as management (e.g. planting and ratooning date). Further research will systematically explore the effects of these factors on N uptake patterns.

Keywords: *Sugarcane, nitrogen uptake pattern, controlled release fertiliser, APSIM*

1. INTRODUCTION

Sugarcane is a dominant cropping system in the tropics and sub-tropics of Australia. High nitrogen (N) input to support sugarcane productivity has, however, been associated with low N use efficiency due to N losses (Thorburn et al. 2015; Verburg et al. 2015). Controlled release fertilisers (CRF) have gained interest for their potential to reduce N losses through better synchronisation of N release with crop N demand.

There is almost no experimental data on N release from CRF specific to conditions experienced in sugarcane soils and the limited data on N uptake patterns typically come from short-term experiments under specific conditions (e.g. Keating *et al.*, 1999). In order to inform the required synchrony there is, therefore, a need to systematically analyse N uptake patterns as a function of soil, crop and management factors as well as consider the effect of seasonal climate variability (Verburg *et al.,* 2014). This is difficult to achieve through experimentation alone, but could be accomplished in conjunction with modelling.

In recent years, the Agricultural Production Systems Simulator (APSIM) model (Holzworth *et al.,* 2014), which has a well-tested sugarcane module (Keating *et al.*, 1999), has been used in many applications concerning the water and nutrient balance of a range of cropping systems including sugarcane. APSIM has been used in a range of applications to simulate the impact of different management systems on sugarcane yield and N loss via deep drainage, denitrification, runoff and sediment loss (Thorburn *et al.,* 2014). The Keating et al. (1999) paper provided simulations of a number of experimental datasets on crop biomass and biomass N accumulation, thus it forms a good starting point for a systematic analysis of N uptake by sugarcane crop. This paper presents a preliminary analysis that characterises the seasonal variability in N uptake patterns and explores what this may mean for the design of CRF release patterns. Selected single year datasets and simulations from Keating et al. (1999) were extrapolated using historical climate data and scenario modelling. The simulated N uptake patterns were then compared with a three-stage, conceptual release pattern commonly attributed to polymer coated fertilisers (Shaviv, 2001).

2. MATERIALS AND METHODS

2.1. Data sources

The experimental data for Australian sugarcane cropping systems were obtained from the Sugarbag database developed in the 1990s which contains a number of N accumulation datasets. Seventeen of these datasets were simulated as part of the model development (Keating et al. 1999). They are still part of the validation dataset of APSIM and checked with every update of the model. Most of these datasets were obtained from experiments under high water and N input conditions. Ten of the 17 datasets containing both biomass and biomass N measurements for plant or ratoon crops from five different locations were selected for this analysis to capture the key climatic differences within the Australian sugarcane industry. APSIM also provided the best descriptions of measured above-ground biomass and biomass N for these datasets. Full details on model performance were presented by Keating et al. (1999). Details of experimental treatments for the ten datasets are provided in Table 1. Long term historical climate data (1958 – 2013) were obtained for representative meteorological stations located closest to each of the experimental sites from the SILO climate data archive (Jeffrey *et al.*, 2001).

Table 1. Details of selected dataset from Sugarbag datasets with high N and water input conditions

Dataset	Site	Ratoon No. (plant = 0)	Planting/ ratooning	Cultivar	Season length (days)	Treatment
1	Harwood	0	21/09/1993	Q117_fum	738	570N, Irrigated
11	Grafton	0	28/09/1994	Q117_fum	342	440N, Irrigated
5	Ayr	0	19/04/1991	Q96	445	252N, Irrigated
6	Ayr	1	1/08/1993	Q117	373	284N, Irrigated
14	Ayr	0	22/04/1992	Q117_fum	478	274N, Irrigated
8c	Bundaberg	1	26/08/1992	CP51	313	340N, Irrigated
2	Ingham	0	23/07/1992	Q117_fum	455	345N, Irrigated
3	Ingham	1	26/08/1992	Q117_fum	421	343N, Irrigated
15	Ingham	0	16/07/1991	Q117	364	354N, Irrigated
16c	Ingham	0	23/07/1992	Q117_fum	391	268N, Irrigated

2.2. Modelling analysis

The modelling analysis consisted of three steps as described below:

Step 1: Simulation of single year datasets with actual management and fertiliser N and irrigation inputs. These were the same as the original simulations included in Keating et al. (1999) as updated in the validation set for APSIM v7.7.

Step 2: Simulation of the same single year datasets using management rules to mimic actual management, but defined in more general terms to allow extrapolation to other years in step 3. In most of the experiments irrigation was used to maintain a high yield. Irrigation schedules in the original simulations (step 1) matched the specific dates in the experimental trials. As there could be big differences in climate and soil water conditions for the same day in different years from 1958 to 2013, a general management schedule was designed using either the available soil water content (e.g. 150 and 80 mm soil water for Ayr and Bundaberg) or the amount of rainfall in the past few days (e.g. less than 18, 15 and 15 mm rainfall in past 3 days for Ingham, Harwood and Grafton, respectively) as a trigger for irrigation. Extra small amounts of N fertiliser were added in conjunction with irrigation during the later growth period in Ayr and Ingham using the total N in the top 3 layers as a trigger. The general management schedule was fine-tuned to ensure that the simulated dynamics of above-ground biomass and biomass N described the measured data and that at the same time the irrigation and fertilisation times and amounts matches those from the experiment as the close as possible.

Step 3: Extrapolation to 55 additional seasons. In these simulations, sugar cropping system was modelled with the same planting/ratooning day and with the same length of growing season as that in the experiment, but started in different years (1958 to 2013; 56 repeated seasons) with the general management rules derived in step 2. Above-ground biomass and biomass N accumulation were simulated to characterise the system's productivity and N accumulation in response to seasonal climate variation. In addition total N uptake, which includes N accumulated in below-ground roots, was predicted.

2.3. Analysis of model output

Nitrogen uptake curves provide guidance on the ideal synchrony for N supply. Conceptually the N release from polymer coated controlled release fertilisers has been presented as a three-stage process (Shaviv, 2001) consisting of (1) an adsorption stage during which water enters the coated granule, but no release occurs, (2) a linear release stage while solid fertiliser is dissolving, maintaining a constant osmotic pressure and hence N release, and (3) a declining stage when the all solid fertiliser has dissolved (Figure 1a).

The simulated outputs for N uptake from step 3 were fitted with a sigmoidal function. The maximum slope of this function was used to derive a rate of N release for the linear stage 2 if the 3-stage release model was synchronised with the predicted N uptake pattern. In addition, the corresponding length of the stage 1 lag as well as the time to first N uptake in the predicted uptake curve were determined.

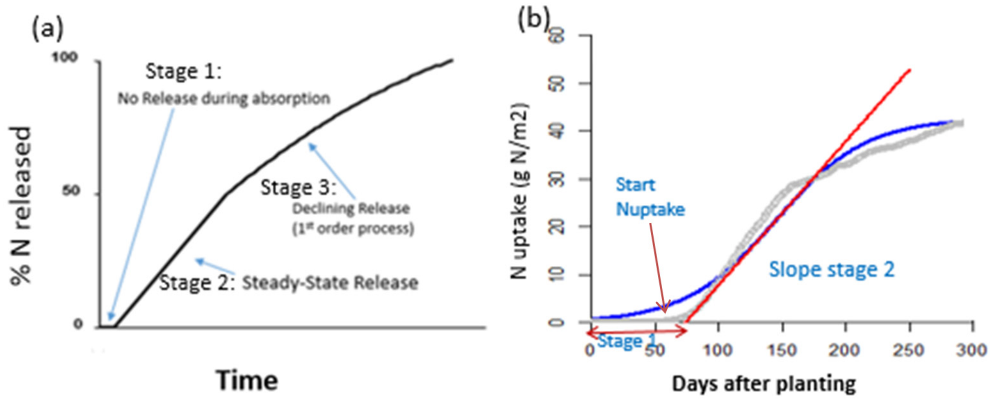

Figure 1. (a) Conceptual three-stage process for N release from controlled release polymer coated fertilisers (based on Shaviv 2001); (b) derivation of parameters describing stage 1 and 2 of release from a conceptual 3-stage model synchronised with predicted N uptake (blue fitted sigmoidal function, red matching linear stage 2) as well as time to first N uptake from the simulated uptake curve (grey).

3. RESULTS

3.1. Variations and consistencies in observed above-ground biomass and biomass N

Above-ground biomass and N accumulation in above-ground biomass followed, in general, a sigmoidal pattern (Figure 2). Nitrogen accumulation ceased well before above-ground biomass reached its plateau. Large variations were found in observed above-ground biomass (Figure 2a, b and c) and biomass N (Figure 2d, e and f), both from site to site and from plant crop to ratoon crop. After 12 to 15 months of growth, above-ground biomass varied from 40 t/ha to about 80 t/ha for plant crop (Figure 2a and b), and from 40 t/ha to 68 t/ha for ratoon crop (Figure 2c). Total biomass N ranged from 20 g/m^2 to about 36 g/m^2 for plant crop (Figures 2d and e), and from 18 g/m^2 to 27 g/m^2 for ratoon crop (Figure 2f). Datasets 5 and 14 came from experiments that included a hilling up treatment (partial filling up of the furrow in which the cane is planted). Interestingly, the aboveground biomass patterns were quite similar when plotted as a function of days after the hilling up treatment, but the total N accumulation in biomass for the two experiments was quite different (Figures 2b and e).

Above-ground biomass and N accumulation in biomass did, however, appear to be fairly consistent during the early growing period across sites although patterns for plant and ratoon crops were different. The growth rate of above-ground biomass was most rapid between 80 and 280 days after planting and between 70 and 250 days after ratooning. The N accumulation rate appeared to be most rapid for a period of 80 - 120 days occurring between 80 and 280 days after planting and between 70 and 160 days post ratooning.

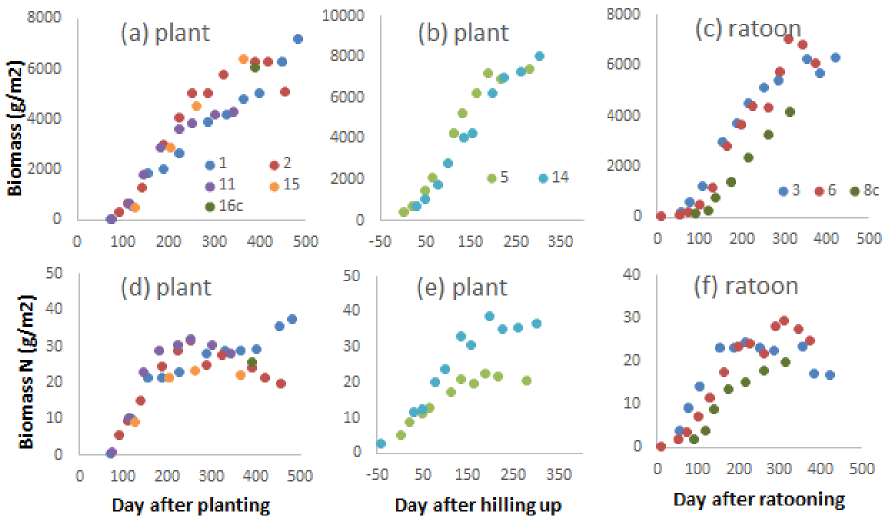

Figure 2. Observed above-ground biomass and nitrogen in above-ground biomass for plant (a, b, d and e) and 1st ratoon crops (c and f) from selected datasets (see Table 1) with high N and water input.

3.2. APSIM simulations of above-ground biomass and biomass N in experimental datasets

In general, the APSIM simulated time-course of above-ground biomass (Figure 3), either using original management from the experimental trial or general rule-based management, agreed well with the observations among all the selected datasets conducted under high N and water input conditions. Except for dataset 1, simulated results using general rule-based management nearly coincided with that using original management. In addition, there are some overestimations for dataset 8c during the early growing period for both simulated results.

During the early growing stages of sugarcane, simulated N accumulation in above-ground biomass (Figure 4), either using original management or general management, also closely followed the measurements. The simulated results using general management nearly coincide with that using original management for at least the first 200 days after planting or ratooning. APSIM with original management overestimated the N accumulation in the simulations of datasets 2, 3 and 15, and underestimated that of dataset 6 and 14. Through optimisation of N supply, simulated N accumulations using general rule-based management were closer to the experimental observations.

Successfully simulating the above-ground biomass and N accumulation in above-ground biomass using general rule-based management provided a basis for extrapolation of the experimental results (biomass, N in biomass) as well as prediction of total N uptake in 55 additional seasons from 1958 to 2013.

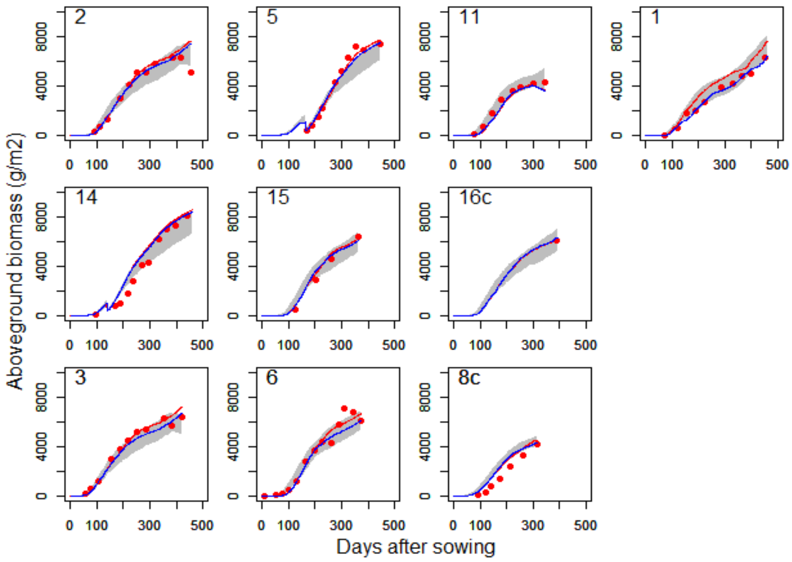

Figure 3. Simulated ranges (grey) of above-ground biomass for plant (datasets 2, 5, 11, 1, 14, 15 and 16c) and 1st ratoon crops (datasets 3, 6 and 8c) from 56 different seasons (1958 – 2013, along with the original (red) and general rule-based (blue) simulations of the original experiments.

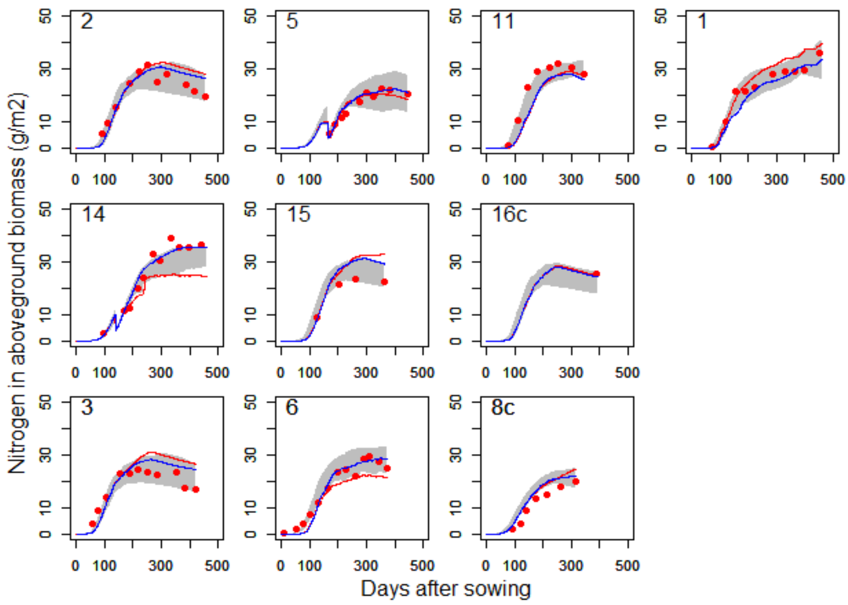

Figure 4. Simulated ranges of nitrogen accumulation in aboveground biomass for plant (datasets 2, 5, 11, 1, 14, 15 and 16c) and 1st ratoon crop (datasets 3, 6 and 8c) from 56 different seasons (1958 – 2013), along with the original (red) and general rule-based (blue) simulations of the original experiments.

3.3. APSIM simulated ranges of aboveground biomass, N accumulation in biomass and N uptake from different seasons (1958 – 2013)

During the early stages of growth (100 - 150 days after planting or ratooning), simulated ranges in above-ground biomass (Figure 3), N accumulation (Figure 4) and total (above-and below-ground) N uptake (Figure 5) were quite small. As a consequence the simulated N uptake pattern was quite well defined and relatively insensitive to seasonal climatic differences. All simulated N uptake patterns exhibited a period of no uptake followed by a relatively sudden transition to a rapid linear increase period. The lengths of these periods were different from site to site and from plant to ratoon crop. Following the linear period, N uptake continued at a slower and more variable rate, causing the simulated ranges to increase with time.

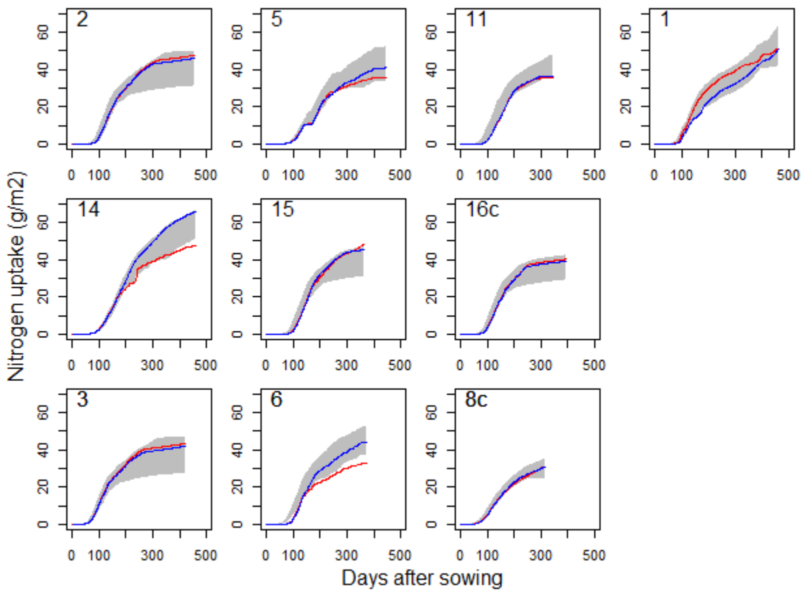

Figure 5. Simulated ranges of total (above- and below-ground) N uptake patterns for plant (datasets 2, 5, 11, 1, 14, 15 and 16c) and 1st ratoon crops (datasets 3, 6 and 8c) from 56 different seasons (1958 – 2013).

3.4. Information for design of CRF release patterns

The number of days to the start of first predicted N uptake showed considerable seasonal variation (Figure 6a). Generally, the simulated range and average for plant crops were much higher than that for ratoon crops. For plant crops, average values were about 40 with variation of 25 days for most of the datasets except for dataset 5 and 14 where the average values were about 30 with variation of 10 days. For the ratoon crops, average values were more consist at about 18 days with variation of less than 10 days.

Variation in the projected stage 1 lag (Figure 6b) and stage 2 linear uptake rate (Figure 6c) for a synchronized 3-stage CRF product was smaller. The stage 1 lag for CRF was around 90 days for plant crop except for datasets 5 and 14, and 75 days for ratoon crop. Datasets 5 and 14, which had hilling up management applied, had a relatively early start to N uptake (Figure 6a), but a longer stage 1 lag (Figure 6b). Average linear N uptake rates were between 0.2 g/m^2 and 0.3 g/m^2 across sites and were similar for plant and ratoon crops.

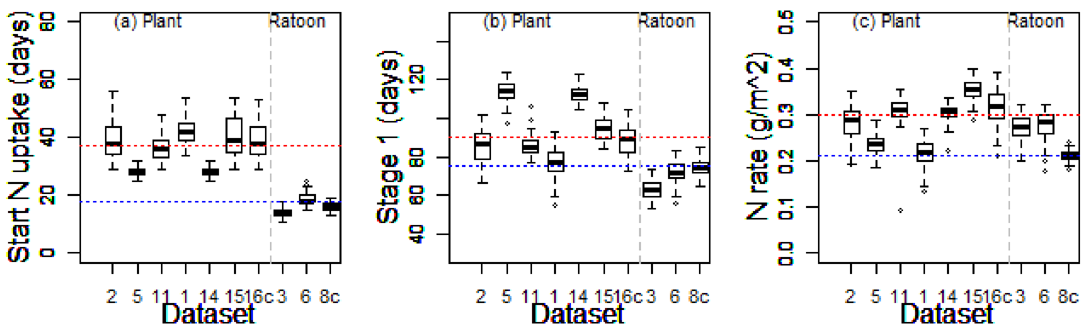

Figure 6. Simulated average and range in (a) the number of days to start of N uptake, (b) stage 1 lag duration (the number of days to start of linear N uptake in a 3-stage release model), and (c) stage 2 linear N uptake rate. The box boundaries indicate the 75 and 25% quartiles, and the whisker caps indicate the 95th and 5th percentiles. The circles are the outliers.

4. DISCUSSION

This study analysed the N uptake patterns of plant and ratoon sugarcane crops from 5 sites in response to seasonal climate conditions by extending field observation data using APSIM modelling. The simulated results provide early information that may inform the design of CRF for Australian sugarcane systems. Our preliminary results suggest that N release from CRF may on average across regions be delayed by 30 to 40 days after planting and 18 days after ratooning respectively (Figure 6a). This result is, however, sensitive to the model's ability to predict early crop N requirements, including by the roots. Anecdotal evidence in the industry suggests that some early N is required. Further work is, therefore, currently underway to confirm early N uptake predictions. If N release from CRF is targeted at the rapid N uptake period, the linear release stage could possibly be delayed by around 90 days for plant crops and 75 days for ratoon crops provided initial soil N, N in planting mix or N mineralisation can supply the relatively small N demand prior to this period (subject to confirmation of its magnitude). The simulations also characterised the N uptake rate during the linear uptake period under high water and N input conditions, which could inform the release rate for CRF stage 2. This rate may change under other management conditions. The pattern of soil N supply should also be considered when designing the N release rate from CRF.

Our results show that N uptake ceased well before sugar biomass reaches its plateau, which agreed well with the experimental findings. Simulated results from 56 repeated seasonal climate conditions show that the variability in N uptake patterns differed from site to site, and from plant to ratoon crop. Narrow ranges during the early growth period allows design of CRF, but wider ranges later leave uncertainty about the total amount of N to be added. The simulated variability in patterns and responses to seasonal climate were caused by a combination of factors including crop class, crop age, genotype as well as management. Further research will systematically explore the effects of these factors on N uptake patterns.

5. CONCLUSION

A simulation based systems approach enabled the quantification of N uptake patterns of sugar systems in response to soil, crop and management factors as well as the characterisation of the impacts from seasonal climate variability. Nitrogen release from CRF should commence between 40 and 90 days after planting and between 18 and 75 days after ratooning, depending on the ability of the soil supply to meet initial N demand The approach used and the results generated in this paper can help to develop N release patterns for CRF to synchronize N release with crop N demand.

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