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Modelling sugarcane nitrogen uptake patterns to inform design of controlled release fertiliser for synchrony of N supply and demand

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ABSTRACT

The use of controlled release fertilisers (CRF) is being promoted in the Australian sugarcane industry to improve nitrogen (N) use efficiency and reduce N losses through better matching of N release with crop N demand. Little is known, however, about the required synchrony due to limited information on both N uptake patterns of sugarcane and N release patterns from CRF under different crop growing conditions. This paper uses APSIM scenario modelling to characterise N uptake patterns of sugarcane plant and ratoon crops in response to seasonal variability and different climatic and management conditions (e.g. level of water and N input, time of planting/ratooning) at five sites within the Australian sugarcane growing region. The results showed considerable variations in crop N uptake patterns across seasons, sites and under different management scenarios. However, for a given site, crop N uptake patterns during the early crop growth stage varied little between seasons (< 0.5 g N/m^2). All the simulated N uptake patterns showed an initial lag period with little N uptake (average < 1.7 g/m2), followed by a relatively sudden transition to a rapid and linear uptake period with the rate and duration of the linear phase depending on management, climatic and soil conditions. Over the course of the season the variation in total N uptake increased especially when the sugarcane system had a limited irrigation allocation or was rainfed. These N uptake patterns could be used to inform the design and management of CRF to optimise synchronisation with sugarcane crop N demand. The predicted average lag periods ranged from 55 days to 137 days. The average lag period was shorter for the ratoon crops (55–83 days) as compared to that for the plant crops (79–137 days) and shorter for later planted or ratooned crops that experienced warmer temperatures in the first months. Temperature also contributed to a location effect, which was particularly strong for plant crops where, for example, the average lag period for early plant crops ranged from 102 days for the most northern tropical site to 137 days for the most southern subtropical site. These differences need to be considered in the design of CRF release patterns and management of timing of application. The predicted average maximum linear N uptake rate ranged from 0.25 to 0.38 g N/m^2/day and driven by direct and indirect effects of solar radiation input. The greater variations in the final total N uptake amount present uncertainty on how much CRF needs to be applied ahead of different seasons. Better seasonal climate forecasting may enable a more precise estimation of total season N requirement by the crop and the amount of CRF required.

1. Introduction

Sugarcane is a dominant crop in the tropics and sub-tropics of Australia. High levels of nitrogen (N) input to support sugarcane productivity have been associated with low N use efficiency due to high N losses (Keating et al., 1997; Bell, 2014; Thorburn et al., 2014; Verburg et al., 2014). The Australian sugarcane industry is under pressure to reduce N losses and increase N use efficiency (State of Queensland, 2013; Bell, 2014). Better estimation of the amount of fertiliser N required and improved synchrony of N supply (from fertiliser and soil) with crop N demand are seen as key solutions to improving N use efficiency and reducing N losses (Bell and Moody, 2014). Controlled release fertilisers (CRFs) have gained interest in the sugarcane industry for precisely this reason (Brodie et al., 2013; Verburg et al., 2016, 2017). Through better matching crop N demand with the controlled N release, CRFs have been shown to increase N uptake efficiency, increase yields, and reduce N losses via leaching, runoff, volatilization, or denitrification (Shaviv and Mikkelsen, 1993; Shaviv, 2001; Kirda et al., 2005; Chu et al., 2007; Grant et al., 2012; Zhu et al., 2012; Shao et al., 2013; Ye et al., 2013).

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The most popular CRFs are polymer coated fertilisers, where the composition of the polymer coating determines the release characteristics, including the shape of the release pattern and the rate of N release. Many of these have been referred to as 'linear release' type CRFs. Shaviv et al. (2001) described their release pattern in three stages (1) a lag stage during which the coated granule absorbs water but does not yet release N, (2) a linear release stage of diffusion through the polymer membrane while solid fertiliser inside is still dissolving and maintaining a constant osmotic pressure, and (3) a first order declining stage starting when all solid fertiliser has dissolved and the concentration inside begins to decrease. Each of these stages are affected by temperature, so the ultimate release pattern and time will depend on local soil temperatures. Sigmoidal release type CRFs are also available, but these are still characterised by the length of an initial lag period during which release is limited and the maximum rate of N release which determines the slope of the sigmoidal function.

Studies have documented that application of CRF increased the yield and NUE of maize (Chu et al., 2007; Shao et al., 2013; Guo et al., 2016), rice in North China Plain (Ye et al., 2013), sugarcane (Isobe, 1971; Isobe, 1972; Di Bella et al., 2013). However, there are almost no studies into the release patterns that are required to achieve synchrony. The limited data on sugarcane N uptake patterns have been mainly measured in short-term experiments conducted under specific conditions (e.g. Wood et al., 1996; Keating et al., 1999; Kingston et al., 2008). These studies indicated that N demand is characterised by an initial lag followed by a period of rapid uptake, but also indicated that the uptake pattern was affected by crop class (plant or ratoon cane), crop age and genotype, as well as seasonal and management effects (Verburg et al., 2014).

Different N demand patterns may require different release patterns to achieve synchronisation. Hauck (1985) commented that 'because uptake and use patterns vary considerably among different plant species grown under similar conditions of N supply, it is unlikely that any single pattern of N release from a material will satisfy the N requirements of all cropping situations.' Therefore a product that suits one crop, may not suit another, and similarly a product that suits a crop in one environment may not provide the required synchrony under other conditions. In order to inform the design of CRF for improved synchrony, a systematic analysis of sugarcane N uptake patterns as a function of soil, climate and management factors is needed, as well as taking into account of the effect of seasonal climate variability (Verburg et al., 2014). This is hard to achieve using an experimental approach alone, but can be accomplished by combining experimental results with simulation modelling.

The Agricultural Production Systems Simulator (APSIM) model (Keating et al., 2003; Holzworth et al., 2014) has a sugarcane module (Keating et al., 1999) that has been tested to simulate the impact of various management practices on sugarcane yield and N loss through deep drainage, denitrification, runoff and sediment loss (Keating et al., 1997; Verburg et al., 1998; Stewart et al., 2006; Thorburn et al., 2010; Thorburn et al., 2011; Biggs et al., 2013).

The study of Keating et al. (1999) included simulations of several experimental datasets on sugarcane crop biomass and biomass N accumulation. Zhao and Verburg (2015) used these simulations as a basis for a preliminary analysis of sugarcane N uptake patterns. After translating the actual fertiliser and irrigation management of ten of the experiments into rule based management, they predicted N uptake patterns for 'virtual repeats' of the experiments in an additional 55 seasons to assess seasonal variability in N uptake patterns and explore what this would mean for the design of CRF release patterns. The results confirmed that N uptake in sugarcane can be characterised by a 2–3 month lag period during which the crop requires relatively little N, followed by a period of 80–120 days of rapid N uptake and a declining N uptake rate after that. While there was considerable variation in crop N uptake patterns across seasons, the initial lag well defined. The seasonal variation was, however, found to be small compared with differences in N uptake patterns between the experiments. With the experimental sites spanning a distance of 1500 km, climatic differences contributed to that, but this was confounded by differences in planting and ratooning times in the different experiments.

The objectives of this study are, therefore, to provide a more systematic analysis of variation in uptake patterns as affected by climatic and management conditions. Specifically we will quantify the variation in sugarcane N uptake patterns across the Australian sugarcane growing region as influenced by climate, rainfall and irrigation input, and time of planting/ratooning. As in the study by Zhao and Verburg (2015) we compare the simulated N uptake patterns to the conceptual three-stage CRF release pattern described above. This allows quantification of the variations in uptake patterns to be expressed in terms that relate to the timing of N supply, namely the lag to the rapid N uptake period and the rate of uptake during this period. We also discuss the implications of these results for the design and management of CRFs and N supply in general.

2. Materials and methods

2.1. Study sites

Five of the study sites from Keating et al. (1999) were selected for simulations of N uptake patterns to capture differences in climatic conditions within the Australian sugarcane cropping region and base the simulations on verified model parameterisations (see Keating et al., 1999 and Zhao and Verburg, 2015). Details for these locations are given in Table 1, where they are presented in order from the northern tropical sites to the southern subtropical sites. Long term historical climate data (1958–2014) for the sites, which include daily records of maximum and minimum temperatures, radiation and precipitation, were obtained for representative meteorological stations in each region from the SILO climate data archive (Jeffrey et al., 2001).

2.2. APSIM modelling of sugarcane N uptake patterns

APSIM version 7.7 was used to simulate the sugarcane N uptake patterns. In APSIM, phenological development of sugarcane crop from planting/ratooning towards flowering is driven by accumulation of thermal time described by the unit °C d (degree days). Five phenological stages are included in the model: planting, sprouting, emergence, stalk growth and flowering. As the physiological basis of flowering is only partly understood, this last stage was de-activated in this version of APSIM following Keating et al. (1999). After planting, sprouting occurs after 250 °C d for plant crops and 100 °C d for ratoon crops (Keating et al., 1999). The shoot will then elongate towards the soil surface at a rate of 0.8 mm per °C d with adequate soil water content. After emergence, growth of aboveground biomass is simulated using stage dependent radiation use efficiency (RUE) together with the intercepted radiation. RUE is reduced by suboptimal temperatures (< 15 °C or > 35 °C) and water and N stress if the water and/or N supply is not sufficient to meet the crop demand. The above-ground biomass is partitioned between leaf, cabbage, structural stalk and sucrose. Green leaf area index (LAI) is used to intercept incident solar radiation. Canopy

Table 1
Details of the location and climate in each study site.

Site	Location	Mean Temperature (°C)	Annual Rainfall (mm)	Annual Solar Radiation (MJ)
Ingham	18.65°S,146.18°E	24.0	2103	7206
Ayr	19.62°S, 147.38°E	23.6	1005	7437
Bundaberg	24.91°S, 152.32°E	21.3	1071	7114
Harwood	29.42°S, 153.25°E	19.2	1305	6588
Grafton	29.68°S, 152.93°E	19.4	1016	6581