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3 Name of nominee: Danielle Skocaj

4 Nominee affiliation: James Cook University and BSES Limited

5 Nominee email address: ds kocaj@bses.com.au

6 Name of supervisor: Dr Yvette Everingham

7 Supervisor affiliation: James Cook University

8 Supervisor email address: yvette.everingham@jcu.edu.au

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1 **Nitrogen Management Guidelines for Sugarcane Production in**
2 **Australia—Can These Be Modified for Wet Tropical Conditions**
3 **Using Seasonal Climate Forecasting?**

4 **Danielle M Skocaj**^{1,*}, **Yvette L Everingham**² and **Bernard L Schroeder**³

5 ¹ BSES Limited and James Cook University, PO Box 566 Tully, QLD, 4854, Australia; E-Mail:

6 dskokaj@bses.com.au

7 ² James Cook University, Townsville, QLD 4811, Australia

8 ³ BSES Limited, PO Box 86 Indooroopilly, QLD 4854, Australia

9 * Author to whom correspondence should be addressed; E-Mail: dskokaj@bses.com.au

10 Tel.: +61-7 4088 0703; Fax: +61-7 4068 1907.

11

12 **Abstract:** Sugarcane is a highly valuable crop grown in tropical and subtropical climates
13 worldwide primarily for the production of sucrose-based products. The Australian
14 sugarcane industry is located in close proximity to sensitive environments and the apparent
15 declining health of the Great Barrier Reef has been linked to damaging levels of land-based
16 pollutants entering reef waters as a result of sugarcane cultivation undertaken in adjacent
17 catchments. Unprecedented environmental scrutiny of N-fertiliser application rates is
18 necessitating improved N-fertiliser management strategies in sugarcane. Over time the focus
19 of N-fertiliser management has shifted from maximising production to optimizing
20 profitability and most recently to improved environmental sustainability. However, current
21 N calculations are limited in their ability to match N-fertiliser inputs to forthcoming crop
22 requirements. Seasonal climate forecasts are being used to improve decision-making
23 capabilities across different sectors of the sugarcane value chain. Climate is a key driver of

1 crop growth, N-demand and N-loss processes, but climate forecasts are not being used to
2 guide N management strategies. Seasonal climate forecasts could be used to develop N-
3 management strategies for 'wet' and 'dry' years by guiding application rate, timing and/or
4 frequency of N inputs and the benefit of using alternative forms of N fertiliser. The use of
5 seasonal climate forecasts may allow more environmentally sensitive yet profitable N-
6 management strategies to be developed for the Australian sugarcane industry.

7 **Keywords:** sugarcane; Australia; nitrogen; seasonal climate forecasting; environment
8

9 1. Introduction

10 Sugarcane, one of the longest cultivated plants in the world, is a highly valuable crop grown in
11 tropical and subtropical climates worldwide. Grown primarily for the production of sucrose-based
12 products, sugarcane can also be used to produce a diverse range of alternative products and offers a
13 renewable alternative to petrochemical resources (Brumbley et al. 2008; Brumbley et al. 2007). This
14 versatility provides a strong economic outlook for the future of the sugarcane industry as the world's
15 population continues to increase and the demand for food and renewable energy sources intensifies.

16 The location of sugarcane production areas in close proximity to sensitive environments
17 necessitates the development and adoption of sustainable production practices. The Australian
18 sugarcane production system has evolved to include a suite of best management practices focused on
19 maintaining productivity, improving profitability and minimising the movement of sediment, nutrients
20 and pesticides off farm (Schroeder et al. 2008; Christiansen 2000; Hurney et al. 2008; Schroeder et al.
21 2009a; Smith 2008). Although these practices have been largely successful in achieving the desired
22 outcomes, loss of nitrogen (N) from sugarcane production remains a serious impairment to improved
23 environmental sustainability and profitability (Calcino et al. 2010; Macdonald et al. 2009; Denmead et

1 al. 2010; Wang et al. 2012; Prasertsak et al. 2002; Vallis and Keating 1994; Thorburn et al. 2011b;
2 Schroeder et al. 2010a).

3 Although sugarcane requires large inputs of N for successful crop growth (van der Laan et al.
4 2011), it is relatively inefficient in the recovery of N fertiliser (Vallis and Keating 1994). Recovery
5 studies of applied N fertiliser in the crop and surrounding soil in Australia indicate maximum
6 recoveries are just over 60% of N applied (Chapman et al. 1991; Vallis and Keating 1994; Prasertsak
7 et al. 2002). The unrecovered N is either held in the soil by microbial immobilization (Jansson and
8 Persson 1982) and/or lost from the sugarcane production system (Wood et al. 2010a). Strategies have
9 been developed to reduce N losses from ammonia volatilisation but they have not reduced
10 denitrification and leaching losses (Chapman et al. 1991; Vallis and Keating 1994). In extreme
11 situations, denitrification can result in 25% of the applied N fertiliser being lost to the atmosphere
12 (Denmead et al. 2010). The magnitude of N losses and low recoveries of fertiliser N by the sugarcane
13 crop are of significant economic and environmental importance (Thorburn et al. 2011c; Bainbridge et
14 al. 2009; Benn et al. 2010; Brodie et al. 2001; Brodie et al. 2010).

15 The focus of N-fertiliser management in the Australian sugarcane industry has recently shifted from
16 production maximization to profit optimization and most recently improved environmental
17 sustainability (Wood et al. 1997; Wood et al. 2003; Schroeder et al. 1998; Thorburn et al. 2011b).
18 Two N management calculation systems developed in the Australian sugarcane industry are SIX
19 EASY STEPS and N Replacement. The SIX EASY STEPS nutrient-management program aims to
20 deliver soil- and site-specific N-fertiliser guidelines for sustainable sugarcane production (Schroeder et
21 al. 2007a; Schroeder et al. 2009b; Schroeder et al. 2005a; Schroeder and Wood 2001; Schroeder et al.
22 2010b; Wood et al. 2003; Schroeder et al. 2009c; Calcino et al. 2010; Schroeder et al. 2010a;
23 Schroeder et al. 2005b; Schroeder et al. 2006). The N Replacement system aims to replace the amount
24 of N removed by the previously harvested crop (Thorburn et al. 2003; Thorburn et al. 2004a).
25 However, both systems are limited in their ability to alter N management strategies to cater for changes

1 in climatic conditions experienced during the current growing season or those predicted for the
2 forthcoming season.

3 The use of seasonal climate forecasting in agricultural production systems is increasing as
4 stakeholders aim to improve decision-making capabilities that are impacted by climate (Sivakumar
5 2006; Hammer et al. 2001). Seasonal climate forecasts are being used to improve decision-making
6 capabilities in the growing, harvesting, milling and marketing sectors of the Australian sugarcane
7 industry (Everingham et al. 2003; Everingham et al. 2001; Everingham et al. 2002a; Everingham et al.
8 2005). Potential exists to increase the application of climate-forecasting information into other areas
9 of the Australian production system to reduce the impact of climate variability on economic losses and
10 environmental degradation.

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

14

15 **2. Literature Review**

16 *2.1. The Sugarcane Plant*

17 Sugarcane is a perennial tropical grass belonging to the Gramineae, genus *Saccharum* (Van
18 Dillewijn 1952; James 2004; Bakker 1999). There are two wild and four domesticated species of
19 *Saccharum*. The wild species are *Saccharum spontaneum* L., which is found throughout tropical
20 Africa, Asia and Oceania, and *Saccharum robustum* Brandes & Jeswiet ex Grassl, which is restricted
21 to Papua New Guinea and neighboring islands. The four domesticated species; *Saccharum*
22 *officinarum* L., *Saccharum edule* Hassk., *Saccharum barberi* Jeswiet and *Saccharum sinense* Roxb.
23 have a higher sucrose content and lower fibre content than the wild species (Bakker 1999; Bull 2000).
24 All current commercial sugarcane cultivars are complex hybrids of two or more species of *Saccharum*
25 (Bull 2000). Unlike other grass crops, which store starch in seed heads, sugarcane has evolved to store

1 sugar in its stalk. The elongation and expansion of the sugarcane stalk provides an ideal area to store
2 sucrose (Van Dillewijn 1952).

3 Commercially, sugarcane is asexually propagated by planting stalk cuttings known as setts or
4 billets. This produces a new sugarcane crop with the same characteristics as the crop from which the
5 cuttings were taken. The setts contain at least one bud, along with all the nutrients and water required
6 for the bud to germinate. On germination, a primary shoot is produced from the bud. In a process
7 known as tillering, the buds on the primary shoot then develop secondary shoots, which in turn may
8 produce tertiary shoots and so on. The primary shoot and tillers grow to produce a 'stool' that consists
9 of stalks of varying weight, height and diameter. The aboveground biomass of the plant crop is
10 harvested around 12-18 months after planting (Wood 1991; Pankhurst et al. 2003). The buds and root
11 primordia of the underground stool that remain after harvest develop to produce a further crop known
12 as a ratoon crop. Ratoon crops are normally harvested at around 12 months of age, but the growth
13 period can be as long as 22-24 months depending on the climatic conditions (mainly temperature and
14 solar radiation) and soil moisture experienced during the growing season (Ellis and Merry 2004). In
15 some circumstances, ratoon crops are 'stood over' to the following harvest. This usually occurs when
16 weather conditions prevent crops of sugarcane being harvested. Successive ratoon crops continue to
17 be produced until the field needs to be replanted due to declining yields. Over time, the soil loses its
18 structure and becomes compacted due to in-field operations (especially harvesting and haul-out of the
19 crop). Damage from pests and diseases increases, soil salinity and sodicity problems are exacerbated,
20 and the stool is damaged by harvesting equipment (Ellis and Merry 2004). Consequently, plant
21 populations decline and productivity reduces to a level where it is uneconomical to continue the crop
22 cycle and replanting is required.

23

24 2.2. *Sugarcane Products and Uses*

25 Sugarcane is the fastest growing, largest biomass and highest sucrose-accumulating agricultural
26 crop in the world. It is primarily grown for the production of sugar-based products, ranging from raw

1 to refined white sugar and specialty products. With these products meeting the dietary requirements of
2 both high and low income consumers around the world, sugarcane is the largest contributor of dietary
3 carbohydrate for human consumption after cereal crops (Brumbley et al. 2008). There is also a small
4 but profitable specialty market for organically produced sugar, most of which is grown and processed
5 in Florida in compliance with strict field and factory protocols (Irvine 2004).

6 Processing sugarcane into raw sugar also produces by-products (bagasse, molasses, filter mud and
7 ash) that have many different uses. Bagasse, the fibrous residue of the sugarcane plant that remains
8 after sugar extraction, can be used to manufacture paper, animal feed and bioenergy (Brumbley et al.
9 2008; Barnes 1974). It is often used in energy cogeneration for sugar milling operations, with surplus
10 energy fed back into local electricity grids (Brumbley et al. 2008; Goldemberg et al. 2008; Alonso-
11 Pippo et al. 2008; Mackintosh 2000).

12 Molasses is the thick, dark, uncrystallized syrup that remains after most of the sucrose has been
13 extracted from the cane juice in the production of raw sugar (Mackintosh 2000). It is used in the
14 production of syrups, animal supplements, ethanol for blending with gasoline or diesel, and distillation
15 of alcoholic beverages (Brumbley et al. 2008; Mackintosh 2000).

16 Filter mud (also known as filter press / cake, or mill mud), ash, molasses and vinasse (a by-product
17 of ethanol production, referred to as dunder in Australia) are also valuable sources of mineral nutrients
18 and organic matter (Calcino 1994; Calcino et al. 2000; Mackintosh 2000). The nutrient composition of
19 these products varies. Generally, filter mud contains significant amounts of calcium (Ca), phosphorus
20 (P) and N, whereas ash contains significant amounts of potassium (K), Ca, magnesium (Mg) and
21 silicon (Si) and molasses and vinasse are high in K (Calcino 1994; Calcino et al. 2000). These
22 products often need to be used in combination with inorganic fertilisers to meet the nutritional
23 requirements of the crop as not all of the nutrients they contain are available immediately for plant
24 uptake (Calcino 1994; Mackintosh 2000; Calcino et al. 2000; Barnes 1974).

25 Sugarcane can also be used to produce biofuels, bioenergy and biopolymers (Brumbley et al. 2008;
26 Brumbley et al. 2007). Biorefineries constructed in Brazil to produce ethanol and bioplastics highlight

1 the potential of sugarcane to offer a renewable and environmentally friendly alternative to
2 petrochemical resources (Brumbley et al. 2008; Ferreira-Leitao et al. 2010; Brumbley et al. 2007).
3 Similarly transgenic approaches to genetic and metabolic engineering have resulted in the production
4 of new high-value products, allowing sugarcane to be used as a biofactory for the production of
5 alternative sugars, bioplastics, high-value proteins and fine chemicals including nutraceuticals,
6 industrial enzymes and pharmaceuticals (Brumbley et al. 2008; Irvine 2004; Brumbley et al. 2007).

7 It is apparent that the sugarcane plant has a diverse range of uses and there is strong potential for
8 market diversification. In the future, it is highly likely that sugarcane will be grown to produce sucrose
9 for human consumption and biomass for the manufacture of fuel, energy and alternative products
10 (Brumbley et al. 2008).

11

12 *2.3. International Sugarcane Industry*

13 Sugarcane is grown between latitudes 35° North and 35° South, from sea-level to 1500 m in over
14 100 countries throughout Africa, North, Central and South America, Asia and Oceania (Barnes 1974;
15 Bakker 1999; Muchow et al. 1997). Brazil, India, China, Thailand, Pakistan, Mexico, Colombia,
16 Australia, Argentina and the United States of America are the largest sugarcane-growing nations
17 supplying over 80% of the total 2009-2010 sugarcane production (F.O.Lichts 2010). Brazil, Thailand
18 and Australia are also major exporters of raw sugar (F.O.Lichts 2010; Hogarth and Ryan 2000).

19 Brazil is the largest sugarcane producer, raw-sugar exporter and manufacturer of sugarcane ethanol.
20 In 2009-2010 Brazil grew around 40% of the total sugarcane produced (F.O.Lichts 2010) and had 325
21 sugar-ethanol plants operational in 2010 (Ferreira-Leitao et al. 2010). The size of the Brazilian
22 sugarcane industry and its flexibility to produce sugar or ethanol have a major influence on the value
23 of raw sugar exports (Hogarth and Ryan 2000). It also makes it difficult for other raw-sugar exporters
24 to secure market share, especially during times of excess production. To remain competitive and
25 profitable, other major raw sugar exporters, such as Australia, have focused on establishing a
26 reputation as a consistent and reliable supplier of high-quality raw sugar, improving production

1 efficiency and reducing operating expenses (Hogarth and Ryan 2000; Mackintosh 2000;
2 CANEGROWERS 2010). Australia is recognized as one of the most cost-effective sugarcane
3 producers in the world, capable of securing market share even during times of excess production
4 (CANEGROWERS 2010; Hogarth and Ryan 2000).

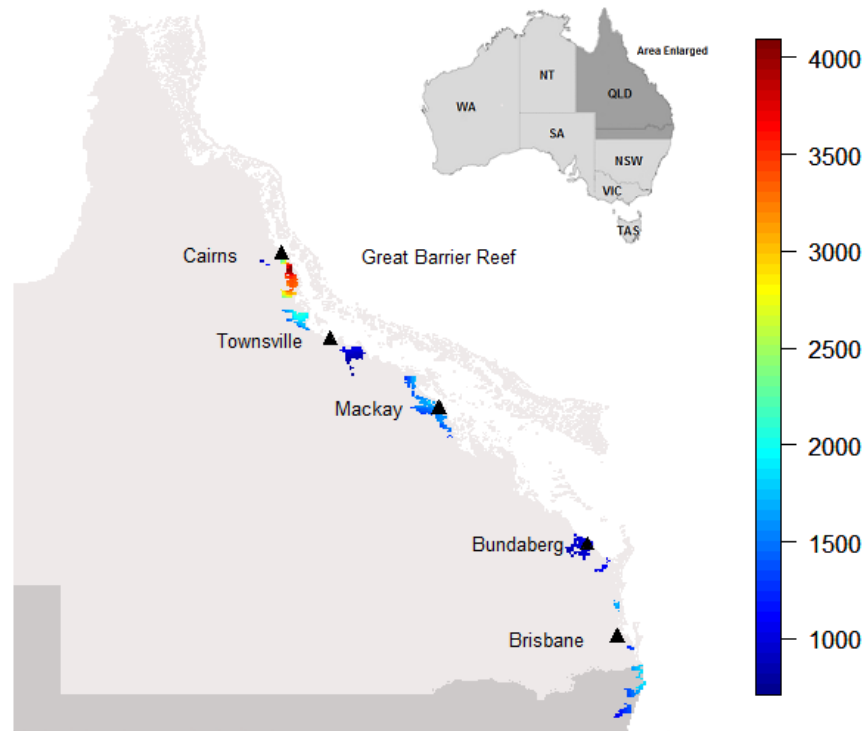
5

6 *2.4. Australian Sugarcane Industry*

7 Generating annual revenue of US\$1.5-2.5 billion, the processing of sugarcane into raw sugar is one
8 of Australia's largest and most important rural industries (CANEGROWERS 2010). Family-owned
9 businesses with an average farm size of 110 ha and some very large corporately-owned cane-farming
10 businesses produce 32 to 35 Mt of sugarcane and 4.5 to 5 Mt of raw sugar annually
11 (CANEGROWERS 2010).

12 In Australia, sugarcane is grown along 2200 km of coastline (Figure 1) from Mossman
13 (S16°30',E145°30') in far north Queensland to Harwood (S29°25',E153°14') in northern New South
14 Wales (Schroeder et al. 2008; CANEGROWERS 2010). Encompassing an area of approximately 500
15 000 ha (Schroeder et al. 2008) the Australian sugarcane industry is split into five discontinuous
16 regions: Northern, Burdekin, Central, Southern and New South Wales. These regions are situated
17 within wet tropical and humid sub-tropical climates and are separated by areas of unsuitable soils or
18 unreliable rainfall (Kingston 2000; Schroeder et al. 2008).

19 **Figure 1.** Geographical location of the Australian sugarcane industry highlighting mean
20 annual rainfall (mm) distribution



1

2 In Queensland, sugarcane is cultivated along the east coast in lowland areas of catchments draining
 3 eastward into the Great Barrier Reef World Heritage Area (Brodie et al. 2001; Wrigley 2007). The
 4 mean annual rainfall ranges from over 4000 mm to less than 1000 mm, necessitating full or
 5 supplementary irrigation in some districts (Barnes 1974; Kingston 2000; Schroeder et al. 2008). In the
 6 Wet Tropics region more than 80% of the total annual rainfall occurs during the wet season that starts
 7 in summer and extends into autumn (Kingston 2000). Summer-dominated rainfall, coupled with the
 8 risk of flooding and cyclonic storms, results in the harvest season operating from June to December to
 9 coincide with normally drier weather.

10 With Queensland producing approximately 95% of Australia's annual raw sugar total, it is not
 11 surprising that sugarcane is the major agricultural crop grown on the east coast (CANEGROWERS
 12 2010; Hogarth and Ryan 2000; Barnes 1974). The ability to grow sugarcane over a large area of
 13 different soil types and climatic conditions, in combination with easy access to required infrastructure,
 14 results in sugarcane being grown in preference to alternative crops. However, the period between crop
 15 cycles provides an ideal opportunity for alternative crop diversification without disrupting sugarcane

1 production (Garside and Bell 1999). Alternatively, sugarcane may be used in longer-term rotation
2 with crops such as bananas in northern Queensland.

3 In New South Wales sugarcane is grown in a subtropical climate on coastal plains traversed by
4 three rivers (Barnes 1974). The mean annual rainfall total ranges from 1300 mm to 1700 mm and,
5 although the majority falls during the wet season, up to 40% of the total annual rainfall can fall over
6 the winter months creating drainage and harvesting problems (Calcino et al. 2008; Kingston 2000).
7 Frequent flooding may occur in late summer and crops can be frosted in some areas during winter
8 (Barnes 1974). The cooler climate of New South Wales results in most sugarcane crops growing for 2
9 years before harvest, compared to 1 year in Queensland (Barnes 1974).

10 The Australian sugarcane industry with 24 sugar mills and six bulk-storage terminals is small
11 compared to its major raw-sugar exporting competitors. Approximately 80% of the raw sugar
12 Australia produces is exported, mainly to China, Indonesia, Japan, Korea, Malaysia, Taiwan, the
13 United States of America and New Zealand (CANEGROWERS 2010; Hogarth and Ryan 2000). The
14 remainder is refined and processed in Australia to produce white sugar, liquid sugar products and
15 specialty products such as golden syrup, coffee sugar, cubed sugar and treacle for domestic
16 consumption.

17 The productivity of Australian sugarcane farms and mills is amongst the highest in the world and
18 production costs are similar to most other larger sugarcane producers (Hogarth and Ryan 2000).
19 Australia is regarded as one of the most competitive, cost-effective and innovative producers and
20 exporters of raw sugar and a leader in the adoption of sustainable farming practices
21 (CANEGROWERS 2010; Hogarth and Ryan 2000).

22

23 2.4.1. Australian Sugarcane Production System

24 The Australian sugarcane farming system focuses on the adoption of best management practices for
25 improved productivity, profitability, sustainability and environmental responsibility (Hurney et al.
26 2008; Garside et al. 2004). Best management practices are recommended across all aspects of the

1 sugarcane farming system and, although growers tailor practices to suit their individual requirements
2 and climatic conditions, certain fundamental principles exist. Multidisciplinary research conducted by
3 the Sugarcane Yield Decline Joint Venture (Garside et al. 1997; Garside 1997; Garside et al. 2001) to
4 investigate the loss of productive capacity of Australian sugarcane growing soils under long-term
5 monoculture promoted the adoption of a sustainable farming system. This farming system
6 recommends inclusion of a break period between crop cycles, preferably incorporating a well-managed
7 legume crop, reducing tillage practices, increasing row spacing to allow for controlled trafficking of
8 machinery, adopting green, cane trash-blanketing (no pre-harvest burning and conservation of crop
9 residues; GCTB) wherever possible and sustainable resource use (Hurney et al. 2008; Garside et al.
10 2004; Bell et al. 2003; Garside et al. 2006). At least some of these practices are commonly adopted
11 within most sugarcane farming enterprises as they have significant potential to reduce production
12 costs, improve operation timeliness and soil health and prevent sugarcane yield decline (Garside et al.
13 2004; Bell et al. 2003; Hurney et al. 2008).

14 The average Australian sugarcane crop cycle consists of plant and four to five ratoon crops with a
15 4-6 month break period between crop cycles to break the sugarcane monoculture (Garside et al. 2009;
16 Pankhurst et al. 2003; Wood 1991; Garside et al. 1997). The break period also provides an ideal
17 opportunity to determine the soil nutrient status, target weed control, reduce pest and disease pressure,
18 undertake land rectification activities, and plant an alternative crop (Hurney et al. 2008). Legume
19 crops grown during the break provide a diverse species break from sugarcane and a source of mineral
20 N, improve soil health and increase productivity (Garside and Bell 2001; Garside and Bell 1999). The
21 most commonly grown legumes are cultivars of soybean (*Glycine max*), cowpea (*Vigna unguiculata*),
22 lab lab (*Lablab purpureus*) and peanut (*Arachis hypogaea*) and, although broadcast planting is still
23 practiced, direct-drill planting into raised mounds or existing cane rows to reduce tillage operations
24 and maximise germination is becoming more popular (Garside and Bell 2001). Legumes are generally
25 grown as green-manure crops in the wetter northern districts, with grain crops produced where weather
26 conditions and machinery availability facilitate harvesting (Garside and Bell 2001; Garside and Bell

1 1999). As the break period usually coincides with the wet season, alternative crops help minimise the
2 risk of erosion and pollutant movement off-farm. Where it is not possible to grow a well-managed
3 legume crop, a bare fallow maintained with knockdown herbicides is the best alternative (Hurney et al.
4 2008). Most Australian sugarcane farming systems use a configuration of single rows separated by
5 about 1.52 m. Transition to controlled-traffic farming systems consisting of single or dual rows
6 separated by 1.8 to 2.0 m is gradually occurring and minimises the adverse effects of soil compaction
7 in the cropping zone (Calcino et al. 2008). This farming system is also better suited to zonal tillage
8 systems that only cultivate the row area. Adoption of minimum or zonal tillage land preparation
9 practices in combination with a greater reliance on chemical weed control have reduced aggressive
10 tillage practices and helped minimise soil disturbance in break and plant crops. Zero tillage, the
11 practice of direct drilling sugarcane setts into undisturbed soil, is not common, as some cultivation is
12 required to reshape the cane drill and prepare an adequate seed bed (Calcino et al. 2008). However, a
13 recently developed direct-drill sugarcane planter based on the double-disk-opener planter concept
14 commonly used in the grains industry has the potential to successfully operate in any cultivation
15 system, including zero tillage (Robotham 2004; Robotham and Chappell 2000).

16 Sustainable use of resources is another important component of the Australian sugarcane production
17 system and focuses on the correct application rate, placement and timing of nutrient, water, herbicide
18 and pesticide inputs to maximise profitability and minimise detrimental offsite impacts (Hurney et al.
19 2008). This type of approach is particularly evident in current nutrient management guidelines that
20 consider nutrient availability based on soil test results, crop requirements, crop class, yield potential
21 and nutrient contributions from other sources such as mill by-products and legumes so that
22 recommended nutrient application rates can be adjusted accordingly (Schroeder et al. 2009c; Schroeder
23 et al. 2007a; Wood et al. 2003; Calcino et al. 2010). It is also illustrated in recently developed
24 guidelines for best-practice integrated weed management (Schroeder et al. 2009a; Calcino et al. 2008).

25 Crop-management practices are highly mechanized and all sugarcane is mechanically planted with
26 whole-stalk or billet planters into a furrow or preformed mounds (Robotham 2004) and mechanically

1 harvested using wheel or track chopper harvesters (Ridge and Norris 2000). Most of the industry has
2 transitioned to green-cane harvesting and trash retention. This has been a catalyst for the adoption of
3 zero or strategic tillage, sub-surface fertiliser application and chemical weed control in ratoon crops
4 (Willcox et al. 2000). It is also considered to be best practice providing agronomic, environmental and
5 financial benefits to the farming system, especially when compared to traditional burnt-cane harvest
6 systems (Schroeder et al. 2009a; Garside et al. 1997; Braunbeck et al. 1999; Smith et al. 1984).

7 When harvested, sugarcane is transported to a mill for processing. In Australia, a cane price
8 formula is used to determine the value of sugarcane delivered to the mill for each grower. The value is
9 shared between growers and millers, roughly on a 2/3 : 1/3 basis (Mackintosh 2000), meaning growers
10 are more focused on sucrose production and profitability, whereas millers are primarily interested in
11 tonnes of cane delivered to the mill (Schroeder et al. 2013).

12 2.4.2. Australian Sugarcane Production Challenges

13 Ongoing constraints to sugarcane productivity in Australia include changes to the bio-physical
14 environment, socio-economic factors, environmental considerations, the influence of pests and
15 diseases and harvest scheduling (Garside et al. 1997; Muchow et al. 1997). In addition, there are a
16 number of other challenges currently confronting the Australian sugarcane industry. These include
17 rising input costs, skilled labour shortage, market diversification, the unknown impact of climate
18 change and restructuring of research, development and extension services. However, it is the intense
19 pressure from tourism, environmental, public and political groups to minimise the environmental
20 impact of sugarcane production practices that takes centre stage (Calcino et al. 2010; Benn et al. 2010).

21 Environmentally sustainable sugarcane production practices are continually being developed in an
22 attempt to deliver superior environmental outcomes without restricting productivity or profitability.
23 Practices such as GCTB, zonal and minimum tillage land preparation, legume cover crops or spray-out
24 fallow management, subsurface fertiliser application and refinement of nutrient-management
25 guidelines all aim to reduce sediment and nutrient movement off farm (Christiansen 2000; Schroeder
26 et al. 2008; Schroeder et al. 2009a; Hurney et al. 2008). Maintenance of grassed filter strips and

1 vegetation along waterways and the installation of sediment traps also help to intercept and retain any
2 sediment, nutrients and pesticides in farm runoff water (Smith 2008; Christiansen 2000). Transition to
3 these farming practices is often voluntary, as they are also associated with agronomic and economic
4 benefits.

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

13

14 2.4.2.1 Nitrogen management in Australian sugarcane production

15 Worldwide there is an increasing realisation that farmers must become more pro-active in managing
16 the effect of their farming system on the surrounding environment (Ellis and Merry 2004; Garside et
17 al. 1997). This is of high importance in the Wet Tropics region of northern Australia, the only place in
18 the world where sugarcane production is surrounded by two adjacent World Heritage Areas of national
19 and international ecological, economic and social significance (Benn et al. 2010; Brodie et al. 2001;
20 Wrigley 2007; Newby and Wegener 2003; Waterhouse et al. 2012). The Wet Tropics World Heritage
21 Area is Australia's most floristically rich environment, providing habitat for 76 species of animals
22 regarded as rare, vulnerable or endangered (Trott 1996) and the Great Barrier Reef World Heritage
23 Area is the world's largest reef ecosystem (Brodie et al. 2001).

24 Even with the adoption of environmentally sustainable sugarcane production practices, there is a
25 risk that 'environmental pollutants', including N, could be lost from the sugarcane production system
26 due to external influences. As N is the nutrient most susceptible to environmental loss and applied in

1 the greatest quantity to optimise yield, greater emphasis needs to be placed on the development of
2 environmentally sustainability yet profitable N-management strategies (Thorburn et al. 2004a;
3 Thorburn et al. 2003; Schroeder et al. 2009b; van der Laan et al. 2011).

4 2.4.2.1.1 Nitrogen sources for sugarcane production

5 Nitrogen in the soil is present in organic (i.e. organic matter) and inorganic (i.e. ammonium (NH_4^+),
6 nitrate (NO_3^-), nitrite (NO_2^-), nitrous oxide (N_2O)) forms. Organic N can represent around 95-99% of
7 the total soil N and is converted to mineral N forms via the decomposition of organic matter in a
8 process known as mineralisation (Glendinning et al. 2000). Only a small proportion of organic N
9 becomes available for plant uptake.

10 Inorganic N represents only 2-3% of the total soil N. The two most abundant forms of inorganic N,
11 also referred to as mineral N (which is readily available for plant uptake), are NH_4^+ and NO_3^-
12 (Glendinning et al. 2000). Ammonium ions are positively charged and held in an exchangeable form
13 on the negatively charged surfaces of clay particles and organic matter (Brady and Weil 2002;
14 Glendinning et al. 2000). Ammonium is, therefore, a relatively immobile form of N and less
15 susceptible to leaching and denitrification losses (Glendinning et al. 2000). Nitrate ions remain in the
16 soil solution as they cannot be absorbed by clay particles or organic matter, and are, hence, a highly
17 mobile form of N (Brady and Weil 2002; Glendinning et al. 2000).

18 The N contained in commonly applied N fertilisers exists in three forms: organic (i.e. urea, mill by-
19 products and manures), NO_3^- and NH_4^+ . In sugarcane, the most commonly applied fertiliser products
20 include granular, liquid, mill by-product and organic forms (Schroeder et al. 2009a). The form of N
21 fertiliser applied is often based on cost as research has demonstrated no difference in cane yields from
22 using ammonium sulphate or urea, provided it is subsurface applied (Leverington 1964).

23 In plant cane, inorganic fertilisers are often applied as mixtures at planting (Calcino et al. 2008). In
24 ratoons, inorganic fertilisers mixtures, also known as “one shot blends”, are often urea-based products
25 containing K (muriate of potash), possibly P (DAP) and S (ammonium sulphate) (Schroeder et al.

1 2009a; Thorburn et al. 2003). Alternatively, ‘straight’ products such as urea and muriate of potash
2 may be applied instead of mixtures. The nutrient compositions for plant and ratoon fertiliser mixtures
3 vary so that the most appropriate product can be selected to meet the nutritional requirements of the
4 block. Liquid fertilisers include commercially available nutrient solutions that are based on inorganic
5 fertiliser products, and dunder-based products that are usually fortified with other nutrients including N
6 (Schroeder et al. 2009a). Mill by-products also provide a significant source of N, but, as it is in an
7 organic form, not all the N is immediately available for plant uptake (Calcino 1994; Mackintosh 2000;
8 Calcino et al. 2000; Barnes 1974). A proportion of the applied fertiliser N remains in the soil, but this
9 residual N contributes only small amounts of N for sugarcane growth (Chapman et al. 1992).

10 Legume break crops can contribute significant amounts of mineral N for sugarcane production.
11 Well-managed soybean (*Glycine max* cv. Leichardt) and cowpea (*Vigna unguiculata* cv. Meringa)
12 crops are capable of supplying 310 and 140 kg N/ha, respectively, excluding the N stored in the below-
13 ground parts of the crop (Garside and Bell 1999; Garside et al. 1996). In most situations symbiotically
14 fixed N accounts for 50-60% of the N accumulated by the legume crop, with the remainder sourced
15 from soil mineral-N reserves (Garside and Bell 1999). Following a legume crop, the amount of N
16 fertiliser applied to plant cane can be reduced or possibly eliminated depending on legume residue
17 management at the end of the break period (Schroeder et al. 2009a; Schroeder et al. 2007b; Garside
18 and Bell 1999).

19 2.4.2.1.2 Nitrogen loss processes

20 Crops seldom assimilate more than 50% of the N applied as fertiliser (Chen et al. 2008). For
21 sugarcane grown in Australia, research using labelled ¹⁵N fertiliser has indicated maximum recoveries
22 in the crop and surrounding soil of just over 60% of the N fertiliser applied (Chapman et al. 1991;
23 Vallis and Keating 1994; Prasertsak et al. 2002). The unrecovered N is either held in the soil by
24 microbial immobilisation (Jansson and Persson 1982) and/or lost from the sugarcane production
25 system by a range processes including volatilisation, denitrification, leaching, erosion or runoff (Wood

1 et al. 2010a). Ammonia volatilisation and denitrification are the dominant processes for gaseous losses
2 of fertiliser N from Australian agriculture (Chen et al. 2008).

3 Surface application of urea to sugarcane trash can result in significant losses of N fertiliser.
4 Between 30% and 70% of the applied N can be lost by ammonia volatilization (Denmead et al. 1990;
5 Prammanee et al. 1988). The process of ammonia volatilization is driven by the addition of small
6 amounts of water (dewfall, intermittent rainfall and condensation of evaporated soil moisture) to the
7 trash layer where urea-based products have been surface-applied (Denmead et al. 1990). Water
8 dissolves the urea and allows the naturally occurring urease enzyme in the sugarcane residues to
9 catalyse the hydrolysis of the dissolved urea to ammonium carbonate (Denmead et al. 1990).
10 Sugarcane trash has a low capacity to retain ammonium and its high urease activity speeds up the
11 hydrolysis process (Freney et al. 1994). Ammonium carbonate is very unstable and, as the water
12 evaporates, ammonia (NH_3^+) gas is released and volatilization commences (Denmead et al. 1990).

13 Nitrate ions are highly susceptible to leaching losses (Brady and Weil 2002; Glendinning et al.
14 2000). As mentioned earlier, NO_3^- are not well held by clay particles or organic matter and move
15 freely with soil water (Glendinning et al. 2000). Nitrate may be washed beyond the root zone
16 following heavy rainfall (or irrigation). The highest leaching losses are most likely to occur on coarse-
17 textured, free-draining soils (i.e. sandy soils) following heavy rainfall (Chen et al. 2008; Glendinning
18 et al. 2000).

19 In addition to existing ammonia volatilization and leaching loss pathways, the moist warm climate
20 of Australian sugarcane production regions combined with GCTB, waterlogging and the addition of N
21 fertiliser also provides conditions conducive to denitrification (Denmead et al. 2010; Allen et al. 2010;
22 Wang et al. 2008b). Denitrification involves the conversion of soil NO_3^- to gaseous forms of N (nitric
23 oxide (NO), nitrous oxide (N_2O) or di-nitrogen nitrogen (N_2)) by microorganisms in anaerobic
24 conditions (i.e. waterlogged soils) (Denmead et al. 2005). This process is driven by the availability of
25 organic residues, NO_3^- and NO_2^- ions, high temperatures, strong acidity and anaerobic conditions

1 (Brady and Weil 2002). Emission of N₂O is of greatest concern from an environmental viewpoint
2 (Wang et al. 2008b; Wang et al. 2012).

3 In sugarcane, high N₂O emissions can be expected from waterlogged soils with a high organic-
4 carbon content, high mineral-N concentration and high temperature (Allen et al. 2010; Allen et al.
5 2008) and where GCTB is practiced because of greater soil moisture retention and increased microbial
6 activity (Weier et al. 1998). It has been estimated that 17% of applied N fertiliser is lost to the
7 atmosphere (Macdonald et al. 2009) with between 1.0% and 6.7% emitted as N₂O (Allen et al. 2010).
8 Nitrous oxide emissions were recently measured under different break and N fertiliser management
9 regimes (Wang et al. 2012). After a bare fallow emissions increased from 6.3 kg to 12.3 kg N₂O N/ha
10 following an increase in plant cane N rates (0 to 150 kg N/ha), with the highest emission, 20.9 kg N₂O
11 N/ha, measured after a soybean break crop and the addition of 75 kg N/ha in plant cane. Relatively
12 high N₂O emissions, 21% of the N fertiliser applied (Denmead et al. 2010), have also been measured
13 from highly organic, acid-sulphate soils in northern NSW (Denmead et al. 2005; Denmead et al. 2010).

14 15 2.4.2.1.3 Consequences of nitrogen losses

16 Loss of N from the sugarcane production system can have serious environmental consequences.
17 The apparent declining health of the Great Barrier Reef has been attributed to damaging levels of land-
18 based pollutants entering reef waters as a result of agricultural activities, the dominant being beef
19 grazing and sugarcane cultivation, undertaken in adjacent catchments (Thorburn et al. 2011c;
20 Bainbridge et al. 2009; Benn et al. 2010; Brodie et al. 2001; Brodie et al. 2010). At a regional scale,
21 the Wet Tropics has been estimated to deliver the highest anthropogenic dissolved inorganic nitrogen
22 (DIN) load to the Great Barrier Reef lagoon (Waterhouse et al. 2012; Kroon et al. 2012). The loss of
23 N fertiliser applied to sugarcane fields contributes a large proportion of the anthropogenic load of DIN
24 in this region (Waterhouse et al. 2012). At the local level, catchment water-quality monitoring
25 programs have been undertaken to identify the source and quantity of land-based pollutants entering
26 reef waters. The monitoring of suspended sediments, nutrients and pesticides in waterways of the

1 Tully-Murray catchment in the Wet Tropics region undertaken by (Bainbridge et al. 2009) is just one
2 example. Although it is difficult to easily isolate pollutant discharge from single land uses within the
3 Tully-Murray catchment, elevated NO_3^- concentrations were measured in waterways draining
4 sugarcane land (Bainbridge et al. 2009).

5 The production of N-containing gases by denitrification contributes to atmosphere pollution.
6 Nitrous oxide in particular is a potent greenhouse gas with a global warming potential 298 times higher
7 than that of carbon dioxide (Wang et al. 2008b; Wang et al. 2012). The release of NO and N_2O into
8 the atmosphere can also contribute to the formation of nitric acid, one of the principal components of
9 acid rain (Brady and Weil 2002).

10 When NO_3^+ is leached from the soil it is often accompanied by basic cations such as Ca, Mg and K
11 (Glendinning et al. 2000). These cations are replaced by hydrogen (H) ions, increasing the acidity of
12 the soil (Glendinning et al. 2000). The nitrification and mineralisation processes are also major causes
13 of soil acidification as the conversion of NH_4^+ to NO_3^- releases hydrogen ions (Glendinning et al.
14 2000; Noble et al. 1997). The form of N fertiliser applied can influence the rate of acidification.
15 However, fertiliser is applied in relatively small amounts (compared to the volume of soil and the
16 soil's pH buffering capacity) and does not have a direct effect on soil pH (Glendinning et al. 2000).
17 Increased NO_3^- concentrations in groundwater or surface water due to leaching can have toxic effects
18 (causing methemoglobinemia or *blue baby syndrome*) if used as drinking water (Brady and Weil
19 2002).

20 The magnitude of N losses and low recoveries of fertiliser N by the sugarcane crop are also of
21 significant economic importance to the sugarcane industry (Haysom et al. 1990). Investment in N
22 fertiliser represents a relatively large component of farm production costs - approximately 30% of the
23 average on-farm budget is associated with nutrient inputs (Schroeder et al. 2005b). Therefore, loss of
24 applied N from the sugarcane production system may represent a serious economic loss to the grower
25 (Anich and Wegener 1992; Wood et al. 2010b; Chen et al. 2008). The magnitude of economic losses
26 will be influenced by the cost of N fertiliser, sugar price and the effect on cane yield. Substantial

1 losses of applied N may severely reduce the amount of N that is available for crop growth. Insufficient
 2 N supply, especially under favourable growing conditions, may restrict sugarcane yield (Schroeder et
 3 al. 2010b). Lower cane yield reduces the economic return on N fertiliser investment. Although the
 4 immediate consequences of N losses are first experienced by the grower, lower cane yields can also
 5 affect the operational efficiency and profitability of other industry sectors (i.e. harvesting contractors).

7 2.4.2.1.4 Strategies to reduce N losses and improve nitrogen-use efficiency

8 Nitrogen management in the Australian sugarcane industry has undergone significant changes since
 9 the 1960s with the aim of improving the use efficiency of N fertiliser. Rate of fertiliser experiments
 10 conducted by the Bureau of Sugar Experiment Stations (now BSES Limited) resulted in the
 11 development of regional yield-response curves for N. This provided a set of generalised N fertiliser
 12 recommendations for plant and ratoon crops that would maximise productivity and achieve an
 13 economic return (Chapman 1994). These recommendations are shown in Table 1, and, although they
 14 were easy to use, they lacked precision. Little emphasis was placed on the N mineralisation potential
 15 of different soil types and there was very little differentiation among regions or soil types (Schroeder et
 16 al. 2005a; Schroeder et al. 1998; Wood et al. 1997).

17 **Table 1.** Generalised N management recommendations for sugarcane in Australia (Calcino 1994;
 18 Chapman 1994; Wood et al. 1997)

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

1 Recently, soil- and site-specific N fertiliser guidelines included in the Australian sugarcane
2 industry's comprehensive SIX EASY STEPS nutrient-management program (Schroeder et al. 2007a;
3 Schroeder et al. 2009b; Schroeder et al. 2005a; Schroeder and Wood 2001; Schroeder et al. 2010b;
4 Wood et al. 2003; Schroeder et al. 2009c; Calcino et al. 2010; Schroeder et al. 2010a; Schroeder et al.
5 2005b) have effectively replaced those generalised N-fertiliser recommendations. The SIX EASY
6 STEPS package aims to promote sustainable nutrient management and ensure that sugarcane
7 production remains profitable irrespective of sugar prices. It is also recognised as part of the
8 Australian sugarcane industry's accepted best management practice (BMP) options (Schroeder et al.
9 2009c). Importantly, it has undergone extensive development and rigorous testing in the field,
10 glasshouse and laboratory for more than a decade (Schroeder et al. 2007b; Salter et al. 2008; Skocaj et
11 al. 2012; Schroeder et al. 2006).

12 In the SIX EASY STEPS program, N fertiliser requirements are calculated by firstly establishing
13 the baseline N requirement for a district yield potential. The district yield potential is the estimated
14 highest average annual district yield multiplied by a factor of 1.2 (Schroeder et al. 2010b). The N
15 requirement suggested by (Keating et al. 1997) of 1.4 kg N/t cane/ha up to 100 t/ha and 1 kg N/t
16 cane/ha is then used in combination with the district yield potential to set the baseline N requirement.
17 Once this is done, the organic carbon (%) value from a soil test result is used to determine the N-
18 mineralisation index of the soil (soils differ in their ability to easily mineralise N from organic matter)
19 and refine the baseline N requirement. Final adjustments are made to account for N contributions from
20 other sources, including legume break crops and mill by-products. The N fertiliser guidelines for the
21 Wet Tropics region as determined by the SIX EASY STEPS program are shown in Table 2. There is
22 flexibility to adjust the baseline N requirement upward or downward by 1 kg N/t cane/ha for blocks,
23 farms or sub-districts that consistently produce above or below the district yield potential. Just as soil
24 tests are considered fundamental to the SIX EASY STEPS process, leaf analysis is also considered to
25 be an important diagnostic tool that may be used for checking on the adequacy of fertiliser inputs
26 (Schroeder et al. 2006).

1 **Table 2. SIX EASY STEPS N fertiliser guidelines for the Wet Tropics region of the Australian**
 2 sugarcane industry (Schroeder et al. 2005a; Schroeder et al. 2007b)

Crop and fallow management	Organic C (%), N mineralisation index and N application rate (kg/ha)						
	< 0.4	0.41 - 0.80	0.81 - 1.20	1.21 - 1.60	1.61 - 2.00	2.01 - 2.40	> 2.40
	Very Low	Low	Mod Low	Mod	Mod High	High	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: <ul style="list-style-type: none"> • 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. • 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. • Ash applied at 100-150 wet t/ha: No modification. 							

1 The N fertiliser requirement for sugarcane grown in South Africa is determined in a somewhat
2 similar method to the SIX EASY STEPS program. Four soil-N mineralisation groups (depending on
3 the organic carbon (%) values) are used to determine the N requirement from soil-test results (Meyer
4 and Wood 1994; Meyer et al. 1986). The N guidelines are based on a series of N response curves that
5 had previously been established for a range of soil types. They incorporate references to bioclimatic
6 regions and moisture regimes (irrigated or rain-fed) as a means of recognizing differences in cane
7 production (yield) capabilities. Crop stage (plant or ratoon) and other growth limiting factors such as
8 salinity, pests and soil depth are also used to adjust N recommendations (Meyer and Wood 1994;
9 Meyer et al. 1986).

10 In contrast to the SIX EASY STEPS philosophy, the Commonwealth Scientific and Industrial
11 Research Organisation (CSIRO) has developed a N-management system that aims to replace the
12 amount of N removed by the previously harvested crop (Thorburn et al. 2003; Thorburn et al. 2004a).
13 This system is referred to as the 'N Replacement' theory. N Replacement uses the yield of the
14 previously harvested crop to set the N requirement for the following crop. The overall objective is to
15 reduce environmental losses of applied N by avoiding over application of N fertiliser when actual
16 yields are lower than the expected yield and relying on soil N reserves to supply additional N
17 requirements when actual yields are higher than the previously harvested crop (Thorburn et al. 2007;
18 Thorburn et al. 2011b). Nitrogen fertiliser requirements for each crop are calculated by multiplying
19 the yield of the previous crop with a N requirement of 1 kg N/t cane/ha for GCTB systems and 1.3 kg
20 N/t cane/ha for burnt systems before discounting other N sources (Thorburn et al. 2007; Thorburn et al.
21 2011b). The N requirement is based on an estimate of the N contained in the cane and sugarcane crop
22 residue (i.e. trash) that is removed from the field through harvesting (and burning in burnt harvesting
23 systems), and the amount of applied N fertiliser that is potentially lost to the environment (Thorburn et
24 al. 2011b). Within this system, environmental losses of N are assumed to be as low as 10% for all
25 soils and circumstances (Thorburn et al. 2011b).

1 The average application rate of N fertiliser for Queensland sugarcane production (plant and ratoon
2 crops combined) has declined steadily from 206 kg N/ha for the 1997 crop to 164 kg N/ha for the 2008
3 crop (Wood et al. 2010a). A grower survey conducted in the Tully and Murray River Catchments of
4 the Wet Tropics region reported that the average rates of N fertiliser for plant and ratoon cane in 2006
5 were 115 and 146 kg N/ha, respectively (McMahon and Hurney 2008). There has been a marked
6 reduction in N application rates in this region since 1996 and a tendency to apply lower N rates since
7 2000 (Shannon 2002). In 2006, 65% of growers surveyed applied <120 kg N/ha to plant crops
8 compared to only 28% in 1996 (McMahon and Hurney 2008; Shannon 2002). For ratoon crops, 65%
9 of growers surveyed applied <160 kg N/ha, an increase of more than 27% of growers since 1996
10 (McMahon and Hurney 2008; Shannon 2002). Average grower N fertiliser application rates have
11 reduced below the baseline N-application rate of 140 kg N/ha for plant cane and 160 kg N/ha for
12 ratoons (prior to adjustment for the N-mineralisation index classes) as specified in the SIX EASY
13 STEPS N guidelines for the Wet Tropics region (Schroeder et al. 2005a; Schroeder et al. 2007b). The
14 trend to lower grower N application rates has also occurred in the Herbert district (Wood et al. 2008).

15 Despite evidence of a voluntary reduction in N application rates, Australian sugarcane growers must
16 now comply with legislation limiting the application of N (and P) fertiliser to optimum amounts (Anon
17 2009a). In response to state-wide water-quality monitoring outcomes, the Queensland Government, as
18 indicated previously, introduced the *Great Barrier Reef Protection Amendment Act 2009* to regulate N
19 inputs by sugarcane farmers and graziers in catchment areas adjacent to the Great Barrier Reef lagoon
20 (Anon 2009a). Specifically, the Act aims to reduce the impact of agricultural activities on the quality
21 of water entering the lagoon and contribute towards achieving water-quality improvement targets for
22 the reef including a minimum 50% reduction in N loads at the end of catchments by 2013 as agreed by
23 the Queensland State and Commonwealth Governments under The Reef Water Quality Protection Plan
24 (Reef Plan) (Wrigley 2007; ReefWaterQualityProtectionPlanSecretariat 2009). The regulated method
25 for determining the optimum amount of N for individual blocks of cane is based on the SIX EASY
26 STEPS N-fertiliser guidelines (Schroeder et al. 2005a; Anon 2009b).

1 In addition to following recommended N rates, a number of other factors that can help reduce N
2 losses and improve N uptake are within growers' control. These include the correct placement and
3 timing of N fertiliser inputs. It is recommended that all forms of N fertiliser be applied subsurface
4 regardless of trash-management practices. In particular, surface application (banded or broadcast) of
5 urea-based products to GCTB systems is not recommended as it results in significant loss of N by
6 ammonia volatilization and reduced cane yields (Prasertsak et al. 2002; Freney et al. 1994; Calcino and
7 Burgess 1995).

8 In plant cane, N fertiliser should be delivered in bands on each side of, and away from, the
9 sugarcane sett when applied at planting and banded in the centre of the cane row before being covered
10 with soil at top dressing (Schroeder et al. 2009a). Subsurface application in ratoons can be achieved
11 by either stool splitting with a single coulter to deliver fertiliser into the cane row or by dual coulters
12 beside the cane row to a depth of 70 mm to 100 mm (Schroeder et al. 2009a; Calcino et al. 2000).
13 Subsurface fertiliser applicators can apply fertiliser mixtures or two fertilisers simultaneously if
14 manufactured as a 'split' fertiliser box (Freney et al. 1994). Stool splitting is the most popular
15 application method (three cane rows treated with each pass instead of two), as it is easier and quicker
16 to use than other methods of subsurface application (McMahon et al. 1994).

17 Where subsurface application of N is not possible (i.e. steep slopes and rocky terrain), strategies to
18 reduce ammonia volatilisation losses include applying urea-based products in bands close to the cane
19 stool and incorporating into the soil with at least 16 mm of overhead irrigation water (or rainfall) or
20 delaying application until there is substantial canopy development (approximately 50 cm high) (Freney
21 et al. 1991; Freney et al. 1994; Calcino and Burgess 1995; Wood et al. 1989; Prammanee et al. 1989).
22 A developed canopy helps attenuate the wind speed over the trash surface allowing the leaves to
23 absorb volatilised ammonia. It also contributes to lower trash temperatures that reduces the ammonia
24 vapour pressure, and shifts the site of overnight dew formation from the trash to the leaves, thereby
25 reducing urea hydrolysis (Freney et al. 1991; Freney et al. 1994; Prammanee et al. 1989; Denmead et
26 al. 1993). A well-established canopy also means that the newly developing root system is capable of

1 relatively rapid uptake of applied N fertiliser (Chapman 1994). However these strategies will not
2 totally eliminate losses from ammonia volatilisation. Losses of greater than 20% of the N from applied
3 urea have been reported even when surface application of urea is followed by reasonably heavy rainfall
4 (Prammanee et al. 1989).

5 The use of urease inhibitors in combination with best practice surface application of urea-based
6 products may reduce ammonia volatilisation losses where subsurface placement is not possible.
7 Urease inhibitors aim to slow the hydrolysis process, thereby allowing the urea to move into the soil
8 (Wood et al. 2010b; Chen et al. 2008). Ammonia is then retained in the soil and less susceptible to
9 volatilisation (Chen et al. 2008). In Australia, several commercially available urease inhibitors are
10 available. One supplier has reported a reduction of loss of ammonia by volatilisation for between 7
11 and 14 days after application (R. Dwyer 2013, pers. comm. 7 February). Inadequate incorporation of
12 urea through the trash blanket and into the soil (i.e. insufficient rainfall, extended dry conditions, thick
13 trash layer) may reduce the effectiveness of urease inhibitors.

14 To minimise N losses, application timing should coincide with the crop's demand for N (Schroeder
15 et al. 2009a; Chapman 1994). To achieve this, N is often split applied in plant cane by applying a low
16 N-concentration fertiliser concurrently at planting and any remaining N requirements as a top-dressing
17 around the first fill-in stage (Schroeder et al. 2009a; Chapman 1994). The best time for ratoon
18 fertiliser application is when the crop is actively growing and is approximately 0.5 m high. At this
19 stage there is a newly developed root system capable of using fertiliser N (Schroeder et al. 2009a;
20 Chapman 1994). This results in more efficient N uptake and allows the crop to act as a nutrient store.
21 Growers are encouraged to avoid applying N fertiliser too early (i.e. straight after harvest when the
22 crop is unable to take up applied N) or too late (i.e. crop may become N deficient or field entry may be
23 restricted) as there is an increased risk of loss to the surrounding environment (Schroeder et al. 2009a;
24 Chapman 1994).

25 Split application of N fertiliser in ratoons has been suggested as a method that may produce tangible
26 environmental benefits by reducing leaching losses (Chapman 1994). However, as this type of

1 strategy has not resulted in higher cane yields, even in waterlogged soils, the majority of growers
2 continue to apply N in a single application (Chapman 1994; Bieske 1972). Research into aspects of
3 waterlogged soils found that split application did not improve N uptake or final cane yields and could
4 not be associated with any economic or environmental benefits (Kingston et al. 2008).

5 To conserve supplies of legume N for use by the following sugarcane plant crop, it is recommended
6 that the crop residue is either left *in situ* or surfaced mulched, as opposed to incorporation, to reduce
7 the rate of N mineralisation and potential of leaching losses (Garside and Bell 2001; Garside and Bell
8 1999).

9 There has been widespread adoption of management strategies, including subsurface N-fertiliser
10 application, to reduce N losses from ammonia volatilisation. However, this has not mitigated N losses
11 from denitrification and leaching (Chapman et al. 1991; Vallis and Keating 1994). Subsurface
12 application of N fertiliser has been estimated to increase denitrification and/or leaching losses from
13 21.8% (following surface application) to 40.1% of the applied N (Prasertsak et al. 2002). To reduce
14 denitrification and leaching losses management practices should aim to remove residual nitrate from
15 the soil profile, maintain fertiliser N in the NH_4^+ form for longer, and lower the NO_3^- concentration in
16 the soil (Weier 1998; Chen et al. 2008). This may be achieved through the use of nitrification
17 inhibitors or controlled-release fertiliser products in combination with best-practice fertiliser placement
18 and timing (Dalal et al. 2003; Weier 1998).

19 The nitrification process transforms NH_4^+ , a relatively immobile form of N, into NO_3^- (Barth et al.
20 2001). The first stage of the nitrification process, bacterial oxidation of NH_4^+ to NO_2^- by *Nitrosomas*
21 bacteria, is closely followed by the second stage, conversion of NO_2^- to NO_3^- by *Nitrobacter* bacteria
22 (Zerulla et al. 2001). Nitrification inhibitors have been specifically developed to delay only the first
23 stage of nitrification by depressing the activities of *Nitrosomas* bacteria in the soil (Zerulla et al. 2001;
24 Barth et al. 2001). This keeps N in the immobile form for longer, thereby reducing N susceptibility to
25 leaching and denitrification losses (Wood et al. 2010b; Barth et al. 2001; Zerulla et al. 2001; Chen et
26 al. 2008).

1 In the past, nitrification products have been too expensive for large-scale agricultural use (Chapman
2 1994; Zerulla et al. 2001). A relatively new nitrification inhibitor, dimethylpyrazol phosphate
3 (DMPP), commercially referred to as ENTEC®, has recently been evaluated in two Australian
4 sugarcane-growing regions on soils with the potential for high denitrification or leaching losses (Wang
5 et al. 2008b; Wang et al. 2012). Although ineffective in reducing N₂O emissions in field plots at
6 Murwillumbah and Mackay, emissions in fertilised chambers were significantly reduced at
7 Murwillumbah (Wang et al. 2008b). At another trial in Mackay, the addition of DMPP to urea resulted
8 in significantly lower N₂O emissions compared to using normal urea (Wang et al. 2012).

9 Controlled-release fertiliser product technology may also contribute to lower N losses, improved N
10 use efficiency and higher cane yields (Shoji et al. 2001). These products include poly-coated urea and
11 sulphur-coated urea, which can be formulated to have different N release rates (Glendinning et al.
12 2000). Previous research into the use of controlled-release fertilisers in Australian sugarcane crops has
13 not been successful (Chapman 1994). Poly-coated slow-release urea was not successful in reducing
14 N₂O emissions from a trial site in Mackay, Queensland (Wang et al. 2008b). However, recent trials
15 have demonstrated that compared to using normal urea, polymer-coated slow-release urea reduced
16 N₂O emission from an acid-sulphate soil in NSW by 30% (Wang et al. 2008b).

17 Further research is required under different climatic and soil conditions to substantiate the
18 effectiveness of DMPP on reducing N₂O emissions from Australian sugarcane fields (Wang et al.
19 2012). In addition, it appears that the success of slow-release N fertiliser products is affected by the
20 solubility of the product, climate, N uptake by the crop and the soil's capacity to retain the mineral N
21 from leaching (Wang et al. 2008b). Incorporation of nitrification inhibitors and controlled release
22 fertiliser products into the sugarcane production system will ultimately be determined by their
23 robustness to reduce N losses in a range of soil types and varying climatic conditions, and economics
24 (Chen et al. 2008). Price and commercial availability are likely to have the greatest influence on the
25 use of these products in sugarcane (Chen et al. 2008; Chapman 1994).

1 Another potential avenue for reducing N losses is the selection of N-efficient sugarcane genotypes.
2 Nitrogen use efficiency (NUE) in plants is complex and refers to the combined efficiencies of internal
3 N use by the plant and N uptake from the soil (and N fertiliser) (Robinson et al. 2007; Robinson et al.
4 2008). Australian sugarcane varieties have not been selected for NUE. However, there is evidence that
5 some of the Australian sugarcane germplasm used for breeding purposes contains considerable
6 genotypic variation for internal NUE (iNUE), i.e. the ability to produce biomass per unit N in plant
7 tissue (Robinson et al. 2007). This suggests there is potential to breed new sugarcane varieties with
8 higher iNUE that could result in the production of significantly more biomass under low N supply
9 (Robinson et al. 2007). Although sugarcane varieties with improved iNUE are not currently available,
10 future N-management strategies may involve planting high iNUE varieties in fields susceptible to
11 denitrification and leaching.

12 It is apparent that N management in Australia focuses on N application rate (i.e. SIX EASY STEPS
13 and N Replacement), fertiliser placement (subsurface) and application timing (matched to crop
14 demand) to improve N uptake by the crop and lower N losses. The benefit of using alternative N
15 forms (nitrification inhibitors and controlled-release products) is still to be validated over a range of
16 climate and soil conditions, but early indications are that they have potential to contribute towards
17 improved N uptake and lower N losses (Wang et al. 2012; Wang et al. 2008b) in the short-term future.
18 A longer-term prospect may be the use of sugarcane varieties with higher iNUE (Robinson et al.
19 2007). Although N application rates have been reduced (both voluntarily and legislatively) in an
20 attempt to reduce N losses by better matching fertiliser inputs to crop requirements, current N
21 calculation methods are limited in their ability to match N fertiliser inputs to forthcoming crop
22 requirements.

23 The SIX EASY STEPS program uses predetermined district yield potential (DYP) values in the
24 determination of N fertiliser recommendations as it assumes that the forthcoming season will be
25 characterised by conditions conducive to producing the yield potential for the district (Schroeder et al.
26 2010b). Despite the ability to adjust these values for specific circumstances when blocks and sub-

1 districts continually underperform, the use of DYP still nonetheless limits the ability to adapt to annual
2 yield fluctuations caused by climatic variability. In contrast, N Replacement focuses on previous crop
3 yields rather than the yield potential for the next season, assumes environmental losses of N are low
4 and does not consider the N mineralisation potential of specific soils (Thorburn et al. 2011b).
5 Refinement of the N Replacement theory may be required to account for higher environmental losses
6 of N or become more site-specific in the calculation of environmental loss values (Thorburn et al.
7 2011b). Different N requirement factors are also used to calculate N fertiliser application rates for
8 each system (Schroeder et al. 2010a). The suitability of these factors for sugarcane grown in the Wet
9 Tropics is uncertain and requires further investigation. Other concerns include potential for greater
10 environmental losses of N when actual yields do not reach the DYP as used in the SIX EASY STEPS
11 program (Thorburn et al. 2011b; Thorburn and Wilkinson 2012) and the possibility that the N
12 Replacement strategy may restrict productivity when favourable growing conditions are experienced
13 and cane yield exceeds the yield of the previously harvested crop (Schroeder et al. 2009b).

14 It is common BMP for nutrients, including N, to be aligned with potential or target yields (Thorburn
15 and Wilkinson 2012). Both the SIX EASY STEPS and South African soil-specific N strategies
16 consider potential yield in calculations of N fertiliser requirements. Although the use of a
17 predetermined district yield potential is most evident in the SIX EASY STEPS strategy, incorporation
18 of different bioclimatic regions and moisture regimes in the South African system acknowledges
19 differences in cane production (yield) potentials throughout the industry (Meyer and Wood 1994;
20 Meyer et al. 1986).

21 To better align N fertiliser inputs with crop requirements, more accurate yield estimates need to be
22 produced and used to calculate requirements for N fertiliser on an annual basis, instead of using a
23 predetermined yield potential. The difficulty of predicting weather conditions for the upcoming
24 growing season has been identified as a limitation to the formulation of N fertiliser input strategies on
25 an annual basis in the SIX EASY STEPS program (Schroeder et al. 2010b). Forecasts of the climatic
26 conditions likely to be experienced during the sugarcane growing season (i.e. spring and summer) may

1 help improve yield estimates used in the generation of N fertiliser guidelines (Schroeder et al. 2010b).
2 Climate forecasts may also improve decisions related to N fertiliser application timing, frequency
3 (single vs. split) and the potential to use alternative N forms (i.e. nitrification inhibitors and controlled
4 release products) to improve N uptake and reduce N losses. Over-fertilisation and environmental
5 losses of N may be reduced by combining these practices into an overall N management strategy
6 which has the flexibility to adapt to climate conditions. However, the possibility of using seasonal
7 climate forecasts to guide N management strategies in sugarcane is uncertain.

8

9 2.4.2.2 Climate and sugarcane production

10 Climatic conditions experienced during the sugarcane growing season have a profound influence on
11 cane and sugar yields and is largely responsible for regional and seasonal productivity fluctuations
12 (Everingham et al. 2001; Everingham et al. 2003; Muchow et al. 1997; Bezuidenhout and Schulze
13 2006; Salter and Schroeder 2012). The ideal growing environment for sugarcane is where rainfall (or
14 irrigation) is well distributed throughout the summer growing season, sunshine is plentiful and there is
15 a relatively dry and cool pre-harvest ripening period (James 2004). In Australia prolonged heavy
16 rainfall during the 2010 harvest season resulted in wet weather harvesting damage, 5.5 Mt of cane
17 being left to standover (Kingston 2011) and unfavourable growing conditions that restricted crop
18 growth and contributed to the extremely poor yields recorded across most districts in 2011. Further
19 losses were suffered in the northern district following the crossing of Tropical Cyclone Yasi over Tully
20 in February 2011. The Tully mill area average cane yield of 47 t cane/ha for the 2011 season was the
21 lowest since 1948 and greatly below the 10-year average of 84 t cane/ha (Anon 2012). Annual
22 productivity variations caused by extreme weather events have implications for all sectors of the sugar-
23 industry value chain.

24 Climate variability also has an indirect impact on industry profitability as it influences planting and
25 harvesting strategies, nutrient, pesticide and irrigation management, season operating times, mill
26 maintenance programs, marketing strategies, sugar transport and storage arrangements (Everingham et

1 al. 2002a; Antony et al. 2002; Everingham et al. 2002b; Muchow et al. 1997). Sugarcane yield
2 estimates before the commencement of the harvest season are required for milling and marketing
3 purposes. The difference between initial estimates and actual sugarcane yields in the Australian
4 sugarcane industry has reported to range from an over estimate of 25% to an underestimate of 22%
5 (Everingham et al. 2003). With the exception of pest or disease outbreak, these large differences can
6 be attributed to swings in climatic conditions. Knowledge of the different climate systems influencing
7 rainfall patterns over sugarcane production areas and the ability to use their signals for forecasting
8 seasonal climatic conditions can help improve management decisions across all sectors of the
9 sugarcane-industry value chain.

10 The El Niño Southern Oscillation (ENSO) is one of the largest sources of inter-annual climate
11 variability over most of the Pacific region including sugarcane production areas in Africa, India,
12 central America and Australia (Partridge 1994; Allan et al. 1996; Aguado and Burt 2004). The oceanic
13 component of ENSO has two extreme but closely linked phases: El Niño and La Niña (Allan et al.
14 1996). El Niño refers to the unusual warming of normally cool water in the central and eastern
15 equatorial Pacific, resulting in widespread rainfall over much of the equatorial Pacific, parts of the
16 Indian Ocean and eastern equatorial Africa, while many areas of western Pacific, Australia, South-East
17 Asia, northern India, southeastern and Sahelian Africa and northeastern South America experience
18 drier conditions than normal and possibly drought (Aguado and Burt 2004; Trenberth 1997; Allan et
19 al. 1996; Partridge 1994; Cai et al. 2001). Conversely, La Niña refers to increased warming of water
20 in the western Pacific Ocean and extensive cooling of water in the central and eastern Pacific Ocean.
21 Rainfall and storm activity increases over Australia, South-East Asia, northern India, southeastern and
22 Sahelian Africa and northeastern South America and reduces over the central and southern region of
23 South America (Partridge 1994; Allan et al. 1996; Aguado and Burt 2004). Tropical cyclones also
24 tend to be more frequent over the western Pacific during La Niña events (Partridge 1994). Once
25 established ENSO events usually last for around 12 months; however, they can be shorter or much
26 longer.

1 The Southern Oscillation represents the atmospheric component of ENSO. Changes in the strength
2 and phase of the Southern Oscillation are measured by the Southern Oscillation Index (SOI) (Partridge
3 1994; McBride and Nicholls 1983; Kuhnel 1994). The most commonly used Troup SOI measures the
4 monthly differences in mean sea-level air pressure between Tahiti (in the central Pacific) and Darwin
5 (Australia), and ranges from around -35 to +35 (Partridge 1994; McBride and Nicholls 1983; Kuhnel
6 1993). Negative (positive) values of the SOI are typically associated with the El Niño (La Niña)
7 phase.

8 Extreme ENSO events have a significant impact on sugarcane productivity and harvest management
9 in the Australian sugarcane industry (Kuhnel 1994). The SOI and sea surface temperatures (SST) for
10 selected regions within the Pacific Ocean have been identified as useful predictors of seasonal rainfall
11 in northeastern Australia where the majority of sugarcane is grown (McBride and Nicholls 1983; Cai et
12 al. 2001; Russell et al. 1992). The SOI alone can be used to forecast sugarcane yields for specific mill
13 and terminal areas, especially in north Queensland (Kuhnel 1993; Kuhnel 1994). The chance of above
14 average cane yields is higher than climatology for mills in the Wet Tropics region, such as Mulgrave
15 and Tully when the October-November SOI remains deeply negative (Everingham et al. 2003). This is
16 because deeply negative SOI values during October-November favor lower summer rainfall, which in
17 these wetter districts generally has a positive impact on cane growth owing to increased solar radiation
18 (Everingham et al. 2003). Similarly, for the Mourilyan terminal region in north Queensland, a deeply
19 negative (deeply positive) SOI value at the end of November suggests it is highly likely that cane
20 yields will be above (below) average for the next harvest season (Everingham et al. 2002a).

21 Seasonal climate forecasting has been used in the Australian sugarcane industry to help manage the
22 impact of climate variability on growing, harvesting, milling and marketing operations (Everingham et
23 al. 2003; Everingham et al. 2001; Everingham et al. 2002a; Everingham et al. 2005). Millers and
24 marketers can use seasonal climate forecasts to improve yield estimates so they can make more
25 informed management decisions related to crop size. Knowledge of crop size allows marketers to
26 refine selling and storage strategies and hopefully increase industry profitability, whereas the miller is

1 better able to plan activities related to mill maintenance programs and harvest logistics (Everingham et
2 al. 2008b; Everingham et al. 2005; Antony et al. 2002; Everingham et al. 2002a; Everingham et al.
3 2002b). For growers, climate forecasts covering the harvest season can be used to develop harvest
4 plans for a 'wet' (or 'dry') harvest to minimise wet weather disruptions and damage to fields and
5 hopefully avoid standover (Everingham et al. 2008b; Antony et al. 2002; Everingham et al. 2002a;
6 Everingham et al. 2002b). Climate forecasts can also be used to improve irrigation scheduling,
7 especially when water supplies are scarce (Everingham et al. 2008a; Everingham et al. 2002b).

8 The South African and Swaziland sugarcane industries have also identified the potential for
9 seasonal climate-forecasting information to improve management decisions in the growing, milling
10 and marketing sectors. In South Africa, sugarcane yields tend to be lower in years when the monthly
11 SOI values for October to November remain deeply negative, as there is a higher probability of low
12 summer rainfall (Singels and Bezuidenhout 1998, 1999). Observed weather data is combined with
13 historical climate sequences representative of likely future climatic conditions or mid to long range
14 climate forecasts and entered into computer crop models such as CANEGRO (Singels and
15 Bezuidenhout 2002; Inman-Bamber 1991) or CANESIM (formerly called IRRICANE) (Singels et al.
16 1998) to forecast seasonal sugarcane yields (Singels et al. 1999; McGlinchey 1999; Bezuidenhout and
17 Schulze 2006; Schmidt et al. 2004). Seasonal sugarcane-yield forecasts can be used to assist irrigation
18 management, harvest scheduling, crop husbandry decisions, planning mill-season length, haulage
19 scheduling and mill maintenance and marketing, pricing and storage strategies in South Africa (Singels
20 et al. 1999; Schmidt et al. 2004). In Swaziland, improved estimation of forthcoming crop yields was
21 identified as having the potential to assist growers estimate transport requirements, ripening strategies
22 and harvest schedules and millers' estimates of season length and harvest commencement, and plan
23 maintenance programs (McGlinchey 1999).

24 It is evident that seasonal climate forecasts can be used to improve decision making capabilities
25 across different sectors of the sugarcane value chain. Regrettably, there is little evidence at the grower
26 level of seasonal climate forecasts being used to guide N-management strategies. If seasonal climate

1 forecasts can be used to guide other crop management decisions such as harvesting and irrigation
2 scheduling, why can't they be used in the development of strategies to help minimise N losses and
3 improve the economic return from N fertiliser investment?

4

5 2.4.2.3 Seasonal climate forecasting for improved nitrogen management

6 There is no doubt that climate has a profound influence on cane growth and final yields and is
7 largely responsible for regional and seasonal productivity fluctuations. In north Queensland sugarcane
8 growing districts, higher (lower) than average rainfall during spring and summer is often linked to
9 lower (higher) cane yields (Schroeder et al. 2010b). The SOI can be used to forecast the occurrence of
10 'wetter' and 'drier' than average rainfall conditions and hence lower or higher cane yields (Section
11 2.4.2.2). As climate influences crop growth, and N-demand and N-loss processes, predictions of
12 climatic conditions during the sugarcane growing season (i.e. spring and summer) could be used to
13 refine N-management strategies.

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

1 Sugarcane growers in the Tully district of the Wet Tropics region identified the potential of using
2 seasonal climate forecasting to assist fertiliser, harvesting, planting and herbicide management
3 decisions (Jakku et al. 2007). In particular, these growers wanted to investigate the possibility of
4 improving N-fertiliser management to reduce environmental losses whilst maintaining or improving
5 productivity (Everingham et al. 2006; Thorburn et al. 2011c). Varying N-fertiliser rates, split
6 applications and the use of seasonal climate forecasts to guide application timing were identified as
7 potential strategies (Thorburn et al. 2011c). Researchers worked with the growers to assess these
8 management strategies using the Agricultural Production Systems sIMulator (APSIM) sugarcane
9 cropping systems model (Keating et al. 2003) and seasonal rainfall forecasts based on the SOI phase
10 system (Stone and Auliciems 1992). Split application of N fertiliser every year was simulated to be
11 the most sustainable strategy, but the response varied with soil type (best response on coarse textured
12 soils). However, growers believed the environmental and economic benefits weren't large enough to
13 routinely implement this practice (Thorburn et al. 2011c). The predicted economic benefit was a 5%
14 median increase in partial gross margin over the long-term (Everingham et al. 2006). This small
15 increase is unlikely to convince growers to adopt this strategy for the inconvenience associated with
16 splitting fertiliser applications, especially at a time when many other crop-management practices also
17 require completion (i.e. weed control, hilling up plant cane, applying pest control). The study also
18 identified that the positive effects of split applications were greatest in years receiving above-average
19 rainfall. This is likely to be due to higher cane yields and lower N losses being modeled following
20 split application of N fertiliser every year (Thorburn et al. 2011c).

21 The impact of splitting N applications based on the SOI phase at the time of fertiliser application
22 (i.e. split if SOI phase consistently positive at time x) was also investigated but predicted to have a
23 lower economic and environmental benefit than splitting in all years (Everingham et al. 2006). This is
24 because there were years when the SOI phase did not correlate with the amount of rainfall received.
25 Here, the management strategy suited the forecasted rainfall, not the observed rainfall.

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

10 The use of seasonal climate forecasting to improve N-management strategies in agriculture is not a
11 new concept with many cropping systems already looking beyond yield-forecasting capabilities. In
12 Australia, SOI phase-based seasonal climate forecasts (Stone and Auliciems 1992; Stone et al. 1996)
13 are used in conjunction with crop growth models to improve N-management decisions in wheat-
14 cropping systems. Although the responsiveness of N-management strategies to ENSO-based climate
15 forecasts appears to be inconsistent, the majority of research indicates that SOI phase-based N
16 management is beneficial in wheat-cropping systems (Hammer et al. 1996; Wang et al. 2008a; Yu et
17 al. 2008; Asseng et al. 2012). As early as 1996, adjusting N-fertiliser rates based on the SOI phase
18 system (Stone and Auliciems 1992; Stone et al. 1996) was simulated to increase profits by up to 20%
19 in the Queensland wheat-belt (Hammer et al. 1996). Since then, research has been directed towards
20 better understanding the potential for seasonal climate forecasting to improve N management at
21 different Australian wheat-growing locations.

22 In southeast Australia, changing application rates for N fertiliser based on SOI phases was predicted
23 to increase wheat gross margins by 8%, 13% and 20% when the April-May SOI phase was
24 negative/falling, zero, and positive/rising, respectively, compared to current N-management practices
25 for the region of a fixed application of 100 kg N/ha (Wang et al. 2008a). In addition, SOI phase-based
26 N management was also compared to using the long-term average optimal N rate (a fixed application

1 of 150 kg N/ha) derived from long-term climate records for the region (Wang et al. 2008a). While SOI
2 phase-based N management was still beneficial, the value was much smaller with gross margins
3 predicted to increase by 3%, 0% and 1% when the April-May SOI phase was negative/falling, zero and
4 positive/rising, respectively (Wang et al. 2008a). Although these financial increases are relatively
5 small, the fact that sugarcane is produced in areas vulnerable to extreme climatic variability and sold in
6 a volatile market, any improvement in gross margins will be beneficial.

7 The value of a 'perfect' climate forecast for N management purposes in a wheat cropping system in
8 southeast Australia has also been simulated for two locations with contrasting rainfall. Compared with
9 the long-term average optimal N rate derived from long-term climate records, adjusting N application
10 rates based on a 'perfect' climate forecast was estimated to generate an average benefit of \$65.2/ha and
11 \$66.5/ha for the high and low rainfall areas, respectively (Yu et al. 2008).

12 More recently different approaches to N-fertiliser management in the Western Australian wheat-belt
13 have been investigated using the Predictive Ocean Atmosphere Model for Australia (POAMA)
14 (Asseng et al. 2012). The POAMA seasonal rainfall-forecasting system could improve gross margins
15 by \$50/ha when used for N management decisions in the southern region of Western Australia's
16 wheat-belt (Asseng et al. 2012).

17 Compared to wheat, the sugarcane industry has spent very little effort investigating the potential for
18 SOI phase-based N management, even though there is relatively high forecasting skill in areas where
19 the majority of sugarcane is grown (McBride and Nicholls 1983; Cai et al. 2001; Russell et al. 1992;
20 Kuhnel 1994; Everingham et al. 2003). Results from the grains industry indicate that there is potential
21 for seasonal climate forecasts to improve N management in Australian sugarcane. The importance of
22 using historical climate knowledge to understand responsiveness to applied N under different climate
23 scenarios should also not be ignored in future attempts to improve sugarcane N management.
24 Historical climate knowledge is an important tool that can be used to improve our understanding of
25 crop performance and N-management strategies under different climate scenarios (Wang et al. 2008a;
26 Yu et al. 2008).

1 Despite considerable research efforts into seasonal climate forecasting for improved N management
2 in grain production, a survey conducted in northern New South Wales revealed that the majority of
3 growers favoured simplistic approaches to varying N fertiliser rates (i.e. block history, recent yields,
4 protein levels and length of fallow) (Hayman and Alston 1999). Soil testing, monitoring stored soil
5 water and using seasonal climate forecasts to guide N management was considered too complex
6 (Hayman and Alston 1999). In addition, it was found that seasonal climate forecasting based on the
7 SOI was seldom used when making decisions about N fertiliser management. However, Australian
8 sugarcane growers are already using a combination of simple and complex approaches to determine
9 the nutritional requirement of each crop (Schroeder et al. 2007b; Schroeder et al. 2005a). If seasonal
10 climate forecasting can be used in a way that removes the perceived inconvenience of split applying N,
11 it is likely to gain acceptance and hopefully result in greater on-ground adoption than experienced
12 elsewhere.

13 Although simulated SOI phase-based N management outcomes in wheat-cropping systems have not
14 always been validated under commercial field conditions, APSIM has undergone extensive
15 development and scientific testing for various Australian wheat-growing locations so that it can be
16 used to evaluate proposed changes to N management (Keating et al. 2003). APSIM has also been used
17 to investigate various issues related to N management in sugarcane (Thorburn et al. 1999; Thorburn et
18 al. 2001; Thorburn et al. 2011a; Stewart et al. 2006; Thorburn et al. 2004b; Verburg et al. 1996;
19 Robertson and Thorburn 2007). To gain recognition as part of the sugarcane industry's accepted best-
20 management practice options, N-management strategies based on seasonal climate forecasts will have
21 to be evaluated thoroughly. This will include rigorous field testing to ensure that simulation-based
22 benefits from crop models such as APSIM are realistically achievable for commercial sugarcane-
23 farming enterprises.

24

25 **3. Conclusions**

1 Losses of nutrients, sediment and pesticides from agricultural production systems, including
2 sugarcane cultivation, have been linked to water quality decline and the subsequent degradation of
3 coastal marine ecosystems (Brodie et al. 2001; Waterhouse et al. 2012; Brodie and Mitchell 2005).
4 Increased emphasis on minimising environmental degradation is likely to place further restrictions on
5 sugarcane production practices into the future and this may reduce profitability. To help ensure that
6 water-quality targets are met and the introduction of more stringent regulations avoided, further
7 research is required to better understand the impact of natural climate variability on sugarcane N-use
8 efficiency. The development of N-management strategies that optimise profit and minimise
9 environmental losses for different climatic conditions will be a major challenge.

10 In Australia, just over 60% of the N fertiliser applied is recovered in the sugarcane crop and
11 surrounding soil (Prasertsak et al. 2002; Chapman et al. 1991; Vallis and Keating 1994). Unrecovered
12 N is either stored in the soil or presumed to be lost from the sugarcane production system, primarily
13 through denitrification and leaching processes as management strategies have been adopted to reduce
14 ammonia volatilisation losses (Prasertsak et al. 2002; Freney et al. 1994; Calcino and Burgess 1995;
15 Freney et al. 1991; Prammanee et al. 1989; Wood et al. 1989). N-loss processes are influenced by soil
16 type, position in the landscape, rainfall amount and intensity, fertiliser form, placement, application
17 timing and rate (Wood et al. 2010a). Sugarcane growers can improve N uptake and reduce the
18 potential for N losses by applying N fertilisers at recommended rates in the correct location and at the
19 right time. The SIX EASY STEPS nutrient-management program incorporates soil type and position
20 in the landscape into the formulation of soil- and site-specific N-management guidelines (Schroeder et
21 al. 2005a; Schroeder et al. 2007b). Although climatic conditions such as rainfall amount and intensity
22 cannot be controlled, options are available to help reduce the impact on N losses.

23 Seasonal climate forecasts are being used to improve decision making capabilities across different
24 sectors of the Australian sugarcane value chain. At the grower level, it is surprising that seasonal
25 climate forecasts are not being used to guide N-management strategies domestically or internationally.
26 Seasonal climate forecasts provide probabilistic information about future climatic conditions. As

1 climate is a key driver of crop growth, and N-demand and N-loss processes, prediction of climatic
2 conditions during the sugarcane growing season (i.e. spring and summer) could be used to refine N-
3 management strategies. It is highly likely that N-management strategies will need to be different for
4 'wet' and 'dry' years. Information generated from the seasonal climate forecast could be used to
5 formulate the most appropriate N-management strategy.

6 Seasonal climate forecasts could be used to guide application timing and/or frequency of N inputs
7 and the benefit of using alternative forms of N fertiliser (i.e. nitrification inhibitors and controlled
8 release products). The current methods that can be used to calculate requirements for N fertiliser in the
9 Australian sugarcane industry are limited in their ability to match N-fertiliser inputs to forthcoming
10 crop yields. The SIX EASY STEPS program uses predetermined yield potentials to determine N-
11 fertiliser requirements, whereas N Replacement uses the yield of the previously harvested crop. As it is
12 common to align N-application rates with potential or target yields, seasonal climate forecasts could be
13 used to improve yield estimates used in the calculation of N-fertiliser requirements in the SIX EASY
14 STEPS program (Schroeder et al. 2010b).

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

20

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3

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