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Nitrogen Management Guidelines for Sugarcane Production in Australia: Can These Be Modified for Wet Tropical Conditions Using Seasonal Climate Forecasting?

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Abstract Sugarcane is a highly valuable crop grown in tropical and subtropical climates worldwide primarily for the production of sucrose-based products. The Australian sugarcane industry is located in close proximity to sensitive environments and the apparent declining health of the Great Barrier Reef has been linked to damaging levels of land-based pollutants entering reef waters as a result of sugarcane cultivation undertaken in adjacent catchments. Unprecedented environmental scrutiny of N fertiliser application rates is necessitating improved N fertiliser management strategies in sugarcane. Over time the focus of N fertiliser management has shifted from maximising production to optimising profitability and most recently to improved environmental sustainability. However, current N calculations are limited in their ability to match N fertiliser inputs to forthcoming crop requirements. Seasonal climate forecasts are being used to improve decision-making capabilities across different sectors of the sugarcane value chain. Climate is a key driver of crop growth, N demand and N loss processes, but climate forecasts are not being used to guide N management strategies. Seasonal climate forecasts could be used to develop N management strategies for 'wet' and 'dry' years by guiding application rate, timing and/or frequency of N inputs and the benefit of using alternative forms of N fertiliser. The use of seasonal climate forecasts may allow more environmentally sensitive yet profitable N management strategies to be developed for the Australian sugarcane industry.

Keywords Sugarcane · Australia · Nitrogen · Seasonal climate forecasting · Environment

Introduction

Sugarcane, one of the longest cultivated plants in the world, is a highly valuable crop grown in tropical and subtropical climates worldwide. Grown primarily for the production of sucrose-based products, sugarcane can also be used to produce a diverse range of alternative products and offers a renewable alternative to petrochemical resources [25, 26]. This versatility provides a strong economic outlook for the future of the sugarcane industry as the world's population continues to increase and the demand for food and renewable energy sources intensifies.

The location of sugarcane production areas in close proximity to sensitive environments necessitates the development and adoption of sustainable production practices. The Australian sugarcane production system has evolved to include a suite of best-management practices (BMPs) focused on maintaining productivity, improving profitability and minimising the movement of sediment, nutrients and pesticides off-farm [39, 74, 123, 124, 139]. Although these practices have been largely successful in achieving the desired outcomes, loss of nitrogen (N) from sugarcane production remains a serious impairment to improved environmental sustainability and profitability [33, 44, 89, 104, 127, 152, 156, 162].

Although sugarcane requires large inputs of N for successful crop growth [157], it is relatively inefficient in the

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recovery of N fertiliser [156]. Recovery studies of applied N fertiliser in the crop and surrounding soil in Australia indicate maximum recoveries are just over 60 % of N applied [36, 104, 156]. The unrecovered N is either held in the soil by microbial immobilisation [79] and/or lost from the sugarcane production system [172]. Strategies have been developed to reduce N losses from ammonia volatilisation but they have not reduced denitrification and leaching losses [36, 156]. In extreme situations, denitrification can result in 25 % of the applied N fertiliser being lost to the atmosphere [44]. The magnitude of N losses and low recoveries of fertiliser N by the sugarcane crop are of significant economic and environmental importance [12, 17, 23, 24, 153].

The focus of N fertiliser management in the Australian sugarcane industry has recently shifted from production maximisation to profit optimisation and most recently improved environmental sustainability [117, 152, 169, 170]. Two N management calculation systems developed in the Australian sugarcane industry are SIX EASY STEPS and N Replacement. The SIX EASY STEPS nutrient-management program aims to deliver soil- and site-specific N fertiliser guidelines for sustainable sugarcane production [33, 116, 118–121, 125–128, 170]. The N Replacement system aims to replace the amount of N removed by the previously harvested crop [147, 148]. However, both systems are limited in their ability to alter N management strategies to cater for changes in climatic conditions experienced during the current growing season or those predicted for the forthcoming season.

The use of seasonal climate forecasting in agricultural production systems is increasing as stakeholders aim to improve decision-making capabilities that are impacted by climate [70, 137]. Seasonal climate forecasts are being used to improve decision-making capabilities in the growing, harvesting, milling and marketing sectors of the Australian sugarcane industry [46, 47, 49, 50]. Potential exists to increase the application of climate-forecasting information into other areas of the Australian production system to reduce the impact of climate variability on economic losses and environmental degradation.

This review aims to provide a general overview of the sugarcane industry before focusing on the Australian sugarcane production system and opportunities to improve N management strategies for superior environmental and economic outcomes.

Literature Review

The Sugarcane Plant

Sugarcane is a perennial tropical grass belonging to the Gramineae, genus *Saccharum* [13, 78, 158]. There are two wild and four domesticated species of *Saccharum*. The wild species are *Saccharum spontaneum* L., which is found throughout tropical Africa, Asia and Oceania, and *Saccharum robustum* Brandes & Jeswiet ex Grassl, which is restricted to Papua New Guinea and neighbouring islands. The four domesticated species; *Saccharum officinarum* L., *Saccharum edule* Hassk., *Saccharum barberi* Jeswiet and *Saccharum sinense* Roxb. have a higher sucrose content and lower fibre content than the wild species [13, 27]. All current commercial sugarcane cultivars are complex hybrids of two or more species of *Saccharum* [27]. Unlike other grass crops, which store starch in seed heads, sugarcane has evolved to store sugar in its stalk. The elongation and expansion of the sugarcane stalk provides an ideal area to store sucrose [158].

Commercially, sugarcane is asexually propagated by planting stalk cuttings known as setts or billets. This produces a new sugarcane crop with the same characteristics as the crop from which the cuttings were taken. The setts contain at least one bud, along with all the nutrients and water required for the bud to germinate. On germination, a primary shoot is produced from the bud. In a process known as tillering, the buds on the primary shoot then develop secondary shoots, which in turn may produce tertiary shoots and so on. The primary shoot and tillers grow to produce a ‘stool’ that consists of stalks of varying weight, height and diameter. The aboveground biomass of the plant crop is harvested around 12–18 months after planting [100, 167]. The buds and root primordia of the underground stool that remain after harvest develop to produce a further crop known as a ratoon crop. Ratoon crops are normally harvested at around 12 months of age, but the growth period can be as long as 22–24 months depending on the climatic conditions (mainly temperature and solar radiation) and soil moisture experienced during the growing season [45]. In some circumstances, ratoon crops are ‘stood over’ to the following harvest. This usually occurs when weather conditions prevent crops of sugarcane being harvested. Successive ratoon crops continue to be produced until the field needs to be replanted due to declining yields. Over time, the soil looses its structure and becomes compacted due to in-field operations (especially harvesting and haul-out of the crop). Damage from pests and diseases increases, soil salinity and sodicity problems are exacerbated, and the stool is damaged by harvesting equipment [45]. Consequently, plant populations decline and productivity reduces to a level where it is uneconomical to continue the crop cycle and replanting is required.

Sugarcane Products and Uses

Sugarcane is the fastest growing, largest biomass and highest sucrose-accumulating agricultural crop in the world. It is primarily grown for the production of sugar-based products, ranging from raw to refined white sugar and specialty products. With these products meeting the dietary requirements of both high and low income consumers around the world, sugarcane is the largest contributor of dietary carbohydrate for human consumption after cereal crops [26]. There is also a small but profitable specialty market for organically produced sugar, most of which is grown and processed in Florida in compliance with strict field and factory protocols [76].

Processing sugarcane into raw sugar also produces by-products (bagasse, molasses, filter mud and ash) that have many different uses. Bagasse, the fibrous residue of the sugarcane plant that remains after sugar extraction, can be used to manufacture paper, animal feed and bioenergy [14, 26]. It is often used in energy cogeneration for sugar milling operations, with surplus energy fed back into local electricity grids [5, 26, 68, 90].

Molasses is the thick, dark, uncrystallised syrup that remains after most of the sucrose has been extracted from the cane juice in the production of raw sugar [90]. It is used in the production of syrups, animal supplements, ethanol for blending with gasoline or diesel, and distillation of alcoholic beverages [26, 90].

Filter mud (also known as filter press/cake, or mill mud), ash, molasses and vinasse (a by-product of ethanol production, referred to as dunder in Australia) are also valuable sources of mineral nutrients and organic matter [29, 31, 90]. The nutrient composition of these products varies. Generally, filter mud contains significant amounts of calcium (Ca), phosphorus (P) and N, whereas ash contains significant amounts of potassium (K), Ca, magnesium (Mg) and silicon (Si) and molasses and vinasse are high in K [29, 31]. These products often need to be used in combination with inorganic fertilisers to meet the nutritional requirements of the crop as not all of the nutrients they contain are available immediately for plant uptake [14, 29, 31, 90].

Sugarcane can also be used to produce biofuels, bioenergy and biopolymers [25, 26]. Biorefineries constructed in Brazil to produce ethanol and bioplastics highlight the potential of sugarcane to offer a renewable and environmentally friendly alternative to petrochemical resources [25, 26, 54]. Similarly transgenic approaches to genetic and metabolic engineering have resulted in the production of new high-value products, allowing sugarcane to be used as a biofactory for the production of alternative sugars, bioplastics, high-value proteins and fine chemicals including nutraceuticals, industrial enzymes and pharmaceuticals [25, 26, 76].

It is apparent that the sugarcane plant has a diverse range of uses and there is strong potential for market diversification. In the future, it is highly likely that sugarcane will be grown to produce sucrose for human consumption and biomass for the manufacture of fuel, energy and alternative products [26].

International Sugarcane Industry

Sugarcane is grown between latitudes 35° North and 35° South, from sea-level to 1,500 m in over 100 countries throughout Africa, North, Central and South America, Asia and Oceania [13, 14, 97]. Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Australia, Argentina and the United States of America are the largest sugarcane-growing nations supplying over 80 % of the total 2009–2010 sugarcane production [55]. Brazil, Thailand and Australia are also major exporters of raw sugar [55, 73].

Brazil is the largest sugarcane producer, raw-sugar exporter and manufacturer of sugarcane ethanol. In 2009–2010 Brazil grew around 40 % of the total sugarcane produced [55] and had 325 sugar–ethanol plants operational in 2010 [54]. The size of the Brazilian sugarcane industry and its flexibility to produce sugar or ethanol has a major influence on the value of raw-sugar exports [73]. It also makes it difficult for other raw-sugar exporters to secure market share, especially during times of excess production. To remain competitive and profitable, other major raw-sugar exporters, such as Australia, have focused on establishing a reputation as a consistent and reliable supplier of high-quality raw sugar, improving production efficiency and reducing operating expenses [34, 73, 90]. Australia is recognised as one of the most cost-effective sugarcane producers in the world, capable of securing market share even during times of excess production [34, 73].

Australian Sugarcane Industry

Generating annual revenue of US$1.5–2.5 billion, the processing of sugarcane into raw sugar is one of Australia's largest and most important rural industries [34]. Family-owned businesses with an average farm size of 110 ha and some very large corporately owned cane-farming businesses produce 32 to 35 Mt of sugarcane and 4.5 to 5 Mt of raw sugar annually [34].

In Australia, sugarcane is grown along 2,200 km of coastline (Fig. 1) from Mossman (16°30′S, 145°30′E) in far north Queensland to Harwood (29°25′S, 153°14′E) in northern New South Wales [34, 123]. Encompassing an area of approximately 500,000 ha [123] the Australian sugarcane industry is split into five discontinuous regions: Northern, Burdekin, Central, Southern and New South Wales. These regions are situated within wet tropical and humid subtropical climates and are separated by areas of unsuitable soils or unreliable rainfall [82, 123].

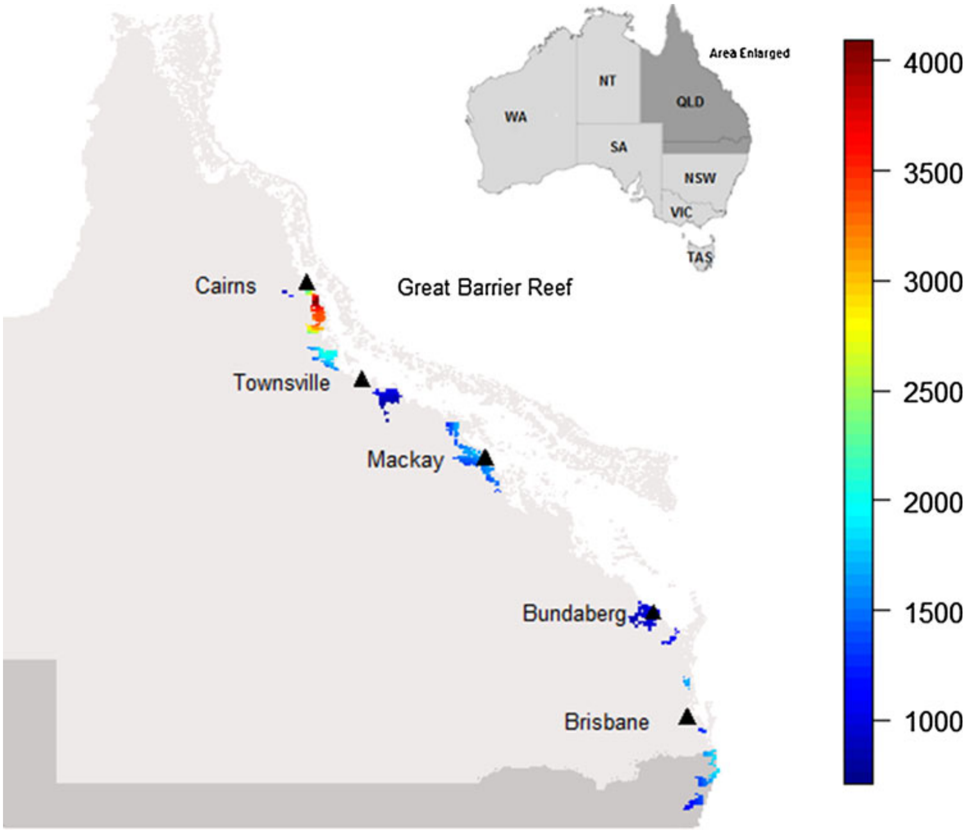

Fig. 1 Geographical location of the Australian sugarcane industry highlighting mean annual rainfall (mm) distribution

In Queensland, sugarcane is cultivated along the east coast in lowland areas of catchments draining eastward into the Great Barrier Reef World Heritage Area [23, 174]. The mean annual rainfall ranges from over 4,000 mm to less than 1,000 mm, necessitating full or supplementary irrigation in some districts [14, 82, 123]. In the Wet Tropics region more than 80 % of the total annual rainfall occurs during the wet season that starts in summer and extends into autumn [82]. Summer-dominated rainfall, coupled with the risk of flooding and cyclonic storms, results in the harvest season operating from June to December to coincide with normally drier weather.

With Queensland producing approximately 95 % of Australia's annual raw sugar total, it is not surprising that sugarcane is the major agricultural crop grown on the east coast [14, 34, 73]. The ability to grow sugarcane over a large area of different soil types and climatic conditions, in combination with easy access to required infrastructure, results in sugarcane being grown in preference to alternative crops. However, the period between crop cycles provides an ideal opportunity for alternative crop diversification without disrupting sugarcane production [59]. Alternatively, sugarcane may be used in longer-term rotation with crops such as bananas in northern Queensland.

In New South Wales sugarcane is grown in a subtropical climate on coastal plains traversed by three rivers [14]. The mean annual rainfall total ranges from 1,300 to 1,700 mm and, although the majority falls during the wet season, up to 40 % of the total annual rainfall can fall over the winter months creating drainage and harvesting problems [32, 82]. Frequent flooding may occur in late summer and crops can be frosted in some areas during winter [14]. The cooler climate of New South Wales results in most sugarcane crops growing for 2 years before harvest, compared to 1 year in Queensland [14].

The Australian sugarcane industry with 24 sugar mills and six bulk-storage terminals is small compared to its major raw-sugar exporting competitors. Approximately 80 % of the raw sugar Australia produces is exported, mainly to China, Indonesia, Japan, Korea, Malaysia, Taiwan, the United States of America and New Zealand [34, 73]. The remainder is refined and processed in Australia to produce white sugar, liquid sugar products and specialty products such as golden syrup, coffee sugar, cubed sugar and treacle for domestic consumption.

The productivity of Australian sugarcane farms and mills is amongst the highest in the world and production costs are similar to most other larger sugarcane producers [73]. Australia is regarded as one of the most competitive, cost-effective and innovative producers and exporters of raw sugar and a leader in the adoption of sustainable farming practices [34, 73].

Australian Sugarcane Production System

The Australian sugarcane-farming system focuses on the adoption of BMPs for improved productivity, profitability, sustainability and environmental responsibility [64, 74]. BMPs are recommended across all aspects of the sugarcane-farming system and, although growers tailor practices to suit their individual requirements and climatic conditions, certain fundamental principles exist. Multidisciplinary research conducted by the Sugarcane Yield Decline Joint Venture [58, 62, 63] to investigate the loss of productive capacity of Australian sugarcane-growing soils under long-term monoculture promoted the adoption of a sustainable farming system. This farming system recommends inclusion of a break period between crop cycles, preferably incorporating a well-managed legume crop, reducing tillage practices, increasing row spacing to allow for controlled trafficking of machinery, adopting green, cane trash-blanketing (no pre-harvest burning and conservation of crop residues; GCTB) wherever possible and sustainable resource use [16, 64, 65, 74]. At least some of these practices are commonly adopted within most sugarcane-farming enterprises as they have significant potential to reduce production costs, improve operation timeliness and soil health and prevent sugarcane yield decline [16, 64, 74].

The average Australian sugarcane crop cycle consists of plant and four to five ratoon crops with a 4- to 6-month break period between crop cycles to break the sugarcane monoculture [62, 66, 100, 167]. The break period also provides an ideal opportunity to determine the soil nutrient status, target weed control, reduce pest and disease pressure, undertake land rectification activities, and plant an alternative crop [74]. Legume crops grown during the break period provide a diverse species change from sugarcane and a source of mineral N, improve soil health and increase productivity [59, 60]. The most commonly grown legumes are cultivars of soybean (*Glycine max*), cowpea (*Vigna unguiculata*), lab lab (*Lablab purpureus*) and peanut (*Arachis hypogaea*) and, although broadcast planting is still practiced, direct-drill planting into raised mounds or existing cane rows to reduce tillage operations and maximise germination is becoming more popular [60]. Legumes are generally grown as green-manure crops in the wetter northern districts, with grain crops produced where weather conditions and machinery availability facilitate harvesting [59, 60]. As the break period usually coincides with the wet season, alternative crops help minimise the risk of erosion and pollutant movement off-farm. Where it is not possible to grow a well-managed legume crop, a bare fallow maintained with knockdown herbicides is the best alternative [74]. Most Australian sugarcane-farming systems use a configuration of single rows separated by about 1.52 m. Transition to controlled-traffic farming systems consisting of single or dual rows separated by 1.8–2.0 m is gradually occurring and minimises the adverse effects of soil compaction in the cropping zone [32]. This farming system is also better suited to zonal tillage systems that only cultivate the row area. Adoption of minimum or zonal tillage land preparation practices in combination with a greater reliance on chemical weed control have reduced aggressive tillage practices and helped minimise soil disturbance in break and plant crops. Zero tillage, the practice of direct drilling sugarcane setts into undisturbed soil, is not common, as some cultivation is required to reshape the cane drill and prepare an adequate seed bed [32]. However, a recently developed direct-drill sugarcane planter based on the double-disk-opener planter concept commonly used in the grains industry has the potential to successfully operate in any cultivation system, including zero tillage [110, 111].

Sustainable use of resources is another important component of the Australian sugarcane production system and focuses on the correct application rate, placement and timing of nutrient, water, herbicide and pesticide inputs to maximise profitability and minimise detrimental offsite impacts [74]. This type of approach is particularly evident in current nutrient-management guidelines that consider nutrient availability based on soil-test results, crop requirements, crop class, yield potential and nutrient contributions from other sources such as mill by-products and legumes so that recommended nutrient application rates can be adjusted accordingly [33, 121, 126, 170]. It is also illustrated in recently developed guidelines for best-practice integrated weed management [32, 124].

Crop-management practices are highly mechanised and all sugarcane is mechanically planted with whole-stalk or billet planters into a furrow or preformed mounds [110] and mechanically harvested using wheel or track chopper harvesters [106]. Most of the industry has transitioned to green-cane harvesting and trash retention. This has been a catalyst for the adoption of zero or strategic tillage, subsurface fertiliser application and chemical weed control in ratoon crops [166]. It is also considered to be best practice providing agronomic, environmental and financial benefits to the farming system, especially when compared to traditional burnt-cane harvest systems [21, 62, 124, 140].

When harvested, sugarcane is transported to a mill for processing. In Australia, a cane price formula is used to determine the value of sugarcane delivered to the mill for each grower. The value is shared between growers and millers, roughly on a 2/3:1/3 basis [90], meaning growers are more focused on sucrose production and profitability, whereas millers are primarily interested in tonnes of cane delivered to the mill [129].

Australian Sugarcane Production Challenges

Ongoing constraints to sugarcane productivity in Australia include changes to the bio-physical environment, socio-economic factors, environmental considerations, the influence of pests and diseases and harvest scheduling [62, 97]. In addition, there are a number of other challenges currently confronting the Australian sugarcane industry. These include rising input costs, skilled labour shortage, market diversification, the unknown impact of climate change and restructuring of research, development and extension services. However, it is the intense pressure from tourism, environmental, public and political groups to minimise the environmental impact of sugarcane production practices that takes centre stage [17, 33].

Environmentally sustainable sugarcane production practices are continually being developed in an attempt to deliver superior environmental outcomes without restricting productivity or profitability. Practices such as GCTB, zonal and minimum tillage land preparation, legume cover crops or spray-out fallow management, subsurface fertiliser application and refinement of nutrient-management guidelines all aim to reduce sediment and nutrient movement off-farm [39, 74, 123, 124]. Maintenance of grassed filter strips and vegetation along waterways and the installation of sediment traps also help to intercept and retain any sediment, nutrients and pesticides in farm runoff water [39, 139]. Transition to these farming practices is often voluntary, as they are also associated with agronomic and economic benefits.

Despite voluntary adoption of these environmentally sustainable sugarcane production practices, regulations (*Great Barrier Reef Protection Amendment Act, 2009*) targeting nutrient and pesticide inputs were introduced by the Queensland Government to improve the quality of water entering the Great Barrier Reef lagoon [7]. The regulations also require sugarcane growers with more than 70 ha in the Wet Tropics catchment to complete an Environmental Risk Management Plan (ERMP) to continue farming [7]. This development has primarily occurred due to unprecedented environmental scrutiny of N application rates and N losses attributed to the Australian sugarcane industry.

Nitrogen Management in Australian Sugarcane Production

Worldwide there is an increasing realisation that farmers must become more pro-active in managing the effect of their farming system on the surrounding environment [45, 62]. This is of high importance in the Wet Tropics region of northern Australia, the only place in the world where sugarcane production is surrounded by two adjacent World Heritage Areas of national and international ecological, economic and social significance [17, 23, 98, 163, 174]. The Wet Tropics World Heritage Area is Australia's most floristically rich environment, providing habitat for 76 species of animals regarded as rare, vulnerable or endangered [155] and the Great Barrier Reef World Heritage Area is the world's largest reef ecosystem [23].

Even with the adoption of environmentally sustainable sugarcane production practices, there is a risk that 'environmental pollutants', including N, could be lost from the sugarcane production system due to external influences. As N is the nutrient most susceptible to environmental loss and applied in the greatest quantity to optimise yield, greater emphasis needs to be placed on the development of environmentally sustainability yet profitable N management strategies [125, 147, 148, 157].

Nitrogen Sources for Sugarcane Production Nitrogen in the soil is present in organic (i.e. organic matter) and inorganic [i.e. ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), nitrous oxide (N_2O)] forms. Organic N can represent around 95–99 % of the total soil N and is converted to mineral N forms via the decomposition of organic matter in a process known as mineralisation [67]. Only a small proportion of organic N becomes available for plant uptake.

Inorganic N represents only 2–3 % of the total soil N. The two most abundant forms of inorganic N, also referred to as mineral N (which is readily available for plant uptake), are NH_4^+ and NO_3^- [67]. Ammonium ions are positively charged and held in an exchangeable form on the negatively charged surfaces of clay particles and organic matter [20, 67]. Ammonium is, therefore, a relatively immobile form of N and less susceptible to leaching and denitrification losses [67]. Nitrate ions remain in the soil solution as they cannot be absorbed by clay particles or organic matter, and are, hence, a highly mobile form of N [20, 67].

The N contained in commonly applied N fertilisers exists in three forms: organic (i.e. urea, mill by-products and manures), NO_3^- and NH_4^+. In sugarcane, the most commonly applied fertiliser products include granular, liquid, mill by-product and organic forms [124]. The form of N fertiliser applied is often based on cost as research has demonstrated no difference in cane yields from using ammonium sulphate or urea, provided it is subsurface applied [88].

In plant cane, inorganic fertilisers are often applied as mixtures at planting [32]. In ratoons, inorganic fertiliser mixtures, also known as "one shot blends", are often urea-based products containing K (muriate of potash), possibly P (DAP) and S (ammonium sulphate) [124, 147]. Alternatively, 'straight' products such as urea and muriate of potash may be applied instead of mixtures. The nutrient compositions for plant and ratoon fertiliser mixtures vary so that the most appropriate product can be selected to meet the nutritional requirements of the block. Liquid fertilisers include commercially available nutrient solutions that are based on inorganic fertiliser products, and dunder-based products that are usually fortified with other nutrients including N [124]. Mill by-products also provide a significant source of N, but, as it is in an organic form, not all the N is immediately available for plant uptake [14, 29, 31, 90]. A proportion of the applied fertiliser N remains in the soil, but this residual N contributes only small amounts of N for sugarcane growth [37].

Legume break crops can contribute significant amounts of mineral N for sugarcane production. Well-managed soybean (*Glycine max* cv. Leichardt) and cowpea (*Vigna unguiculata* cv. Meringa) crops are capable of supplying 310 and 140 kg N/ha, respectively, excluding the N stored in the below-ground parts of the crop [59, 61]. In most situations symbiotically fixed N accounts for 50–60 % of the N accumulated by the legume crop, with the remainder sourced from soil mineral N reserves [59]. Following a legume crop, the amount of N fertiliser applied to plant cane can be reduced or possibly eliminated depending on legume residue management at the end of the break period [59, 122, 124].

Nitrogen Loss Processes Crops seldom assimilate more than 50 % of the N applied as fertiliser [38]. For sugarcane grown in Australia, research using labelled ^{15}N fertiliser has indicated maximum recoveries in the crop and surrounding soil of just over 60 % of the N fertiliser applied [36, 104, 156]. The unrecovered N is either held in the soil by microbial immobilisation [79] and/or lost from the sugarcane production system by a range processes including volatilisation, denitrification, leaching, erosion or runoff [172]. Ammonia volatilisation and denitrification are the dominant processes for gaseous losses of fertiliser N from Australian agriculture [38].

Surface application of urea to sugarcane trash can result in significant losses of N fertiliser. Between 30 and 70 % of the applied N can be lost by ammonia volatilisation [41, 102]. The process of ammonia volatilisation is driven by the addition of small amounts of water (dewfall, intermittent rainfall and condensation of evaporated soil moisture) to the trash layer where urea-based products have been surface-applied [41]. Water dissolves the urea and allows the naturally occurring urease enzyme in the sugarcane residues to catalyse the hydrolysis of the dissolved urea to ammonium carbonate [41]. Sugarcane trash has a low capacity to retain ammonium and its high urease activity speeds up the hydrolysis process [57]. Ammonium carbonate is very unstable and, as the water evaporates, ammonia (NH_3^+) gas is released and volatilisation commences [41].

Nitrate ions are highly susceptible to leaching losses [20, 67]. As mentioned earlier, NO_3^- are not well held by clay particles or organic matter and move freely with soil water [67]. Nitrate may be washed beyond the root zone following heavy rainfall (or irrigation). The highest leaching losses are most likely to occur on coarse-textured, free-draining soils (i.e. sandy soils) following heavy rainfall [38, 67].

In addition to existing ammonia volatilisation and leaching loss pathways, the moist warm climate of Australian sugarcane production regions combined with GCTB, waterlogging and the addition of N fertiliser also provides conditions conducive to denitrification [4, 44, 161]. Denitrification involves the conversion of soil NO_3^- to gaseous forms of N [nitric oxide (NO), nitrous oxide (N_2O) or di-nitrogen nitrogen (N_2)] by microorganisms in anaerobic conditions (i.e. waterlogged soils) [43]. This process is driven by the availability of organic residues, NO_3^- and NO_2^- ions, high temperatures, strong acidity and anaerobic conditions [20]. Emission of N_2O is of greatest concern from an environmental viewpoint [161, 162].

In sugarcane, high N_2O emissions can be expected from waterlogged soils with a high organic carbon content, high mineral-N concentration and high temperature [3, 4] and where GCTB is practiced because of greater soil moisture retention and increased microbial activity [165]. It has been estimated that 17 % of applied N fertiliser is lost to the atmosphere [89] with between 1.0 and 6.7 % emitted as N_2O [4]. Nitrous oxide emissions were recently measured under different break and N fertiliser management regimes [162]. After a bare fallow emissions increased from 6.3 kg to 12.3 kg N_2O-N/ha following an increase in plant cane N rates (0–150 kg N/ha), with the highest emission, 20.9 kg N_2O-N/ha, measured after a soybean break crop and the addition of 75 kg N/ha in plant cane. Relatively high N_2O emissions, 21 % of the N fertiliser applied [44], have also been measured from highly organic, acid-sulphate soils in northern NSW [43, 44].

Consequences of Nitrogen Losses Loss of N from the sugarcane production system can have serious environmental consequences. The apparent declining health of the Great Barrier Reef has been attributed to damaging levels of land-based pollutants entering reef waters as a result of agricultural activities, the dominant being beef grazing and sugarcane cultivation, undertaken in adjacent catchments [12, 17, 23, 24, 153]. At a regional scale, the Wet Tropics has been estimated to deliver the highest anthropogenic dissolved inorganic nitrogen (DIN) load to the Great Barrier Reef lagoon [85, 163]. The loss of N fertiliser applied to sugarcane fields contributes a large proportion of the anthropogenic load of DIN in this region [163]. At the local level, catchment water-quality monitoring programs have been undertaken to identify the source and quantity of land-based pollutants entering reef waters. The monitoring of suspended sediments, nutrients and pesticides in waterways of the Tully–Murray catchment in the Wet Tropics region undertaken by Bainbridge et al. [12] is just one example. Although it is difficult to easily isolate pollutant discharge from single land uses within the Tully–Murray catchment, elevated NO_3^- concentrations were measured in waterways draining sugarcane land [12].

The production of N-containing gases by denitrification contributes to atmospheric pollution. Nitrous oxide in particular is a potent greenhouse gas with a global warming potential 298 times higher than that of carbon dioxide [161, 162]. The release of NO and N_2O into the atmosphere can also contribute to the formation of nitric acid, one of the principal components of acid rain [20].

When NO_3^+ is leached from the soil it is often accompanied by basic cations such as Ca, Mg and K [67]. These cations are replaced by hydrogen (H) ions, increasing the acidity of the soil [67]. The nitrification and mineralisation processes are also major causes of soil acidification as the conversion of NH_4^+ to NO_3^- releases hydrogen ions [67, 99]. The form of N fertiliser applied can also influence the rate of acidification. However, fertiliser is applied in relatively small amounts (compared to the volume of soil and the soil's pH buffering capacity) and does not have a direct effect on soil pH [67]. Increased NO_3^- concentrations in groundwater or surface water due to leaching can have toxic effects (causing methemoglobinemia or *blue baby syndrome*) if used as drinking water [20].

The magnitude of N losses and low recoveries of fertiliser N by the sugarcane crop are also of significant economic importance to the sugarcane industry [72]. Investment in N fertiliser represents a relatively large component of farm production costs—approximately 30 % of the average on-farm budget is associated with nutrient inputs [119]. Therefore, loss of applied N from the sugarcane production system may represent a serious economic loss to the grower [6, 38, 173]. The magnitude of economic losses will be influenced by the cost of N fertiliser, sugar price and the effect on cane yield. Substantial losses of applied N may severely reduce the amount of N that is available for crop growth. Insufficient N supply, especially under favourable growing conditions, may restrict sugarcane yield [128], thereby reducing the economic return on N fertiliser investment. Although the immediate consequences of N losses are first experienced by the grower, lower cane yields can also affect the operational efficiency and profitability of other industry sectors (i.e. harvesting contractors).

Strategies to Reduce N Losses and Improve Nitrogen-Use Efficiency Nitrogen management in the Australian sugarcane industry has undergone significant changes since the 1960s with the aim of improving the use efficiency of N fertiliser. Rate of fertiliser experiments conducted by the Bureau of Sugar Experiment Stations (now BSES Limited) resulted in the development of regional yield-response curves for N. This provided a set of generalised N fertiliser recommendations for plant and ratoon crops that would maximise productivity and achieve an economic return [35]. These recommendations are shown in Table 1, and, although they were easy to use, they lacked precision. Little emphasis was placed on the N mineralisation potential of different soil types and there was very little differentiation among regions or soil types [117, 118, 169].

Recently, soil- and site-specific N fertiliser guidelines included in the Australian sugarcane industry's comprehensive SIX EASY STEPS nutrient-management program [33, 116, 118, 119, 121, 125–128, 170] have effectively replaced those generalised N fertiliser recommendations. The SIX EASY STEPS program aims to promote sustainable nutrient management and ensure that sugarcane production remains profitable irrespective of sugar prices. It is also recognised as part of the Australian sugarcane industry's accepted BMP options [126]. Importantly, it has undergone extensive development and rigorous testing in the field, glasshouse and laboratory for more than a decade [114, 120, 122, 138].

In the SIX EASY STEPS program, N fertiliser requirements are calculated by firstly establishing the baseline N requirement for a district yield potential (DYP). The DYP is the estimated highest average annual district yield multiplied by a factor of 1.2 [128]. The N requirement suggested by Keating et al. [80] of 1.4 kg N/t cane/ha up to 100 t cane/ha and 1 kg N/t cane/ha is then used in combination with the DYP to set the baseline N requirement. Once this is done, the organic carbon (%) value from a soil-test result is used to determine the N mineralisation index of the soil (soils differ in their ability to easily mineralise N from organic matter) and refine the baseline N requirement. Final adjustments are made to account for N contributions from other sources, including legume break crops and mill by-products. The N fertiliser guidelines for the Wet Tropics region as determined by the SIX EASY STEPS program are shown in Table 2. There is flexibility to adjust the baseline N requirement upward or downward by 1 kg N/t cane/ha for blocks, farms or sub-districts that consistently produce above or below the DYP. Just as soil tests are considered fundamental to the SIX EASY STEPS process, leaf analysis is also considered to be an important diagnostic tool that may be used for checking on the adequacy of fertiliser inputs [120].

Table 1 Generalised N management recommendations for sugarcane in Australia [29, 35, 169]

Sugar price	N fertiliser rate (kg/ha)			
	Fallow plant		Replant and ratoons	
	Burdekin	Other districts	Burdekin	Other districts
<A$300/t	135	120	210	160
>A$300/t	150	120–150	270	160–200
Dryland and/or richland	80	80	120	120

The N fertiliser requirement for sugarcane grown in South Africa is determined in a somewhat similar method to the SIX EASY STEPS program. Four soil N mineralisation groups [depending on the organic carbon (%) values] are used to determine the N requirement from soil-test results (95, 96]. The N guidelines are based on a series of N response curves that had previously been established for a range of soil types. They incorporate references to bioclimatic regions and moisture regimes (irrigated or rain-fed) as a means of recognising differences in cane production (yield) capabilities. Crop stage (plant or ratoon) and other growth limiting factors such as salinity, pests and soil depth are also used to adjust N recommendations [95, 96].

In contrast to the SIX EASY STEPS philosophy, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has developed a N management system that aims to replace the amount of N removed by the previously harvested crop [147, 148]. This system is referred to as the 'N Replacement' theory. N Replacement uses the yield of the previously harvested crop to set the N requirement for the following crop. The overall objective is to reduce environmental losses of applied N by avoiding over application of N fertiliser when actual yields are lower than the expected yield and relying on soil N reserves to supply additional N requirements when actual yields are higher than the previously harvested crop [150, 152]. Nitrogen fertiliser requirements for each crop are calculated by multiplying the yield of the previous crop with a N requirement of 1 kg N/t cane/ha for GCTB systems and 1.3 kg N/t cane/ha for burnt systems before discounting other N sources [150, 152]. The N requirement is based on an estimate of the N contained in the cane and sugarcane crop residue (i.e. trash) that is removed from the field through harvesting (and burning in burnt harvesting systems), and the amount of applied N fertiliser that is potentially lost to the environment [152]. Within this system, environmental losses of N are assumed to be as low as 10 % for all soils and circumstances [152].

The average application rate of N fertiliser for Queensland sugarcane production (plant and ratoon crops combined) has declined steadily from 206 kg N/ha for the 1997 crop to 164 kg N/ha for the 2008 crop [172]. A grower survey conducted in the Tully and Murray River Catchments of the Wet Tropics region reported that the average rates of N fertiliser for plant and ratoon cane in 2006 were 115 and 146 kg N/ha, respectively [93]. There has been a marked reduction in N application rates in this region since 1996 and a tendency to apply lower N rates since 2000 [130]. In 2006, 65 % of growers surveyed applied <120 kg N/ha to plant crops compared to only 28 % in 1996 [93, 130]. For ratoon crops, 65 % of growers surveyed applied <160 kg N/ha, an increase of more than 27 % of growers since 1996 [93, 130]. Average grower N fertiliser application rates have reduced below the baseline

Table 2 SIX EASY STEPS N fertiliser guidelines for the Wet Tropics region of the Australian sugarcane industry [118, 122]

Crop and fallow management	Organic C (%), N mineralisation index and N application rate (kg/ha)						
	<0.4 Very low	0.41–0.80 Low	0.81–1.20 Mod low	1.21–1.60 Mod	1.61–2.00 Mod high	2.01–2.40 High	>2.40 Very high
Ratoon	160	150	140	130	120	110	100
Replant	160	150	140	130	120	110	100
Plant cane after grass/bare fallow	140	130	120	110	100	90	80
Plant cane after poor green-manure legume crop	90	80	70	60	50	40	30
Plant cane after good green-manure legume crop	0	0	0	0	0	0	0
Plant cane after good legume crop harvested for grain	70	60	50	40	30	20	10

Modifications to N rates are recommended where mill by-products have been used: (1) Mill mud applied at 100–150 wet t/ha: Subtract 80 kg N/ha for plant, 40 kg N/ha for 1st ratoon, 20 kg N/ha for 2nd ratoon. (2) Mud/ash mixture applied at 100–150 wet t/ha: Subtract 50 kg N/ha for plant, 20 kg N/ha for 1st ratoon, 10 kg N/ha for 2nd ratoon. (3) Ash applied at 100–150 wet t/ha: No modification

N application rate of 140 kg N/ha for plant cane and 160 kg N/ha for ratoons (prior to adjustment for the N mineralisation index classes) as specified in the SIX EASY STEPS N guidelines for the Wet Tropics region [118, 122]. The trend to lower grower N application rates has also occurred in the Herbert district [171].

Despite evidence of a voluntary reduction in N application rates, Australian sugarcane growers must now comply with legislation limiting the application of N (and P) fertiliser to optimum amounts [7]. In response to state-wide water-quality monitoring outcomes, the Queensland Government, as indicated previously, introduced the *Great Barrier Reef Protection Amendment Act 2009* to regulate N inputs by sugarcane farmers and graziers in catchment areas adjacent to the Great Barrier Reef lagoon [7]. Specifically, the Act aims to reduce the impact of agricultural activities on the quality of water entering the lagoon and contribute towards achieving water-quality improvement targets for the reef including a minimum 50 % reduction in N loads at the end of catchments by 2013 as agreed by the Queensland State and Commonwealth Governments under The Reef Water Quality Protection Plan (Reef Plan) [105, 174]. The regulated method for determining the optimum amount of N for individual blocks of cane is based on the SIX EASY STEPS N fertiliser guidelines [8, 118].

In addition to following recommended N rates, a number of other factors that can help reduce N losses and improve N uptake are within growers' control. These include the correct placement and timing of N fertiliser inputs. It is recommended that all forms of N fertiliser be applied subsurface regardless of trash-management practices. In particular, surface application (banded or broadcast) of urea-based products to GCTB systems is not recommended as it results in significant loss of N by ammonia volatilisation and reduced cane yields [30, 57, 104].

In plant cane, N fertiliser should be delivered in bands on each side of, and away from, the sugarcane sett when applied at planting and banded in the centre of the cane row before being covered with soil at top dressing [124]. Subsurface application in ratoons can be achieved by either stool splitting with a single coulter to deliver fertiliser into the cane row or by dual coulters beside the cane row to a depth of 70 to 100 mm [31, 124]. Subsurface fertiliser applicators can apply fertiliser mixtures or two fertilisers simultaneously if manufactured as a 'split' fertiliser box [57]. Stool splitting is the most popular application method (three cane rows treated with each pass instead of two), as it is easier and quicker to use than other methods of subsurface application [94].

Where subsurface application of N is not possible (i.e. steep slopes and rocky terrain), strategies to reduce ammonia volatilisation losses include applying urea-based products in bands close to the cane stool and incorporating into the soil with at least 16 mm of overhead irrigation water (or rainfall) or delaying application until there is substantial canopy development (approximately 50 cm high) [30, 56, 57, 103, 168]. A developed canopy helps attenuate the wind speed over the trash surface allowing the leaves to absorb volatilised ammonia. It also contributes to lower trash temperatures that reduces the ammonia vapour pressure, and shifts the site of overnight dew formation from the trash to the leaves, thereby reducing urea hydrolysis [42, 56, 57, 103]. A well-established canopy also means that the newly developing root system is capable of relatively rapid uptake of applied N fertiliser [35]. However, these strategies will not totally eliminate losses from ammonia volatilisation. Losses of greater than 20 % of the N from applied urea have been reported even when surface application of urea is followed by reasonably heavy rainfall [103].

The use of urease inhibitors in combination with best practice surface application of urea-based products may reduce ammonia volatilisation losses where subsurface placement is not possible. Urease inhibitors aim to slow the hydrolysis process, thereby allowing the urea to move into the soil [38, 173]. Ammonia is then retained in the soil and less susceptible to volatilisation [38]. In Australia, several commercially available urease inhibitors are available. One supplier has reported a reduction of loss of ammonia by volatilisation for between 7 and 14 days after application (R. Dwyer 2013, pers. comm. 7 February). Inadequate incorporation of urea through the trash blanket and into the soil (i.e. insufficient rainfall, extended dry conditions, thick trash layer) may reduce the effectiveness of urease inhibitors.

Application timing should coincide with the crop's demand for N [35, 124]. To achieve this, N is often split applied in plant cane by applying a low N concentration fertiliser concurrently at planting and any remaining N requirements as a top-dressing around the first fill-in stage [35, 124]. The best time for ratoon fertiliser application is when the crop is actively growing and is approximately 0.5 m high. At this stage there is a newly developed root system capable of using fertiliser N [35, 124]. This results in more efficient N uptake and allows the crop to act as a nutrient store. Growers are encouraged to avoid applying N fertiliser too early (i.e. straight after harvest when the crop is unable to take up applied N) or too late (i.e. crop may become N deficient or field entry may be restricted) as there is an increased risk of N loss to the surrounding environment [35, 124] and lower cane yield.

Split application of N fertiliser in ratoons has been suggested as a method that may produce tangible environmental benefits by reducing leaching losses [35]. However, as this type of strategy has not resulted in higher cane yields, even in waterlogged soils, the majority of growers continue to apply N in a single application [19, 35]. Research in waterlogged soils found that split application did not improve N uptake or final cane yields and could not be associated with any economic or environmental benefits [84].

To conserve supplies of legume N for use by the following sugarcane plant crop, it is recommended that the crop residue is either left in situ or surfaced mulched, as opposed to incorporation, to reduce the rate of N mineralisation and potential of leaching losses [59, 60].

There has been widespread adoption of management strategies, including subsurface N fertiliser application, to reduce N losses from ammonia volatilisation. However, this has not mitigated N losses from denitrification and leaching [36, 156]. Subsurface application of N fertiliser has been estimated to increase denitrification and/or leaching losses from 21.8 % (following surface application) to 40.1 % of the applied N [104]. To reduce denitrification and leaching losses management practices should aim to remove residual nitrate from the soil profile, maintain fertiliser N in the NH_4^+ form for longer, and lower the NO_3^- concentration in the soil [38, 164]. This may be achieved through the use of nitrification inhibitors or controlled-release fertiliser products in combination with best-practice fertiliser placement and timing [40, 164].

The nitrification process transforms NH_4^+, a relatively immobile form of N, into NO_3^- [15]. The first stage of the nitrification process, bacterial oxidation of NH_4^+ to NO_2^- by *Nitrosomonas* bacteria, is closely followed by the second stage, conversion of NO_2^- to NO_3^- by *Nitrobacter* bacteria [176]. Nitrification inhibitors have been specifically developed to delay only the first stage of nitrification by depressing the activities of *Nitrosomonas* bacteria in the soil [15, 176]. This keeps N in the immobile form for longer, thereby reducing N susceptibility to leaching and denitrification losses [15, 38, 173, 176].

In the past, nitrification products have been too expensive for large-scale agricultural use [35, 176]. A relatively new nitrification inhibitor, dimethylpyrazol phosphate (DMPP), commercially referred to as ENTEC®, has recently been evaluated in two Australian sugarcane-growing regions on soils with the potential for high denitrification or leaching losses [161, 162]. Although ineffective in reducing N_2O emissions in field plots at Murwillumbah and Mackay, emissions in fertilised chambers were significantly reduced at Murwillumbah [161]. At another trial in Mackay, the addition of DMPP to urea resulted in significantly lower N_2O emissions compared to using normal urea [162].

Controlled-release fertiliser product technology may also contribute to lower N losses, improved N-use efficiency and higher cane yields [131]. These products include poly-coated urea and sulphur-coated urea, which can be formulated to have different N release rates [67]. Previous research into the use of controlled-release fertilisers in Australian sugarcane crops has not been successful [35]. Poly-coated slow-release urea was not successful in reducing N_2O emissions from a trial site in Mackay, Queensland [161]. However, recent trials have demonstrated that compared to using normal urea, polymer-coated slow-release urea reduced N_2O emission from an acid-sulphate soil in NSW by 30 % [161].

Further research is required under different climatic and soil conditions to substantiate the effectiveness of DMPP on reducing N_2O emissions from Australian sugarcane fields [162]. In addition, it appears that the success of slow-release N fertiliser products is affected by the solubility of the product, climate, N uptake by the crop and the soil's capacity to retain the mineral N from leaching [161]. Incorporation of nitrification inhibitors and controlled-release fertiliser products into the sugarcane production system will ultimately be determined by their robustness to reduce N losses in a range of soil types and varying climatic conditions, and economics [38]. Price and commercial availability are likely to have the greatest influence on the use of these products in sugarcane [35, 38].

Another potential avenue for reducing N losses is the selection of N efficient sugarcane genotypes. Nitrogen-use efficiency (NUE) in plants is complex and refers to the combined efficiencies of internal N use by the plant and N uptake from the soil (and N fertiliser) [108, 109]. Australian sugarcane varieties have not been selected for NUE. However, there is evidence that some of the Australian sugarcane germplasm used for breeding purposes contains considerable genotypic variation for internal NUE (iNUE), i.e. the ability to produce biomass per unit N in plant tissue [108]. This suggests there is potential to breed new sugarcane varieties with higher iNUE that could result in the production of significantly more biomass under low N supply [108]. Although sugarcane varieties with improved iNUE are not currently available, future N management strategies may involve planting high iNUE varieties in fields susceptible to denitrification and leaching.

It is apparent that N management in Australia focuses on N application rate (i.e. SIX EASY STEPS and N Replacement), fertiliser placement (subsurface) and application timing (matched to crop demand) to improve N uptake by the crop and lower N losses. The benefit of using alternative N forms (nitrification inhibitors and controlled-release products) is still to be validated over a range of climate and soil conditions, but early indications are that they have potential to contribute towards improved N uptake and lower N losses [161, 162] in the short-term future. A longer-term prospect may be the use of sugarcane varieties with higher iNUE [108]. Although N application rates have been reduced (both voluntarily and legislatively) in an attempt to reduce N losses by better matching fertiliser inputs to crop requirements, current N calculation methods are limited in their ability to match N fertiliser inputs to forthcoming crop requirements.

The SIX EASY STEPS program uses predetermined DYP values in the determination of N fertiliser recommendations as it assumes that the forthcoming season will be characterised by conditions conducive to producing the yield potential for the district [128]. Despite the ability to adjust these values for specific circumstances when blocks and sub-districts continually underperform, the use of DYP still nonetheless limits the ability to adapt to annual yield fluctuations caused by climatic variability. In contrast, N Replacement focuses on previous crop yields rather than the yield potential for the next season, assumes environmental losses of N are low and does not consider the N mineralisation potential of specific soils [152]. Refinement of the N Replacement theory may be required to account for higher environmental losses of N or become more site-specific in the calculation of environmental loss values [152]. Different N requirement factors are also used to calculate N fertiliser application rates for each system [127]. The suitability of these factors for sugarcane grown in the Wet Tropics is uncertain and requires further investigation. Other concerns include potential for greater environmental losses of N when actual yields do not reach the DYP as used in the SIX EASY STEPS program [144, 152] and the possibility that the N Replacement strategy may restrict productivity when favourable growing conditions are experienced and cane yield exceeds the yield of the previously harvested crop [125].

It is common BMP for nutrients, including N, to be aligned with potential or target yields [144]. Both the SIX EASY STEPS and South African soil-specific N strategies consider potential yield in calculations of N fertiliser requirements. Although the use of a predetermined DYP is most evident in the SIX EASY STEPS strategy, incorporation of different bioclimatic regions and moisture regimes in the South African system acknowledges differences in cane production (yield) potentials throughout the industry [95, 96].

To better align N fertiliser inputs with crop requirements, more accurate yield estimates need to be produced and used to calculate requirements for N fertiliser on an annual basis, instead of using a predetermined yield potential. The difficulty of predicting weather conditions for the upcoming growing season has been identified as a limitation to the formulation of N fertiliser input strategies on an annual basis in the SIX EASY STEPS program [128]. Forecasts of the climatic conditions likely to be experienced during the sugarcane-growing season (i.e. spring and summer) may help improve yield estimates used in the generation of N fertiliser guidelines [128]. Climate forecasts may also improve decisions related to N fertiliser application timing, frequency (single vs. split) and the potential to use alternative N forms (i.e. nitrification inhibitors and controlled-release products) to improve N uptake and reduce N losses. Over-fertilisation and environmental losses of N may be reduced by combining these practices into an overall N management strategy which has the flexibility to adapt to changes in climatic conditions. However, the possibility of using seasonal climate forecasts to guide N management strategies in sugarcane is uncertain.

Climate and Sugarcane Production

Climatic conditions experienced during the sugarcane-growing season have a profound influence on cane and sugar yields and is largely responsible for regional and seasonal productivity fluctuations [18, 46, 49, 97, 113]. The ideal growing environment for sugarcane is where rainfall (or irrigation) is well distributed throughout the summer growing season, sunshine is plentiful and there is a relatively dry and cool pre-harvest ripening period [78]. In Australia prolonged heavy rainfall during the 2010 harvest season resulted in wet weather harvesting damage, 5.5 Mt of cane being left to standover [83] and unfavourable growing conditions that restricted crop growth and contributed to the extremely poor yields recorded across most districts in 2011. Further losses were suffered in the northern district following the crossing of Tropical Cyclone Yasi over Tully in February 2011. The Tully mill area average cane yield of 47 t cane/ha for the 2011 season was the lowest since 1948 and greatly below the 10-year average of 84 t cane/ha [9]. Annual productivity variations caused by extreme weather events have implications for all sectors of the sugar-industry value chain.

Climate variability also has an indirect impact on industry profitability as it influences planting and harvesting strategies, nutrient, pesticide and irrigation management, season operating times, mill maintenance programs, marketing strategies, sugar transport and storage arrangements [10, 47, 48, 97]. Sugarcane yield estimates before the commencement of the harvest season are required for milling and marketing purposes. The difference between initial estimates and actual sugarcane yields in the Australian sugarcane industry has reported to range from an over estimate of 25 % to an underestimate of 22 % [49]. With the exception of pest or disease outbreak, these large differences can be attributed to swings in climatic conditions. Knowledge of the different climate systems influencing rainfall patterns over sugarcane production areas and the ability to use their signals for forecasting seasonal climatic conditions can help improve management decisions across all sectors of the sugarcane industry value chain.

The El Niño Southern Oscillation (ENSO) is one of the largest sources of inter-annual climate variability over most of the Pacific region including sugarcane production areas in Africa, India, central America and Australia [1, 2, 101]. The oceanic component of ENSO has two extreme but closely linked phases: El Niño and La Niña [2]. El Niño refers to the unusual warming of normally cool water in the central and eastern equatorial Pacific, resulting in widespread rainfall over much of the equatorial Pacific, parts of the Indian Ocean and eastern equatorial Africa, while many areas of western Pacific, Australia, South-East Asia, northern India, southeastern and Sahelian Africa and northeastern South America experience drier conditions than normal and possibly drought [1, 2, 28, 101, 154]. Conversely, La Niña refers to increased warming of water in the western Pacific Ocean and extensive cooling of water in the central and eastern Pacific Ocean. Rainfall and storm activity increases over Australia, South-East Asia, northern India, southeastern and Sahelian Africa and northeastern South America and reduces over the central and southern region of South America [1, 2, 101]. Tropical cyclones also tend to be more frequent over the western Pacific during La Niña events [101]. Once established ENSO events usually last for around 12 months; however, they can be shorter or much longer.

The Southern Oscillation represents the atmospheric component of ENSO. Changes in the strength and phase of the Southern Oscillation are measured by the Southern Oscillation Index (SOI) [87, 91, 101]. The most commonly used Troup SOI measures the monthly differences in mean sea-level air pressure between Tahiti (in the central Pacific) and Darwin (Australia), and ranges from around -35 to $+35$ [86, 91, 101]. Negative (positive) values of the SOI are typically associated with the El Niño (La Niña) phase.

Extreme ENSO events have a significant impact on sugarcane productivity and harvest management in the Australian sugarcane industry [87]. The SOI and sea surface temperatures (SSTs) for selected regions within the Pacific Ocean have been identified as useful predictors of seasonal rainfall in northeastern Australia where the majority of sugarcane is grown [28, 91, 112]. The SOI alone can be used to forecast sugarcane yields for specific mill and terminal areas, especially in north Queensland [86, 87]. The chance of above-average cane yields is higher than climatology for mills in the Wet Tropics region, such as Mulgrave and Tully when the October–November SOI remains deeply negative [49]. This is because deeply negative SOI values during October–November favour lower summer rainfall, which in these wetter districts generally has a positive impact on cane growth owing to increased solar radiation [49]. Similarly, for other sugarcane regions in north Queensland, a deeply negative (deeply positive) SOI value at the end of November suggests it is highly likely that cane yields will be above (below) average for the next harvest season [47].

Seasonal climate forecasting has been used in the Australian sugarcane industry to help manage the impact of climate variability on growing, harvesting, milling and marketing operations [46, 47, 49, 50]. Millers and marketers can use seasonal climate forecasts to improve yield estimates so they can make more informed management decisions related to crop size. Knowledge of crop size allows marketers to refine selling and storage strategies and hopefully increase industry profitability, whereas the miller is better able to plan activities related to mill maintenance programs and harvest logistics [10, 47, 48, 50, 53]. For growers, climate forecasts covering the harvest season can be used to develop harvest plans for a ‘wet’ (or ‘dry’) harvest to minimise wet weather disruptions and damage to fields and hopefully avoid standover [10, 47, 48, 53]. Climate forecasts can also be used to improve irrigation scheduling, especially when water supplies are scarce [48, 52].

The South African and Swaziland sugarcane industries have also identified the potential for seasonal climate-forecasting information to improve management decisions in the growing, milling and marketing sectors. In South Africa, sugarcane yields tend to be lower in years when the monthly SOI values for October to November remain deeply negative, as there is a higher probability of low summer rainfall [132, 133]. Observed weather data is combined with historical climate sequences representative of likely future climatic conditions or mid- to long-range climate forecasts and entered into computer crop models such as CANEGRO [75, 134] or CANESIM (formerly called IRRICANE) [135] to forecast seasonal sugarcane yields [18, 92, 115, 136]. Seasonal sugarcane yield forecasts can be used to assist irrigation management, harvest scheduling, crop husbandry decisions, planning mill-season length, haulage scheduling and mill maintenance and marketing, pricing and storage strategies in South Africa [115, 136]. In Swaziland, improved estimation of forthcoming crop yields was identified as having the potential to assist growers estimate transport requirements, ripening strategies and harvest schedules and millers’ estimates of season length and harvest commencement, and plan maintenance programs [92].

It is evident that seasonal climate forecasts can be used to improve decision-making capabilities across different sectors of the sugarcane value chain. Regrettably, there is little evidence at the grower level of seasonal climate forecasts being used to guide N management strategies. If seasonal climate forecasts can be used to guide other crop-management decisions such as harvesting and irrigation scheduling, why can’t they be used in the development of strategies to help minimise N losses and improve the economic return from N fertiliser investment?

Seasonal Climate Forecasting for Improved Nitrogen Management There is no doubt that climate has a profound influence on cane growth and final yields and is largely responsible for regional and seasonal productivity fluctuations. In north Queensland sugarcane-growing districts, higher (lower) than average rainfall during spring and summer is often linked to lower (higher) cane yields [128]. The SOI can be used to forecast the occurrence of 'wetter' and 'drier' than average rainfall conditions and hence lower or higher cane yields (refer to "Climate and Sugarcane Production"). As climate influences crop growth, N demand and N loss processes, predictions of climatic conditions during the sugarcane-growing season (i.e. spring and summer) could be used to refine N management strategies.

It is reasonable to hypothesise that different N management strategies will need to be developed for 'wet' and 'dry' years. In developing N management strategies, seasonal climate forecasts might be used to guide changes to N application rates, timing and/or frequency of N inputs, and the benefit of using alternative forms of N fertiliser (i.e. nitrification inhibitors and controlled-release products). For example, in the Wet Tropics region the N management strategy in a 'wet' year may consist of lower application rates of N and the use of a nitrification inhibitor or controlled-release fertiliser. To obtain the greatest benefit, existing management practices, such as subsurface placement, which aim to reduce the potential for environmental losses of N, will need to be incorporated into the devised management strategy. Seasonal climate forecasts may also allow the most appropriate N management strategy to be identified before N fertiliser is applied. The important question, "can we achieve superior environmental and economic outcomes by integrating seasonal climate forecasts into the development of sugarcane N management strategies?" will need to be answered.

Sugarcane growers in the Tully district of the Wet Tropics region identified the potential of using seasonal climate forecasting to assist fertiliser, harvesting, planting and herbicide management decisions [77]. In particular, these growers wanted to investigate the possibility of improving N fertiliser management to reduce environmental losses whilst maintaining or improving productivity [51, 153]. Varying N fertiliser rates, split applications and the use of seasonal climate forecasts to guide application timing were identified as potential strategies [153]. Researchers worked with the growers to assess these management strategies using the Agricultural Production Systems sIMulator (APSIM) sugarcane cropping systems model [81] and seasonal rainfall forecasts based on the SOI phase system [142]. Split application of N fertiliser every year was simulated to be the most sustainable strategy, but the response varied with soil type (best response on coarse-textured soils). However, growers believed the environmental and economic benefits weren't large enough to routinely implement this practice [153]. The predicted economic benefit was a 5 % median increase in partial gross margin over the long-term [51]. This small increase is unlikely to convince growers to adopt this strategy for the inconvenience associated with splitting fertiliser applications, especially at a time when many other crop-management practices also require completion (i.e. weed control, hilling up plant cane, applying pest control). The study also identified that the positive effects of split applications were greatest in years receiving above-average rainfall. This is likely to be due to higher cane yields and lower N losses being modelled following split application of N fertiliser every year [153].

The impact of splitting N applications based on the SOI phase at the time of fertiliser application (i.e. split if SOI phase consistently positive at time x) was also investigated but predicted to have a lower economic and environmental benefit than splitting in all years [51]. This is because there were years when the SOI phase did not correlate with the amount of rainfall received. Here, the management strategy suited the forecasted rainfall, not the observed rainfall.

In using seasonal climate forecasts to guide the development of N management strategies it is important to be aware of the limitations. Seasonal climate forecasts provide probabilistic information about future climatic conditions and are unable to precisely predict future climatic conditions. A mismatch between the N management strategy and actual climatic conditions may restrict crop growth and reduce profitability in years predicted to experience above-average rainfall that actually receive below-average rainfall (i.e. in the Wet Tropics region). As there will always be uncertainty regarding the accuracy of the climate forecast, it would be advantageous to incorporate different levels of risk exposure into N management strategies. This would allow individual growers to select the level of risk exposure with which they are most comfortable.

The use of seasonal climate forecasting to improve N management strategies in agriculture is not a new concept with many cropping systems already looking beyond yield-forecasting capabilities. In Australia, SOI phase-based seasonal climate forecasts [142, 143] are used in conjunction with crop growth models to improve N management decisions in wheat-cropping systems. Although the responsiveness of N management strategies to ENSO-based climate forecasts appears to be inconsistent, the majority of research indicates that SOI phase-based N management is beneficial in wheat-cropping systems [11, 69, 160, 175]. As early as 1996, adjusting N fertiliser rates based on the SOI phase system [142, 143] was simulated to increase profits by up to 20 % in the Queensland wheat-belt [69]. Since then, research has been directed towards better understanding the potential for seasonal climate forecasting to improve N management at different Australian wheat-growing locations.

In southeast Australia, changing application rates for N fertiliser based on SOI phases was predicted to increase wheat gross margins by 8, 13 and 20 % when the April–May SOI phase was negative/falling, zero, and positive/rising, respectively, compared to current N management practices for the region of a fixed application of 100 kg N/ha [160]. In addition, SOI phase-based N management was also compared to using the long-term average optimal N rate (a fixed application of 150 kg N/ha) derived from long-term climate records for the region [160]. While SOI phase-based N management was still beneficial, the value was much smaller with gross margins predicted to increase by 3, 0 and 1 % when the April–May SOI phase was negative/falling, zero and positive/rising, respectively [160]. Although these financial increases are relatively small, the fact that sugarcane is produced in areas vulnerable to extreme climatic variability and sold in a volatile market, any improvement in gross margins will be beneficial.

The value of a 'perfect' climate forecast for N management purposes in a wheat-cropping system in southeast Australia has also been simulated for two locations with contrasting rainfall. Compared with the long-term average optimal N rate derived from long-term climate records, adjusting N application rates based on a 'perfect' climate forecast was estimated to generate an average benefit of $65.2/ha and $66.5/ha for the high and low rainfall areas, respectively [175].

More recently different approaches to N fertiliser management in the Western Australian wheat-belt have been investigated using the Predictive Ocean Atmosphere Model for Australia (POAMA) [11]. The POAMA seasonal rainfall-forecasting system could improve gross margins by $50/ha when used for N management decisions in the southern region of Western Australia's wheat-belt [11].

Compared to wheat, the sugarcane industry has spent very little effort investigating the potential for SOI phase-based N management, even though there is relatively high forecasting skill in areas where the majority of sugarcane is grown [28, 49, 87, 91, 112]. Results from the grains industry indicate that there is potential for seasonal climate forecasts to improve N management in Australian sugarcane. Historical climate knowledge is an important tool that can be used to improve our understanding of crop performance and N management strategies under different climate scenarios, and should not be ignored in future attemps to improve N management in sugarcane [160, 175].

Despite considerable research efforts into seasonal climate forecasting for improved N management in grain production, a survey conducted in northern New South Wales revealed that the majority of growers favoured simplistic approaches to varying N fertiliser rates (i.e. block history, recent yields, protein levels and length of fallow) [71]. Soil testing, monitoring stored soil water and using seasonal climate forecasts to guide N management was considered too complex [71]. In addition, it was found that seasonal climate forecasting based on the SOI was seldom used when making decisions about N fertiliser management. However, Australian sugarcane growers are already using a combination of simple and complex approaches to determine the nutritional requirement of each crop [118, 122]. If seasonal climate forecasting can be used in a way that removes the perceived inconvenience of split applying N, it is likely to gain acceptance and hopefully result in greater on-ground adoption than experienced elsewhere.

Although simulated SOI phase-based N management outcomes in wheat-cropping systems have not always been validated under commercial field conditions, APSIM has undergone extensive development and scientific testing for various Australian wheat-growing locations so that it can be used to evaluate proposed changes to N management [81]. APSIM has also been used to investigate various issues related to N management in sugarcane [107, 141, 145, 146, 149, 151, 159]. To gain recognition as part of the sugarcane industry's accepted BMP options, N management strategies based on seasonal climate forecasts will have to be evaluated thoroughly. This will include rigorous field testing to ensure that simulation-based benefits from crop models such as APSIM are realistically achievable for commercial sugarcane-farming enterprises.

Conclusions

Losses of nutrients, sediment and pesticides from agricultural production systems, including sugarcane cultivation, have been linked to water-quality decline and the subsequent degradation of coastal marine ecosystems [22, 23, 163]. Increased emphasis on minimising environmental degradation is likely to place further restrictions on sugarcane production practices into the future and this may reduce profitability. To help ensure that water-quality targets are met and the introduction of more stringent regulations avoided, further research is required to better understand the impact of natural climate variability on sugarcane N-use efficiency. The development of N management strategies that optimise profit and minimise environmental losses for different climatic conditions will be a major challenge.

In Australia, just over 60 % of the N fertiliser applied is recovered in the sugarcane crop and surrounding soil [36, 104, 156]. Unrecovered N is either stored in the soil or presumed to be lost from the sugarcane production system, primarily through denitrification and leaching processes as management strategies have been adopted to reduce ammonia volatilisation losses [30, 56, 57, 103, 104, 168]. N loss processes are influenced by soil type, position in the landscape, rainfall amount and intensity, fertiliser form, placement, application timing and rate [172]. Sugarcane growers can improve N uptake and reduce the potential for N losses by applying N fertilisers at recommended rates in the correct location and at the right time. The SIX EASY STEPS nutrient-management program incorporates soil type and position in the landscape into the formulation of soil- and site-specific N management guidelines [118, 122]. Although climatic conditions such as rainfall amount and intensity cannot be controlled, options are available to help reduce the impact on N losses.

Seasonal climate forecasts are being used to improve decision-making capabilities across different sectors of the Australian sugarcane value chain. At the grower level, it is surprising that seasonal climate forecasts are not being used to guide N management strategies domestically or internationally. Seasonal climate forecasts provide probabilistic information about future climatic conditions. As climate is a key driver of crop growth, N demand and N loss processes, prediction of climatic conditions during the sugarcane-growing season (i.e. spring and summer) could be used to refine N management strategies. It is highly likely that N management strategies will need to be different for ‘wet’ and ‘dry’ years. Information generated from the seasonal climate forecast could be used to formulate the most appropriate N management strategy.

Seasonal climate forecasts could be used to guide application timing and/or frequency of N inputs and the benefit of using alternative forms of N fertiliser (i.e. nitrification inhibitors and controlled-release products). The current methods that can be used to calculate requirements for N fertiliser in the Australian sugarcane industry are limited in their ability to match N fertiliser inputs to forthcoming crop yields. The SIX EASY STEPS program uses predetermined yield potentials to determine N fertiliser requirements, whereas N Replacement uses the yield of the previously harvested crop. As it is common to align N application rates with potential or target yields, seasonal climate forecasts could be used to improve yield estimates used in the calculation of N fertiliser requirements in the SIX EASY STEPS program [128].

The use of seasonal climate forecasts may allow more environmentally sensitive, yet profitable, N management strategies to be developed for the Australian sugarcane industry. The Wet Tropics sugarcane production area provides an ideal case study environment to test this hypothesis, given the skill in climate-forecasting capabilities for this region, the potential for high N losses, and the proximity of the district to sensitive ecosystems.

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