Addressing the nitrogen problem in sugarcane production to reduce pollution of the Great Barrier Reef

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Abstract
The N pollution footprint of sugarcane cropping is large due to inefficiencies caused by mismatched N supply and crop N demand over sugarcane's long N accumulation phase. The Great Barrier Reef lagoon receives excessive N loads that contribute to the rapidly declining reef health. Exceeding international average nitrous oxide emission rates several fold, sugarcane soils contribute significantly to Australia's agricultural emissions. Nitrogen pollution reduction schemes over recent decades have mostly targeted reducing N fertiliser rates in line with expected yields and improving soil quality. Overall, these measures have not resulted in the desired N pollution reduction and further innovation is needed to address this problem. We present research that aims to aid agronomic innovation with (i) next-generation fertilisers that are based on repurposed nutrient-rich wastes and sorbent materials to better match N supply and crop demand and to improve soil function and carbon levels, (ii) understanding of soil N cycling and microbial processes, (iii) legume companion cropping as a source of biologically fixed N, and (iv) genetic improvement of sugarcane that more effectively captures and uses N. We conclude that evidence-based innovation has to support crop growers across climate and soil gradients in the 400,000 hectares of catchments of the Great Barrier Reef. This should include investment into new technologies to support ecologically-sound agriculture and a circular economy without waste and pollution.

Key Words
companion cropping, crop breeding, waste repurposing

Introduction
High-production cropping ensures adequate N supply via fertiliser application, but inefficiencies result in off-site N losses that have caused a near tripling of reactive N in the biosphere over the past century. Global analysis of N fertiliser use in sugarcane production showed that only 40-50% of fertiliser N is exported with the crop at harvest and fertiliser use efficiencies range from 10 to 90% based on N application rates from 60 to 755 kg N/ha (Robinson et al. 2011).

Targets for improving N use efficiency in sugarcane cropping need to integrate agronomic measures in combination with plant selection and breeding to address the difficulties of the cropping system, which is vulnerable to climate extremes and multiple soil and management constraints. At the core of these measures is the need to; (i) select sugarcane cultivars with efficient N uptake and use for production; (ii) synchronise soil N supply and crop demand to avoid oversupply of N that is vulnerable to loss; (iii) increase N supply from biological N fixation and repurposed wastes including sugar mill materials; and (iv) improve soil function to support root health and the storage and release of N.

Such strategies are being pursued with intensity in the Australian sugarcane industry (Bell et al. 2015), as the adjacent world-heritage listed Great Barrier Reef is experiencing a dramatic decline in coral health with around half of coral death attributed to nutrient pollution (Brodie et al. 2013). Industry-wide approaches to resolve the N problem include well-established methods such as targeted variable N application, and measures of intervention that are at various stages of experimentation as outlined below.

Experimental Approaches and Outcomes

Selecting and breeding N use efficient sugarcane cultivars

Genetic improvement of N use in tropical biomass crops has received little attention compared with long studied grains (Garnett et al. 2015). Genetic variation for nitrogen use efficiency (NUE) was identified in a mapping population using glasshouse-based research (Figure 1A, B; Robinson et al. 2007). Transgenic sugarcane lines have demonstrated improved NUE compared with non-transgenic controls in a pot trial under low N conditions (Snyman et al. 2015).

Differences in NUE at limiting N for young plants in controlled conditions prompted larger scale field screening of 64 genotypes, including commercial cultivars (*Saccharum* spp hybrids), Australian breeding lines and introgression clone backcrosses of *S. spontaneum* and *Erianthus* spp, over three years at low (20-40 kg N ha^{-1} yr^{-1}) and industry-recommended (160-200 kg N $ha^{-1}yr^{-1}$) fertiliser rates at two locations in North Queensland. Yield reduction with low N supply over a three year crop cycle (plant to 2^{nd} ratoon) at the two sites averaged 22% and 45%, respectively, highlighting environmental drivers of soil and climate on performance at low N fertiliser supply. Yield and N accumulation patterns demonstrate that sugarcane genotypes differ in their ability to acquire and use N (Robinson et al. 2015).

Early crop vigour appears to be an important trait in situations where N loss occurs early in the crop season in rain-fed and irrigated Australian sugarcane regions. Early vigour is particularly significant because soluble N is in excess at the start of the crop cycle when the crops' sink capacity is limited due to comparatively slow growth in the early stage, when wet season rains and flood irrigation cause N losses from soil. A low capacity of young sugarcane to store excess N prevents the ready uptake and storage of N in the form of nitrate. This is of concern because nitrate is a dominant N form in sugarcane soils and is highly vulnerable to loss. We have not yet identified wild or commercial sugarcanes that have a considerable ability to acquire and store nitrate when other N sources, particularly ammonium, are present in the high concentrations that typify the first 3-4 months of the crop season. However, high nitrate-accumulation occurs in related species *Erianthus*, and progenies of sugarcane and *Erianthus* have a stronger ability to acquire and store nitrate (Robinson et al. 2011), indicating that nitrate accumulation could be targeted as a trait for sugarcane.

Enhanced efficiency fertilisers

Developing enhanced efficiency fertilisers for N supply (EEF-N) for sugarcane cropping has followed on from uses in temperate crop systems and is aimed at delaying N release or N stabilisation in urea with polymer coating, urease or nitrification inhibitors (Verburg et al. 2015). Responses of crop yields and nitrous oxide emissions to EEF-N have been varied, with some success recorded but also instances where EEF-N did not translate into reduced N losses or better yields (Wang et al. 2014). This illustrates that release of N from EEF may not be optimal and requires further characterisation (which is ongoing) in the context of climate, soil properties and crop management.

Recycling sugarcane and animal wastes

Recycling sugarcane biomass via green-cane trash blanketing, leaf and immature stalk residue on site at harvest, retains ~20-40 kg N per hectare and is now practiced on ~80% of the 390,000 hectares under sugarcane cultivation in Australia (Bell et al. 2007). Similarly, N can be recycled from sugarcane processing residues (mill mud, ash, dunder) and non-sugarcane materials (compost, animal and human wastes). The use of alternative N sources reduces the reliance on synthetic N, avoids pollution of sites where wastes are currently used or stored (e.g. sugarcane field in the vicinity of sugarcane mills), and could provide a slow but optimal supply of N to crops including organic N forms (Paungfoo-Lonhienne et al. 2012). In addition, organic materials may improve soil function. Ongoing research is generating knowledge required to avoid potential negative effects such as increased N_2O emission (do Carmo et al. 2013). One approach is functional optimisation of nutrient-rich waste formulations with sorbent materials for slow release of nutrients to reduce gaseous N losses (Figure 1C; Redding 2011, Pratt et al. 2015).

Legume intercropping

Partial replacement of synthetic fertiliser by biologically fixed N from legume companion crops has the potential to reduce nitrous oxide emissions and N runoff. A significant proportion of the Australian sugarcane industry uses legume rotations (i.e. planting one or more legume crops after a ~3-6 year sugarcane ratoon cycle; Bell et al. 2007). Research is underway to evaluate legume companion cropping where legumes are grown simultaneously with sugarcane and are left on site to decay (Figure 1D). At three commercial sugarcane farms in Queensland, sugarcane yields, soil N and nitrous oxide emission of sugarcane-legume companion systems with reduced fertiliser applications are being compared to standard commercial production. While biological N fixation may contribute only a proportion of the sugarcane crops' N needs, additional benefits, including pathogen suppression, can result from legume companion cropping as demonstrated in other crop systems (Brooker et al. 2015).

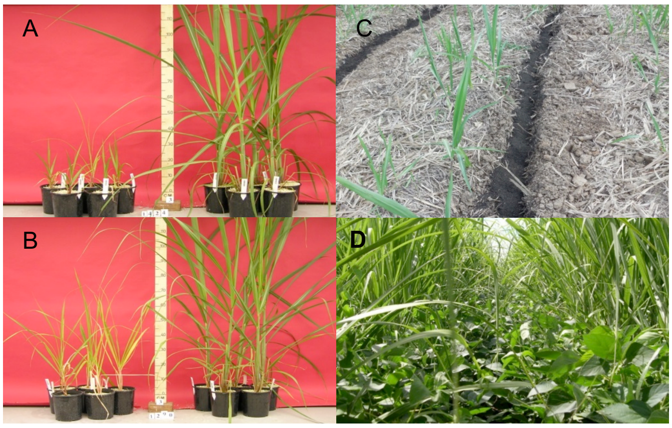

Figure 1. Genotypic variation in NUE illustrated by biomass production in poorly performing (A) and vigorous (B) genotypes from a mapping population grown at limiting N (left) and replete N (right) (Robinson et al. 2007). (C) Novel fertiliser formulations comprised of biochar and poultry manure to evaluate yield response and N losses. (D) Sugarcane-legume intercropping at Dalbeg, Queensland (photo courtesy Bryan Granshaw).

Soil health, soil microbes and N fertiliser

Soils can lose some of their physical, chemical and biological functions due to long-term sugarcane cropping. Pertinent problems in Australia include (i) soil compaction caused by heavy machinery, (ii) loss of soil organic matter, (iii) declining soil pH often below pH 5, and (iv) unfavourable soil biology that negatively affects crop health and vigour (Pankhurst et al. 2003). Soil fumigation with biocides can result in ~30% yield increases in the plant and ratoon crops (Garside and Bell 2011), indicating a significant role for soil biology. Insight into the complexity of interacting factors contributing to soil health can be gained by characterising root and soil microbial communities and their responsiveness to management practices, including fertiliser rate. Culture-independent fungal community profiling indicated N fertiliser application rate strongly modifies the composition but not the taxon richness of fungal communities in sugarcane soil and rhizosphere (Paungfoo-Lonhienne et al. 2015). Increased N fertiliser dosage has a potential negative impact on carbon cycling in soil decreasing decomposer fungal genera diversity and promoting fungal genera with known pathogenic traits (Paungfoo-Lonhienne et al. 2015). Assessment of the types and relative abundance of N-metabolising bacteria at the same sites indicated root-associated diazotrophs did not increase in response to lower N fertiliser rates over a three year timeframe (Yeoh et al. 2015). Lower N fertiliser rates did improve the presence of beneficial predatory nematodes and reduce plant-pathogenic nematodes (Stirling et al. 2015). In addition to indirect changes to the microbial community changes described above, much research is focussed on designing microbial inoculants to enrich plant growth -promoting bacteria in cropping systems (Paungfoo-Lonhienne et al. 2014).

Conclusions

Clearly, the N problem in sugarcane production has to be addressed via multiple strategies and novel technologies that accommodate site-specific constraints and opportunities presented by nutrient-rich wastes that are under-used and are currently disposed of in the vicinity of sugarcane mills. Fundamental understanding of the mechanisms involved in crop N uptake and use, soil N transformations and soil biology combined with relevant field experimentation with targeted investment is necessary to achieve a sustainable sugar industry. This change has to be rapid and unite legislative and economic considerations that not only consider the costs of N at the farm gate but also the costs to the environment.

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