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Improving sugarcane nitrogen management in the Wet Tropics using seasonal climate forecasting

Thesis submitted by

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in June 2015

for the degree of Doctor of Philosophy

in the College of Science, Technology and Engineering

James Cook University

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Abstract

The Wet Tropics sugar industry experiences one of the highest levels of inter-annual climate variability in the world. This has a significant impact on cane yields and nitrogen losses and makes the task of applying the right amount of nitrogen fertiliser to optimise profitability and minimise environmental losses extremely challenging. Improvements in fertiliser nitrogen use efficiency will be required to ensure the economic and environmental sustainability of the Wet Tropics sugar industry.

The size of the crop (cane yield) largely determines how much nitrogen fertiliser should be applied. Spring-summer rainfall was found to have a strong influence on Tully cane yields. Nitrogen fertiliser requirements in dry (i.e. low spring-summer rainfall) and wet (i.e. high spring-summer rainfall) years for ratoon sugarcane crops grown on the Bulgun series soil were investigated in a simulation study. As the majority of nitrogen fertiliser is typically applied to ratoon sugarcane crops during spring, seasonal climate forecasting indices based on sea surface temperature anomalies in the central equatorial Pacific Ocean were also investigated for their utility to predict nitrogen fertiliser requirements with sufficient lead-time.

The simulation study identified nitrogen fertiliser requirements are on average, 25% lower in wet years, defined as the June to August Oceanic Niño Index being in the La Niña phase, for ratoon sugarcane crops grown on the Bulgun series soil. The June to August Oceanic Niño Index can be used to predict nitrogen fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil. Sugarcane growers should consider reducing nitrogen fertiliser application rates to ratoon sugarcane crops grown on the Bulgun series soil when the June to August Oceanic Niño Index is in the La Niña phase. This is because the chance of experiencing high spring-summer rainfall at Tully increases when the June to August Oceanic Niño Index is in the La Niña phase.

Given that high spring-summer rainfall is associated with lower cane yields, reducing nitrogen fertiliser rates in wet years will improve fertiliser nitrogen use efficiency. Reducing nitrogen fertiliser rates below the SIX EASY STEPS nitrogen guidelines to sugarcane ratoon crops grown on the Bulgun series soil, every year, will also improve fertiliser nitrogen use efficiency. Despite delivering an environmental benefit, reducing

nitrogen fertiliser rates every year will reduce productivity and profitability. Future research should focus on understanding the full economic, environmental and social benefits of these strategies

Older ratoons were found to recover less nitrogen in total, than younger ratoons, but were more reliant on fertiliser nitrogen. This indicates nitrogen fertiliser guidelines should be reviewed for ratoon sugarcane crops grown on the Bulgun series soil. The current SIX EASY STEPS nitrogen management guidelines do not differentiate nitrogen fertiliser requirements between ratoon sugarcane crops. More research is required to quantify the nitrogen recovery of successive ratoon sugarcane crops grown on other major soil types occurring throughout the Wet Tropics region before revising the SIX EASY STEPS N management guidelines.

This thesis significantly advances the application of climate forecasting indices for nitrogen fertiliser management in agricultural crops and improves the understanding of nitrogen recovery by sugarcane crops. The knowledge generated will contribute towards the development of nitrogen fertiliser management practices that will ensure both the economic and environmental sustainability of the Wet Tropics sugar industry.

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Publications

Chapter	Details of publication(s)	Status
1	Skocaj, D.M., Everingham, Y.L., Schroeder, B.L., (2013) Nitrogen Management Guidelines for Sugarcane Production in Australia: Can These Be Modified for Wet Tropical Conditions Using Seasonal Climate Forecasting? Springer Science Reviews, **1**(1-2): 51-71.	Published
2	Skocaj, D.M., Everingham, Y.L., (2014) Identifying climate variables having the greatest influence on sugarcane yields in the Tully Mill area. Proceedings of the Australian Society of Sugar Cane Technologists **36**: CD-ROM: 9pp.	Published
3	Skocaj, D.M., Hurney, A.P., Inman-Bamber, N.G., Schroeder, B.L., Everingham, Y.L., (2013) Modelling sugarcane yield response to applied nitrogen fertiliser in a wet tropical environment. Proceedings of the Australian Society of Sugar Cane Technologists: **35**: CD-ROM: 9pp.	Published
4	Skocaj, D.M., Everingham, Y.L., Schroeder, B.L., (in preparation) Should N fertiliser application rates for sugarcane be reduced in wet years? Insights from a simulation study. To be submitted to Agronomy for Sustainable Development	In preparation
5	Skocaj, D.M., Schroeder, B.L., Everingham, Y.L., (in preparation) Understanding nitrogen recovery and fertiliser nitrogen use efficiency of sugarcane ratoon crops: results from small plot N rate field experiments conducted on a Grey Dermosol in the Wet Tropics region of North Queensland, Australia. To be submitted to Field Crops Research	In preparation

Thesis Overview

The Wet Tropics sugar industry of northern Australia experiences one of the highest levels of climate variability in the world (Nicholls et al., 1997). This has a significant impact on cane yields (Everingham et al., 2001, Everingham et al., 2003) and nitrogen (N) losses (Brodie et al., 2012), and makes the task of applying the right amount of nitrogen fertiliser to optimise profitability and minimise environmental losses extremely challenging. Improvements in fertiliser nitrogen use efficiency will be required to ensure the economic and environmental sustainability of the Wet Tropics sugar industry and meet water quality improvement targets. Water quality improvement targets include a 50% reduction in dissolved inorganic nitrogen levels entering the Great Barrier Reef Lagoon by 2018 (*Reef 2050 Long-Term Sustainability Plan*, Commonwealth of Australia 2015). To improve sugarcane nitrogen management in the Wet Tropics, this thesis had four main objectives:

1. to identify atmospheric climate variables having the greatest influence on Tully sugarcane yields;
2. to investigate the capability of a crop model to simulate cane yield response to nitrogen fertiliser in a wet tropical environment;
3. to determine the impact of climatic conditions on the nitrogen fertiliser requirements of sugarcane growing on the Bulgun series soil;
4. to evaluate nitrogen recovery and fertiliser nitrogen use efficiency of ratoon sugarcane crops growing on the Bulgun series soil;

The objectives of this thesis required the integration of a sugarcane crop model, statistical methods and small-plot N fertiliser rate response field experiments. The Agricultural Productions Systems Simulator (Keating et al., 1999) 'Sugar' module was the crop model used and is referred to as APSIM-Sugar throughout the thesis. The Bulgun series soil was selected because it is widespread throughout the Wet Tropics sugar industry and is a major soil type of the Tully mill area. A flow diagram of the thesis structure is presented in Figure 1a.

This thesis is composed of six chapters. The literature review presented in Chapter 1 provides an overview of the operating environment of the Australian sugarcane industry. It discusses the evolution of sugarcane nitrogen management and the impact of climatic conditions on sugarcane production, describes climate systems influencing rainfall patterns over sugarcane production areas and outlines how seasonal climate forecasting is currently used to improve management decisions. In addition, the information presented in Chapter 1 motivated the thesis objectives which are investigated in subsequent chapters.

Chapter 2 identifies the atmospheric climate variables and time of year having the greatest influence on sugarcane yields in the Tully mill area. The influence of spring-summer rainfall on cane yields illustrated the need to better understand the impact of natural climate variability on sugarcane N fertiliser requirements. Chapter 3 investigates the capability of APSIM-Sugar to simulate cane yields under wet tropical conditions. As APSIM-Sugar was able to explain how cane yields, as recorded in previous N fertiliser rate response field experiments may have been achieved, it was then used to perform a much larger simulation study in Chapter 4. This simulation study investigated if N fertiliser requirements differ between dry (i.e. low spring-summer rainfall) and wet (i.e. high spring-summer rainfall) years for sugarcane ratoon crops grown on the Bulgun series soil. Seasonal climate forecasting indices based on sea surface temperature anomalies in the central equatorial Pacific Ocean were also investigated for their utility to predict N fertiliser requirements with sufficient lead-time for growers to respond to this forecast.

The results of three small-plot N fertiliser rate response experiments conducted in the Wet Tropics between 2011 and 2014 were used to investigate the nitrogen recovery and fertiliser nitrogen use efficiency of ratoon sugarcane crops grown on the Bulgun series soil in Chapter 5. The thesis conclusion provided in Chapter 6 integrates the research outcomes and areas of future research identified in Chapters 2 to 5.

All chapters were structured as independent papers. Chapter 1 “Nitrogen Management Guidelines for Sugarcane Production in Australia—Can These Be Modified for Wet Tropical Conditions Using Seasonal Climate Forecasting?” (Skocaj et al., 2013a) was published as a peer reviewed journal paper in Springer Science Reviews. This manuscript was awarded Springer Science Reviews’ best literature review for 2013. Chapter 2 was published as a peer reviewed conference paper “Identifying climate variables having the greatest influence on sugarcane yields in the Tully Mill area” (Skocaj and Everingham, 2014) and the results presented at the 36th Conference of the Australian Society of Sugar Cane Technologists (28th April to 1st May 2014, Gold Coast, Queensland, Australia). This manuscript was awarded the H. William Kerr Memorial Bursary for the best agricultural student paper presented at the conference. Chapter 3 was also published as a peer reviewed conference paper “Modelling sugarcane yield response to applied nitrogen fertiliser in a wet tropical environment” (Skocaj et al., 2013b) and the results presented at the 35th Conference of the Australian Society of Sugar Cane Technologists (16th to 18th April 2013, Townsville, Queensland, Australia). Manuscripts based on the research reported in Chapters 4 and 5 are being prepared for submission to Agronomy for Sustainable Development and Field Crops Research respectively.

Figure 1.a. Flow diagram of thesis structure

Current N fertiliser guidelines are based on either a district yield potential (Schroeder et al., 2010b) or the cane yield of the previously harvested crop (Thorburn et al., 2003, Thorburn et al., 2004a). As crop size (cane yield t cane/ha) is the primary determinant of N fertiliser requirements (Keating et al., 1997), current N fertiliser guidelines are limited in their ability to match N fertiliser inputs to forthcoming cane yields. As shown in Fig. 1b, in Tully the majority of N fertiliser is typically applied to ratoon sugarcane crops during spring. Spring-summer rainfall was found to have a strong influence on Tully cane yields (Chapter 2). Therefore, knowledge of spring-summer rainfall before the majority of N fertiliser is applied (i.e. at the beginning of September) would improve the ability to match N fertiliser inputs to forthcoming cane yields.

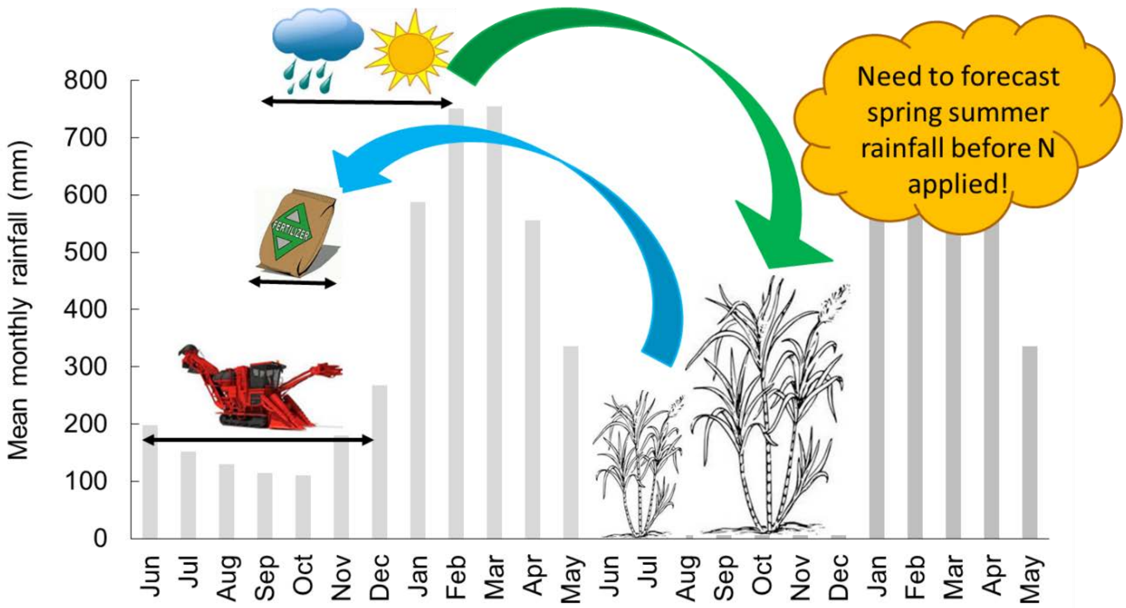

Figure 1.b. Long-term mean monthly rainfall for Tully Sugar Mill over two successive growing seasons (defined as June to May) in relation to the sugarcane harvest period, application of N fertiliser to ratoon sugarcane crops and forthcoming cane yields which are strongly influenced by spring summer rainfall and the primary determinant of N fertiliser requirements.

The use of climate forecasts to predict N fertiliser requirements has not previously been investigated for sugarcane. The simulation modelling reported in Chapter 4 supports a reduction in N fertiliser application rates in wet years, for ratoon sugarcane crops grown on the Bulgun series soil, when the June-August Oceanic Niño Index is in the La Niña phase. The link between N fertiliser inputs and the June-August Oceanic Niño Index exists because the chance of experiencing high spring-summer rainfall increases when the June-August Oceanic Niño Index is in the La Niña phase. High spring summer-rainfall is associated with lower cane yields at Tully because of increased waterlogging and lower solar radiation.

The fate of fertiliser N not recovered by the sugarcane crop, immobilised in soil N pools and/or lost from the sugarcane production system, is of significant importance for the economic and environmental sustainability of the Wet Tropics sugar industry. The small-plot N fertiliser rate response field experiments (Chapter 5) highlight older ratoons recover less N in total, than younger ratoons, but are more reliant on fertiliser N than soil N sources. This is a major outcome as pervious research has not quantified differences in fertiliser N recovery between ratoon crops. The SIX EASY STEPS N fertiliser guidelines for the Wet Tropics region (Schroeder et al., 2007) do not differentiate N fertiliser requirements between ratoon sugarcane crops. However, these results suggest current N fertiliser guidelines should be reviewed for ratoon sugarcane crops grown on the Bulgun series soil.

This thesis has identified strategies to improve sugarcane N management in the Wet Tropics which will lead to greater fertiliser nitrogen use efficiency and support environmental guidelines for improving water quality in the Great Barrier Reef Lagoon. This includes reducing N fertiliser rates in wet years to ratoon sugarcane crops grown on Bulgun series soil and differentiating N fertiliser rates between ratoon crop classes. Fertiliser N-use efficiency can also be improved by reducing N fertiliser rates below the SIX EASY STEPS N guidelines to ratoon sugarcane crops grown on Bulgun series soil, every year, but this will reduce grower and industry profitability

The sugar industry in partnership with the broader society should explore the full economic, environmental and social benefits of these strategies. For example, preliminary investigations conducted in Chapter 5 identified that whilst reducing N fertiliser rates to ratoon sugarcane crops grown on the Bulgun series soil every year would deliver an environmental benefit, this strategy would reduce profitability. The knowledge generated from this thesis will contribute towards the development of N fertiliser management practices that will ensure both the economic and environmental sustainability of the Wet Tropics sugar industry.

Chapter 1

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

This chapter provides a general overview of sugarcane production before focusing on the operating environment of the Australian sugarcane industry. It discusses the evolution of sugarcane nitrogen management and the impact of climatic conditions on sugarcane production, describes climate systems influencing rainfall patterns over sugarcane production areas and outlines how seasonal climate forecasting is currently used to improve management decisions. It highlights a pressing need for N management strategies that deliver superior environmental and economic outcomes and motivates the thesis objectives which are investigated in subsequent chapters. This chapter has been published and the citation is: Skocaj DM, Everingham YL and Schroeder BL (2013) Nitrogen Management Guidelines for Sugarcane Production in Australia—Can These Be Modified for Wet Tropical Conditions Using Seasonal Climate Forecasting? Springer Science Reviews **1** (1-2): 51-71

1.1. Introduction

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

The location of sugarcane production areas in close proximity to sensitive environments necessitates the development and adoption of sustainable production practices. The Australian sugarcane production system has evolved to include a suite of best management practices focused on maintaining productivity, improving profitability and minimising the movement of sediment, nutrients and pesticides off farm (Christiansen, 2000, Hurney et al., 2008, Schroeder et al., 2008, Smith, 2008, Schroeder et al., 2009a). Although these practices have been largely successful in achieving the desired outcomes, loss of nitrogen (N) from sugarcane production remains a serious impairment to improved environmental sustainability and profitability (Vallis and Keating, 1994, Prasertsak et al., 2002, Macdonald et al., 2009, Calcino et al., 2010, Denmead et al., 2010, Schroeder et al., 2010a, Thorburn et al., 2011b, Wang et al., 2012).

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

The focus of N-fertiliser management in the Australian sugarcane industry has recently shifted from production maximization to profit optimization and most recently improved environmental sustainability (Schroeder et al., 1998, Wood et al., 1997, Wood et al., 2003, Thorburn et al., 2011b). Two N management calculation systems developed in the Australian sugarcane industry are SIX EASY STEPS and N Replacement. The SIX EASY STEPS nutrient-management program aims to deliver soil- and site-specific N-fertiliser guidelines for sustainable sugarcane production (Schroeder and Wood, 2001, Wood et al., 2003, Schroeder et al., 2005a, Schroeder et al., 2005b, Schroeder et al., 2006, Schroeder et al., 2007a, Schroeder et al., 2009b, Schroeder et al., 2009c, Calcino et al., 2010, Schroeder et al., 2010a, Schroeder et al., 2010b). The N Replacement system aims to replace the amount of N removed by the previously harvested crop (Thorburn et al., 2003, Thorburn et al., 2004). However, both systems are limited in their ability to alter N management strategies to cater for changes in climatic conditions experienced during the current growing season or those predicted for the forthcoming season.

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

1.2. The Sugarcane Plant

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

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

1.3. Sugarcane Products and Uses

Sugarcane is the fastest growing, largest biomass and highest sucrose-accumulating agricultural crop in the world. It is primarily grown for the production of sugar-based products, ranging from raw to refined white sugar and specialty products. With these products meeting the dietary requirements of both high and low income consumers around the world, sugarcane is the largest contributor of dietary carbohydrate for human consumption after cereal crops (Brumbley et al., 2008). There is also a small but profitable specialty market for organically produced sugar, most of which is grown and processed in Florida in compliance with strict field and factory protocols (Irvine, 2004).

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

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

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

Sugarcane can also be used to produce biofuels, bioenergy and biopolymers (Brumbley et al., 2007, Brumbley et al., 2008). Biorefineries constructed in Brazil to produce ethanol and bioplastics highlight the potential of sugarcane to offer a renewable and environmentally friendly alternative to petrochemical resources (Brumbley et al., 2007, Brumbley et al., 2008, Ferreira-Leitao et al., 2010). Similarly transgenic approaches to genetic and metabolic engineering have resulted in the production of new high-value products, allowing sugarcane to be used as a biofactory for the production of alternative sugars, bioplastics, high-value proteins and fine chemicals including nutraceuticals, industrial enzymes and pharmaceuticals (Irvine, 2004, Brumbley et al., 2007, Brumbley et al., 2008).

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

1.4. International Sugarcane Industry

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

Brazil is the largest sugarcane producer, raw-sugar exporter and manufacturer of sugarcane ethanol. In 2009-2010 Brazil grew around 40% of the total sugarcane produced (F.O.Lichts, 2010) and had 325 sugar-ethanol plants operational in 2010 (Ferreira-Leitao et al., 2010). The size of the Brazilian sugarcane industry and its flexibility to produce sugar or ethanol have a major influence on the value of raw sugar exports (Hogarth and Ryan, 2000). It also makes it difficult for other raw-sugar exporters to secure market share, especially during times of excess production. To remain competitive and profitable, other major raw sugar exporters, such as Australia, have focused on establishing a reputation as a consistent and reliable supplier of high-quality raw sugar, improving production efficiency and reducing operating expenses (Hogarth and Ryan, 2000, Mackintosh, 2000, CANEGROWERS, 2010). Australia is recognized as one of the most cost-effective sugarcane producers in the world, capable of securing market share even during times of excess production (Hogarth and Ryan, 2000, CANEGROWERS, 2010).

1.5. Australian Sugarcane Industry

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

In Australia, sugarcane is grown along 2200 km of coastline (Figure 1.1) from Mossman (S16°30',E145°30') in far north Queensland to Harwood (S29°25',E153°14') in northern New South Wales (Schroeder et al., 2008, CANEGROWERS, 2010). Encompassing an area of approximately 500 000 ha (Schroeder et al., 2008) the Australian sugarcane industry is split into five discontinuous regions: Northern, Burdekin, Central, Southern and New South Wales. These regions are situated within wet tropical and humid sub-tropical climates and are separated by areas of unsuitable soils or unreliable rainfall (Kingston, 2000, Schroeder et al., 2008).

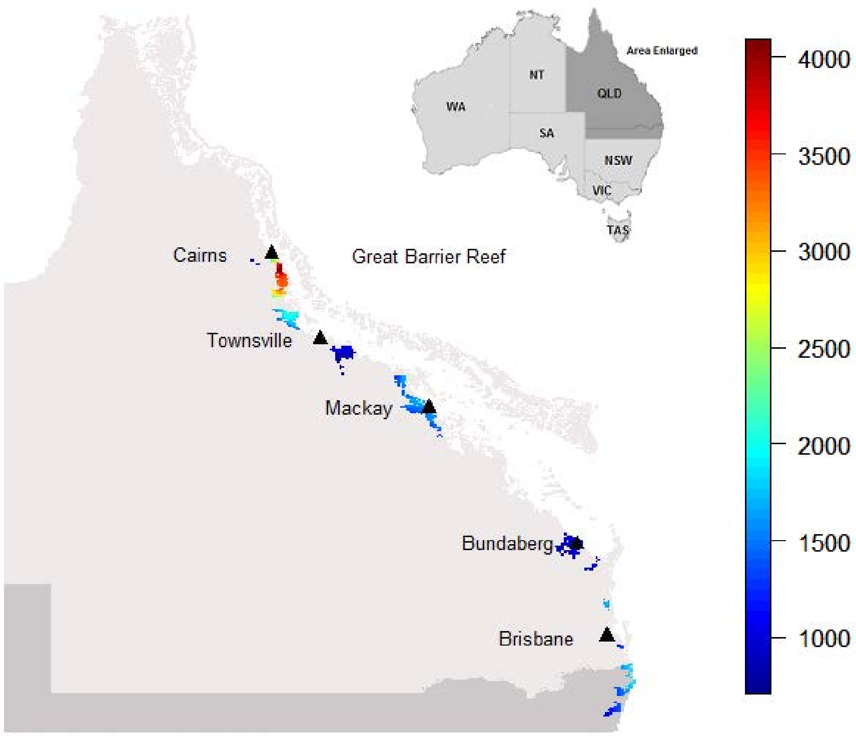

Figure 1.1. Geographical location of the Australian sugarcane industry highlighting mean annual rainfall (mm) distribution.

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

With Queensland producing approximately 95% of Australia's annual raw sugar total, it is not surprising that sugarcane is the major agricultural crop grown on the east coast (Barnes, 1974, Hogarth and Ryan, 2000, CANEGROWERS, 2010). The ability to grow sugarcane over a large area of different soil types and climatic conditions, in combination with easy access to required infrastructure, results in sugarcane being grown in preference to alternative crops. However, the period between crop cycles provides an ideal opportunity for alternative crop diversification without disrupting sugarcane production (Garside and Bell, 1999). Alternatively, sugarcane may be used in longer-term rotation with crops such as bananas in northern Queensland.

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

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

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

1.5.1. Australian Sugarcane Production System

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

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

Bell, 1999, Garside and Bell, 2001). As the break period usually coincides with the wet season, alternative crops help minimise the risk of erosion and pollutant movement off-farm. Where it is not possible to grow a well-managed legume crop, a bare fallow maintained with knockdown herbicides is the best alternative (Hurney et al., 2008). Most Australian sugarcane farming systems use a configuration of single rows separated by about 1.52 m. Transition to controlled-traffic farming systems consisting of single or dual rows separated by 1.8 to 2.0 m is gradually occurring and minimises the adverse effects of soil compaction in the cropping zone (Calcino et al., 2008). This farming system is also better suited to zonal tillage systems that only cultivate the row area. Adoption of minimum or zonal tillage land preparation practices in combination with a greater reliance on chemical weed control have reduced aggressive tillage practices and helped minimise soil disturbance in break and plant crops. Zero tillage, the practice of direct drilling sugarcane setts into undisturbed soil, is not common, as some cultivation is required to reshape the cane drill and prepare an adequate seed bed (Calcino et al., 2008). However, a recently developed direct-drill sugarcane planter based on the double-disk-opener planter concept commonly used in the grains industry has the potential to successfully operate in any cultivation system, including zero tillage (Robotham and Chappell, 2000, Robotham, 2004).

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

Crop-management practices are highly mechanized and all sugarcane is mechanically planted with whole-stalk or billet planters into a furrow or preformed mounds (Robotham, 2004) and mechanically harvested using wheel or track chopper harvesters (Ridge and Norris, 2000). Most of the industry has transitioned to green-cane harvesting and trash retention. This has been a catalyst for the adoption of zero or strategic tillage, subsurface fertiliser application and chemical weed control in ratoon crops (Willcox et al., 2000). It is also considered to be best practice providing agronomic, environmental and financial benefits to the farming system, especially when compared to traditional burnt-cane harvest systems (Smith et al., 1984, Garside et al., 1997, Braunbeck et al., 1999, Schroeder et al., 2009a).

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

1.5.2. Australian Sugarcane Production Challenges

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

Environmentally sustainable sugarcane production practices are continually being developed in an attempt to deliver superior environmental outcomes without restricting productivity or profitability. Practices such as GCTB, zonal and minimum tillage land preparation, legume cover crops or spray-out fallow management, subsurface fertiliser application and refinement of nutrient-management guidelines all aim to reduce sediment and nutrient movement off farm (Christiansen, 2000, Hurney et al., 2008, Schroeder et al., 2008, Schroeder et al., 2009a). Maintenance of grassed filter strips and vegetation along waterways and the installation of sediment traps also help to intercept and retain any sediment, nutrients and pesticides in farm runoff water

(Christiansen, 2000, Smith, 2008). Transition to these farming practices is often voluntary, as they are also associated with agronomic and economic benefits.

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

1.5.2.1. Nitrogen management in Australian sugarcane production

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

Even with the adoption of environmentally sustainable sugarcane production practices, there is a risk that 'environmental pollutants', including N, could be lost from the sugarcane production system due to external influences. As N is the nutrient most susceptible to environmental loss and applied in the greatest quantity to optimise yield, greater emphasis needs to be placed on the development of environmentally sustainability yet profitable N-management strategies (Thorburn et al., 2003, Thorburn et al., 2004a, Schroeder et al., 2009b, van der Laan et al., 2011).

1.5.2.1.1. Nitrogen sources for sugarcane production

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

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

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

In plant cane, inorganic fertilisers are often applied as mixtures at planting (Calcino et al., 2008). In ratoons, inorganic fertilisers mixtures, also known as “one shot blends”, are often urea-based products containing K (muriate of potash), possibly P (DAP) and S (ammonium sulphate) (Schroeder et al., 2009a, Thorburn et al., 2003). Alternatively, ‘straight’ products such as urea and muriate of potash may be applied instead of mixtures. The nutrient compositions for plant and ratoon fertiliser mixtures vary so that the most appropriate product can be selected to meet the nutritional requirements of the block. Liquid fertilisers include commercially available nutrient solutions that are based on inorganic fertiliser products, and dunder-based products that are usually fortified with other nutrients including N (Schroeder et al., 2009a). Mill by-products also provide a significant source of N, but, as it is in an organic form, not all the N is immediately available for plant uptake (Barnes, 1974, Calcino, 1994, Calcino et al., 2000, Mackintosh, 2000). A proportion of the applied fertiliser N remains in the soil, but this residual N contributes only small amounts of N for sugarcane growth (Chapman et al., 1992).

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

1.5.2.1.2. Nitrogen loss processes

Crops seldom assimilate more than 50% of the N applied as fertiliser (Chen et al., 2008). For sugarcane grown in Australia, research using labelled ^{15}N fertiliser has indicated maximum recoveries in the crop and surrounding soil of just over 60% of the N fertiliser applied (Chapman et al., 1991, Vallis and Keating, 1994, Prasertsak et al., 2002). The unrecovered N is either held in the soil by microbial immobilisation (Jansson and Persson, 1982) and/or lost from the sugarcane production system by a range processes including volatilisation, denitrification, leaching, erosion or runoff (Wood et al., 2010a). Ammonia volatilisation and denitrification are the dominant processes for gaseous losses of fertiliser N from Australian agriculture (Chen et al., 2008).

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

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

In addition to existing ammonia volatilization and leaching loss pathways, the moist warm climate of Australian sugarcane production regions combined with GCTB, waterlogging and the addition of N fertiliser also provides conditions conducive to denitrification (Wang et al., 2008b, Allen et al., 2010, Denmead et al., 2010). Denitrification involves the conversion of soil NO_3^- to gaseous forms of N (nitric oxide (NO), nitrous oxide (N_2O) or di-nitrogen nitrogen (N_2)) by microorganisms in anaerobic conditions (i.e. waterlogged soils) (Denmead et al., 2005). This process is driven by the availability of organic residues, NO_3^- and NO_2^- ions, high temperatures, strong acidity and anaerobic conditions (Brady and Weil, 2002). Emission of N_2O is of greatest concern from an environmental viewpoint (Wang et al., 2008b, Wang et al., 2012).

In sugarcane, high N_2O emissions can be expected from waterlogged soils with a high organic-carbon content, high mineral-N concentration and high temperature (Allen et al., 2008, Allen et al., 2010) and where GCTB is practiced because of greater soil moisture retention and increased microbial activity (Weier et al., 1998). It has been estimated that 17% of applied N fertiliser is lost to the atmosphere (Macdonald et al., 2009) with between 1.0% and 6.7% emitted as N_2O (Allen et al., 2010). Nitrous oxide emissions were recently measured under different fallow management and N fertiliser management regimes (Wang et al., 2012). After a bare fallow emissions increased from 6.3 kg to 12.3 kg N_2O N/ha following an increase in plant cane N rates (0 to 150 kg N/ha), with the highest emission, 20.9 kg N_2O N/ha, measured after a soybean break crop and the addition of 75 kg N/ha in plant cane. Relatively high N_2O emissions, 21% of the N fertiliser applied (Denmead et al., 2010), have also been measured from highly organic, acid-sulphate soils in northern NSW (Denmead et al., 2005, Denmead et al., 2010).

1.5.2.1.3. Consequences of nitrogen losses

Loss of N from the sugarcane production system can have serious environmental consequences. The apparent declining health of the Great Barrier Reef has been attributed to damaging levels of land-based pollutants entering reef waters as a result of agricultural activities, the dominant being beef grazing and sugarcane cultivation, undertaken in adjacent catchments (Brodie et al., 2001, Bainbridge et al., 2009, Benn et al., 2010, Brodie et al., 2010, Thorburn et al., 2011c). At a regional scale, the Wet Tropics has been estimated to deliver the highest anthropogenic dissolved inorganic nitrogen (DIN) load to the Great Barrier Reef lagoon (Waterhouse et al., 2012, Kroon et al., 2012). The loss of N fertiliser applied to sugarcane fields contributes a large proportion of the anthropogenic load of DIN in this region (Waterhouse et al., 2012). At the local level, catchment water-quality monitoring programs have been undertaken to identify the source and quantity of land-based pollutants entering reef waters. The monitoring of suspended sediments, nutrients and pesticides in waterways of the Tully-Murray catchment in the Wet Tropics region undertaken by (Bainbridge et al., 2009) is just one example. Although it is difficult to easily isolate pollutant discharge from single land uses within the Tully-Murray catchment, elevated NO_3^- concentrations were measured in waterways draining sugarcane land (Bainbridge et al., 2009).

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

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

The magnitude of N losses and low recoveries of fertiliser N by the sugarcane crop are also of significant economic importance to the sugarcane industry (Haysom et al., 1990). Investment in N fertiliser represents a relatively large component of farm production costs - approximately 30% of the average on-farm budget is associated with nutrient inputs (Schroeder et al., 2005b). Therefore, loss of applied N from the sugarcane production system may represent a serious economic loss to the grower (Anich and Wegener, 1992, Chen et al., 2008, Wood et al., 2010b). The magnitude of economic losses will be influenced by the cost of N fertiliser, sugar price and the effect on cane yield. Substantial losses of applied N may severely reduce the amount of N that is available for crop growth. Insufficient N supply, especially under favourable growing conditions, may restrict sugarcane yield (Schroeder et al., 2010b). Lower cane yield reduces the economic return on N fertiliser investment. Although the immediate consequences of N losses are first experienced by the grower, lower cane yields can also affect the operational efficiency and profitability of other industry sectors (i.e. harvesting contractors).

1.5.2.1.4. Strategies to reduce N losses and improve nitrogen-use efficiency

Nitrogen management in the Australian sugarcane industry has undergone significant changes since the 1960s with the aim of improving the use efficiency of N fertiliser. Rate of fertiliser experiments conducted by the Bureau of Sugar Experiment Stations (now Sugar Research Australia™) resulted in the development of regional yield-response curves for N. This provided a set of generalised N fertiliser recommendations for plant and ratoon crops that would maximise productivity and achieve an economic return (Chapman, 1994). These recommendations are shown in Table 1.1, and, although they were easy to use, they lacked precision. Little emphasis was placed on the N mineralisation potential of different soil types and there was very little differentiation among regions or soil types (Schroeder et al., 2005a, Schroeder et al., 1998, Wood et al., 1997).

Table 1.1. Generalised N management recommendations for sugarcane in Australia (Calcino, 1994, 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

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

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

Table 1.2. SIX EASY STEPS N fertiliser guidelines for the Wet Tropics region of the Australian 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: • Mill mud applied at 100-150 wet t/ha: Subtract 80 kg N/ha for plant, 40 kg N/ha for first ratoon, 20 kg N/ha for second ratoon. • Mud/ash mixture applied at 100-150 wet t/ha: Subtract 50 kg N/ha for plant, 20 kg N/ha for first ratoon, 10 kg N/ha for secondd ratoon. • Ash applied at 100-150 wet t/ha: No modification.							

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

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

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

Despite evidence of a voluntary reduction in N application rates, Australian sugarcane growers must now comply with legislation limiting the application of N (and P) fertiliser to optimum amounts (Anon, 2009a). In response to state-wide water-quality monitoring outcomes, the Queensland Government, as indicated previously, introduced the Great Barrier Reef Protection Amendment Act 2009 to regulate N inputs by sugarcane farmers and graziers in catchment areas adjacent to the Great Barrier Reef lagoon (Anon, 2009a). Specifically, the Act aims to reduce the impact of agricultural activities on the quality of water entering the lagoon and contribute towards achieving water-quality improvement targets for the reef including a minimum 50% reduction in N loads at the end of catchments by 2018 as agreed by the Queensland State and Commonwealth Governments under The Reef Water Quality Protection Plan (Reef Plan) (Wrigley, 2007, ReefWaterQualityProtectionPlanSecretariat, 2009). The regulated method for determining the optimum amount of N for individual blocks of cane is based on the SIX EASY STEPS N-fertiliser guidelines (Schroeder et al., 2005a, Anon, 2009b).

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

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

Where subsurface application of N is not possible (i.e. steep slopes and rocky terrain), strategies to reduce ammonia volatilisation losses include applying urea-based products in bands close to the cane stool and incorporating into the soil with at least 16 mm of overhead irrigation water (or rainfall) or delaying application until there is substantial canopy development (approximately 50 cm high) (Prammanee et al., 1989, Wood et al., 1989, Freney et al., 1991, Freney et al., 1994, Calcino and Burgess, 1995). A developed canopy helps attenuate the wind speed over the trash surface allowing the leaves to absorb volatilised ammonia. It also contributes to lower trash temperatures that reduces the ammonia vapour pressure, and shifts the site of overnight dew formation from the trash to the leaves, thereby reducing urea hydrolysis (Prammanee et al., 1989, Freney et al., 1991, Denmead et al., 1993, Freney et al., 1994). A well-established canopy also means that the newly developing root system is capable of relatively rapid uptake of applied N fertiliser (Chapman, 1994). However these strategies will not totally eliminate losses from ammonia volatilisation. Losses of greater than 20% of the N from applied urea have been reported even when surface application of urea is followed by reasonably heavy rainfall (Prammanee et al., 1989).

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

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

Split application of N fertiliser in ratoons has been suggested as a method that may produce tangible environmental benefits by reducing leaching losses (Chapman, 1994). However, as this type of strategy has not resulted in higher cane yields, even in waterlogged soils, the majority of growers continue to apply N in a single application (Bieske, 1972, Chapman, 1994). Research into aspects of waterlogged soils found that split application did not improve N uptake or final cane yields and could not be associated with any economic or environmental benefits (Kingston et al., 2008).

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

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

The nitrification process transforms NH_4^+, a relatively immobile form of N, into NO_3^- (Barth et al., 2001). The first stage of the nitrification process, bacterial oxidation of NH_4^+

to NO_2^- by Nitrosomas bacteria, is closely followed by the second stage, conversion of NO_2^- to NO_3^- by Nitrobacter bacteria (Zerulla et al., 2001). Nitrification inhibitors have been specifically developed to delay only the first stage of nitrification by depressing the activities of Nitrosomas bacteria in the soil (Zerulla et al., 2001, Barth et al., 2001). This keeps N in the immobile form for longer, thereby reducing N susceptibility to leaching and denitrification losses (Barth et al., 2001, Zerulla et al., 2001, Chen et al., 2008, Wood et al., 2010b).

In the past, nitrification products have been too expensive for large-scale agricultural use (Chapman, 1994, Zerulla et al., 2001). A relatively new nitrification inhibitor, dimethylpyrazol phosphate (DMPP), commercially referred to as ENTEC®, has recently been evaluated in two Australian sugarcane-growing regions on soils with the potential for high denitrification or leaching losses (Wang et al., 2008b, Wang et al., 2012). Although ineffective in reducing N_2O emissions in field plots at Murwillumbah and Mackay, emissions in fertilised chambers were significantly reduced at Murwillumbah (Wang et al., 2008b). At another trial in Mackay, the addition of DMPP to urea resulted in significantly lower N_2O emissions compared to using normal urea (Wang et al., 2012).

Controlled-release fertiliser product technology may also contribute to lower N losses, improved N use efficiency and higher cane yields (Shoji et al., 2001). These products include poly-coated urea and sulphur-coated urea, which can be formulated to have different N release rates (Glendinning et al., 2000). Previous research into the use of controlled-release fertilisers in Australian sugarcane crops has not been successful (Chapman, 1994). Poly-coated slow-release urea was not successful in reducing N_2O emissions from a trial site in Mackay, Queensland (Wang et al., 2008b). However, recent trials have demonstrated that compared to using normal urea, polymer-coated slow-release urea reduced N_2O emission from an acid-sulphate soil in NSW by 30% (Wang et al., 2008b).

Further research is required under different climatic and soil conditions to substantiate the effectiveness of DMPP on reducing N_2O emissions from Australian sugarcane fields (Wang et al., 2012). In addition, it appears that the success of slow-release N fertiliser products is affected by the solubility of the product, climate, N uptake by the crop and the soil's capacity to retain the mineral N from leaching (Wang et al., 2008b). Incorporation of nitrification inhibitors and controlled release fertiliser products into the sugarcane production system will ultimately be determined by their robustness to reduce

N losses in a range of soil types and varying climatic conditions, and economics (Chen et al., 2008). Price and commercial availability are likely to have the greatest influence on the use of these products in sugarcane (Chapman, 1994, Chen et al., 2008).

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

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

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

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

To better align N fertiliser inputs with crop requirements, more accurate yield estimates need to be produced and used to calculate requirements for N fertiliser on an annual basis, instead of using a predetermined yield potential. The difficulty of predicting weather conditions for the upcoming growing season has been identified as a limitation to the formulation of N fertiliser input strategies on an annual basis in the SIX EASY STEPS program (Schroeder et al., 2010b). Forecasts of the climatic conditions likely to be experienced during the sugarcane growing season (i.e. spring and summer) may help improve yield estimates used in the generation of N fertiliser guidelines (Schroeder et al., 2010b). Climate forecasts may also improve decisions related to N fertiliser application timing, frequency (single vs. split) and the potential to use alternative N forms (i.e. nitrification inhibitors and controlled release products) to improve N uptake and reduce N losses. Over-fertilisation and environmental losses of N may be reduced by combining these practices into an overall N management strategy which has the flexibility to adapt to climate conditions. However, the success of using seasonal climate forecasts to guide N management strategies in sugarcane is uncertain.

1.5.2.2. Climate and sugarcane production

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

Climate variability also has an indirect impact on industry profitability as it influences planting and harvesting strategies, nutrient, pesticide and irrigation management, season operating times, mill maintenance programs, marketing strategies, sugar transport and storage arrangements (Muchow et al., 1997, Antony et al., 2002, Everingham et al., 2002a, Everingham et al., 2002b). Sugarcane yield estimates before the commencement of the harvest season are required for milling and marketing purposes. The difference between initial estimates and actual sugarcane yields in the Australian sugarcane industry has reported to range from an over estimate of 25% to an underestimate of 22% (Everingham et al., 2003). With the exception of pest or disease outbreak, these large differences can be attributed to swings in climatic conditions. Knowledge of the different climate systems influencing rainfall patterns over sugarcane production areas and the ability to use their signals for forecasting seasonal climatic conditions can help improve management decisions across all sectors of the sugarcane-industry value chain.

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

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

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

Seasonal climate forecasting has been used in the Australian sugarcane industry to help manage the impact of climate variability on growing, harvesting, milling and marketing operations (Everingham, et al., 2001, Everingham et al., 2002a, Everingham et al., 2003, Everingham et al., 2005). Millers and marketers can use seasonal climate forecasts to improve yield estimates so they can make more informed management decisions related to crop size. Knowledge of crop size allows marketers to refine selling and storage strategies and hopefully increase industry profitability, whereas the miller is better able to plan activities related to mill maintenance programs and harvest logistics (Everingham et al., 2002a, Everingham et al., 2002b, Antony et al., 2002, Everingham et al., 2005, Everingham et al., 2008b). For growers, climate forecasts covering the harvest season can be used to develop harvest plans for a ‘wet’ (or ‘dry’) harvest to minimise wet weather disruptions and damage to fields and hopefully avoid standover (Everingham et al., 2002a, Everingham et al., 2002b, Antony et al., 2002, Everingham et al., 2005, Everingham et al., 2008b). Climate forecasts can also be used to improve irrigation scheduling, especially when water supplies are scarce (Everingham et al., 2002b, Everingham et al., 2008a).

The South African and Swaziland sugarcane industries have also identified the potential for seasonal climate-forecasting information to improve management decisions in the growing, milling and marketing sectors. In South Africa, sugarcane yields tend to be lower in years when the monthly SOI values for October to November remain deeply negative, as there is a higher probability of low summer rainfall (Singels and Bezuidenhout, 1998, Singels and Bezuidenhout, 1999). Observed weather data is combined with historical climate sequences representative of likely future climatic conditions or mid to long range climate forecasts and entered into computer crop models such as CANEGRO (Inman-Bamber, 1991, Singels and Bezuidenhout, 2002) or

CANESIM (formerly called IRRICANE) (Singels et al., 1998) to forecast seasonal sugarcane yields (McGlinchey, 1999, Singels et al., 1999, Schmidt et al., 2004, Bezuidenhout and Schulze, 2006). Seasonal sugarcane-yield forecasts can be used to assist irrigation management, harvest scheduling, crop husbandry decisions, planning mill-season length, haulage scheduling and mill maintenance and marketing, pricing and storage strategies in South Africa (Singels et al., 1999, Schmidt et al., 2004). In Swaziland, improved estimation of forthcoming crop yields was identified as having the potential to assist growers estimate transport requirements, ripening strategies and harvest schedules and millers' estimates of season length and harvest commencement, and plan maintenance programs (McGlinchey, 1999).

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

1.5.2.3. Seasonal climate forecasting for improved nitrogen management

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

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

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

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

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

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

In southeast Australia, changing application rates for N fertiliser based on SOI phases was predicted to increase wheat gross margins by 8%, 13% and 20% when the April-

May SOI phase was negative/falling, zero, and positive/rising, respectively, compared to current N-management practices for the region of a fixed application of 100 kg N/ha (Wang et al., 2008a). In addition, SOI phase-based N management was also compared to using the long-term average optimal N rate (a fixed application of 150 kg N/ha) derived from long-term climate records for the region (Wang et al., 2008a). While SOI phase-based N management was still beneficial, the value was much smaller with gross margins predicted to increase by 3%, 0% and 1% when the April-May SOI phase was negative/falling, zero and positive/rising, respectively (Wang et al., 2008a). Although these financial increases are relatively small, the fact that sugarcane is produced in areas vulnerable to extreme climatic variability and sold in a volatile market, any improvement in gross margins will be beneficial.

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

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

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

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

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

1.6. Conclusion

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

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

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

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

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

1.7. Summary

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

Chapter 2

Identifying Climate Variables Having the Greatest Influence on Sugarcane Yields in the Tully Mill Area

This Chapter discusses the approach used to identify the atmospheric climate variables and time of year having the greatest influence on Tully mill average sugarcane yields Knowledge of the key atmospheric climate variables and time of year influencing cane yields will allow the impact of climatic conditions on N fertiliser requirements to be investigated. This Chapter has been published and the citation is: Skocaj, D.M., Everingham, Y.L., (2014) Identifying climate variables having the greatest influence on sugarcane yields in the Tully Mill area. Proceedings of the Australian Society of Sugar Cane Technologists **36**: CD-ROM: 9pp.

2.1. Introduction

Large fluctuations in cane yield from one season to the next influences the profitability of all sectors of the sugar industry. The greatest fluctuations often occur in rainfed environments, such as the Wet Tropics, where water supply cannot be controlled. The Wet Tropics sugarcane production area is characterised by high rainfall, excessive soil wetness, low solar radiation and vulnerability to extreme inter-annual climate variability. This provides a difficult management environment, can reduce yield potential and often results in extreme year-to-year cane yield variability. For example the Tully mill area average cane yield of 47 t cane /ha in 2011 was 47.8% lower than 2010 and the lowest since 1948 (Anon, 2012). As crop size is the main determinant of N fertiliser requirements (Keating et al., 1997) the impact of climate variability on cane yields makes it difficult to determine how much N fertiliser is required.

Previous research has highlighted the effect of some non-varietal factors on cane yield variability (e.g. (Smith, 1991, Leslie and Wilson, 1996, Hurney and Bown, 2000, Lawes et al., 2001, Lawes et al., 2002). These factors can be broadly classified as being related to management (time of ratooning, fallow vs plough-out replant, crop cycle duration, cultivation, nutrition and weed, pest and disease control) and location (climate, soil type, topography). Management and location are largely responsible for productivity differences between farms and districts, but these differences tend to remain consistent over time (consistently above or below mill average cane yields). However, at the farm level, where the grower tends not to change management practices dramatically from one year to the next, changes in climatic conditions are believed to be strongly associated with annual fluctuations in cane yield.

It is widely accepted that weather conditions influence cane growth, but specific knowledge relating key atmospheric variables with final cane yield is limited. Research conducted by (Smith, 1991) on the effect of rainfall variation on cane yield showed that rainfall was responsible for between 34 and 61% (33 and 76%) of the variation in plant (ratoon) cane yields over a 20-year period (1969 to 1988) for three mill areas in far north Queensland. A review of productivity trends in the Wet Tropics over a 35-year period identified excessive wetness, especially early in the growing season, and low solar radiation adversely effected sugarcane productivity (Leslie and Wilson, 1996, Wilson and Leslie, 1997). Analyses of Tully block productivity data for the period 1988 to 1999 showed that the year of harvest and the month when the crop was ratooned accounted for 20.9% and 11.4% of the variation in cane yield respectively (Lawes et al., 2001). Subsequent investigations identified crops ratooned from October to December had significantly lower yields the following harvest than those ratooned between July and September (Lawes et al., 2002). However, analysis of block productivity data alone was unable to identify the possible causal factors associated with the year and time of ratooning effect (Lawes et al., 2002). A different modelling approach was taken by (Everingham et al., 2003) who discovered a link between the Southern Oscillation Index (SOI) and cane yields. They found deeply negative SOI values during October-November favoured above average cane yields for the Mulgrave and Tully mill areas, and could therefore be used to predict cane yields. Conversely, positive SOI values during October-November favoured below average cane yields.

Knowledge of the key atmospheric variables (rainfall, solar radiation, temperature) and time of year influencing cane yields may help refine yield forecasting techniques and improve decision making capabilities throughout the sugar industry. At the grower level this may include the fine-tuning of N fertiliser inputs. Therefore the aim of this chapter is to i) identify which atmospheric variables and time of year have the greatest influence on Tully mill cane yields and ii) investigate if these atmospheric variables remain important irrespective of the historical time period analysed.

2.2. Materials and Methods

2.2.1. Data collection and pre-processing techniques

Average annual cane yields (t cane/ha) for the Tully mill area from 1933 to 2012 (80 years) were obtained from Tully Sugar Limited and are shown in Fig. 2.1. Many factors influence cane yields so it was important to remove the influence of technological improvement, whilst still maintaining year-to-year variability in yields that is largely attributed to climate variation. To do this average cane yields for the Tully mill area were detrended according to the procedure outlined by (Everingham et al., 2003). The detrended cane yields are shown in Fig. 2.2.

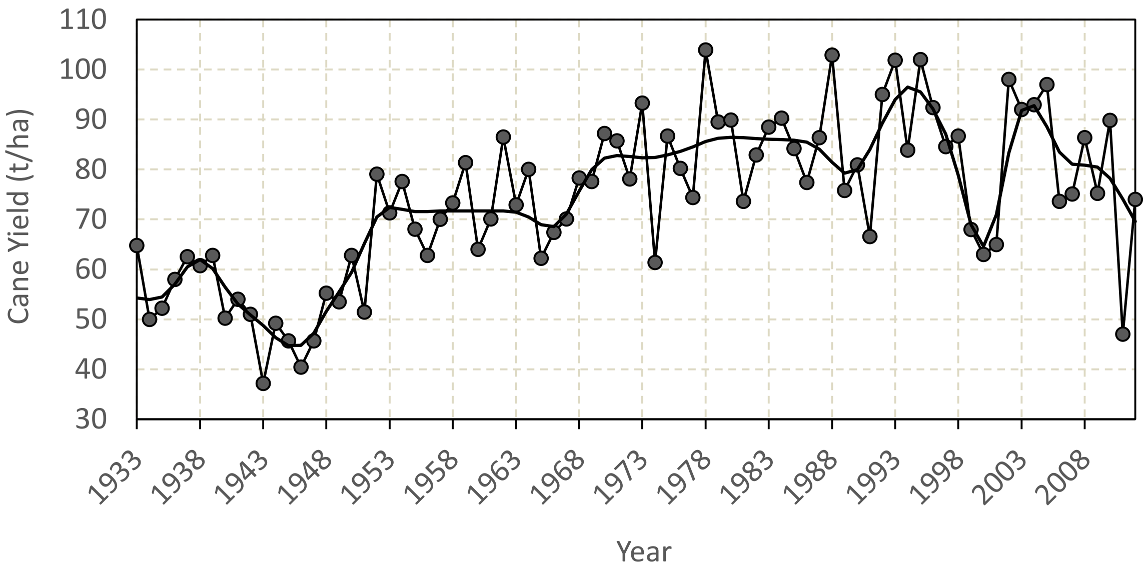

Figure 2.1. Original and smoothed annual sugarcane yields (t cane/ha) for the Tully Mill area from 1933 to 2012.

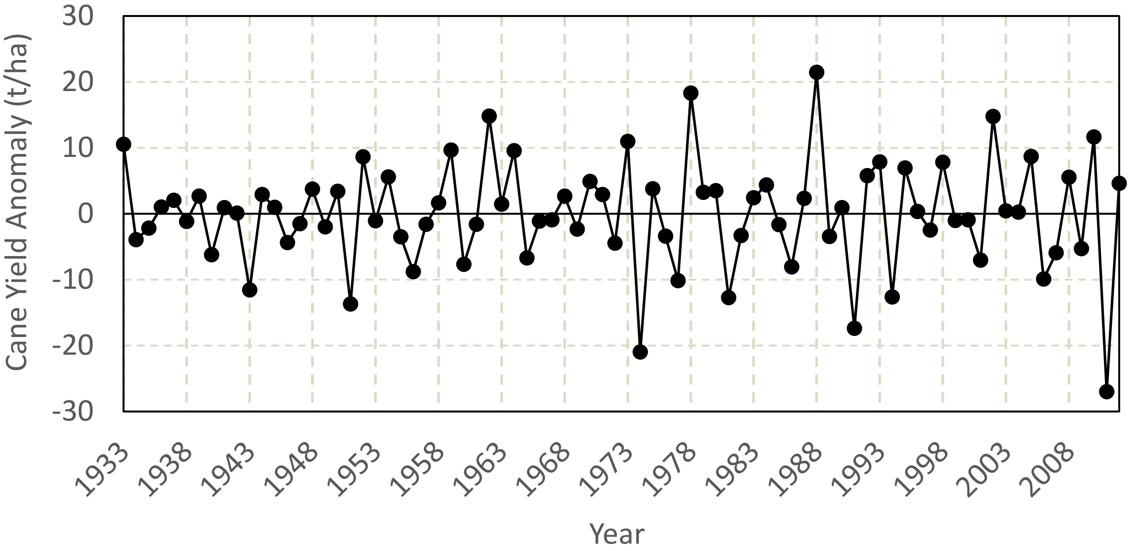

Figure 2.2. The difference between the original and smoothed annual sugarcane yields (t cane/ha) for the Tully Mill area from 1933 to 2012.

Average daily atmospheric values of minimum temperature, maximum temperature and radiation were obtained from the SILO climate data archive (Jeffrey et al., 2001) using the patched point option for the Tully Sugar Mill meteorological station (station number 32042). The patched point data option was selected as it uses original Bureau of Meteorology observations for a particular meteorological station with missing or suspect data 'patched' with interpolated values (which are estimates). Unfortunately minimum and maximum temperature and radiation are not measured at the Tully Sugar Mill station so interpolated values for these variables were used in the analysis. Total daily rainfall data was obtained from Tully Sugar Limited. The 80 year average monthly rainfall, temperature and radiation for Tully Sugar Mill is shown in Fig. 2.3.

The climate data were aligned with the growing season, which was defined from June to May. Single-, two-, three-, four-, five- and six-monthly rolling and seasonal (summer, autumn, winter and spring) average minimum temperature, maximum temperature and radiation values were then calculated. For rainfall the total single-, two-, three-, four-, five- and six-monthly rolling, seasonal and annual values were calculated from the daily dataset. This provided a total of 245 different variables for inclusion in the analysis.

Lastly, the climate data was related to the Tully mill area detrended cane yield for the following year i.e. climate data from June 1932 to May 1933 was analysed against 1933 cane yields and so on.

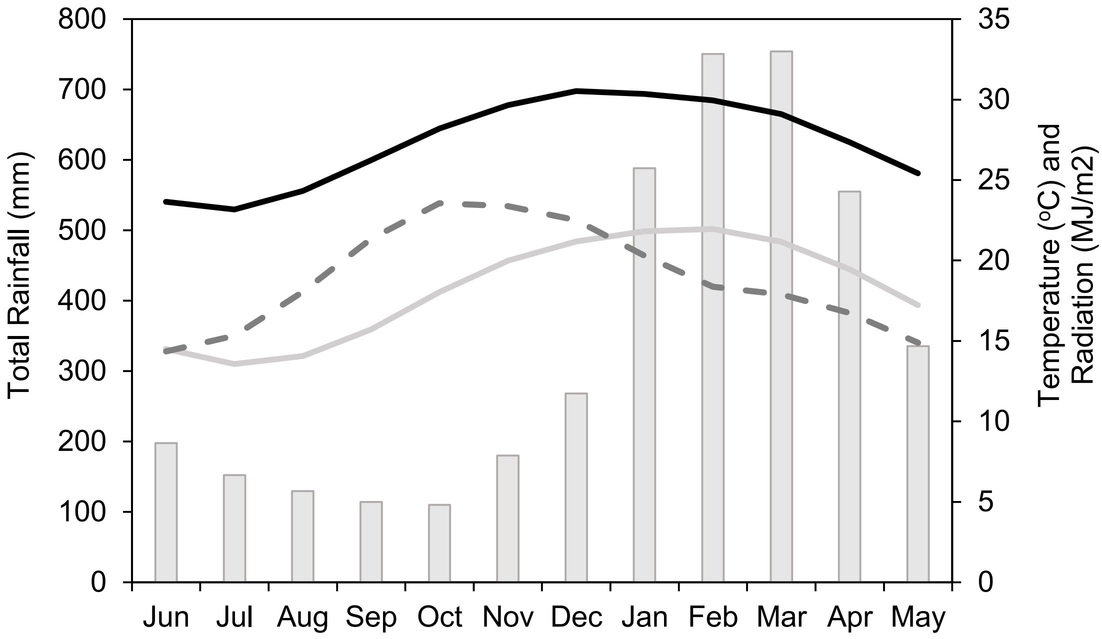

Figure 2.3. Average monthly rainfall (grey bars), minimum temperature (solid grey line), maximum temperature (solid black line) and radiation (dashed grey line) for Tully Sugar Mill for the period 1933 to 2012.

2.2.2. Analysis Method

A stepwise linear regression model (Norušis, 1997) was used to identify which of the 245 variables (independent variables) best explained detrended cane yields (the dependent variable). In this model the selection of independent variables proceeds by steps. Firstly, in a process termed forward selection, the independent variable resulting in the largest increase in multiple R^2 is added to the model (Norušis, 1997). A variable is only added if the change in R^2 reaches a predetermined significance level. The significance level was set at 0.05 so it was not too easy for variables to enter the model (Norušis, 1997). Next, backward elimination removes the variable that changes R^2 the least, provided that the change in R^2 meets the observed significance level of 0.1 (Norušis, 1997). The process of forward selection and backward elimination continues until no more variables meet the entry criterion. The order in which variables are entered into the model is also important. Variables entered into the model earlier can be considered more important in explaining the relationship with detrended cane yields than those entered later.

The analysis was run over different historical periods to investigate if the independent variables and/or sequence of those selected changed over time. The time blocks analysed were 1933-2012 (80 years), 1943-2012 (70 years), 1953-2012 (60 years), 1963-2012 (50 years), 1973-2012 (40 years), 1983-2012 (30 years), 1993-2012 (20 years) and 2003-2012 (10 years). The analysis was completed using IBM® SPSS® Statistics for Windows Version 21 (IBM Corp. Released 2012. Armonk, NY: IBM Corp).

To be conservative an additional stopping rule was applied to identify the minimum number of independent variables to include in the final model according to the procedure outlined by (Coakes and Steed, 2006). The ratio of cases to independent variables was selected using the minimum requirement of having at least five times more cases than independent variables. For example, a maximum of 16 variables could be used for the 80-year time block, and 2 variables for the 10-year time block.

The adjusted R-squared (R^2_{adj}) value was used to determine the amount of variability in detrended cane yields explained by the model. It was used instead of the R^2 value as it has been adjusted for the number of variables (predictors) included in the model. R^2 tends to overestimate the strength of the association especially if the model has more than one predictor (independent variable) (Norušis, 1997). The R^2_{adj} value is explained by:

$$R^2_{adj} = 1 - \frac{\left(1-R^2\right)(N-1)}{N-k-1} \tag{2.1}$$

R^2 = sample R-square, k = number of predictors and N = total sample size.

The estimate of the residual mean square (S^2) also called the estimate of the error variance was used to investigate the spread of values about the regression models (Norušis, 1997). The larger the S^2 the more the values are spread out (Norušis, 1997). An S^2 of zero indicates that all values are identical. The S^2 was calculated using the following formula:

$$S^2 = \frac{\text{RSS}}{\text{Residual df}} \tag{2.2}$$

RSS = residual sum of squares and Residual df = residual degrees of freedom.

The beta coefficient was used to indicate the impact of each climate variable selected in the final models on detrended cane yields as the climate variables were measured in different units (rainfall is reported in mm and temperature in °C). The sign of the beta coefficient indicates if the variable had a positive or negative impact on detrended cane yields. Beta coefficients are the same as partial regression coefficients when all independent variables have been computed in standardised form (Norušis, 1997).

2.2. Results

The R^2_{adj} for each stepwise model is shown in Table 2.1. For example, the R^2_{adj} values from the 1943-2012 linear models that contain (1) SONDJF rainfall, (2) SONDJF rainfall and July minimum temperature, (3) SONDJF rainfall and July minimum temperature and May maximum temperature are (1) 0.258, (2) 0.331 and (3) 0.369, respectively.

Table 2.1. The climate variables selected, R^2_{adj}, S^2 and final beta coefficients of the stepwise linear regression models explaining Tully detrended cane yields for eight different time blocks.

Years		Variables included in model	R^2_{adj}	S^2	Beta coefficient
1933-2012	80	1. JASOND rainfall	0.235	50.71	-0.236
		2. DJF rainfall	0.291	47.01	-0.260
		3. July minimum temperature	0.338	43.86	-0.263
		4. May maximum temperature	0.369	41.82	+0.197
1943-2012	70	1. SONDJF rainfall	0.258	54.33	-0.396
		2. July minimum temperature	0.331	49.00	-0.297
		3. May maximum temperature	0.369	46.18	+0.217
1953-2012	60	1. SONDJF rainfall	0.238	59.33	-0.509
		2. July minimum temperature	0.322	52.78	-0.307
1963-2012	50	1. SONDJF rainfall	0.295	58.94	-0.476
		2. July minimum temperature	0.357	53.74	-0.284
1973-2012	40	1. ONDJF rainfall	0.300	69.80	-0.486
		2. July minimum temperature	0.401	59.72	-0.346
1983-2012	30	1. ONDJF rainfall	0.268	67.37	-0.652
		2. NDJ radiation	0.382	56.86	-0.606
		3. May maximum temperature	0.461	49.63	+0.365
		4. ASON radiation	0.555	40.97	+0.524

		5. NDJF maximum temperature	0.624	10.62	-0.365
1993-2012	20	1. JASO rainfall	0.424	53.41	-2.030
		2. ASO rainfall	0.539	42.76	+1.432
		3. May minimum temperature	0.701	27.71	+0.556
		4. AM rainfall	0.769	21.42	-0.295
2003-2012	10	1. JAS rainfall	0.893	13.39	-0.695
		2. JAS minimum temperature	0.941	7.40	-0.339

(The number beside each climate variable indicates the step at which the variable entered the model).

The R^2_{adj} value for the final model increased as the length of time decreased. For the 80-, 70-, 60-, 50-, 40-, 30-, 20- and 10-year time blocks the model explained 36.9, 36.9, 32.2, 35.7, 40.1, 62.4, 76.9 and 94.1% of the variation in detrended cane yields, respectively.

The variables selected by the model differ depending on the historical time period analysed (see Table 2.1.). For example, JASOND rainfall accounted for 23.5% of the variability in detrended cane yields for the last 80 years. The combination of JASOND rainfall, DJF rainfall and July minimum and May maximum temperature accounted for 36.9% of the variability for the same time period. However, for the last 10 years JAS rainfall accounted for 89.3% of the variability in detrended cane yields and when combined with JAS minimum temperature, 94.1%.

Total rainfall for the six-month period July to December (JASOND) was the first variable selected for the longest time block analysed, 80 years. For the 50-, 60- and 70-year time blocks total, six-monthly rainfall was also important. However, the time of year shifted and it was the combined total of spring and summer (SONDJF) rainfall first selected by the model. The 30- and 40- year time blocks changed slightly and total rainfall for the five-month period October to February (ONDJF) was the first variable selected. The model entered July to September (JAS) and July to October (JASO) rainfall first for the 10- and 20-year datasets respectively.

The beta coefficients of the final stepwise model for each time block are also shown in Table 2.1. Rainfall, except for ASO rainfall in the last 20 years, always had a negative impact on detrended cane yields. Other variables having a negative impact on yield were

July minimum temperature (80-, 70-, 60-, 50- and 40-year time blocks), NDJ radiation and NDJF maximum temperature (30 years) and JAS minimum temperature (10 years). Variables having a positive impact on yield included May maximum temperature (80-, 70- and 30-year time blocks), May minimum temperature (20 years) and ASON radiation (30 years).

The final R^2_{adj} value for each of the different time blocks analysed is shown in Fig. 2.4.a. After decreasing rapidly over the short term (last 10 to 40 years) the adjusted R^2_{adj} value reached a plateau when 40 or more years' of data were supplied to the model. Changes to the final estimate of the residual mean square (S^2) for each of the different time blocks analysed is shown in Figure 2.4.b. After increasing rapidly over the last 10 to 40 years the S^2 also reached a peak when blocks of 40 or more years were used by the model and then started to decrease slowly.

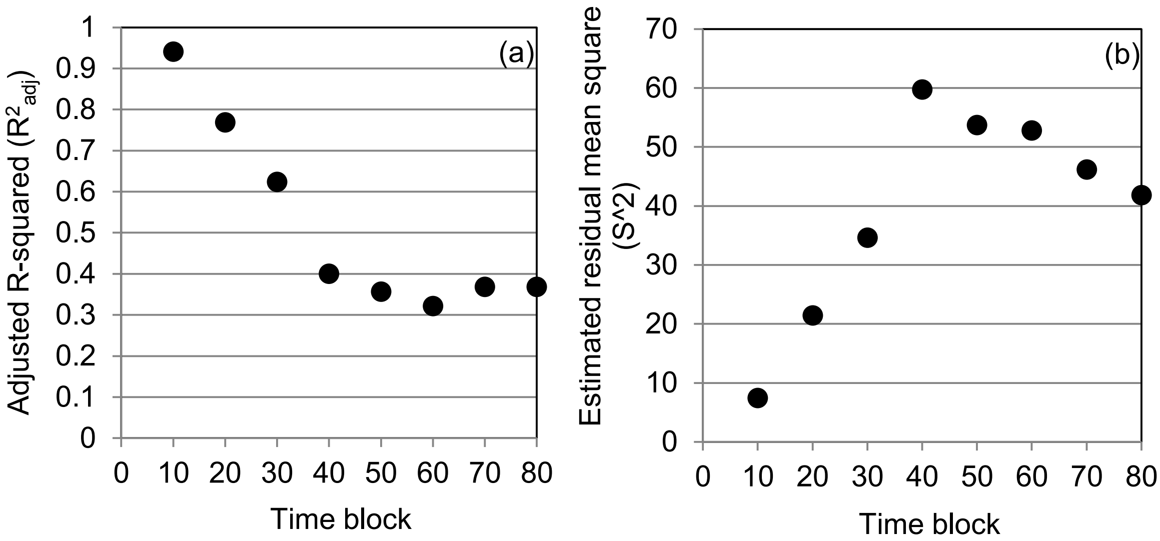

Figure 2.4. (a) Changes in the R^2_{adj} and S^2 (b) values for each time block analysed

The predicted detrended cane yield anomaly for the different time blocks was calculated using the corresponding regression model. The spread of the predicted yield anomalies about the actual yield anomalies for the 80-, 70-, 60-, 50-, 40-, 30-, 20- and 10-year models are shown in Fig. 2.5 a, b, c, d, e, f, g and h, respectively. The plots with a greater sample size (Fig. 2.5 a-e) tended to have a higher amount of scatter than those with a small sample size (Fig. 2.5.f-h).

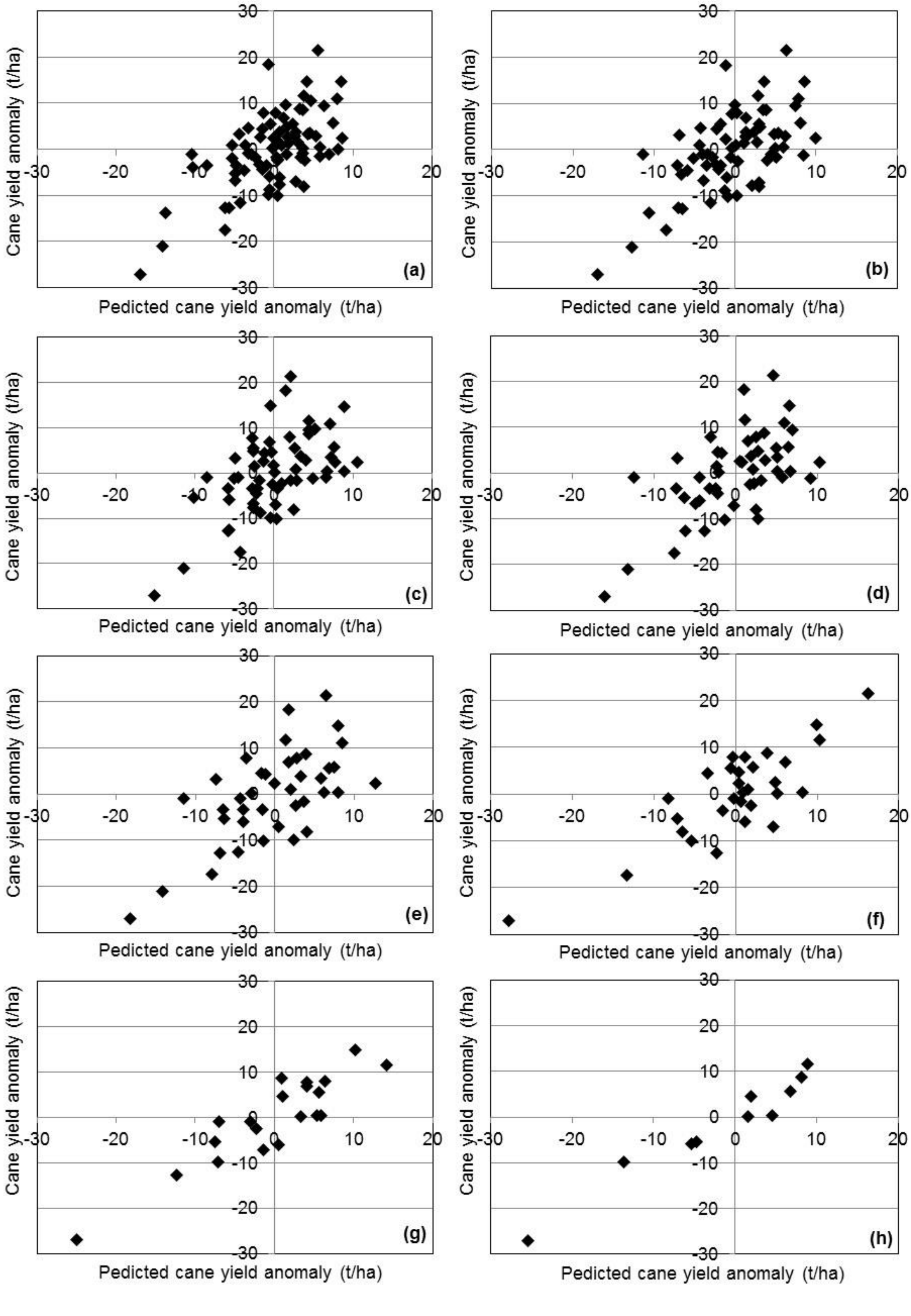

Figure 2.5. Actual (y axis) vs. predicted (x axis) cane yield anomalies from the regression models for each of the eight historical time blocks analysed. (a) 1933-2012, (b) 1943-2012, (c) 1953-2012, (d) 1963-2012, (e) 1973-2012, (f) 1983-2012, (g) 1993-2012 and (h) 2003-2013.

2.4. Discussion

Rainfall has been selected as the first explanatory factor in all models and usually reduced detrended cane yields. Excessive rainfall coincides with low solar radiation and extreme waterlogging which adversely affects crop growth, increases nutrient losses (especially nitrogen) and may prevent crop production practices being completed in a timely manner (which may increase weed competition, delay fertiliser application or hilling up of plant cane). Young roots of early ratoon cane can also be permanently injured by relatively short (approximately one week) periods of waterlogging (Rudd and Chardon, 1977). In addition, the productivity review conducted by (Leslie and Wilson, 1996) mentioned an environment of extreme soil wetness was having a major influence on cane growth, especially early ratoon cane up to 1 m high, for Babinda.

Previous research has also linked rainfall to cane yield variability. (Smith, 1991) used stepwise linear regression analysis to identify the main weather parameters (total rainfall and number of wet days from July to June and monthly rainfall) associated with changes in cane yield for mill areas including Tully. A rainfall model combining December and January rainfall was shown to account for 39% and 47% of the variability in plant and ratoon cane yields respectively for the Tully mill area over the 20 years analysed (1969 to 1988). Everingham *et al.* (2003) inferred that the link between October-November SOI phase and cane yields could be due to an association between the October-November SOI phase and summer rainfall (i.e. deeply negative October-November SOI phase is associated with lower summer rainfall). Most recently a productivity review of the Herbert region found a strong correlation between November rainfall and final cane yields using linear regression analysis. November rainfall accounted for 43.4% of the annual cane yield variation experienced in the Herbert region over an 18 year period, although there were large differences between productivity zones (Garside, 2013, Garside et al., 2014). However, the rainfall variables identified in this analysis were not the same as in previous research.

Previous research identified November or December and January or summer rainfall as having the greatest impact on yields in the Wet Tropics region whereas in our analysis the models commonly entered rainfall around spring and summer as the first variable. It was surprising to find that rainfall earlier in the growing season (late winter, early spring) was more important in the 10- and 20-year models than rainfall later in the growing season (around spring and summer) which was important for the 30-, 40-, 50-, 60- and

70-year datasets. This may be due to the fact that this analysis considered different historical time periods, climate variables other than rainfall and much longer time blocks (Smith, 1991, Leslie and Wilson, 1996, Garside et al., 2014).

Where radiation has been selected we suspect this is because of its association with rainfall (high solar radiation = low rainfall and vice versa) and its importance in physiological processes (photosynthesis). However, we cannot confidently explain the physiological phenomenon associated with the selection of other common variables (i.e. May maximum temperature and July minimum temperature). May coincides with the very end of the growing season and only a small proportion of the next crop is exposed to conditions in July.

This analysis focused on trying to quantify the impact of atmospheric variables on detrended cane yields and if the same atmospheric variables (and time of year) remained important irrespective of the historical time period analysed. The amount of variability in detrended cane yields attributable to climatic conditions ranged from 32.2% (1953-2012) to 94.1% (2003-2012). There are obviously other factors such as mechanisation, time of ratooning, land expansion, changes to farming systems and growing inputs (e.g. N fertiliser, herbicides) influencing detrended cane yields that was not incorporated into the models. The data presented in Table 2.1 shows there were some commonality in the variables entered early (i.e. rainfall around spring and summer) in the model. July minimum temperature was also commonly selected as a late entry in models with 40 or more years of data. However there were no other variables consistently entered late in the model across the different time blocks.

The stepwise approach was sensitive to the length of the time block. The R^2_{adj} steadily decreased and the S^2 steadily increased until the time interval reached 40 years. Once the time interval reaches 40 years and beyond there is little change in the R^2_{adj} or S^2 values. This conclusion is limited to the 40 year time block pertaining to 1973-2012. Different conclusions could be obtained if different time blocks were considered. Although more research is needed, it is reasonable to hypothesise that the true amount of variability explained by atmospheric variables via a simple linear regression approach is between 30 and 40%. Model confidence is clearly dependent on the length of the time block.

2.5. Conclusion and future work

The key research findings include:

- The amount of variability in detrended cane yields explained by the climate variables was highly dependent on the length of the time block. The R^2_{adj} ranged from 32.2% (1953-2012) to 94.1% (2003-2012).
- The R^2_{adj} steadily decreased and the S^2 increased until the time interval reached 40 years of data. This suggests model confidence may have been inflated when less than 40 years of data was entered.
- Model confidence depends on the length of the time block.
- Rainfall mostly had a negative impact on detrended cane yields and was the first variable selected in all models. However, there has been a shift in the time of year having the greatest influence on detrended cane yields. In the 10- and 20-year analysis rainfall earlier in the growing season (late winter, early spring) was more important than rainfall later in the growing season (spring and summer/ late spring and summer).
- July minimum temperature featured as a late entry in models with 40 or more years of data (the 1933-, 1943-, 1953-, 1963- and 1973-2012 models). May maximum temperature was also a late entry in the 80-, 70- and 30-year models. However, other variables (i.e. NDJ and ASON radiation, NDJF maximum temperature, May and JAS minimum temperature, AM rainfall) entering late into the models were not common, suggesting that they might be unstable predictors.

The atmospheric data were from a point source but detrended cane yields were representative of all districts supplying Tully mill. Future research could include rerunning the analysis with plant and ratoon yield data to see if the model is sensitive to crop class and completing the analysis for different mill areas and districts within a mill area (where sufficient climate data is available). Although the methods and results have been generated for the Tully mill area, the methodological approach can be easily adapted to other sugarcane growing regions inside and outside of Australia. This would allow the identification of spatial differences across a region (Wet Tropics) and within a mill area (i.e. Mossman, Mulgrave, Tablelands, South Johnstone, Tully), which may facilitate the fine tuning of yield forecasting and harvest scheduling. The time of ratooning effect on cane yields could also be incorporated into future investigations. Lawes et al., (2002) identified year and the time of ratooning as having a major influence on cane yield variation in the Tully mill area and suggested that these factors may provide a surrogate measure of the conditions experienced when new ratoon crops are initiated. Obviously the time of ratooning determines the timing of the crop-growth period. It would be informative to investigate if crops ratooned early in the season (July to September) are less sensitive to rainfall around spring and summer than crops ratooned later (October to December). It is also possible that the SOI or sea surface temperatures (SST) may be better suited than atmospheric variables for the prediction of sugarcane yields in the Wet Tropics region.

2.6. Summary

Large fluctuations in cane yield from one season to the next are problematic for all sectors of the sugar industry. The Wet Tropics region is characterised by high rainfall, excessive soil wetness, low solar radiation and vulnerability to extreme climatic variability. Although many different factors influence productivity, annual fluctuations in cane yield at the farm level in this region are thought to be strongly associated with changes in climatic conditions. To investigate this further, a stepwise linear regression model used atmospheric variables at different times of the growing season to explain Tully mill detrended cane yield data for eight different time blocks. These time blocks ranged from 10 to 80 years. The regression models explained between 32.2 and 94.1% of the variation in detrended cane yields for the Tully mill area. Rainfall, most commonly around spring and summer, was always the first variable entered into the models making it an important predictor. However, the other variables selected for late entry changed over time. The identification of spring summer rainfall as an important predictor of Tully cane yields will be useful in investigating the impact of climatic conditions on N fertiliser requirements.

Chapter 3

Modelling Sugarcane Yield Response to Applied Nitrogen Fertiliser in a Wet Tropical Environment

This Chapter investigates the capability of APSIM-Sugar to simulate cane yield response to applied N fertiliser in a wet tropical environment. It also provides a preliminary insight into the impact of natural climate variability on the N fertiliser requirements of sugarcane grown in the Wet Tropics. The knowledge generated in this Chapter assisted the parameterisation of APSIM-Sugar in Chapter 4. This Chapter has been published and the citation is: Skocaj, D.M., Hurney, A.P., Inman-Bamber, N.G., Schroeder, B.L., Everingham, Y.L., (2013) Modelling sugarcane yield response to applied nitrogen fertiliser in a wet tropical environment. Proceedings of the Australian Society of Sugar Cane Technologists: **35**: CD-ROM: 9pp.

3.1. Introduction

Nitrogen management in the Australian sugar industry has undergone significant changes in an attempt to improve profitability and environmental sustainability. Generalised N fertiliser recommendations for plant and ratoon crops based on regional yield response curves to applied N have been replaced with soil- and site-specific N fertiliser guidelines (Schroeder et al., 2005a).

Recognised as current industry best management practice (BMP), the SIX EASY STEPS N guidelines enable the fine tuning of N fertiliser inputs for specific sites and soil types whilst ensuring sugarcane production remains profitable and sustainable (Schroeder et al., 2009b). However, using a constant district yield potential (DYP) in the calculation of N fertiliser requirements limits the ability to adapt to annual yield fluctuations caused by natural climatic variability. A constant DYP is used because of the difficulty associated in predicting weather conditions in advance of the growing season (Schroeder et al., 2010b). In the Wet Tropics, where extreme inter-annual climate variability is evident, it is possible that the crop's N requirement may be under/overestimated in some years as current N fertiliser guidelines do not consider the impact of natural climate variability on final yields.

It is difficult to determine the climatic impact on sugarcane N fertiliser requirements in experimental field trials as their duration is often limited to short timescales that do not encapsulate different climatic conditions. Crop growth models have been used to help understand N cycling in the sugarcane production system and shown to be successful in investigating specific issues related to N management over longer timescales.

In particular, APSIM-Sugar has been used to investigate the impact of trash management on sugarcane yields and N dynamics, N leaching below the root zone and management options to reduce N losses and improve N fertiliser use efficiency (Verburg et al., 1996, Thorburn et al., 1999, Robertson and Thorburn, 2000, Thorburn et al., 2001a, Thorburn et al., 2004b, Stewart et al., 2006, Robertson and Thorburn, 2007b, Thorburn et al., 2011a). The results from field experiments are often used to validate the performance of APSIM-Sugar before undertaking simulations to investigate longer-term treatment effects. For field experiments conducted in Ingham, APSIM-Sugar was able to simulate differences between low, medium and high N supply regimes for plant and ratoon crops. The plant crop experienced high supply of N from soil organic sources and APSIM-Sugar was able to successfully predict final yield and green biomass N uptake responses (Keating et al., 1999). In the first ratoon crop observed green biomass values were 2861, 4400 and 5886 g m^{-2} and the simulated green biomass values were 2713, 3877 and 5236 g m^{-2} for the low, medium and high N regimes, respectively (Keating et al., 1999). In a different study, simulated cane yields and changes in soil C and N for different residue management regimes agreed closely with the results of experiments conducted in Australia and South Africa (Thorburn *et al.* 1999 and 2005). Based on the outcomes of these simulations, it seems appropriate to use APSIM-Sugar to investigate the impact of different climatic conditions on N fertiliser requirements.

This chapter aims to:

(i) demonstrate the ability of APSIM-Sugar to reproduce experimental N rate response results under wet tropical conditions,

(ii) determine the optimum amount of N fertiliser required for each crop, and

(iii) compare the optimum N rates with the SIX EASY STEPS recommended N rate for the site.

3.2. Materials and Methods

3.2.1. Trial site

The N rate field experiment used to calibrate APSIM-Sugar was conducted at BSES Limited Tully (17° 59'S, 145° 55'E) on a clay soil of the Coom series (Murtha, 1986). The experiment was initially set up in 1990 to investigate long-term effects of green-cane trash blanketing (GCTB) in a wet tropical environment. The period 2004 to 2009 was used to coincide with an experiment investigating cane yield response to N fertiliser following long-term GCTB as described by Hurney and Schroeder (2012).

The experiment was established in 2004, in the plant crop (Pl) and continued until the fourth ratoon crop was harvested in 2009. A split-plot design was used to allow four N treatments to be incorporated into the three different farming system treatments. This analysis focuses on the farming system treatment that consisted of GCTB, conventional cultivation (CP) in plant and zero tillage in ratoon crops (CP GCTB). This farming system is commonly practiced in the Tully mill area. The four N treatments applied to the plant (0, 50, 100 and 150 kg N/ha) and ratoon crops (0, 80, 160 and 240 kg N/ha) were replicated three times. Further details of trial design, establishment, management and results have been previously reported by Hurney and Schroeder (2012).

3.2.2. Crop simulation

The APSIM-Sugar (v7.4) cropping systems model (Keating et al., 2003) configured with modules for soil N (Probert et al., 1998), soil water (Probert et al., 1998), sugarcane growth (Keating et al., 1999), surface organic matter (Probert et al., 1998, Thorburn et al., 2001), fertilizer and manager was used to simulate cane yield results. The default settings in APSIM-Sugar and the 'sugar.ini' file (v5.2) were used as a starting point for site characterisation. The default soil type parameters were derived from measurements previously taken at the trial site (Robertson and Thorburn, 2007, Thorburn et al., 2011b, Hurney and Schroeder, 2012, Thorburn et al., 2012).

Default settings were adjusted where information relating to soil characteristics (i.e. initial soil N and organic carbon values), trial establishment and management (i.e. fertiliser application and harvesting dates), and trial sampling (i.e. stalk population) was available according to the data reported by Hurney and Schroeder (2012). Daily climate data were obtained from the SILO climate data archive (Jeffrey et al., 2001) maintained by the Queensland Climate Change Centre of Excellence for the meteorological station, Tully Sugar Mill, (station number 32042), which is located approximately 5 km north of the experimental site. Default settings relating to waterlogging and nitrogen stress were altered by trial and error to get simulated cane yields within the spread of the replicate cane yields for the majority of N treatments and crops.

To simulate the transient effect of waterlogging, the value of the APSIM-Sugar ‘water logging stress factor’ (*oxdef_photo*) was set to 0.63 and 0.53 in the plant and ratoon crops respectively, when more than 80% of the root system was exposed to saturated or near saturated soil water conditions. *Oxdef_photo* reduces photosynthetic activity via an effect on radiation use efficiency (RUE). Therefore the values used in the simulation reduced photosynthesis by 37% and 47% in the plant and ratoon crops respectively.

Lodging was not observed during the trial however the lodging option was used to simulate the longer lasting effects of waterlogging. Following a rainfall event of more than 200 mm, RUE was reduced by setting the *lodge_redn_photo* value to 0.70 for the ratoon crops only. Summer rainfall was generally above average for all the ratoon crops with crop age ranging from less than one month to just over two months of age at the start of summer. As the plant crop was over three months of age at the start of summer, waterlogging was considered to have the greatest impact on ratoon cane growth.

N stress factors differ between photosynthetic, leaf and stalk expansion processes. For this simulation only the N stress factor for photosynthesis (*nfact_photo*) was decreased from 1.0 to 0.8 to increase the sensitivity to nitrogen stress in both the plant and ratoon crops. This N stress factor reduces photosynthetic activity via an effect on RUE with an *nfact_photo* value of 1 indicating no stress and 0 complete stress. The value used in this simulation reduced photosynthesis by 20% in the plant and ratoon crops.

As the original trial was not designed for model calibration, critical information about the soil water table and crop development was not available. Access to this type of data would have allowed further adjustment of model settings to more accurately reflect field conditions and crop growth characteristics.

3.2.3. Calculation of optimum nitrogen fertiliser rate

The annual cane yield response to applied N fertiliser was generated for observed mean and simulated cane yields. A linear model was fitted to explain how cane yields varied with N fertiliser rates and between mean observed and simulated cane yields for each crop. The final model contains only significant terms which have been determined by a backwards stepwise regression routine with the p-value criterion to enter/exit set at 0.05 and 0.10, respectively. The final model was then used to determine the N rate producing 95% of the maximum cane yield for each crop (Schroeder et al., 2005a). Optimum N rates were rounded to the nearest 10 kg/ha.

An economic assessment of applying the optimum and recommended N rates was undertaken by calculating the partial net return per hectare to the grower and industry (grower and miller) using the following equations:

Grower partial net return = (gross income calculated from the Tully cane payment formula) – (cane yield x estimated harvesting costs plus levies) – (fertiliser cost).

(3.1)

Industry partial net return = (sugar yield x price of sugar) – (fertiliser cost x application rate kg/ha) – (cane yield x estimated harvesting costs plus levies).

(3.2)

For simplicity, a CCS value of 12.5 was used to calculate sugar yields and economic returns. This value remained constant for both the observed and simulated scenarios across all crop classes.

3.3. Results and Discussion

3.3.1. Simulating cane yield response to applied nitrogen fertiliser under wet tropical conditions

The observed and APSIM-Sugar simulated cane yield responses to N fertiliser for plant, first, second, third and fourth ratoon crops and the global R^2 values are shown in Figure 3.1. For all crops, the observed cane yield response to N fertiliser differed to the simulated cane yield response.

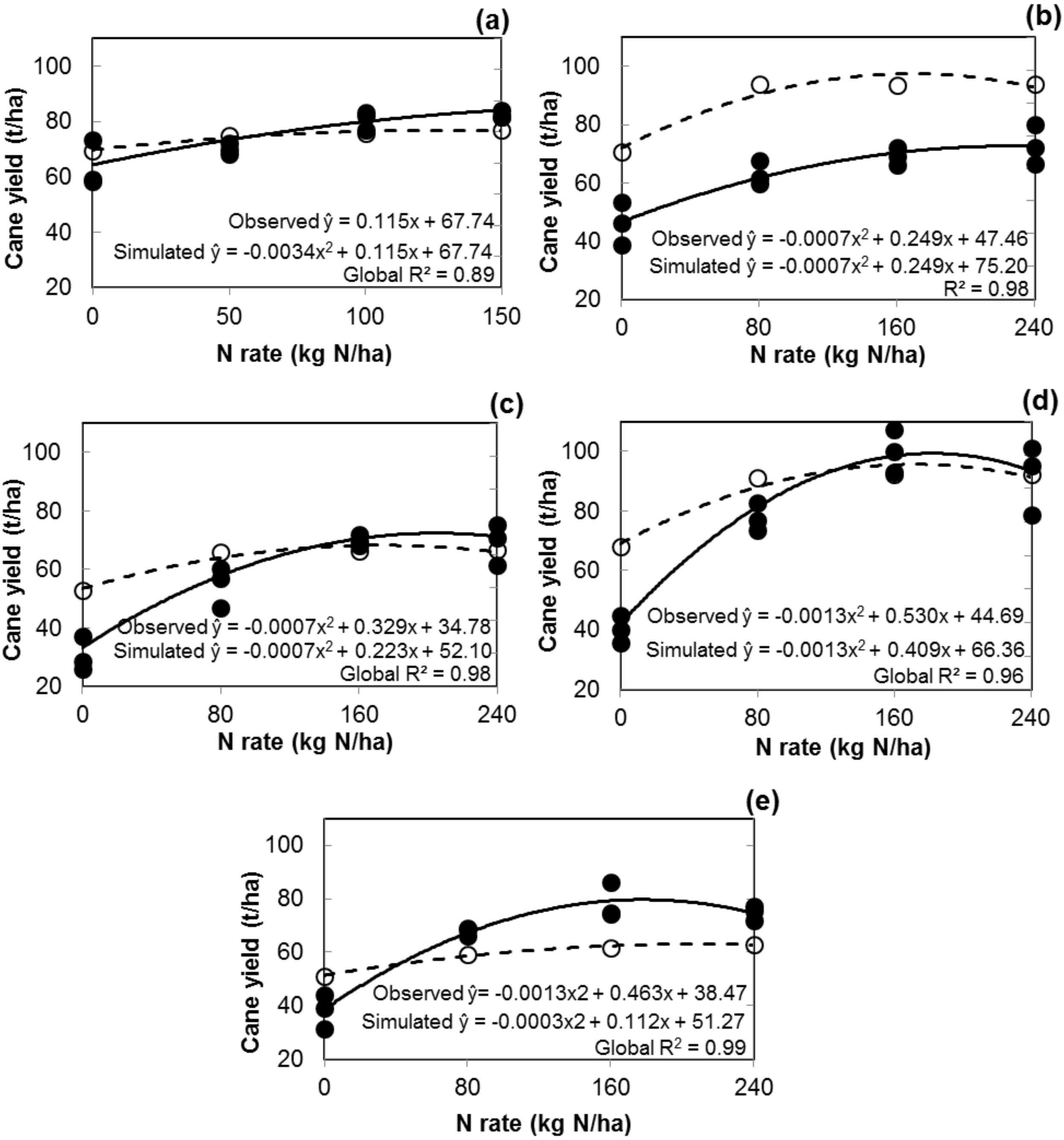

Figure 3.1.a (2005 Pl), b (2006 1R), c (2007 2R), d (2008 3R) and e (2009 4R) – Comparison between observed replicate cane yields (solid circles), observed mean cane yields (solid line) and APSIM-Sugar simulated cane yields (hollow circles and broken line) for four different N fertiliser rates.

In the plant crop, the observed cane yield showed a significant response to applied N ($P<0.001$) (Hurney and Schroeder, 2012). This was not reflected by the simulated cane yield response (see Figure 3.1.a).

APSIM-Sugar consistently over-predicted cane yields for the first ratoon crop (see Figure 3.1.b.). The simulated yields were more than 20 t cane/ha higher than the observed mean cane yields for all N rates. The first ratoon was damaged by tropical cyclone Larry on 20 March 2006. No attempt was made to alter the APSIM-Sugar settings to reflect the impact of the cyclone and the extreme wet weather that followed. However, the observed and simulated first ratoon cane yield response curves were parallel and the only difference was the intercept.

Leaf shredding immediately after the cyclone would have reduced green leaf area, therefore reducing photosynthetic activity, and the prolonged rainfall that followed caused extensive waterlogging. Waterlogging was manually factored into the simulation (irrespective of weather conditions or crop stage), with the same settings (*oxdef_photo* = 0.53 and for >200 mm rainfall *lodge_redn_photo* = 0.70) used for all ratoon crop simulations. Top death and severe side shooting due to heavy flowering was also observed at harvest but could not be accounted for in the model as detailed information relating to the severity and extent of damage was not available.

APSIM-Sugar was useful in predicting cane yields for the higher N rates (160 and 240 kg N/ha) in the second and third ratoon crops but was limited in its ability to predict mean observed cane yields at the lower N rates (see Figure 3.1.c). When no N fertiliser was applied (i.e. 0 kg N/ha), simulated cane yields were higher than mean observed cane yields.

It is suspected that waterlogging may have been responsible for some of the very low yields recorded. The fourth ratoon crop received the highest total rainfall during the growing season (4795 mm) with approximately 52% of the total occurring during January and February 2009.

This would have resulted in prolonged waterlogging during the early to mid-stages of crop growth (third ratoon harvested 25 September 2008 and fertiliser applied on 20 November 2008). The observed and simulated cane yield responses differed for the fourth ratoon crop with APSIM-Sugar underestimating mean cane yields for all N rates except the 0 kg N/ha treatment (Figure 3.1.e). It is difficult to represent excessively wet conditions in the model as the physiology of waterlogging in sugarcane is not well understood.

The settings used to represent the transient *(oxdef_photo = 0.53)* and longer term effects of waterlogging *(for rainfall events >200 mm lodge_redn_*photo = 0.70*)* in the ratoon simulations appears to have severely restricted cane growth in the fourth ratoon. As waterlogging occurred during the early to mid-stages of growth, these setting may have had a longer lasting effect on simulated biomass accumulation and hence final yield. Settings used to simulate the effects of waterlogging may need to be adjusted for individual crops depending on the severity of waterlogging and occurrence in relation to crop growth stage.

When the longer term effects of waterlogging setting was turned off and the waterlogging stress factor reduced *(oxdef_photo = 0.73)* simulated cane yields increased and were closer to individual replicate cane yields (Figure 3.2).

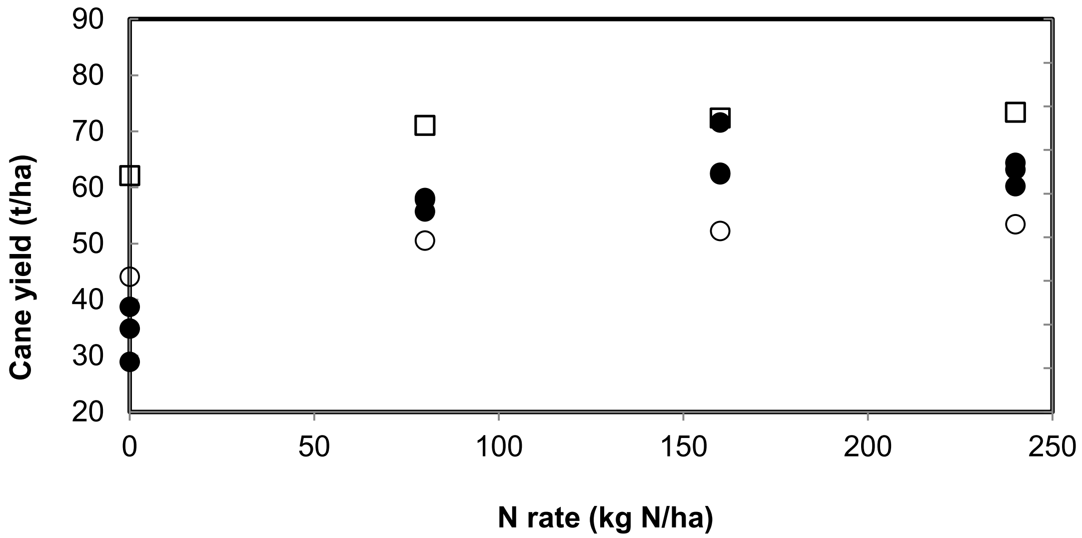

Figure 3.2. Changes to cane yield (t cane/ha) resulting from different waterlogging stress values (hollow circle = *oxdef_photo* 0.53, *lodge_redn_photo* 0.70 and hollow square = *oxdef_photo* 0.73, *lodge_redn_photo* 0.99) compared to the 2009 fourth ratoon observed mean cane yields with standard errors (solid circle) for four different N fertiliser rates (0, 80, 160 and 240 kg N/ha).

Waterlogging settings and values may also need to be crop-stage specific. Differences in the amount, timing and distribution of rainfall and the crop stage influence the duration and severity of waterlogging. Although the model does consider the transient effect of waterlogging, the longer term effects are not represented in the model because not enough information is available on the physiological impact of waterlogging on sugarcane growth.

It is possible that factors other than waterlogging may have contributed to the extremely low yields recorded during some years of the trial. However, as detailed information relating to factors such as lodging, suckering and flowering were not available it was not possible to identify the extent to which these other factors may have contributed to the low yields.

Unfortunately the N balance could not be examined in greater detail either, as data relating to changes in soil N values between crops for each of the different N rates was not available.

3.3.2. Optimum nitrogen fertiliser rates and economic impact of applying optimum nitrogen fertiliser rates compared to the SIX EASY STEPS nitrogen management guidelines

The optimum N rates, to achieve 95% of the maximum yield, for each crop, as determined from the quadratic equations generated from the observed and simulated cane yield response curves (see Figures 3.1.a-e) are reported in Table 3.1. The observed optimum N rate and associated cane yield could not be calculated for the plant crop because the cane yield response was linear. Based on the organic carbon (%) value for this site, the SIX EASY STEPS N management guidelines for the Wet Tropics region recommends an application of 110 kg N/ha for plant and 130 kg N/ha for each of the four ratoon crops (Schroeder et al., 2007). Overall the observed optimum N rates reported in Table 3.1 were fairly similar to the SIX EASY STEPS recommended N rates.

Table 3.1. Comparison between the observed and simulated N rate scenarios producing 95% of the maximum yield and the estimated cane yield.

Crop class	Observed		Simulated	
	Cane yield (t/ha)	N rate (kg N/ha)	Cane yield (t/ha)	N rate (kg N/ha)
P	-	-	65	0
1R	66	110	93	100
2R	70	160	66	90
3R	93	140	93	100
4R	76	120	59	90

It is interesting that the observed optimum N rate was highest in the second ratoon the wettest year of the trial where more than 4000 mm of rainfall was recorded during the growing season. A major portion of this rainfall occurred between January and early April, coinciding with the mid to late stages of crop growth, but well after the addition of N fertiliser.

The outcome of the observed optimum N rate scenario suggests extra N (above the SIX EASY STEPS guidelines) would possibly be required in high rainfall years to account for increased losses of N. However, Hurney and Schroeder (2010) reported crop yields and response to N were lowest in such conditions and suggested that waterlogging and reduced solar radiation interfered with normal crop physiological process to restrict crop growth.

Although the observed optimum N rates were less variable across years than the simulated, both highlight that seasonal climatic conditions do influence N requirements and cane yields. The simulated optimum N rates were generally lower than the observed and this is likely to be the result of the model overestimating cane yields at lower N rates (refer to Fig. 3.1. a-e).

The large difference between the observed and simulated first ratoon cane yields (25 t cane/ha) was probably due to the effects of cyclone Larry. Such circumstances are not easily reproduced in a model.

The grower and industry partial net returns associated with applying the observed optimum N rate compared to the SIX EASY STEPS recommended N rate for the ratoon crops are reported in Table 3.2. The grower and industry partial net returns are not reported for the plant crop as the observed cane yield response was linear.

Table 3.2. Calculated grower and industry partial net returns from applying the appropriate SIX EASY STEPS N rate and the observed optimum N rate (to produce 95% of the maximum yield). Equations 3.1 and 3.2 were used to calculate the grower and industry partial net returns, respectively.

Crop Class	Grower partial net return ($/ha)	
	SIX EASY STEPS	Observed
1R	1875	1848
2R	1806	1882
3R	2690	2646
4R	2141	2126
Overall difference from using the observed optimum N rate -$10/ha		
Crop Class	Industry partial net return ($/ha)	
	SIX EASY STEPS	Observed
1R	3523	3449
2R	3400	3572
3R	4984	4919
4R	3999	3961
Overall difference from using the observed optimum N rate -$5/ha		

The economic analysis indicates that the observed optimum N rate did not increase grower or industry partial net returns compared to the SIX EASY STEPS rate. In the second ratoon crop, the calculated grower and industry partial net returns were increased by $76 and $172/ha, respectively, when using the observed optimum N rate.

3.4. Conclusion and future work

This simulation analysis has shown that it is possible to use the APSIM-Sugar framework to explain how mean cane yields, as recorded in experimental field trials under wet tropical conditions, might have been achieved.

As time constraints prevent experimental trials being conducted over long time scales to encapsulate natural climate variability for a range of locations and soil types, the use of APSIM-Sugar is an option for investigating the possible impacts of different climate patterns on sugarcane N fertiliser use efficiency. However, it is important to collect all necessary data in relation to soil (e.g., horizons, texture, bulk density, soil chemical properties, soil mineral N levels, soil carbon concentration and quality), water (e.g., hydraulic conductivity, water table depth) and crop development (e.g., date and severity of lodging, crop rooting depth, amount of trash prior to harvest, fresh and dry matter biomass, partitioning of biomass into dead leaf, green leaf and stalk, N concentration of biomass, date of crop management practices and application of crop inputs) from field trials to correctly calibrate the model.

Determining the optimum N rate for each year based on the observed and simulated cane yield response curves to applied N has shown that N requirements do vary from one year to the next, primarily in response to climate. However, the current BMP N fertiliser guidelines neither under estimated nor overestimated N requirements when compared to the observed optimum N rates. The simulated optimal N rates were often lower than the SIX EASY STEPS N rate because of difficulties associated with model calibration leading to an overestimate of yield at lower N rates. This reinforces the need to have access to a reliable crop model that is able to simulate yields under the extreme wet conditions of the north Queensland Wet Tropics. It also highlights the necessity to collect and use additional data from field trials to improve model calibration.

The variability in observed optimum N fertiliser rates and associated cane yields suggests that the impact of climate variability needs to be addressed in the quest for sustainable sugarcane production in the Wet Tropics. This will have important consequences for maintaining cane growth and improving N fertiliser use efficiency.

This simulation analysis has also highlighted limitations in the ability of the APSIM-Sugar to accurately simulate the effect of waterlogging on crop growth in high rainfall environments. This is not surprising given the effect of waterlogging on physiological processes is not well understood for sugarcane. Further research to better understand the physiological impact of waterlogging on sugarcane growth, especially at different crop-growth stages is required before settings in APSIM-Sugar can be fine-tuned. In the meantime it may be possible to manually alter waterlogging stress values for specific crop years depending on the amount, distribution and frequency of rainfall in relation to crop growth stages when calibrating the model.

Difficulty in predicting weather conditions for the upcoming growing season has been identified as the primary factor preventing the formulation of N fertiliser input strategies on an annual basis in response to climate variability (Wood et al., 2010b). Advances in seasonal climate-forecasting tools have improved the ability to predict cane yields in most Australian sugarcane growing regions, including the Wet Tropics (Everingham et al., 2003, Everingham et al., 2008). The incorporation of seasonal climate forecasting into the SIX EASY STEPS framework for yield prediction purposes may allow N guidelines to be tailored to an annual DYP in response to a seasonal climate outlook.

3.5. Summary

The capability of the APSIM-Sugar model to simulate N management in the sugarcane farming system is well demonstrated for most Australian production areas. In particular, the APSIM-Sugar model has been used to investigate the impact of trash management on sugarcane yields and N dynamics, N leaching below the root zone and management options to reduce N losses and improve N fertiliser use efficiency. APSIM-Sugar was used to gain a preliminary insight into the impact of natural climate variability on the N fertiliser requirements of sugarcane. APSIM-Sugar was calibrated against a small-plot, N-rate field experiment conducted at BSES Limited Tully from 2004 to 2009. Next, the optimum amount of N required for each year of the trial that would produce 95% of the maximum yield along with the grower and industry economic returns were calculated from the simulated and observed response curves for comparison to the recommended N rate for the site as determined by the SIX EASY STEPS N-management guidelines. Although the APSIM-Sugar model provided indicative cane yields using the Tully trial data, problems were encountered with waterlogged conditions and when N rates were varied. The SIX EASY STEPS N guidelines did not grossly under estimate or overestimate N requirements compared to the optimum N rate for each year. However, fine tuning will improve the ability of this system to adapt to annual yield fluctuations caused by natural climatic variability. To improve the ability of this system to better match N fertiliser inputs to crop requirements an accurate prediction of annual cane yield is required.

Chapter 4

Should Nitrogen Fertiliser Application Rates for Sugarcane be reduced in Wet Years? Insights from a Simulation Study

This Chapter investigates the impact of climatic conditions on N fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil. It is well recognised that crop size is a key determinant of N fertiliser requirements. Consequently, the results that emanated from Chapter 2, which determined the time of year that rainfall has the greatest impact on Tully cane yields and Chapter 3, which guided the parameterisation of APSIM-Sugar, were used in the simulation of optimum N fertiliser requirements for a 45 year base period. At the time of submitting this thesis, the contents of this chapter had not been published or submitted for review. It is intended to submit this chapter to Agronomy for Sustainable Development.

4.1. Introduction

The Wet Tropics region of northern Australia experiences one of the highest levels of climate variability in the world (Nicholls et al., 1997). The El Niño Southern Oscillation (ENSO) is one of the largest sources of climate variability in this region (Partridge, 1994, Allan et al., 1996, Aguado and Burt, 2004). Natural swings in year-to-year climate variability, especially has a significant impact on cane yield (Everingham et al., 2001, Everingham et al., 2003), N losses (Brodie et al., 2012) and makes the task of applying the right amount of N fertiliser to optimise profitability and minimise environmental losses extremely challenging.

The SIX EASY STEPS (Schroeder et al., 2005a, Schroeder et al., 2010a, Schroeder et al., 2010b) and N Replacement (Thorburn et al., 2007, Thorburn et al., 2011a) strategies have improved nitrogen use efficiency compared to previous N fertiliser recommendations used in the Australian sugar industry (Chapman, 1994), but they are both limited in their ability to match N fertiliser inputs to forthcoming cane yields. Using a constant district yield potential (i.e. 120 t cane/ha for the Wet Tropics every year) to calculate N fertiliser inputs limits the ability of the current SIX EASY STEPS N guidelines to adapt to seasonal changes in cane yields caused by climate variability. The SIX EASY STEPS strategy aims to limit productivity losses by assuming the best possible growing conditions will be experienced in the forthcoming season. However, this increases the risk of environmental N losses when actual yields fail to reach the district yield potential (Thorburn et al., 2011b). In comparison, the N Replacement strategy focuses on previous crop yields rather than the yield potential of the forthcoming season (Thorburn et al., 2003, Thorburn et al., 2004) and this may restrict productivity when crop growing conditions are favourable to producing a crop much larger than the previous season (Skocaj et al., 2012). The size of the crop largely determines how much N fertiliser is required (Keating et al., 1997). Crop size (cane yield t cane/ha) is largely determined by the climatic conditions experienced during the growing season. So instead of linking N fertiliser inputs to a fixed yield target or yield of the previous crop, it may be more appropriate to base N fertiliser inputs on a seasonal yield potential as determined by the climatic conditions experienced during the growing season (Skocaj et al., 2013a, Bell and Moody, 2015).

Simulation studies investigating the impact of climatic conditions on sugarcane yields and nitrogen use efficiency have reported substantial differences in cane yields and N losses between years and soil types (Thorburn et al., 2011c, Thorburn et al., 2015). For Tully, high rainfall years were likely to result in lower cane yields, higher N losses and lower nitrogen use efficiency (Thorburn et al., 2011c, Thorburn et al., 2015). Crops also tended to be N limited in wet years, but rainfall distribution over the growing season was also important (Thorburn et al., 2015). Wet years have been traditionally defined based on the total amount of rainfall received over the growing season (i.e. June to May). If a wet year can be predicted accurately and early enough i.e. before growers apply N fertiliser, economic and environmental benefits are likely to result from altering N fertiliser rates. This is because there is an increased chance of experiencing lower cane yields and higher N losses in wet years.

Recent research has identified spring-summer rainfall as having the greatest influence on Tully mill cane yields (Skocaj and Everingham, 2014). In Tully, the majority of N fertiliser is applied to ratoon sugarcane crops during spring, well before the amount of spring-summer rainfall is known. Previous research has shown climate forecasting indices are capable of forecasting rainfall in Australian sugarcane growing regions (Stone and Auliciems, 1992, Everingham, 2007, Everingham et al., 2008).

The Oceanic Niño Index (ONI) has the potential to forecast rainfall / identify the state of ENSO before the majority of N fertiliser is applied to ratoon sugarcane crops. The Oceanic Niño Index is a principal measure for monitoring, assessing and predicting the El Niño-Southern Oscillation and is based on the three-month running-mean sea-surface temperature (SST) departures from average in the Niño 3.4 region (Smith and Reynolds, 2003). Typically, if the running average of SST anomalies for the previous three months is greater than plus 0.5°C, then an El Niño phase month is defined (Everingham, 2007). A La Niña month exists if the running average of SST anomalies for the previous three months is less than minus 0.5°C (Everingham, 2007). If the previous three month running average of SST anomalies is between minus 0.5°C and plus 0.5°C, inclusively, then neutral conditions exist (Everingham, 2007).

The Australian grains industry is using yield forecasts to guide in-season N fertiliser application rates (Hammer et al., 1996, Wang et al., 2008a, Yu et al., 2008, Hochman et al., 2009, Asseng et al., 2012). Yield forecasting in the grains industry has progressed to use a combination of crop modelling, measurements of pre-sowing field conditions, details of agronomic practices relevant to the current season, historical climate data and seasonal climate forecasts. A model-based decision support tool, known as Yield Prophet ® has been developed to disseminate yield forecasts to grain growers (Hochman et al., 2009). Yield Prophet ® allows grain growers to investigate 'what if' scenarios related to in-season N fertiliser management (i.e. if additional N should be applied as a topdressing).

Unlike the grains industry, there is limited potential to alter in-season N management in sugarcane crops. Nitrogen fertiliser is most commonly applied in a single application, below the surface, soon after harvesting. Despite having a much longer growing season, there is only a short period of time when climatic conditions and crop size are conducive to completing agronomic activities (i.e. fertilising and spraying) and a high risk of not being able to re-enter fields to apply more N fertiliser if required (i.e. split application). For sugarcane crops it is therefore more important to be able to predict how much N fertiliser is required at the start of the season.

As crop size (cane yield t cane/ha) is the main determinant of N fertiliser requirements, the impact of spring-summer rainfall on Tully cane yields is also likely to influence N fertiliser requirements. Therefore this chapter will investigate i) the impact of spring-summer rainfall on the N fertiliser requirements of ratoon sugarcane crops grown on the Bulgun series soil and ii) if the Oceanic Niño Index can be used to predict how much N fertiliser to apply.

4.2. Materials and Methods

APSIM-Sugar (Keating et al., 1999) is a dedicated sugarcane model with well-developed capability for simulating N dynamics in sugarcane production systems in Australia, South Africa and Brazil (Thorburn et al., 2005 and Thorburn et al., 2015). APSIM-Sugar (v7.4) was used to investigate the impact of climatic conditions on N fertiliser requirements for a sugarcane production system representative of the Wet Tropics sugar industry.

Annual cane yield response curves were generated for simulated first, second, third and fourth ratoon crop classes over a 45 year period. The simulation was designed so each crop class was grown in every year. Next, the optimum N fertiliser rate, defined as the N rate producing 95% of the maximum cane yield, was identified for every crop class and year. The strength of the relationship between spring-summer rainfall and optimum N rates was investigated. The relationship between the June to August Oceanic Niño Index and optimum N rates was also investigated. Specific details on this methodological approach follows.

4.2.1. Using APSIM-Sugar to simulate optimum nitrogen fertiliser requirements

4.2.1.1. APSIM-Sugar model configuration

APSIM-Sugar (Keating et al., 1999) (v7.4) was configured with APSIM-SoilN (Probert et al., 1998), APSIM-SoilWat (Probert et al., 1998), APSIM-SurfaceOM (Probert et al., 1998), APSIM-Plant (Robertson et al., 2002), meteorological (Met) and fertiliser management (Fertiliser) modules. Farming operations such as planting, fertilisation, harvesting and ending the soybean cover crop were specified through the MANAGER module.

The sugarcane production system simulated was representative of the Wet Tropics region (McMahon and Hurney, 2008a) and included plant cane and four ratoon crops, green cane trash blanketing, zero tillage in ratoons and a fallow period between crop cycles where a soybean break crop was grown. The sugarcane crop was always planted on the 10th August and harvested 370 days after planting (e.g. 15th September). All ratoon crops were grown for 365 days and harvested mid-September (e.g. 15th or 16th September). Harvest dates were kept the same irrespective of crop class to remove any influence of time of ratooning effects on cane yields (Lawes et al., 2002) and all crops were harvested green with the residue retained on the soil surface.

Plant cane N fertiliser rates were discounted 70 kg N/ha to account for the mineral N supplied by a soybean cover crop in line with normal grower practice and SIX EASY STEPS N management guidelines for the Wet Tropics region (Schroeder et al., 2007b). Following an application of 50 kg N/ha to the plant crop, at planting, either 0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210 or 240 kg N/ha was applied every year as urea, 80 mm below the soil surface, six weeks after harvest.

Simulations were started in 1934, 1935, 1936, 1937, 1938 and 1939. This resulted in a plant, first, second, third and fourth ratoon crop being simulated for every year (see Fig. 4.1). Simulated ratoon cane yields between 1970 and 2014 were used to determine optimum N fertiliser rates. This meant a minimum of 31 years of sugarcane production (a plant crop followed by four ratoon crops and a legume cover crop) was simulated prior to 1970, to allow soil organic matter pools in the model to reach their dynamic equilibrium. Optimum N fertiliser rates were not determined for the plant crop as a soybean break crop was included in the simulation to represent a typical Wet Tropics sugarcane production system. Legume break crops can contribute significant amounts of N (Garside et al., 1996, Garside and Bell, 1999). As legume N is readily available for plant uptake plant crops tend to be less responsive to applied N fertiliser than ratoon sugarcane crops.

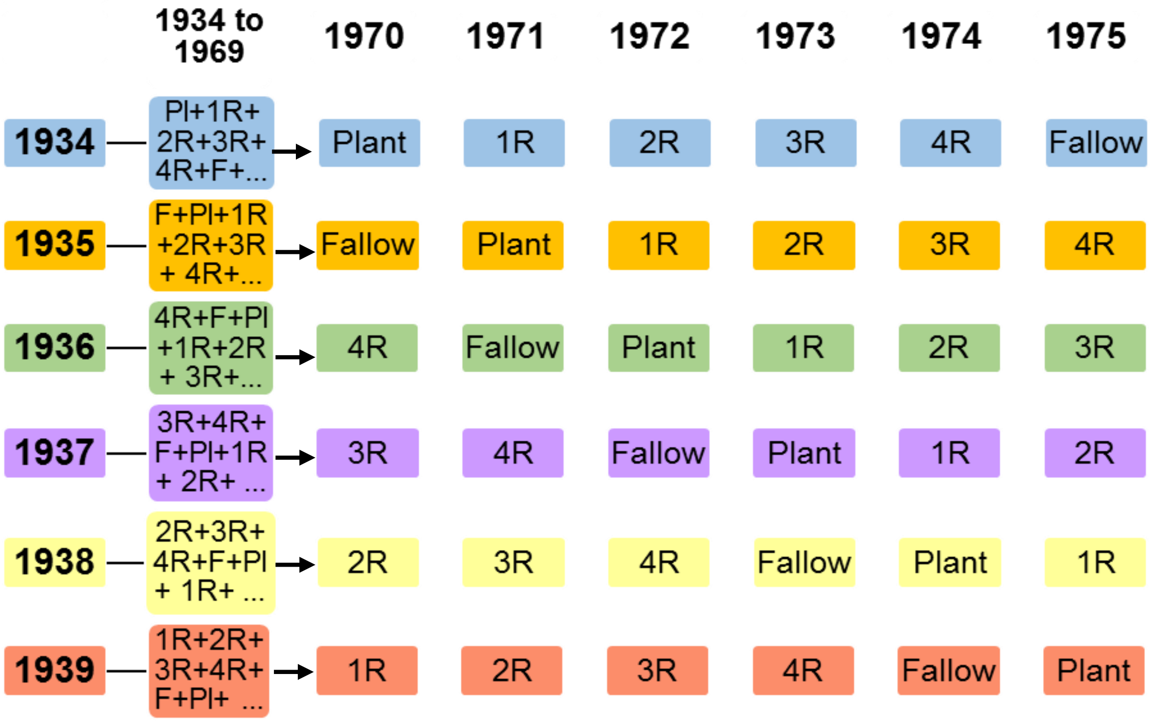

Figure 4.1. Graphical representation of simulation design.

4.2.1.2. Parameterisation of APSIM-Sugar

The results from a small-plot N fertiliser rate response field experiment conducted on a Bulgun series soil at Tully between 2011 and 2014 were used to define key parameters in APSIM-Sugar. The experiment assessed the impact of twelve different N fertiliser application rates on crop growth, cane yield, crop N uptake and changes in soil mineral N levels. The soil sample results were used to parameterise an existing APSIM soil file (Tully No. 648) to represent a Bulgun series soil. The initial mean nitrate N (NO_3^- kg/ha), ammonium N (NH_4^+ kg/ha) and organic carbon (total %) values entered into APSIM-Sugar are reported in Appendices 1 and 2. Soil chemical (e.g. pH, electrical conductivity, nutrients) and textural values for the 0-20 and 40-60 cm depths were altered according to soil sample results. The mean bulk density (g/cc) and volumetric water content (lower extractable limit, drained upper limit and saturated water content) values entered into APSIM-Sugar are reported in Appendix 3.

The sugarcane variety selected was Q117 because it was used in the calibration of APSIM-Sugar (Keating et al., 1999) and no other currently grown commercial sugarcane cultivars (including Q208[Φ] which was grown in the Tully small-plot N rate response field experiment) have been parameterised (Sexton et al., 2014). The stalk population for the plant crop remained the same at 10 stalks/m^2 for all N fertiliser application rates. The mean ratoon stalk population entered for each N fertiliser treatment was calculated from the final harvest stalk populations measured at the Tully small-plot N fertiliser rate response field experiment over three successive ratoon crops (i.e. first, second and third ratoon crops). A response curve was estimated by fitting a second order polynomial using least squares regression to describe mean stalk population from N (refer to Fig. 4.2).

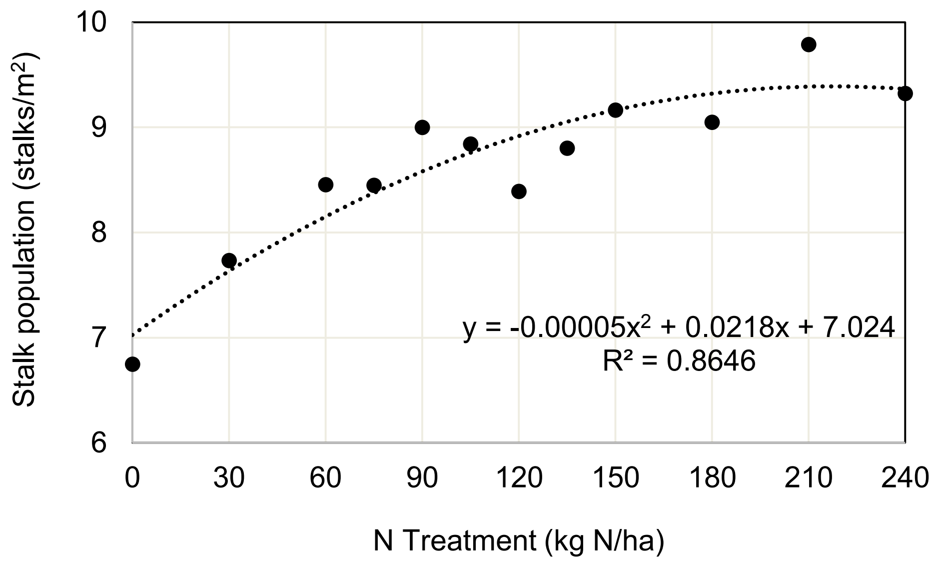

Figure 4.2. Relationship between mean stalk population (stalks/m^2) and N fertiliser rate (kg N/ha) over three successive ratoon crops based on observed field experiment data.

Daily climate data (minimum and maximum temperature, rainfall, vapour pressure, solar radiation and evaporation) were obtained from the SILO climate data archive using the patched point dataset option (Jeffrey et al., 2001) for the Tully sugar mill meteorological station (station number 32042).

4.2.1.3. Representing water and nitrogen stress in APSIM-Sugar

The high rainfall environment of the Wet Tropics region often results in sugarcane crops experiencing short to prolonged periods of waterlogging. Waterlogging is known to have an adverse effect on cane growth and hence final cane yields (Rudd and Chardon, 1977, Leslie and Wilson, 1996). APSIM-Sugar only considers the transient effect of waterlogging because not enough information is available on the longer term effects on cane growth. To simulate the transient effect of waterlogging, the value of the APSIM 'waterlogging stress factor' (*oxdef_photo*) was set to 0.63 and 0.53 in the plant and ratoon crops respectively when >80% of the root system was exposed to saturated or near saturated soil water conditions. *Oxdef_photo* reduces photosynthetic activity via an effect on radiation use efficiency (RUE). Therefore the values used in the simulations reduced photosynthesis by 37% and 47% in the plant and ratoon crops respectively. The lodging option was used to simulate the longer lasting effects of waterlogging. Following a rainfall event of >200 mm, RUE was reduced by setting the *lodge_redn_photo* value to 0.70 for the ratoon crops only. The *lodge_redn_photo* setting decreases radiation use after lodging with a value of 1 indicating no effect and 0 complete stress (e.g. no crop growth).

As N is required in the largest quantity to optimise crop growth, simulated crops were made slightly more sensitive to N stress by altering the N stress factor in APSIM-Sugar. The N stress factor for photosynthesis (*nfact_photo*) was decreased from 1.0 to 0.8 to increase the sensitivity to nitrogen stress in both plant and ratoon crops. The *nfact_photo* setting reduces photosynthetic activity via an effect on RUE with a value of 1 indicating no stress and 0 complete stress.

4.2.2. Defining optimum nitrogen fertiliser rates

A second order polynomial was fitted to describe the APSIM-sugar simulated cane yields as a function of N fertiliser rates (kg N/ha). This was done for every first, second, third and fourth ratoon crop that were simulated every year between 1970 and 2014. The N rate producing the highest yield for each crop class and year was identified. This allowed the optimum N fertiliser rate and cane yield corresponding to 95% of the maximum yield to be determined for every crop class and year (Schroeder et al., 2005a, Skocaj et al., 2013a).

4.2.3. Investigating the relationship between spring-summer rainfall and nitrogen fertiliser requirements

Given that total spring-summer (SONDJF) rainfall was found to have a strong influence on Tully mill cane yields (Skocaj and Everingham 2014), the influence of spring-summer rainfall on optimum N fertiliser requirements was investigated. Total spring-summer rainfall recorded at Tully sugar mill for the last 45 years (1970 to 2014) was sorted in ascending order and split into three equal groups (terciles). Every year from 1970 to 2014 was categorised as being in either tercile 1 (dry), 2 (normal) or 3 (wet) according to the total rainfall observed over SONDJF.

Boxplots were inspected to gauge the relationship between spring-summer rainfall terciles and N fertiliser requirements. This was more formally tested using the Kruskal Wallis and Mann-Whitney statistical significance tests. Outliers were omitted from the dataset before undertaking the statistical analysis.

4.2.4. Investigating the relationship between ENSO and nitrogen fertiliser requirements

The impact of ENSO on optimum N fertiliser requirements was also investigated because of its influence on north Queensland sugarcane yields (Kuhnel, 1994, Everingham et al., 2001, Everingham et al., 2003). The June to August Niño 3.4 sea surface temperature anomalies for the period 1969 to 2013 were downloaded from the Climate Prediction Center website (http://www.cpc.ncep.noaa.gov). These sea surface temperature anomalies pertain to version 3b of the extended reconstructed sea surface temperature (Smith and Reynolds, 2003). El niño years were defined when the June to August Oceanic Niño Index was greater than plus 0.5^{o}C. La Niña years were defined by the June to August Oceanic Niño Index being less than minus 0.5^{o}C. Years when the June to August Oceanic Niño Index was between minus 0.5^{o}C and plus 0.5^{o}C, inclusively, were deemed to be in the neutral phase.

Boxplots and probability of exceedance diagrams were produced to determine the shift in the distribution of optimum N fertiliser requirements between El Niño, neutral and La Niña years. Kruskal Wallis and Mann-Whitney statistical significance tests were implemented to test for statistical significance of the shifts in these distributions. Outliers were omitted from the dataset before undertaking the statistical analysis.

4.3. Results

The categorisation of total spring-summer rainfall for the period 1970 to 2014 into terciles resulted in dry years (i.e. tercile 1) being defined as receiving less than or equal to 1492 mm of rainfall over spring-summer and wet years (i.e. tercile 3) as receiving at least 2184 mm of rainfall. Remaining years were classified as normal years (i.e. tercile 2). The differences in simulated optimum N rates between rainfall terciles according to ratoon crop class are shown in Figure 4.3.

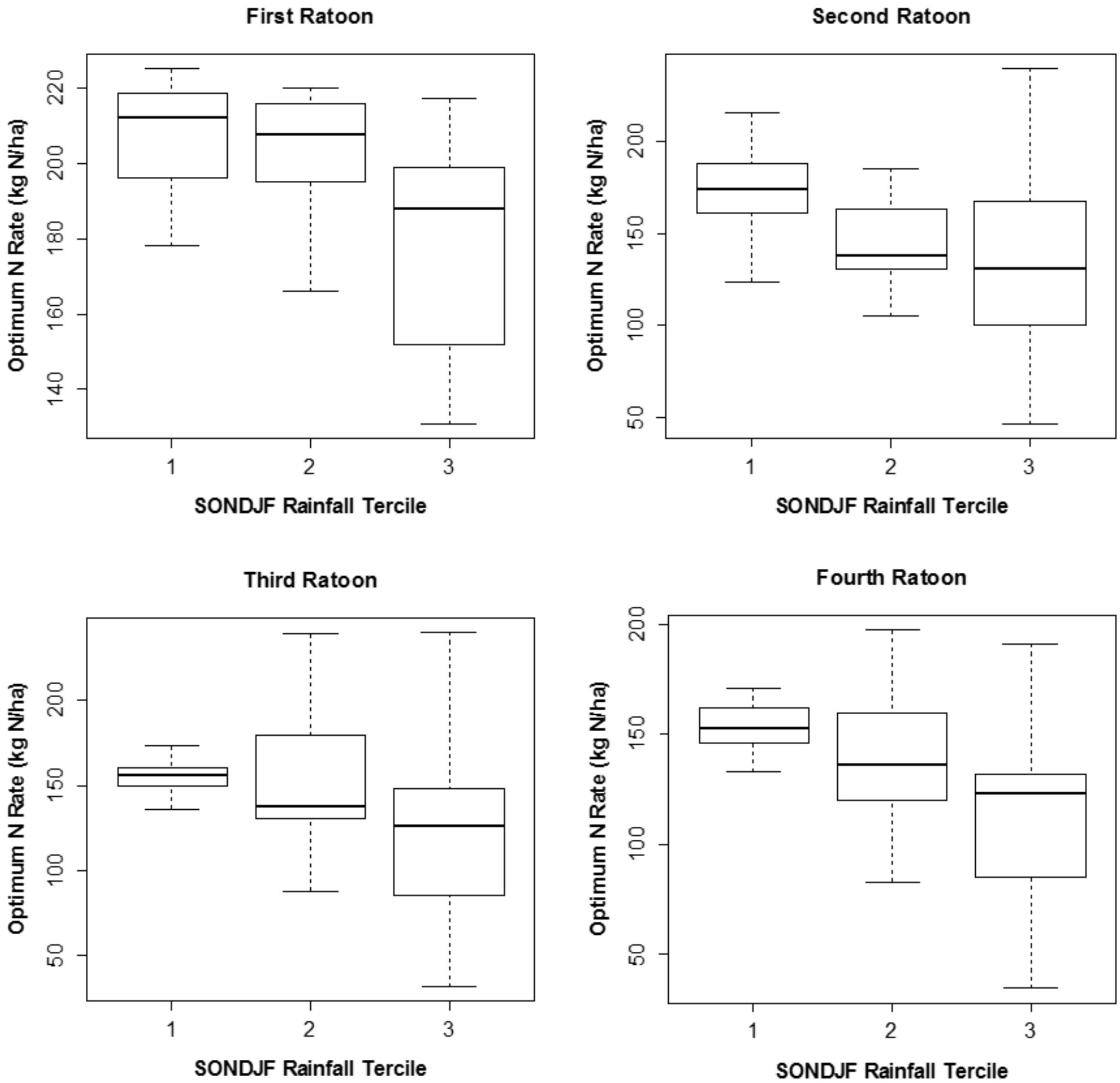

Figure 4.3. Relationship between simulated optimum N rates and spring-summer (SONDJF) rainfall terciles for first, second, third and fourth ratoon sugarcane crops grown on Bulgun series soil. Spring-summer (SONDJF) rainfall tercile 1, 2 and 3 corresponds to dry, normal and wet years, respectively.

The Kruskal Wallis procedure found spring-summer rainfall had a significant effect on optimum N rates for the 1st (p=0.0042), 2nd (p=0.0103) and 4th (p=0.0011) ratoon crops, and approached statistical significance for the third ratoon (p=0.0575). Inspection of the boxplots and Mann-Whitney post-hoc comparisons indicated less N fertiliser is required in wet years, especially for first and fourth ratoon crops. With the exception of second ratoon crops, there was typically no difference in optimum N fertiliser rates between dry and normal years (see Table 4.1.).

Table 4.1. Statistical analyses of the impact of spring-summer rainfall terciles on simulated optimum N rates for first, second, third and fourth ratoon sugarcane crops grown on Bulgun series soil. Significance levels below the Bonferroni adjusted significance level of 0.0167 for post-hoc comparisons have been asterisked.

Ratoon crop class	Kruskal-Wallis Test p-values	Mann-Whitney U test p-values comparing the optimum N rate between spring-summer rainfall terciles		
		Tercile 1 vs 2	Tercile 2 vs 3	Tercile 1 vs 3
1R	0.0042	0.3942	0.0145*	0.0025*
2R	0.0103	0.0023*	0.5336	0.0344
3R	0.0575	0.4895	0.0890	0.0270
4R	0.0011	0.0761	0.0495	0.0003*

Table 4.2. Statistical analyses of the impact of June to August Oceanic Niño Index phases on simulated optimum N rates for first, second, third and fourth ratoon sugarcane crops grown on Bulgun series soil. Significance levels below the Bonferroni adjusted significance level of 0.0167 for post-hoc comparisons have been asterisked.

Ratoon crop class	Kruskal-Wallis Test p-values	Mann-Whitney U test p-values comparing the optimum N rate between June to August ONI phases		
		El Niño vs Neutral	Neutral vs La Niña	El Niño vs La Niña
1R	0.0006	0.0274	0.0020*	0.0044*
2R	0.0437	0.5309	0.0315	0.0310
3R	0.0031	0.9999	0.0016*	0.0067*
4R	0.0001	0.0024*	0.0024*	0.0035*

The differences in simulated optimum N rates between June to August Oceanic Niño Index phases according to ratoon crop class are shown in Figure 4.4. The optimum N rates for all ratoon crops differed significantly with the June to August Oceanic Niño Index phase (refer to Table 4.2). There was a strong trend for optimum N rates to be lower in La Niña years. With the exception of fourth ratoon crops there was no significant difference in optimum N rates between El Niño and Neutral years. These findings are more distinctly seen in the probability of exceedance diagrams shown in Fig. 4.5. Using the fourth ratoon crop (see Fig. 4.5. Fourth ratoon) as an example, there is on a 20% chance that more than 150 kg N/ha will be required when the June to August Oceanic Niño Index phase is La Niña, but when the June to August Oceanic Niño Index phase is El Niño there is an 80% chance that more than 150 kg N/ha will be required.

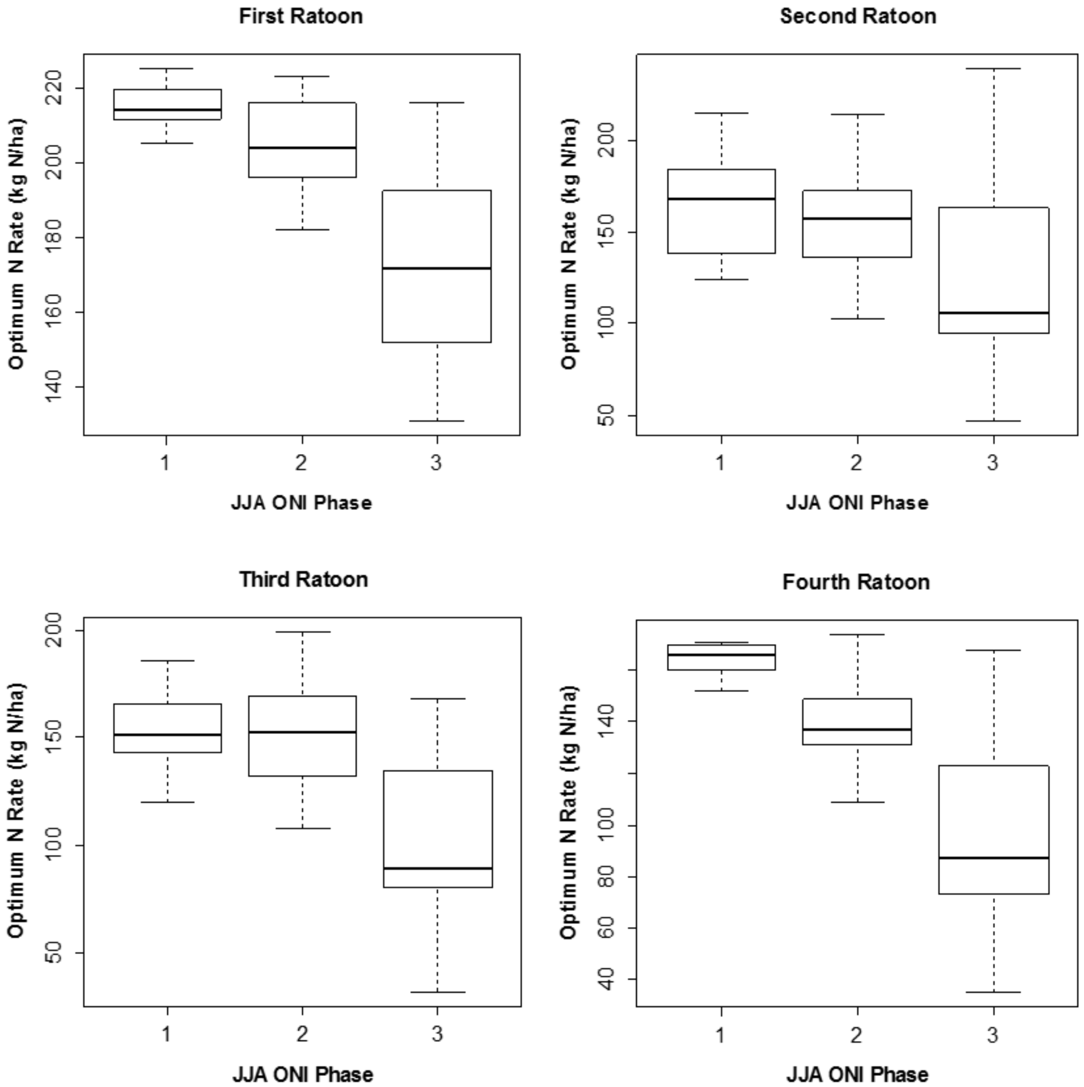

Figure 4.4. Relationship between simulated optimum N rates and June to August Oceanic Niño Index (JJA ONI) phase for first, second, third and fourth ratoon sugarcane crops grown on Bulgun series soil. The June to August Oceanic Niño Index (JJA ONI) phase 1, 2 and 3 corresponds to El Niño, Neutral and La Niña phases, respectively.

The probability of exceedance diagrams shown in Fig. 4.5. allow the chance of optimum N rates being adequate for first, second, third or fourth ratoon sugarcane crops grown on the Bulgun series soil to be assessed for the different June to August Oceanic Niño Index phases.

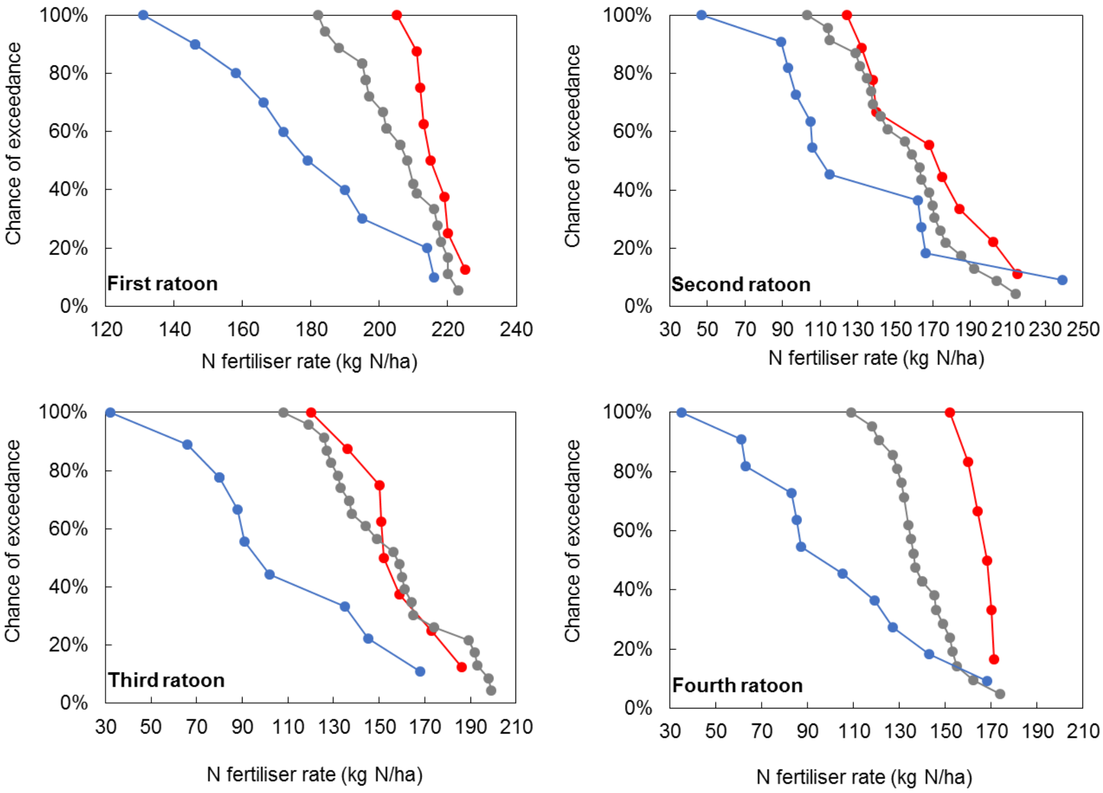

Figure 4.5. The percent chance of exceedance (y axis) and optimum N fertiliser rate (x axis) when the June to August Oceanic Niño Index phase is El Niño (●——●), Neutral (●——●) or La Niña (●——●) for first, second, third and fourth ratoon sugarcane crops simulated on the Bulgun series soil.

4.4. Discussion

Current N fertiliser guidelines are based on either a district yield potential (Schroeder et al., 2010b) or the cane yield of the previously harvested crop (Thorburn et al., 2003, Thorburn et al., 2004). The Wet Tropics sugarcane production region experiences extreme inter-annual climate variability and this has a strong impact on crop size. As crop size (cane yield) is the primary determinant of N fertiliser requirements, current N fertiliser guidelines are limited in their ability to match N fertiliser inputs to forthcoming cane yields. In Tully the majority of N fertiliser is typically applied to ratoon sugarcane crops during spring. Spring-summer rainfall was found to have a strong influence on Tully cane yields (Skocaj and Everingham, 2014). However, sugarcane growers typically apply the same amount of N fertiliser to ratoon crops each year regardless of the impact of spring-summer rainfall on cane yields.

In this simulation study, the relationship between spring-summer rainfall and optimum N fertiliser rates indicates N fertiliser rates should be reduced in wet years for sugarcane ratoon crops grown on the Bulgun series soil. Wet years have been defined as those when total rainfall over the spring-summer period is in the upper tercile or tercile 3. There was typically no difference in optimum N fertiliser rates between dry and normal years. This means N fertiliser application rates should remain the same in dry and normal years. In practice a climate forecasting system capable of predicting spring-summer rainfall before the majority of N fertiliser is applied, will be required to identify which years are likely to be wet so that N fertiliser application rates can be reduced. However the simulation study also indicated N fertiliser application rates should be reduced for ratoon sugarcane crops grown on the Bulgun series soil when the June to August Oceanic Niño Index is in the La Niña phase.

This means the June-August Oceanic Niño Index can be used to predict how much N fertiliser to apply to ratoon sugarcane crops grown on the Bulgun series soil. The link between N fertiliser inputs and the June-August Oceanic Niño Index exists because the chance of experiencing high spring-summer rainfall increases when the June-August Oceanic Niño Index is in the La Niña phase. High spring summer-rainfall is associated with low cane yields at Tully owing to increased waterlogging and lower solar radiation.

As APSIM-Sugar simulates potential cane yields the simulated optimum N fertiliser rates are higher than current industry recommendations. For ratoon sugarcane crops the SIX EASY STEPS N fertiliser guidelines for the Wet Tropics region recommends between 100 and 160 kg N/ha be applied depending on the organic carbon (%) value of the soil (Schroeder et al., 2007b). For Bulgun soils, the recommended SIX EASY STEPS N rate would normally range from 110 to 130 kg N/ha depending on the soil organic carbon (%) (Schroeder et al., 2007b). The simulated optimum N fertiliser rates therefore should not be interpreted as being absolute. Despite the simulated optimum N fertiliser rates being higher than recommended the percentage reduction in N fertiliser rates between wet (i.e. La Niña) and dry-to-normal (i.e. El Niño and Neutral) years is realistic. On average N fertiliser rates should be reduced by 25% when the June to August Oceanic Niño Index is in the La Niña phase (i.e. predicting the forthcoming spring-summer to be wet) for ratoon sugarcane crops grown on the Bulgun series soil. With at least 50% of the N fertiliser applied lost from agricultural systems worldwide and the majority of losses occur during the year of fertiliser application (Dobermann, 2005), reducing N fertiliser application rates in ratoon sugarcane crops grown on the Bulgun series soil in wet years, defined when the June to August Oceanic Niño Index is in the La Nina phase, may help improve fertiliser nitrogen use efficiency in the Wet Tropics sugar industry.

The ability to use climate forecasting indices to predict N fertiliser requirements for sugarcane crops is markedly different to how climate forecasting indices are being used to guide N fertiliser management in the Australian grains industry. In the grains industry N fertiliser management involves a combination of anticipatory (before planting) and responsive (in-season) decision processes to reduce N losses and improve nitrogen use efficiency (Dobermann, 2005). Climate forecasting indices are used in predicting crop growth and yields so that farmers can make more informed decisions on in-season N fertiliser applications. For the sugar industry it is more important to be able to predict the total N fertiliser requirements at the start of the season, before N fertiliser is applied, because in-season application of N fertiliser is not practiced.

4.5. Conclusion and future work

In regions prone to extreme climate variability, such as the Wet Tropics, historically, it has been difficult to match N fertiliser inputs to forthcoming cane yields. This typically results in sugarcane growers applying a similar rate of N fertiliser to ratoon crops every year to minimise the risk of yield loss if ideal, or close to ideal, growing conditions are experienced. Previous research identified spring-summer rainfall as having a strong influence on Tully mill cane yields (Skocaj and Everingham, 2014). This simulation study has identified spring-summer rainfall also influences N fertiliser requirements and that the June to August Oceanic Niño Index can be used to predict annual N fertiliser requirements. It is suggested that sugarcane growers should consider reducing N fertiliser rates to ratoon sugarcane crops grown on the Bulgun series soil when the June to August Oceanic Niño Index is in the La Niña phase. However, seasonal climate forecasts only provide probabilistic information about future climatic conditions, so there will always be some uncertainty regarding the accuracy of climate forecasts. Future research should be directed towards understanding the overall economic, environmental and social benefits for the Wet Tropics region of using the June to August Oceanic Niño

Index to predict N fertiliser application rates for ratoon sugarcane crops grown on the Bulgun series soil.

Reducing N fertiliser application when the June to August Oceanic Niño Index is in the La Niña phase only pertains to ratoon sugarcane crops grown on the Bulgun series soil. Future research should be directed towards understanding the impact of spring-summer rainfall on the N fertiliser requirements of ratoon crops grown on other major soil types in the Wet Tropics and if the June to August Oceanic Niño Index can be used to predict N fertiliser requirements for these soil types. The methodological framework presented can also be easily adapted to investigate the impact of climatic conditions on the N fertiliser requirements of ratoon sugarcane crops grown in other regions experiencing climate variability. This includes the Herbert and Central cane growing regions. Recent reviews of sugarcane productivity have shown that excessive rainfall has a significantly negative impact on cane yields in the Herbert and Central cane growing regions (Salter and Schroeder 2012, Garside et al., 2014, Everingham et al., 2015). These regions are also located in close proximity to the Great Barrier Reef and have the same water quality improvement targets as the Wet Tropics sugar industry.

4.6. Summary

Crop size (cane yield t cane/ha) is the main determinant of N fertiliser requirements. The size of the sugarcane crop at Tully is strongly influenced by spring-summer rainfall. However, current N fertiliser guidelines do not consider the impact of spring-summer rainfall on crop size and hence N fertiliser requirements. The aim of this chapter was to investigate the impact of spring-summer rainfall on N fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil and if existing climate forecasting indices be used to predict how much N fertiliser to apply in the Wet Tropics. Optimum N fertiliser rates were simulated for first, second, third and fourth ratoon sugarcane crops grown on the Bulgun series soil for a 45 year period using APSIM-Sugar. The relationship between spring-summer rainfall and optimum N fertiliser rates was investigated. The impact of ENSO on optimum N fertiliser requirements was also investigated using the June to August Oceanic Niño Index. The results indicate the June to August Oceanic Niño Index can be used to predict how much N fertiliser to apply to ratoon sugarcane crops grown on the Bulgun series soil. Nitrogen fertiliser rates should be reduced in wet years, defined when the June to August Oceanic Niño Index is in the

La Niña phase. The relationship between optimum N fertiliser rates between El Niño and Neutral phase years was less evident. The link between N fertiliser inputs and the June-August Oceanic Niño Index exists because the chance of experiencing high spring-summer rainfall increases when the June-August Oceanic Niño Index is in the La Niña phase. High spring summer-rainfall is associated with low cane yields at Tully due to increased waterlogging and lower solar radiation.

Chapter 5

Understanding fertiliser N recovery and nitrogen use efficiency of sugarcane ratoon crops: results from small-plot N rate field experiments on a Grey Dermosol in the Wet Tropics region of North Queensland, Australia

This Chapter investigates fertiliser N recovery and fertiliser nitrogen use efficiency of successive ratoon sugarcane crops grown on the Bulgun series soil using the results of three small-plot N fertiliser rate response experiments conducted in the Wet Tropics between 2011 and 2014. A better understanding of fertiliser N recovery between successive ratoon sugarcane crops and the economic impact of improving fertiliser nitrogen use efficiency will contribute towards the development of environmentally sustainable and economically effective N management strategies. At the time of submitting this thesis, the contents of this chapter had not been published or submitted for review. It is intended to submit this chapter to Field Crops Research.

5.1. Introduction

Nitrogen is required in relatively large quantities to optimise productivity in sugarcane, but compared to other crops it appears to be an inefficient user of N fertiliser (Chapman et al., 1992, Chapman et al., 1994, Vallis and Keating, 1994, Prasertsak et al., 2002, Ladha et al., 2005). The amount of N fertiliser recovered by sugarcane crops commonly ranges from 20% to 40% of the N fertiliser applied (Vallis et al., 1996). Similar N fertiliser recovery values have been reported for Australian cereal crops (Ladha et al.., 2005), but the amount of nitrogen fertiliser applied to thqese crops is much lower than sugarcane crops. The fate of N fertiliser not recovered by the crop, immobilised in soil N pools and/or lost from the sugarcane production system has serious economic and environmental consequences. The Wet Tropics region is estimated to deliver the highest anthropogenic dissolved inorganic nitrogen load to the Great Barrier Reef lagoon with the loss of N fertiliser applied to sugarcane fields a major contributor (Waterhouse et al., 2012, Kroon et al., 2012).

Voluntary adoption of improved N management practices such as the SIX EASY STEPS N management guidelines in the Wet Tropics region has reduced N fertiliser application rates (i.e. the period between 1996 and 2006) (McMahon and Hurney, 2008a, Calcino et al., 2010), improved fertiliser nitrogen use efficiency and increased profitability compared to traditional grower practice (Schroeder et al., 2009c, Skocaj et al., 2012). However, catchment modelling indicates it will be difficult to achieve the water quality target of at least a 50% reduction in DIN levels by 2018 (Reef 2050 Long-Term Sustainability Plan, Commonwealth of Australia 2015) even with full adoption of current best practice N management, (Webster et al., 2012, Thorburn and Wilkinson, 2013) let alone the new target for an 80% reduction in DIN levels by 2025 (Reef 2050 Long-Term Sustainability Plan, Commonwealth of Australia 2015). It appears that major improvements in fertiliser nitrogen use efficiency will be required to meet water quality improvement targets and ensure the sustainability of the Wet Tropics sugar industry, without simply reducing N fertiliser application rates.

From an agronomic perspective it is common to consider nitrogen use efficiency in terms of the yield per kilogram of N applied, otherwise termed yield efficiency (Wood and Kingston, 1999). The aim of any cropping system should be to increase yield efficiency. Yield efficiency can be increased by obtaining (1) the same yield with less N fertiliser, or (2) a higher yield with less N fertiliser or (3) a higher yield with the same amount of N fertiliser (Wood and Kingston, 1999). Increasing yield efficiency can be difficult to accomplish in regions like the Wet Tropics which experience extreme climatic and cane yield variability (Nicholls et al., 1997).

The Australian sugar industry commonly uses the fertiliser N-use efficiency factor to assess N fertiliser performance, (Bell and Moody, 2015, Bell et al., 2015, Schroeder et al., 2010a, Schroeder et al., 2015). Fertiliser N-use efficiency,

$$Fertiliser\ N - use\ efficiency\ (t\ cane/kg\ N\ ) = \frac{Cane\ Yield\ (t\ cane/ha)}{N\ fertiliser\ applied\ (kg\ N/ha)} \tag{5.1}$$

otherwise known as the partial factor productivity of applied N (PFP_N) (Dobermann, 2005) or the Apparent Agronomic Efficiency of Fertiliser N (Apparent $AgronEff_{Fert}$) (Bell and Moody, 2015, Bell et al., 2015), is the broadest measure of nitrogen use efficiency and is often used when the cane yield for nil N fertiliser applied has not been measured. It is the most important nitrogen use efficiency measure for farmers as it integrates the use efficiency of both applied and soil N resources (Dobermann, 2005).

The aim of current N fertiliser strategies is to improve nitrogen use efficiency by ensuring that the fertiliser N-use efficiency is as high as possible (Schroeder et al., 2015). Ideally, nitrogen use efficiency should be improved without adversely affecting productivity and profitability. Current N fertiliser strategies (i.e. SIX EASY STEPS and N Replacement) are based on yield targets (i.e. District Yield Potential (DYP) or preceding crop yield respectively) and the amount of applied N required to produce one tonne of cane (1.4 kg N/t cane up to 100 t cane/ha and 1.0 kg N/t cane/ha thereafter for the SIX EASY STEPS, or 1.0 kg N/t cane in green cane systems N Replacement). This results in each strategy having different fertiliser N-use efficiency targets.

The fertiliser N-use efficiency targets of the SIX EASY STEPS N management guidelines for the Wet Tropics region (refer to Table 5.1.) range from 0.75 t cane/kg N to 1.20 t cane/kg N for ratoon sugarcane crops grown on soils with very low and very high soil organic (C) values, respectively (Schroeder et al., 2010a, Schroeder et al., 2015). In contrast the N-use efficiency target of the N-Replacement strategy for green cane trash blanketed production systems remains constant at 1.0 kg t cane/kg N, as N fertiliser applications are linked to cane yields (Schroeder et al., 2015).

Table 5.1. Fertiliser N-use efficiency targets for ratoon sugarcane crops in the Wet Tropics region (where the DYP = 120 t cane/ha) according to the SIX EASY STEPS N management guidelines (Schroeder et al., 2010a).

Wet Tropics Ratoon Sugarcane Crops	**Soil organic carbon (%)**						
	0–0.4	**0.4–0.8**	**0.8–1.2**	**1.2–1.6**	**1.6–2.0**	**2.0–2.4**	**> 2.4**
District Yield Potential (t cane/ha)	120						
Recommended N fertiliser rate (kg N/ha)	160	150	140	130	120	110	100
Target fertiliser N-use efficiency (t cane/kg N)	0.75	0.80	0.86	0.92	1.00	1.09	1.20

Bell and Moody (2015) have suggested that using the fertiliser N-use efficiency factor to assess fertiliser N performance may be inappropriate as it does not clearly differentiate between the contribution of soil (i.e. soil organic N pool) and applied N (i.e. fertiliser and legume N) sources on productivity. They propose that the so-called Agronomic Efficiency of Fertiliser N ($AgronEff_{Fert}$) is possibly a better way of defining fertiliser nitrogen use efficiency as it represents the efficiency of N recovery from applied N and the efficiency with which the plant uses each addition unit of N acquired (Dobermann, 2005, Bell and Moody, 2015). The Agronomic efficiency of fertiliser N,

$$Agronomic\ efficiency\ of\ fertiliser\ N\ (t\ cane/kg\ N) = \frac{Cane\ Yield\ Y_N - Y_{0N}\ (t\ cane/ha)}{N\ fertiliser\ applied\ (kg\ N/ha)} \tag{5.2}$$

differs from the more commonly used fertiliser N-use efficiency measure as it takes into account the yield produced in the absence of applied N fertiliser. Therefore it can only be used if cane yield is measured at nil N applied.

The majority of previous experiments have focused on quantifying the recovery of fertiliser N in sugarcane crops but have not investigated if the amount of fertiliser N recovered differs between successive ratoon crops(Takahashi, 1970a, Takahashi, 1970b, Chapman et al., 1991, Chapman et al., 1992, Chapman et al., 1994, Vallis et al., 1996). In relation to the Wet Tropics region there have been few experiments investigating the recovery of fertiliser N by sugarcane crops (Prasertsak et al., 2002, Meier et al., 2006) or the economic impact of improving fertiliser nitrogen use efficiency (Schroeder et al., 2009b). The aim of the research reported in this chapter was to investigate the:

i) total amount of N recovered by ratoon sugarcane crops grown on the Bulgun series soil,
ii) amount of fertiliser N recovered by successive ratoon sugarcane crops grown on the Bulgun series soil,
iii) fertiliser nitrogen use efficiency of ratoon sugarcane crops grown on the Bulgun series soil, and
iv) impact of improving fertiliser nitrogen use efficiency on grower and industry profitability

5.2. Materials and Methods

Small-plot N rate field experiments were conducted between 2011 and 2014 in the Wet Tropics region of the Australian sugar industry. Annual cane yield response curves to applied N were generated and the so-called 'Optimum 90' and 'Optimum 95' N rates were identified. The amount of N recovered in the aboveground components of the sugarcane crop was measured and the contribution of soil and applied N sources in the total amount of N recovered determined. The fertiliser N-use efficiency and $AgronEff_{Fert}$ was determined to compare fertiliser N performance between ratoon crops. Finally the impact of using the Optimum 90 and 95 N rates on fertiliser N-use efficiency and profitability was compared to the SIX EASY STEPS recommended N rates.

5.2.1. Experimental details

Three small-plot N rate field experiments were established in commercial sugarcane blocks after harvesting the plant crop in 2011 and continued for three ratoon crops (first, second and third ratoon). All sites were located on Grey Dermosols (Isbell, 1996) and in particular on Bulgun series soil (Cannon et al., 1992). This soil type is representative of poorly-drained alluvial soils occurring throughout the Wet Tropics region. A common variety (Q208⁽ᴾ⁾, a major Australian commercial variety of the Australian Sugar Industry), crop class (first ratoon), row spacing (1.60 m) and row direction (North-South) were used across sites. The geographical location of the sites, referred to as T1 (17° 58' 42.3912"S, 145° 55'29.0886"E), T2 (17° 46' 15.9384"S, 146° 1' 45.0042"E) and T3 (18°0' 7.1634"S, 145° 57' 52.1994"E) are shown in Fig. 5.1.

There were twelve N treatments (0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210 and 240 kg N/ha) applied in a randomized complete block design at each site and the same N treatment was applied to the same plot location every year of the experiment. The experimental details of each site are shown in Table 5.2. Maps of the experimental design and treatment layout for each site are shown in Appendices 4 and 5 respectively.

Figure 5.1. Location of experimental sites, north Queensland, Australia (Source: Google earth, imagery date 4/10/2013, date accessed 17/04/2015)

Table 5.2. Experimental details of the Wet Tropics small-plot N rate field experiments.

	T1	T2	T3
Soil series	Bulgun	Bulgun	Bulgun
Variety	Q208$^{\Phi}$	Q208$^{\Phi}$	Q208$^{\Phi}$
Crop class	1R, 2R, 3R	1R, 2R, 3R	1R, 2R, 3R
Row direction	N-S	N-S	N-S
Row spacing (m)	1.60	1.60	1.60
Rows/plot	6	6	6
Plot length (m)	30	27	27
Plot area (m^2)	288	259.2	259.2
No. of N Treatments	12	12	12
N rate (kg N/ha)	0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210, 240	0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210, 240	0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210, 240
Replicates	4	4	3

The N source used was urea and it was applied subsurface to each side of the cane row approximately six weeks after harvest using a single row, variable rate side applicator. The fertiliser and harvest dates for each site and ratoon crop are shown in Table 5.3.

Nutritional requirements, other than N, were determined using the SIX EASY STEPS nutrient management guidelines for the Wet Tropics region (Schroeder et al., 2007b).

Table 5.3. Fertiliser application and harvest dates for the Wet Tropics small-plot N rate field experiments.

Site	Activity	Crop Class		
		1R	2R	3R
T1	Fertilised	19-20/09/2011	24-25/09/2012	25-26/09/2013
	Harvested	8/08/2012	13/08/2013	4/09/2014
T2	Fertilised	21/09/2011	8/10/2012	14/10/2013
	Harvested	10/08/2012	15/08/2013	5/09/2014
T3	Fertilised	20-21/09/2011	25-26/09/2012	26-27/09/2013
	Harvested	7/09/2012	24/09/2013	2/09/2014

Cane yield was determined using the procedures outlined by (Hogarth and Skinner, 1967, Muchow et al., 1993, Thomas et al., 1993). This involved hand cutting and weighing cane from a 16 m^2 area in the centre two rows of every plot. Twenty stalks were randomly selected and partitioning into millable stalk (MS), green leaves and cabbage[1] (LC) and dead leaves/trash. Moisture content and N concentration of the MS and LC components were determined by shredding six randomly stalks and tops from the partitioned hand harvested material, collecting a subsample of shredded material and recording the fresh weight recording the dry subsample weight. The dried samples were then ground using a micro hammer mill and sent to the laboratory for N analysis. Another six stalks (green leaf and cabbage removed) were again randomly selected from the hand harvested material for CCS determination by NIR methodology (Berding et al., 2003). The remaining centre two rows were mechanically harvested, the weight recorded and combined with the hand harvested MS weight to calculate the cane yield (t cane/ha) of each plot.

5.2.2. Determining cane yield response to applied nitrogen fertiliser

Cane yield response curves were generated for first, second and third ratoon crops at each experimental site. A linear model was fitted to explain how mean cane yields varied with N fertiliser rates and between ratoon crop classes at each site. The final model

[1] Cabbage refers to the top of the sugarcane stalk that remains after cutting between the 5th and 6th dewlaps of non-flowered stalks or between the 7th and 8th dewlaps of flowered stalks

contains only significant terms which have been determined by a backward stepwise regression routine with the p-value criterion to enter/exit set at 0.05 and 0.10, respectively.

5.2.3. Determining optimum nitrogen fertiliser rates

The final model was then used to identify the N rate producing the highest yield for every crop. This allowed the optimum N fertiliser rate and cane yield corresponding to 90% (Optimum 90) and 95% (Optimum 95) of the maximum yield to be determined for every crop class and year (Schroeder et al., 2005a, Skocaj et al., 2013a).

5.2.4. Determining nitrogen recovery

The amount of N taken up by the crop was determined using the moisture content and N concentration results of the MS and LC components of the sugarcane crop. This is commonly referred to as crop N recovery (kg N/ha). Crop N recovery was then expressed in terms of the percentage of N recovered relative to the amount of N fertiliser applied according to the following equation:

$$N\ recovery\ (\%) = \frac{Crop\ N\ recovery N_{x^2}\ \ (kg\ N/ha)}{N\ fertiliser\ applied\ (kg\ N/ha)}$$

(5.3)

The contribution of fertiliser N in the total amount of N recovered by the crop was calculated according to the following equation:

$$Recovery\ of\ fertiliser\ N\ (\%) = \frac{Crop\ N\ recovery N_x -\ N_0\ (kg\ N/ha)}{N\ fertiliser\ applied\ (kg\ N/ha)}$$

(5.4)

5.2.5. Assessing nitrogen use efficiency

The fertiliser N-use efficiency and $AgronEff_{Fert}$ were calculated for every N treatment and crop according to equations 5.1 and 5.2, respectively. A linear model was fitted to

[2] N_x refers to the crop N recovery value for a N fertiliser rate treatment (kg N/ha) other than 0 kg N/ha

explain how the natural log of fertiliser N-use efficiency and $AgronEff_{Fert}$ varied with the natural log of N fertiliser rates and between ratoon crop classes at each site. The final models contain only significant terms which have been determined by a backward stepwise regression routine with the p-value criterion to enter/exit set at 0.05 and 0.10, respectively. The final models were then used to investigate differences in the fertiliser N-use efficiency and $AgronEff_{Fert}$ response curves between ratoon crops at each site.

The impact of applying the Optimum 90 and 95 N rates on nitrogen use efficiency was assessed by calculating the fertiliser N-use efficiency for every crop according to equation 5.1. These values were then compared to the fertiliser N-use efficiency of using the SIX EASY STEPS recommended N rate at each site.

5.2.6. Economic assessment of optimum nitrogen fertiliser rates

An economic assessment of using the SIX EASY STEPS recommended N rate compared to the Optimum 90 and Optimum 95 N rates was undertaken by calculating the partial net return per hectare to the grower and industry (grower and miller) using the following equations:

Grower partial net return ($/ha) = ((grower gross income ($/ha) – (cane yield (t cane/ha) x harvesting and levies costs ($/t))) – (nitrogen fertiliser rate (kg N/ha) x price urea ($/t) / 460)).

(5.5)

Industry partial net return ($/ha) = (((sugar yield (t sugar/ha) x price of sugar ($/t)) – (nitrogen fertiliser rate (kg N/ha) x price urea ($/t) / 460)) – (cane yield (t cane/ha) x harvesting and levies costs ($/t))).

(5.6)

The grower gross income ($/ha) was calculated using the following equation:

Grower gross income ($/ha) = ((Cane Yield (t cane/ha) x (0.009 x world sugar price ($/t))) x (N treatment mean CCS-4)) + price adjustment

(5.7)

Equation (5.7), incorporates the Tully Sugar Limited cane price formula. For simplicity, a world sugar price of $420/t, urea fertiliser cost of $720/t, harvesting and levies cost of

$9.40/t and price adjustment of $1.60 were used in the economic analysis. These values were based on the 2014 season and remained constant across all crops and sites. The annual mean CCS value of each N treatment (for each site) was used in the economic analysis and to calculate annual sugar yields.

5.3. Results and Discussion

5.3.1. Rainfall

The total monthly rainfall recorded at Tully Sugar Mill over the growing season (June to May) for the first (2011-2012), second (2012-2013) and third (2013-2014) ratoon crops compared to the longer-term mean monthly rainfall is shown in Fig. 5.2. Total rainfall over the spring summer months has been identified as an important predictor of Tully cane yields (Skocaj and Everingham, 2014). Total rainfall over the spring summer months for the first, second and third ratoon crops was 2375.8 mm, 1645 mm and 2052.5 mm, respectively. Rainfall distribution over the SONDJF period differed between crops with the first ratoon receiving much higher rainfall in October and November, not long after N fertiliser was applied. In comparison, the majority of rainfall in the second and third ratoons occurred towards the end of summer.

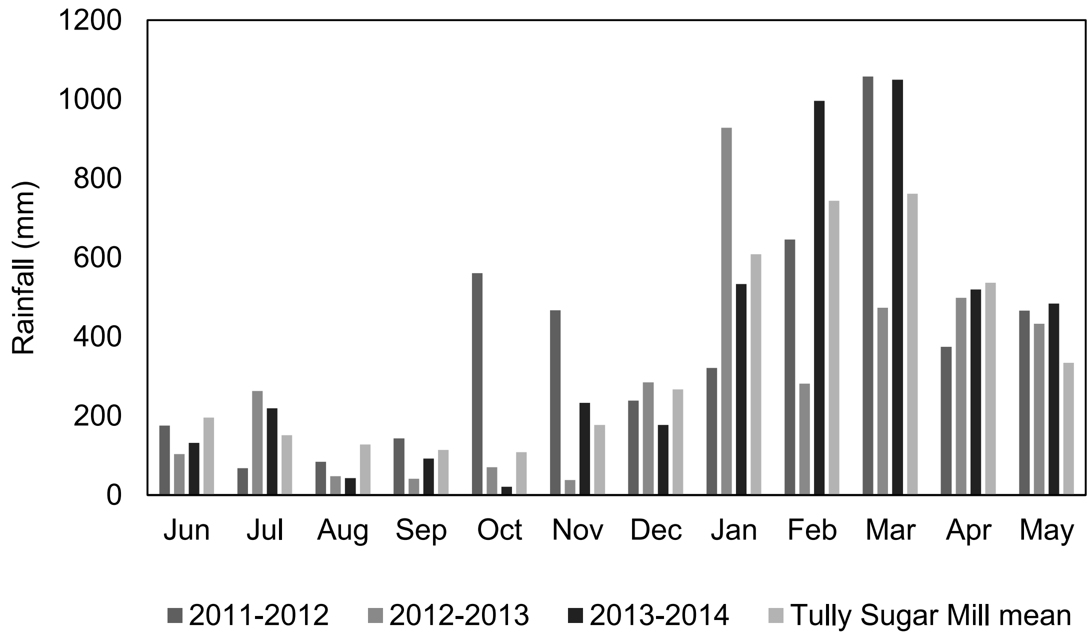

Figure 5.2. Monthly rainfall for the 2011-2012 (first ratoon), 2012-2013 (second ratoon) and 2013-2014 (third ratoon) growing seasons compared to the long-term mean monthly rainfall for Tully Sugar Mill.

5.3.2. Cane yield response to applied nitrogen fertiliser

The cane yield response to applied N; final model used to calculate the Optimum 90 and Optimum 95 N rates; standard error of the regression coefficients of the final models and global R^2 values for first, second and third ratoon crops at each site are shown in Fig. 5.3. The cane yield response to applied N for the first ratoon crop at site T3 (Fig. 5.3) relates to hand harvested mean cane yields as the mechanically harvested cane yields were not available.

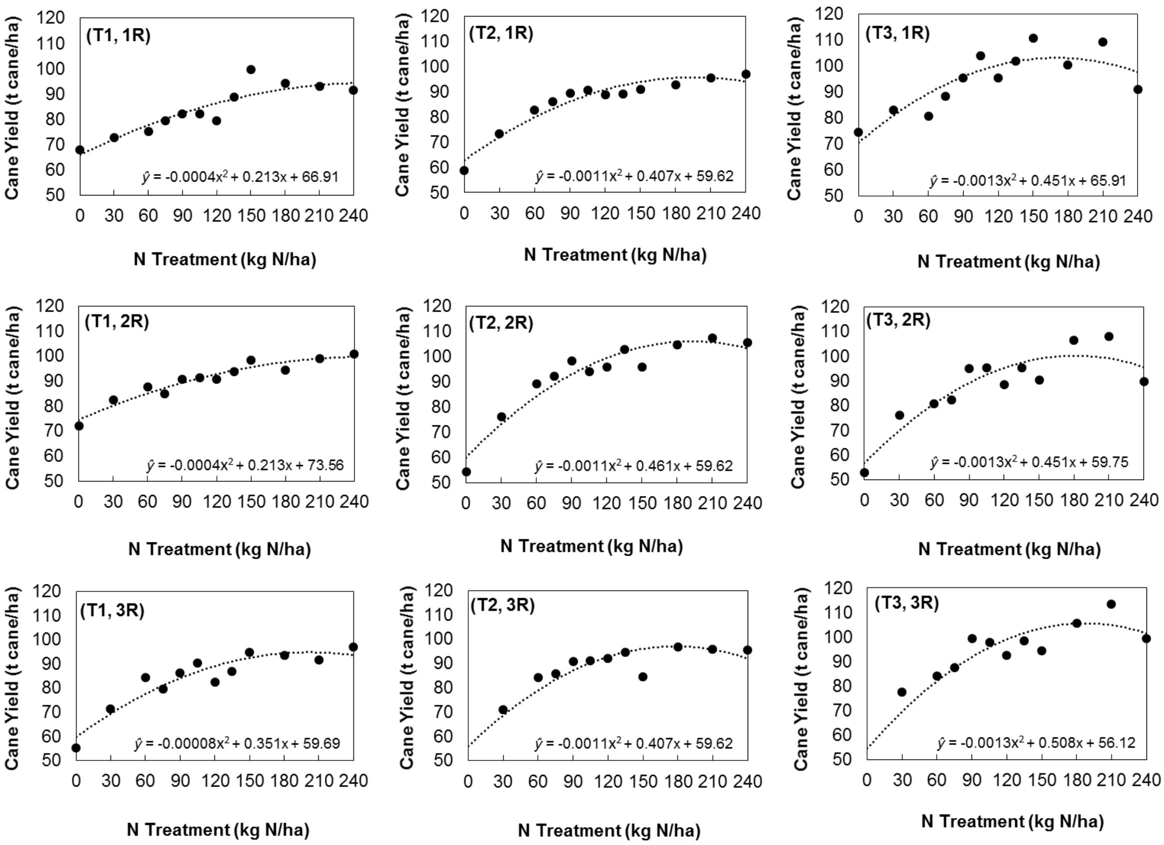

Figure 5.3. Cane yield response curves for N applied to the first (1R), second (2R) and third (3R) ratoon crops at the T1, T2 and T3 small plot N rate field experiments. The solid circles represent mean cane yields and the dotted lines represent the cane yield response to N. The model for the first, second and third ratoon crops was determined from the final model for each site. The final model for T1 was $\hat{y} = -0.0004x^2(\pm0.0001) - 0.0004x^2{\times}z_3(\pm0.0002) + 0.213x(\pm0.038) + 0.138x{\times}z_3(\pm0.067) + 66.91(\pm2.29) + 6.65z_2(\pm1.55) - 7.22z_3(\pm3.81)$ and $R^2 = 0.88$. The final model for T2 was $\hat{y} = -0.0011x^2(\pm0.0001) + 0.407x(\pm0.035) + 0.054x{\times}z_2(\pm0.011) + 59.62(\pm1.97)$ and $R^2 = 0.90$. The final model for T3 was $\hat{y} = -0.0013x^2(\pm0.0002) + 0.451x(\pm0.053) + 0.057x{\times}z_3(\pm0.033) + 65.91(\pm3.53) - 6.16z_2(\pm2.59) - 9.79z_3(\pm4.61)$ and $R^2 = 0.83$. Here, $z_i = 1$ for the i^{th} ratoon, and zero for other ratoons, for i=1, 2 and 3.

The cane yield response to N fertiliser was identical for the first and third ratoon crops at the T2 site but differed for all the other crops at sites T1 and T3. At site T1 the first and second ratoon cane yield responses were parallel and the only difference was the intercept. Total spring-summer rainfall was highest in the first ratoon crop and lowest in the second ratoon crop. The difference in rainfall may have contributed to the cane yield response to N fertiliser differing between ratoon crops, especially at sites T1 and T2. The first and second ratoon cane yield responses were also parallel at site T3 but the intercept differed. In comparison to site T1, the intercept was higher for the first ratoon crop at T3. However, hand harvested cane yields were used to generate the cane yield response to N fertiliser for the first ratoon crop at site T3. This may be why the second ratoon crop at site T3 appears to have behaved differently to sites T1 and T2.

5.3.3. Optimum nitrogen fertiliser rates

The average organic carbon (%) values for 0-20cm soil depth were 1.90%, 2.20% and 1.50% for sites T1, T2 and T3, respectively. Based on these organic carbon values, the SIX EASY STEPS N management guidelines for the Wet Tropics region (Schroeder et al., 2007b) recommends 120, 110 and 130 kg N/ha be applied to ratoon sugarcane crops at the T1, T2 and T3 sites, respectively. However, 110 and 130 kg N/ha were not included as N treatments in the small-plot N fertiliser rate field experiments. To maintain consistency and allow comparisons to be made between the Optimum 90, Optimum 95 and SIX EASY STEPS N rates, the annual cane yield response functions shown in Fig. 5.3 were also used to calculate the cane yield for the SIX EASY STEPS N rate at each of the experiment sites. The Optimum 90, Optimum 95 and SIX EASY STEPS N rates and cane yields are reported in Table 5.4.

Using the first ratoon crop at the T2 site as an example (Table 5.4), the SIX EASY STEPS N rate of 110 kg N/ha resulted in a cane yield of 90.71 t cane/ha. In contrast, the Optimum 90 cane yield (86.63 t cane/ha) was associated with an N application rate of 88 kg N/ha, and the Optimum 95 cane yield (91.44 t cane/ha) corresponded to an N application rate of 115 kg N/ha.

Table 5.4. Optimum 90, Optimum 95 and SIX EASY STEPS N rates and cane yields for the first, second and third ratoon crops at sites T1, T2 and T3 calculated using the final models shown in Fig. 5.3.

Site and crop	Optimum 90		Optimum 95		SIX EASY STEPS	
	N Rate (kg N/ha)	Cane Yield (t cane/ha)	N Rate (kg N/ha)	Cane Yield (t cane/ha)	N Rate (kg N/ha)	Cane Yield (t cane/ha)
Site T1						
1R	104	84.44	148	89.13	120	86.32
2R	99	90.41	144	95.44	120	92.96
3R	97	85.38	128	90.13	120	89.12
Site T2						
1R	88	86.63	115	91.44	110	90.71
2R	107	95.86	135	101.18	110	96.60
3R	88	86.63	115	91.44	110	90.71
Site T3						
1R	94	94.40	110	99.65	130	102.50
2R	89	88.86	111	93.79	130	96.34
3R	105	95.09	131	100.37	130	100.18

5.3.4. Nitrogen recovery

The amount of N recovered in MS and LC at final harvest is reported in Tables 5.5, 5.6 and 5.7 for sites T1, T2 and T3, respectively. Crop N recoveries for the third ratoon crop at site T2 (Table 5.6) were not reported because the N concentration of MS and LC was not analysed.

There were significant differences in the amount of N recovered (across ratoons and experimental sites) between N treatments but the order of significance varied between ratoon crops. As expected, the very high N rates tended to have significantly higher crop N recovery (kg N/ha) than the very low N rates. The amount of N recovered in the first ratoon crop at T3 was much higher than the first ratoon crops at the other sites, but there was no significant difference in crop N recovery between N fertiliser rates. This was possibly due to herbicide damage which resulted in the crop having a lower moisture content than the first ratoon crops at the T1 and T2 sites. The N recovery results of the first ratoon crop at T3 will therefore not be included in the discussion.

The amount of N recovered also differed between ratoon crops. At all sites N recovery reduced as the crop cycle progressed from first to third ratoon.

Table 5.5. Crop N recovery (kg N/ha) for each ratoon crop and N treatment at site T1. Equation 5.3 was used to calculate crop N recovery (%).

N rate (kg N/ha)	Crop N recovery (kg N/ha)		
	1R	2R	3R
0	53.85^{B}	45.81^{C}	35.48^{D}
30	56.21^{B}	49.89^{BC}	40.34^{CD}
60	63.08^{AB}	60.87^{ABC}	61.87^{ABCD}
75	67.43^{AB}	56.83^{ABC}	52.32^{ABCD}
90	64.64^{AB}	66.90^{ABC}	63.62^{ABCD}
105	55.17^{B}	67.99^{ABC}	49.93^{BCD}
120	62.20^{AB}	67.77^{ABC}	54.49^{ABCD}
135	71.85^{AB}	66.38^{ABC}	57.49^{ABCD}
150	80.08^{AB}	66.98^{ABC}	67.27^{ABC}
180	69.46^{AB}	71.04^{AB}	67.85^{ABC}
210	78.25^{AB}	73.96^{A}	77.41^{AB}
240	86.35^{A}	76.46^{A}	79.80^{A}
Tukey HSD (0.05)	25.15	23.70	28.84
$^{A-D}$ Means with the same letter in the same column are not significantly different (p=0.05)			

Table 5.6. Crop N recovery (kg N/ha) for each ratoon crop and N treatment at site T2. Equation 5.3 was used to calculate crop N recovery (%).

N rate (kg N/ha)	Crop N recovery (kg N/ha)		
	1R	2R	3R
0	44.09^{D}	31.24^{G}	Not measured
30	56.39^{CD}	37.50^{GF}	
60	63.83^{BCD}	42.27^{EFG}	
75	71.33^{ABCD}	56.51^{DEF}	
90	68.00^{BCD}	57.94^{DEF}	
105	75.64^{ABC}	61.91^{CDE}	
120	78.62^{ABC}	68.09^{BCD}	
135	84.38^{ABC}	77.06^{ABCD}	
150	89.61^{AB}	77.28^{ABCD}	
180	91.92^{AB}	93.55^{A}	
210	99.88^{A}	89.44^{AB}	
240	89.31^{AB}	83.29^{ABC}	
Tukey HSD (0.05)	28.77	23.68	
$^{A-D}$ Means with the same letter in the same column are not significantly different (p=0.05)			

Table 5.7. Crop N recovery (kg N/ha) for each ratoon crop and N treatment at site T3. Equation 5.3 was used to calculate crop N recovery (%).

N rate (kg N/ha)	Crop N recovery (kg N/ha)		
	1R	2R	3R
0	76.20	31.79^{F}	24.47^{D}
30	109.30	48.85^{EF}	38.99^{CD}
60	96.77	45.08^{DEF}	39.59^{BCD}
75	104.06	53.76^{CDE}	37.95^{CD}
90	108.20	59.57^{BCDE}	54.16^{ABC}
105	135.05	67.88^{BC}	52.67^{ABC}
120	105.74	63.54^{BCD}	57.10^{ABC}
135	131.10	65.45^{BCD}	61.90^{ABC}
150	129.90	65.17^{BCD}	58.38^{ABC}
180	137.56	74.43^{AB}	64.60^{ABC}
210	139.66	92.03^{A}	66.15^{AB}
240	146.78	75.74^{AB}	69.08^{A}
Tukey HSD (0.05)	ns	18.36	26.94
$^{A-D}$ Means with the same letter in the same column are not significantly different (p=0.05)			

The inclusion of nil N fertiliser treatments in these experiments allowed the contribution of soil and fertiliser N sources recovered in the sugarcane crops (MS and LC components) at final harvest to be quantified. The results are reported in Tables 5.8, 5.9 and 5.10 for site T1, T2 and T3, respectively. Crop N and fertiliser N recoveries for the third ratoon crop at site T2 were once again not reported (see above).

Using the 120 kg N/ha fertiliser rate at the T1 site as an example (Table 5.8), crop N recovery of the first ratoon was 52% and fertiliser N recovery was 7%. Crop N recovery of the second ratoon (56%) was similar to the first ratoon (52%) but lower in the third ratoon (45%). The fertiliser N recovery of the second (18%) and third ratoon (16%) crops was higher than the first ratoon (7%).

Table 5.8. Crop N recovery (%) and fertiliser N recovery (%) for first, second and third ratoon crops at site T1. Crop N recovery (%) and fertiliser N recovery (%) were calculated using equations 5.3 and 5.4, respectively.

N Rate (kg N/ha)	1R		2R		3R	
	Crop N Recovery (%)	Fertiliser N Recovery (%)	Crop N Recovery (%)	Fertiliser N Recovery (%)	Crop N Recovery (%)	Fertiliser N Recovery (%)
30	187	8	166	14	134	16
60	105	15	101	25	103	44
75	90	18	76	15	70	22
90	72	12	74	23	71	31
105	53	1	65	21	48	14
120	52	7	56	18	45	16
135	53	13	49	15	43	16
150	53	17	45	14	45	21
180	39	9	39	14	38	18
210	37	12	35	13	37	20
240	36	14	32	13	33	18

Table 5.9. Crop N recovery (%) and fertiliser N recovery (%) for first and second ratoon crops at site T2. Crop N recovery (%) and fertiliser N recovery (%) were calculated using equations 5.3 and 5.4, respectively.

N Rate (kg N/ha)	1R		2R	
	N Recovery	Contribution Fertiliser N	N Recovery	Contribution Fertiliser N
30	188	41	125	21
60	106	33	70	18
75	95	36	75	34
90	76	27	64	30
105	72	30	59	29
120	66	29	57	31
135	63	30	57	34
150	60	30	52	31
180	51	27	52	35
210	48	27	43	28
240	37	19	35	22

Table 5.10. Crop N recovery (%) and fertiliser N recovery (%) for first, second and third ratoon crops at site T3. Crop N recovery (%) and fertiliser N recovery (%) were calculated using equations 5.3 and 5.4, respectively.

N Rate (kg N/ha)	1R		2R		3R	
	N Recovery	Contribution Fertiliser N	N Recovery	Contribution Fertiliser N	N Recovery	Contribution Fertiliser N
30	364	110	163	57	130	48
60	161	34	75	22	66	25
75	139	37	72	29	51	18
90	120	36	66	31	60	33
105	129	56	65	34	50	27
120	88	25	53	26	48	27
135	97	41	48	25	46	28
150	87	36	43	22	39	23
180	76	34	41	24	36	22
210	67	30	44	29	32	20
240	61	29	32	18	29	19

The total amount of N recovered decreased as the crop cycle progressed from first to third ratoon. This indicates older ratoons are less efficient at recovering N than younger ratoons. The N recovered by sugarcane crops is derived from applied (fertiliser) and soil (mineralised from soil organic matter) N sources. Research conducted in Australia and overseas has focused on quantifying fertiliser N recovery using isotopically-labelled N fertilisers but information on the recovery of fertiliser N when urea is banded sub-surface to ratoon sugarcane crops, typical of current best practice in the Wet Tropics, is limited. Previous research conducted in first ratoon crops in the Wet Tropics region reported N fertiliser recovery values of 3.8% (Meier et al., 2006) and 24.8% (Prasertsak et al., 2002). The results from these small-plot N fertiliser rate field experiments compare favourably. The amount of fertiliser N recovered in the sugarcane tops, leaves and stalks of first ratoon crops in the small-plot N fertiliser rate response experiments ranged from 1% to 18% at T1 and 19% to 41% at T2.

The amount of fertiliser N recovered in the second ratoon crops in these experiments ranged from 13% to 25% at T1 and 18% to 35% at T2. These recoveries were generally higher than previous research which reported 15% of the applied N was recovered by second ratoon crops (Chapman et al., 1994). The recovery of fertiliser N was higher in these experiments because urea was applied sub-surface directly beneath the cane row instead of the centre of the interrow. This highlights the influence of fertiliser placement on N fertiliser recovery and supports current best practice placement of N fertiliser.

Fertiliser N recovery at T1 was consistently lower than the other experimental sites, irrespective of crop class despite the total amount of N recovered being similar. This suggests greater amounts of soil N were available for crop uptake at the T1 site.

Previous research on N fertiliser recovery has focused on single N fertiliser application rates for only one ratoon crop. In these experiments there were no apparent trends between N fertiliser recovery and the amount of N fertiliser applied (i.e. fertiliser N recovery did not increase with increasing N fertiliser rates) but the amount of N fertiliser recovered differed between ratoon crops. More fertiliser N was recovered as the crop cycle progressed from first to third ratoon especially at sites T1 and T2. Despite the third ratoon crops recovering less N in total, the fact more fertiliser N was recovered indicates older ratoons are more reliant on fertiliser N than younger ratoons. This is because the first ratoon crops were able to recover a greater proportion of soil N than the third ratoons. This confers with the results reported in Fig. 5.6 which highlighted the efficiency of the first ratoon crops at T1 and T3 were lower than the third ratoon crops.

Climatic conditions are also likely to influence N fertiliser recovery. The categorisation of total spring-summer rainfall for the period 1970 to 2014 into terciles (in Chapter 4) resulted in wet years being defined as receiving more than 2184 mm of rainfall over spring-summer. The monthly rainfall for the first ratoon, second and third ratoon crops shown in Fig. 5.2 indicates the small-plot N rate response field experiments were conducted in years experiencing normal / slightly above normal spring-summer rainfall. In very wet years, the amount of N fertilised recovered may be lower than what was measured in the small-plot N rate response field experiments. The potential for N losses and the crop experiencing waterlogged conditions is greater in wet years and this is likely to reduce the ability of the crop to acquire N fertiliser.

5.3.5. Nitrogen use efficiency of ratoon sugarcane crops grown on Bulgun series soil

Responses in fertiliser N-use efficiency to the amount of N fertiliser applied to the first, second and third ratoon crops for each of the small-plot N fertiliser rate field experiments are shown in Fig. 5.4. Responses were generated by fitting a liner model to the fertiliser N-use efficiency values for the different N fertiliser rates. Fertiliser N-use efficiency decreased with increasing N fertiliser rates in all crops and at all sites. However, the response patterns differed between ratoon crops. At each site the first and third ratoon fertiliser N-use efficiency responses were identical but the second ratoon differed.

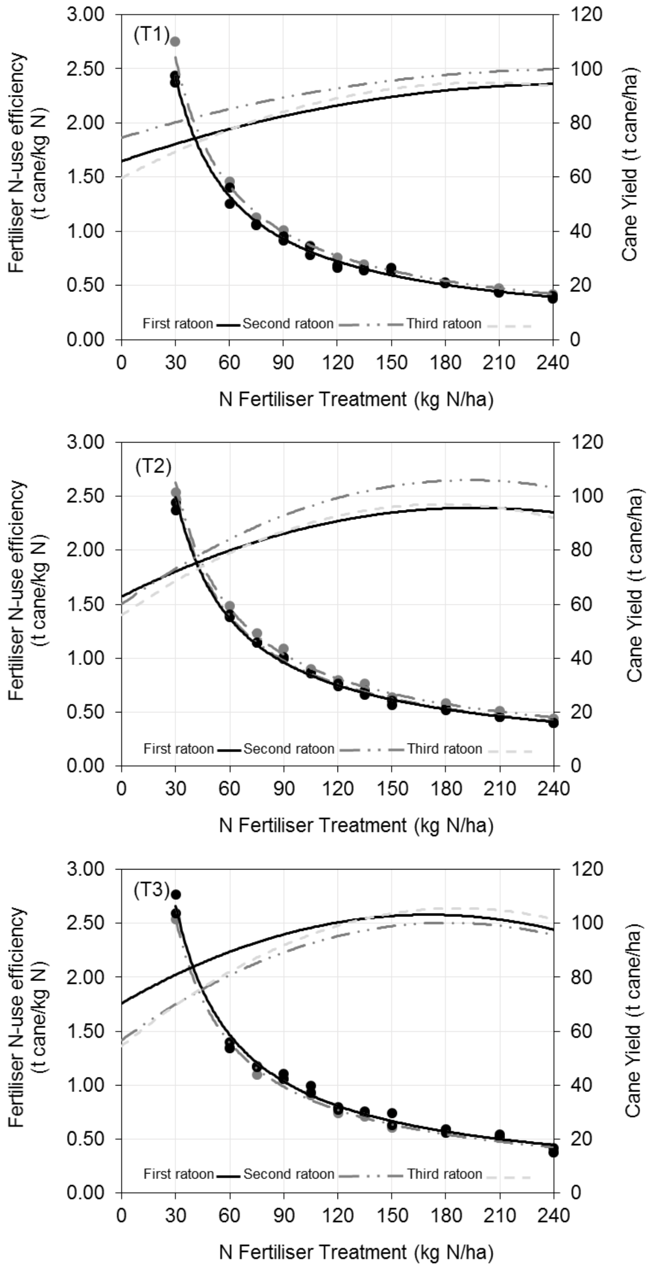

Figure 5.4. Response of sugarcane to N fertiliser application on Bulgun series soil in the Wet Tropics between 2011 and 2014: relationship between mean fertiliser N-use efficiency (t cane/kg N) and N fertiliser rate on the primary y axis and the relationship between mean cane yield (t cane/ha) and N fertiliser rate on the secondary y axis for first (1R▁▁), second (2R▁ . . .) and third (3R▁ ▁) ratoon crops at sites T1, T2 and T3, respectively. The model for the first, second and third ratoon crops was determined from the final model for each site. The final model for T1 was $\ln\hat{y}$ = 3.86 (±0.060) + $0.07z_2$ (±0.016) – 0.87lnx (±0.13) and R^2 0.99. The final model for T2 was $\ln\hat{y}$ = 3.87(±0.048) - 0.87lnx (±0.010) + $0.02z_2$×lnx (±0.002) and R^2 0.99. The final model for T3 was $\ln\hat{y}$ = 3.90 (±0.094) – $0.05z_2$ (±0.024) - 0.86lnx (±0.020) and R^2 0.98. Here, z_i = 1 for the i^{th} ratoon, and zero for other ratoons, for i=1, 2 and 3. The cane yield response to applied N fertiliser was derived from Fig. 5.3.

The combined response in fertiliser N-use efficiency to the amount of N fertiliser applied was determined for all ratoon crops in the small-plot N fertiliser rate field experiments. This is shown in Fig 5.5. The relationship between fertiliser N-use efficiency and fertiliser N rates was identical for the first and third ratoon crops across all sites but differed for the second ratoon crops.

As mentioned previously total rainfall over the spring-summer period has a significant impact on Tully cane yields. Spring-summer rainfall differed between ratoon crops (i.e. the first ratoon was the wettest and second ratoon the driest) and may have contributed to the different fertiliser N-use efficiency response patterns. The slope of the response curves in Fig 5.5 was the same for all ratoon crops but the scaling factor differed. This suggests fertiliser N-use efficiency is also sensitive to spring-summer rainfall.

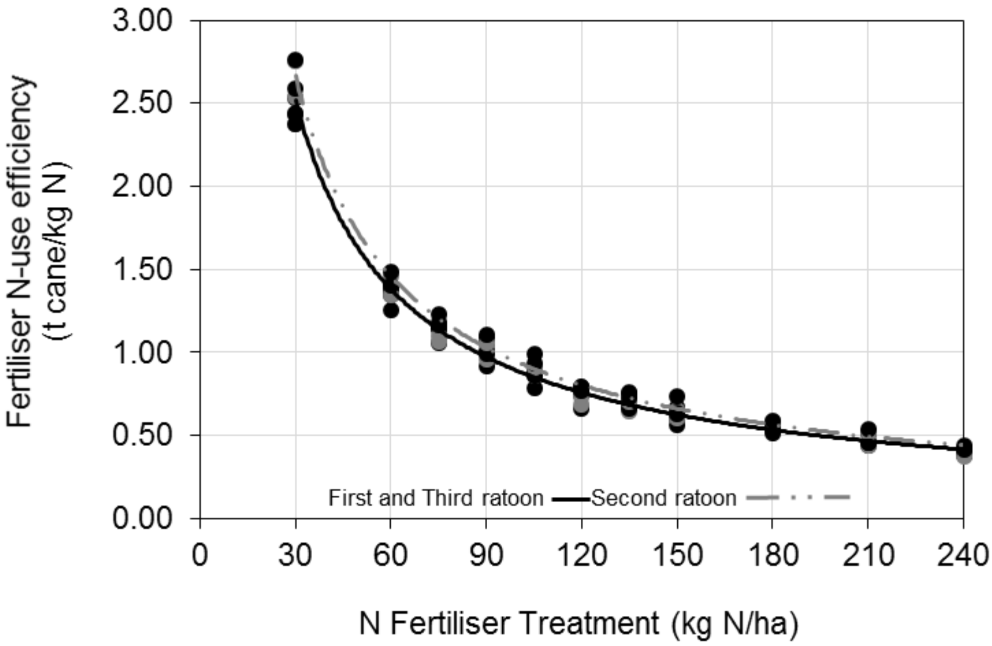

Figure 5.5. Relationship between fertiliser N-use efficiency (t cane/kg N) and N fertiliser for the first (1R) and third (3R) ratoon crops (——) compared to the second (2R) ratoon crops (– – –) in the small-plot N rate field experiments conducted in the Wet Tropics between 2011 and 2014. The final model was $\ln\hat{y}$ = 3.87 (±0.051) + 0.03z_2 (±0.013) - 0.87lnx (±0.011) + and R^2 0.99. Here, z_i = 1 for the i^{th} ratoon, and zero for other ratoons, for i=1, 2 and 3.

The inclusion of nil N fertiliser treatments in the small-plot N fertiliser rate field experiments allowed the $AgronEff_{Fert}$ to be determined. The $AgronEff_{Fert}$ responses for first, second and third ratoon crops, the standard error of the regression coefficients of the final models and global R^2 values are shown in Fig. 5.6 for sites T1, T2 and T3, respectively. As the $AgronEff_{Fert}$ only measures the impact of fertiliser N on cane yields, values are much lower than those shown for the fertiliser N-use efficiency in Fig. 5.4. The $AgronEff_{Fert}$ decreased with increasing N fertiliser rates except for the first ratoon crop at T1. The rate of decrease remained the same for all crop classes at site T2. However, the $AgronEff_{Fert}$ response differed between ratoon crops. The $AgronEff_{Fert}$ was lower in the first ratoon crops. As the crop cycle progressed from first to third ratoon the $AgronEff_{Fert}$ increased. This was especially evident at sites T1 and T3.

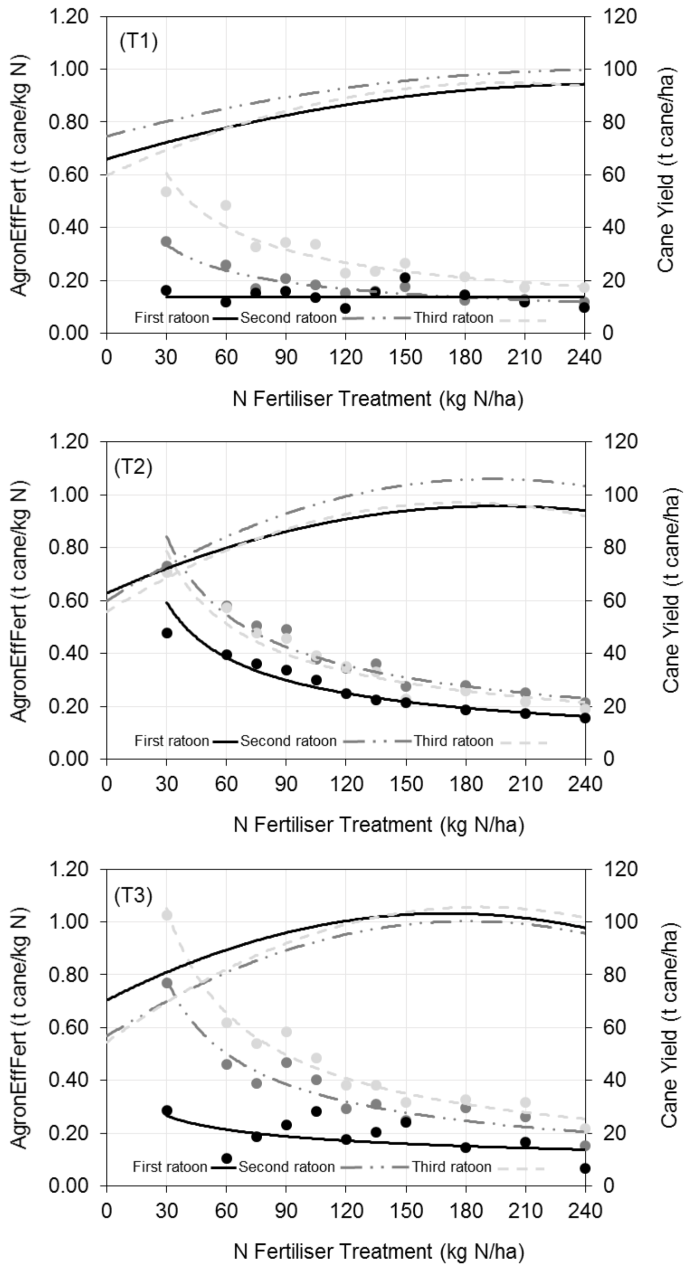

Figure 5.6. Response of sugarcane to N fertiliser application on Bulgun series soil in the Wet Tropics between 2011 and 2014: relationship between mean $AgronEff_{Fert}$ and N rate, and mean cane yield and N rate for first (1R——), second (2R— · · –) and third (3R– – –) ratoon crops at sites T1, T2 and T3, respectively. The model for the first, second and third ratoon crops was determined from the final model for each site. The final model for T1 was $\ln\hat{y}$ = -1.98 (±0.051) + 2.61z_2 (±0.421) + 3.49z_3 (±0.421) - 0.50z_2×lnx (±0.088) - 0.59z_3×lnx (±0.088) and R^2 0.87. The final model for T2 was $\ln\hat{y}$ = 1.59 (±0.146) + 0.35z_2 (±0.043) + 0.28z_3 (±0.043) - 0.62lnx (±0.030) and R^2 0.94. The final model for T3 was $\ln\hat{y}$ = -0.26 (±0.639) + 2.20z_2 (±0.903) + 2.62z_3 (±0.903) - 0.31lnx (±0.135) - 0.33z_2×lnx (±0.191) - 0.37z_3×lnx (±0.191) and R^2 0.82. Here, z_i = 1 for the i^{th} ratoon, and zero for other ratoons, for i=1, 2 and 3. The cane yield response to applied N fertiliser was derived from Fig. 5.3.

Differences in the $AgronEff_{Fert}$ response curves between ratoon crops shown in Fig. 5.6 indicates a greater reliance on fertiliser N as the crop cycle progressed from first to third ratoon. The lower $AgronEff_{Fert}$ efficiency values of the first ratoon crops at T1 and T3 indicates the first ratoon crop was less efficient in using N fertiliser and suggests soil N was sufficient to meet crop N demand. This is supported by the N recovery results. Although less fertiliser N was recovered in the first ratoon crops, the total amount of N recovered was higher than the second and third ratoons. This means younger ratoons are either more efficient at accessing and utilising soil N (soil organic N pool) sources or soil N sources depleted as the crop cycle progressed and were insufficient to meet the crop demand.

The relationship between fertiliser N-use efficiency and N recovery in the aboveground components of the sugarcane crop (i.e. MS and LC) is shown in Fig. 5.7 for each ratoon crop and experimental site. The results showed that fertiliser N-use efficiency is highly correlated with crop N recovery – when fertiliser N-use efficiency increases, the amount of N recovered by the crop also increases.

The positive correlation between fertiliser N-use efficiency and N recovery implies fertiliser N-use efficiency is a reliable indicator of N recovery (%) in the aboveground components of the sugarcane crop (i.e. millable stalk, green leaves and cabbage). The response pattern differed between ratoon crops to reflect the lower N recovery of older ratoons. Measuring crop moisture content and N concentration to determine N recovery is expensive and labour intensive. If N rate response field experiments are being conducted with limited resources, the amount of N recovered by the crop can be inferred by measuring fertiliser N-use efficiency.

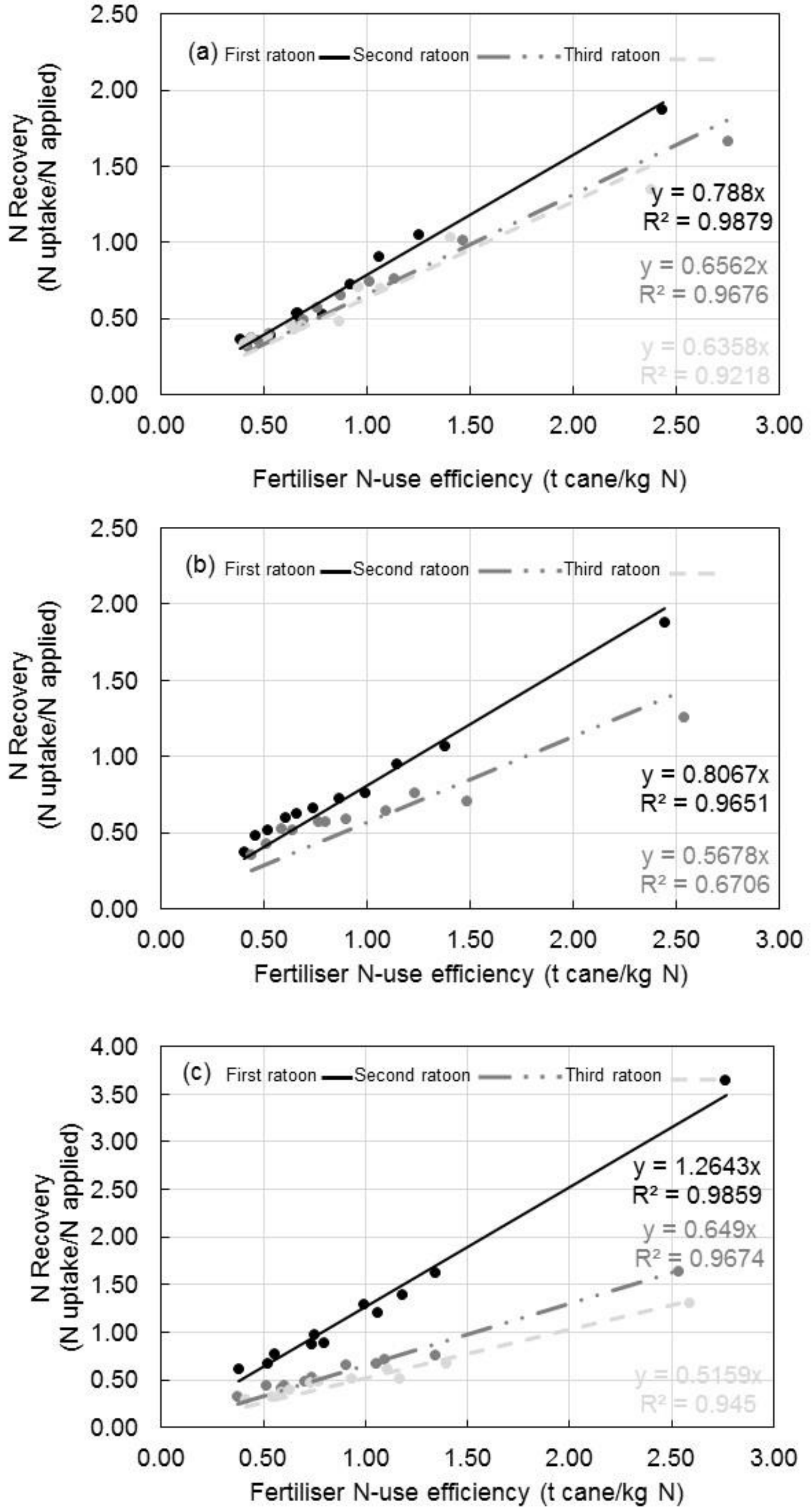

Figure 5.7. Relationship between mean fertiliser N-use efficiency (t cane/kg N) and mean N recovery in MS and LC for first (—), second (— · · —) and third (– – –) ratoon crops at sites T1 (a), T2 (b) and T3 (c), respectively.

5.3.6. Impact of optimum nitrogen fertiliser rates on fertiliser N-use efficiency

The N fertiliser rate and fertiliser N-use efficiency values for the Optimum 90, Optimum 95 and SIX EASY STEPS are reported in Table 5.11. Using the first ratoon crop at site T2 as an example, the fertiliser N-use efficiency of SIX EASY STEPS was 0.82 t cane/kg N. In contrast the Optimum 90 resulted in a fertiliser N-use efficiency of 0.98 t cane/kg N and the Optimum 95 corresponded to a fertiliser N-use efficiency of 0.80 t cane/kg N.

The Optimum 95 N rates and fertiliser N-use efficiency values were similar to SIX EASY STEPS for most crops. However, the Optimum 90 N rates were much lower than SIX EASY STEPS and resulted in greater fertiliser N-use efficiency.

Table 5.11. Fertiliser N-use efficiency (t cane/kg N) for first, second and third ratoon crops of the small-plot N rate field experiments comparing the SIX EASY STEPS recommended N rate with Optimum 90 and Optimum 95 N rates based on the N rates and cane yields reported in Table 5.4. Fertiliser N-use efficiency (t cane/kg N) was calculated using equation 5.1.

Site / Crop	Optimum 90		Optimum 95		SIX EASY STEPS	
	N rate (kg N/ha)	Fertiliser-N use efficiency (t cane/kg N)	N rate (kg N/ha)	Fertiliser-N use efficiency (t cane/kg N)	N rate (kg N/ha)	Fertiliser-N use efficiency (t cane/kg N)
Site T1						
1R	104	0.81	148	0.60	120	0.72
2R	99	0.91	144	0.66	120	0.77
3R	97	0.88	128	0.70	120	0.74
Site T2						
1R	88	0.98	115	0.80	110	0.82
2R	107	0.90	135	0.75	110	0.88
3R	88	0.98	115	0.80	110	0.82
Site T3						
1R	94	1.00	110	0.91	130	0.79
2R	89	1.00	111	0.84	130	0.74
3R	105	0.91	131	0.77	130	0.77

5.3.7. Economic assessment of using optimum nitrogen fertiliser rates

The grower and industry marginal economic returns ($/ha) for each ratoon crop and site are shown in Table 5.12. Using the first ratoon crop at site T2 as an example, the grower marginal economic return of using the SIX EASY STEPS N rate was $1891.26/ha. In contrast, the grower marginal economic return of using the Optimum 90 N rate was $58.42/ha lower than SIX EASY STEPS.

The impact of Optimum 90 and 95 N rates on grower and industry marginal economic returns differed between sites. The SIX EASY STEPS N rates were always the most economically effective at T3. The grower and industry marginal economic returns for the Optimum 95 N rates were better than the SIX EASY STEPS N rates for the T1 and T2 sites. The Optimum 90 N rates reduced grower and industry marginal economic returns at all sites but the greatest losses occurred at T3. The reduction in grower and industry marginal economic returns was due to Optimum 90 N rates resulting in lower cane yields (as shown in Table 5.4).

Table 5.12. Expected grower and industry partial net returns ($/ha) for first, second and third ratoon crops of the small-plot N rate field experiments from applying the SIX EASY STEPS, Optimum 90 and Optimum 95 N rates. The Optimum 90 and Optimum 95 grower and industry partial net returns ($/ha) are reported relative to SIX EASY STEPS. Equations 5.5 and 5.6 were used to calculate the grower and industry partial net returns, respectively.

Site / Crop	Grower Marginal ($/ha)			Industry Marginal ($/ha)		
	SIX EASY STEPS	Optimum 95	Optimum 90	SIX EASY STEPS	Optimum 95	Optimum 90
Site T1						
1R	1778.33	17.54	(20.19)	3537.31	72.54	(60.73)
2R	1926.75	18.81	(25.09)	3818.75	69.32	(77.04)
3R	1839.47	10.44	(49.01)	3635.25	49.01	(107.20)
Site T2						
1R	1891.26	8.71	(58.42)	3737.43	23.53	(141.63)
2R	2025.14	64.97	(12.12)	3991.29	158.27	(27.20)
3R	1891.26	8.71	(58.42)	3737.43	23.53	(141.63)
Site T3						
1R	2127.95	(33.48)	(127.77)	4214.27	(91.53)	(292.76)
2R	1987.93	(28.22)	(105.85)	3948.78	(80.17)	(258.22)
3R	2075.21	2.75	(76.57)	4114.28	6.62	(180.25)

5.3.8. Implications of improving fertiliser N-use efficiency on grower and industry profitability

There were no consistent trends in fertiliser N-use efficiency between ratoon crops for the SIX EASY STEPS, Optimum 90 or Optimum 95 N rates (i.e. fertiliser N-use efficiency did not always decrease as the crop cycle progressed from first to third ratoon). As spring-summer rainfall has a strong influence on Tully mill cane yields (Skocaj and Everingham, 2014) it will also influence fertiliser N-use efficiency. Despite differences in the amount and distribution of spring-summer rainfall between ratoon crops there were only slight differences in fertiliser N-use efficiency between ratoon crops at sites T1 and T2 for the SIX EASY STEPS N rates. Fertiliser N-use efficiency increased slightly in the second ratoon crop with the occurrence of higher cane yields because of lower spring-summer rainfall. However the impact of climate variability on fertiliser N-use efficiency was subtle compared to that observed in the Tully and Johnstone SIX EASY STEPS validation strip trials (Schroeder et al., 2009c, Skocaj et al., 2012). In that case, the effect of climate variability on fertiliser N-use efficiency was most prominent in a well-drained site at Tully (Skocaj et al., 2012). Fertiliser N-use efficiency reduced between the first and second ratoon crops (0.29 t cane/kg N) because crop growth was restricted by unfavourable climatic conditions (i.e. extremely high summer rainfall), but then increased in the third ratoon with the return of more favourable climatic conditions (Skocaj et al., 2012).

Reducing N fertiliser rates below SIX EASY STEPS N guidelines to sugarcane grown on Bulgun soils will improve fertiliser N-use efficiency. The Optimum 90 N rates resulted in the greatest improvement in fertiliser N-use efficiency especially at the T3 site. At this site fertiliser N-use efficiency increased, on average by 0.26 t cane/kg N and meets the SIX EASY STEPS fertiliser N-use efficiency target of t cane/kg N. However, the Optimum 90 N rates still failed to achieve the SIX EASY STEPS fertiliser N-use efficiency targets of 1.0 and 1.09 t cane/kg N for the T1 and T2 sites, respectively.

Ideally improvements in fertiliser N-use efficiency should also be economically effective. If applying the Optimum 90 N rate, grower and industry marginal economic returns would be reduced, on average, by $59.27/ha and $142.96/ha respectively compared to applying the SIX EASY STEPS N rates. This is primarily driven by a reduction in cane yields. If these average economic losses are applied to the area of Bulgun series soil in the Tully mill area (ratooned and fertilised), it would equate to an average annual grower financial loss of $107,810 and average annual industry financial loss of $260,040.

Economic losses at the T3 site were more pronounced because this site had a lower organic carbon (%) level and therefore higher N fertiliser requirement than the other sites. Previous research conducted in the Tully and Herbert districts has also reported that the marginal economic returns of the most N-use efficient management strategies were always lower than following SIX EASY STEPS N guidelines (Schroeder et al., 2009b, Schroeder et al., 2015).

Improving fertiliser N-use efficiency is of environmental importance given the current operating environment of the Wet Tropics sugar industry. Reducing N fertiliser rates every year (i.e. Optimum 90 N rates) will improve fertiliser N-use efficiency but reduce grower and industry profitability. The impact of reducing N fertiliser rates on profitability will be the greatest in years where growing conditions are conducive to high cane yields (i.e. low spring-summer rainfall). In years with favourable growing conditions it is possible that the crop may become N limited if N fertiliser rates are reduced below the SIX EASY STEPS N management guidelines. However, an alternative could be to reduce N fertiliser rates in wet years. Chapter 4 indicated N fertiliser requirements are lower in wet years. Reducing N rates in wet years is likely to have a positive impact on NUE without adversely impacting productivity or profitability. The challenge will be ensuring the crop is able to acquire fertiliser N in wet years.

Sugarcane is the dominant crop grown in the Wet Tropics (Kingston et al., 1991) because it is able to grow on a wide range of soil types, withstand extreme climate variability and be harvested during the dry season. If improvements in fertiliser N-use efficiency are not economically effective, the viability of the Wet Tropics sugar industry will be jeopardised and finding an alternative crop that can be grown as widespread in this environment is highly unlikely. Therefore, if the environmental benefit of improving fertiliser N-use efficiency is deemed more valuable than the financial (and productivity) losses incurred, an incentive may be required to persuade growers to reduce N fertiliser rates below SIX EASY STEPS.

5.4. Conclusion and future work

The third ratoon crops recovered less N in total than the first and second ratoon crops but were more reliant on fertiliser N whereas the majority of N recovered by the first ratoon crops was supplied by soil N sources. The SIX EASY STEPS N management guidelines do not differentiate N fertiliser requirements between ratoon crop classes

(Schroeder et al., 2007b). However, these results indicate that N fertiliser guidelines should be re-evaluated for ratoon crops grown on the Bulgun series soil. Although these results are limited to a single poorly-drained alluvial soil type (Bulgun series soil) within the Wet Tropics region, it is reasonable to formulate an hypothesis that these results will also be relevant to other poorly-drained alluvial soils with similar soil organic carbon (%) and physical characteristics and positions in the landscape to the Bulgun series soil. The $AgronEff_{Fert}$ and N recovery of ratoon sugarcane crops grown on a diverse range of soil types throughout the Wet Tropics should be investigated before undertaking any revisions of the SIX EASY STEPS N management guidelines for the Wet Tropics region. Further research will be required to understand the $AgronEff_{Fert}$ and N recovery of successive ratoon sugarcane crops grown on other soil types in regions outside the Wet Tropics. In addition, a better understanding of the amount and rate of N mineralised from soil organic matter pools will contribute to the fine-tuning of N fertiliser guidelines, especially for first ratoon sugarcane crops.

Improving fertiliser nitrogen use efficiency is an ongoing concern for the sustainability of sugarcane enterprises operating adjacent to environmentally sensitive areas. Striking a balance between applying too much N and not enough will be challenging. Not applying enough N fertiliser has the potential to reduce yields and profitability, while applying too much may lead to greater environmental losses. Minimising environmental losses of N from sugarcane production systems is of high environmental and societal importance. However, for the Australian sugar industry to remain viable it is imperative that improvements in fertiliser nitrogen use efficiency do not compromise productivity and profitability. The Optimum 90 N approach increased fertiliser N-use efficiency compared to SIX EASY STEPS but was not economically effective and resulted in lower grower and industry economic returns.

5.5. Summary

Small-plot N fertiliser rate response experiments conducted in ratoon sugarcane crops grown on the Bulgun series soil in the Wet Tropics region between 2011 and 2014 were used to investigate the i) total N and fertiliser N recoveries of successive ratoon sugarcane crops, ii) fertiliser nitrogen use efficiency of ratoon sugarcane crops, and iii) impact of improving fertiliser nitrogen use efficiency on grower and industry profitability. The fate of N fertiliser not recovered by the crop, immobilised in the soil and/or lost from the sugarcane production system is of economic and environmental importance. The total amount of N recovered decreased as the crop cycle progressed indicating older ratoons are less efficient at recovering N. The amount of fertiliser N recovered in the aboveground crop components was comparable to previous research conducted in the Wet Tropics but differences were observed between ratoon crops. The third ratoon crops recovered less N, in total, than the first ratoon crops, but were more reliant on fertiliser N indicating a need to re-evaluate ratoon N fertiliser guidelines for sugarcane crops grown on the Bulgun series soil. Major improvements in fertiliser nitrogen use efficiency are required to ensure the economic and environmental sustainability of the Wet Tropics. Reducing N rates below SIX EASY STEPS N guidelines will improve fertiliser N-use efficiency but will compromise grower and industry profitability. The focus of future research should be the identification of sustainable N management practices, which improve fertiliser nitrogen use efficiency to protect the environment and are economically effective to ensure the longevity of the Wet Tropics sugar industry.

Chapter 6

Thesis Conclusion

Sugarcane is the dominant agricultural crop grown in the Wet Tropics region of northern Australia. Applying the right amount of N fertiliser to optimise profitability and minimise environmental losses is extremely challenging. The Wet Tropics sugar industry of northern Australia experiences one of the highest levels of climate variability in the world (Nicholls et al., 1997) and this has a significant impact on cane yields (Everingham et al., 2001, Everingham et al., 2003) and nitrogen (N) losses (Brodie et al., 2012). Nitrogen fertiliser lost from the sugarcane production system is of critical importance for the economic and environmental sustainability of the Wet Tropics sugar industry. Sugarcane production in the Wet Tropics region has been estimated to deliver high loads of dissolved inorganic nitrogen to the Great Barrier Reef lagoon (Waterhouse et al., 2012, Kroon et al., 2012). Improvements in fertiliser nitrogen use efficiency that are not associated with a reduction in grower and industry profitability, are needed to ensure the economic and environmental sustainability of the Wet Tropics sugar industry.

A review of the literature (Chapter 1) highlighted the need to better understand the impact of climate variability on sugarcane N fertiliser requirements. The Wet Tropics region experiences one of the highest levels of natural climate variability in the world (Nicholls et al., 1997) and this has a significant impact on crop size (Everingham et al., 2001, Everingham et al., 2003). However, current N fertiliser guidelines do not consider the impact of climate variability on crop size and hence N fertiliser requirements. As crop size largely determines how much N fertiliser is required (Keating et al., 1997), knowing the size of the crop before applying N fertiliser will improve the ability to match annual N fertiliser inputs to crop requirements. To better match N fertiliser inputs to crop requirements and improve sugarcane nitrogen management in the Wet Tropics, this thesis had four main objectives:

1. to identify the atmospheric climate variables and time of year having the greatest influence on Tully sugarcane yields (Chapter 2);

2. to investigate the capability of APSIM-Sugar to simulate cane yield response to nitrogen fertiliser in a wet tropical environment (Chapter 3);
3. to determine the impact of climatic conditions on nitrogen fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil (Chapter 4); and
4. to assess nitrogen fertiliser recovery and nitrogen use efficiency of successive ratoon sugarcane crops grown on the Bulgun series soil (Chapter 5).

6.1. Objective 1: to identify the atmospheric climate variables and time of year having the greatest influence on Tully sugarcane yields

To better match N fertiliser inputs to crop requirements the key atmospheric variables (i.e. rainfall, solar radiation, temperature) and time of year influencing cane yields needs to be known. The aim of this chapter was to i) identify which atmospheric variables and time of year have the greatest influence on Tully mill cane yields and ii) investigate if these atmospheric variables remain important irrespective of the historical time period analysed. A stepwise linear regression model used atmospheric climate variables at different times of the growing season to explain Tully mill detrended cane yields for eight different time blocks, ranging from 10 to 80 years. Rainfall, most commonly around spring and summer, was always the first variable entered into the models for 40 years or more, making it an important predictor of Tully cane yields. This differed to previous research which identified rainfall at different times of the growing season (i.e. November, December and January or summer) as having the greatest impact on cane yields in the Wet Tropics region.

Compared to previous research these analyses considered a diverse range of climate variables, not just rainfall, and investigated much longer time blocks. It also highlighted the need to consider the length of the time block when interpreting model confidence. The regression models explained between 32.2 and 94.1% of the variation in de-trended cane yields for the Tully mill area. However, model confidence was highly dependent on the length of the time block. The R^2_{adj} steadily decreased and the S^2 steadily increased until the time interval reached 40 years. Once the time interval reached 40 years and beyond there was little change in the R^2_{adj} or S^2 values. The methodological approach used to identify the atmospheric climate variables having the greatest influence on Tully sugarcane yields can be easily adapted for other sugarcane growing regions inside and outside of Australia and for other cropping systems.

6.2. Objective 2: to investigate the capability of APSIM-Sugar to simulate cane yield response to nitrogen fertiliser in a wet tropical environment

It is difficult to determine the impact of climatic conditions on sugarcane N fertiliser requirements in experimental field trials as their duration is often limited to short timescales that do not encapsulate different climatic conditions. Crop growth models have been used to help understand N cycling in the sugarcane production system and shown to be successful in investigating specific issues related to N management over longer timescales. The main aim of this chapter was to demonstrate the ability of APSIM-Sugar to reproduce experimental N fertiliser rate trial results under wet tropical conditions. APSIM-Sugar was parameterised using the results from a small-plot N fertiliser rate field experiment conducted at Tully from 2004 to 2009. APSIM-Sugar was able to explain how sugarcane yields, as recorded in experimental field trials under wet tropical conditions, might have been achieved. Some problems were encountered with simulating cane yields in severely waterlogged conditions and at lower N fertiliser rates. More research is required to understand the physiological impact of waterlogging on sugarcane growth so that it can be better represented in APSIM-Sugar.

Annual cane yield to applied N fertiliser response curves generated for the APSIM-Sugar simulated cane yields and N-rate field experiment observed cane yields were used to calculate the optimum amount of N required each year. The optimum amount of N fertiliser required was defined as producing 95% of the maximum cane yield in each year. The simulated optimum N rates were often much lower than the observed due to difficulties in calibrating APSIM-Sugar. However both the simulated and observed optimum N rates varied from one year to the next in response to changes in climatic conditions. The differences in optimum N rates between years supported a more thorough investigation into the impact of climatic conditions on N fertiliser requirements be undertaken.

6.3. Objective 3: To determine the impact of climatic conditions on nitrogen fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil

Crop size is the main determinant of N fertiliser requirements. The size of the sugarcane crop at Tully is strongly influenced by spring-summer rainfall (Chapter 2). However, current N fertiliser guidelines do not consider the impact of spring-summer rainfall on crop size (cane yield t cane/ha) and hence N fertiliser requirements. The aim of this chapter was to investigate the impact of spring-summer rainfall on the N fertiliser requirements for ratoon sugarcane crops grown on the Bulgun series soil and if existing climate forecasting indices be used to predict how much N fertiliser to apply in the Wet Tropics. The results emanating from Chapter 3 and a small-plot N fertiliser rate response trial conducted at Tully between 2011 and 2014 guided the parameterisation of APSIM-Sugar. Optimum N fertiliser rates were simulated for first, second, third and fourth ratoon sugarcane crops grown on the Bulgun soil series for a 45 year period using APSIM-Sugar. Given spring-summer rainfall has a strong influence on Tully cane yields the relationship between spring-summer rainfall and optimum N fertiliser rates was investigated. The impact of ENSO on optimum N fertiliser requirements was also investigated using the June to August Oceanic Niño Index.

The results indicate the June to August Oceanic Niño Index can be used to predict how much N fertiliser to apply to ratoon sugarcane crops grown on the Bulgun series soil. Nitrogen fertiliser rates could be reduced in wet years, defined when the June to August Oceanic Niño Index is in the La Niña phase. Simulated optimum N fertiliser rates were on average 25% lower in years when the June to August Oceanic Niño Index was in the La Niña phase. There was typically no difference in optimum N fertiliser rates between El Niño and Neutral phase years. The link between N fertiliser inputs and the June-August Oceanic Niño Index exists because the chance of experiencing high spring-summer rainfall increases when the June to August Oceanic Niño Index is in the La Niña phase. High spring summer-rainfall is associated with low cane yields at Tully due to increased waterlogging and lower solar radiation. Identifying N fertiliser requirements are lower in wet years will contribute towards the development of more environmentally sensitive yet profitable N-management strategies for sugarcane crops grown in the Wet Tropics region.

Climate forecasting indices are not currently being used to predict N fertiliser requirements for agricultural crops. The Australian grains industry was the most advanced in using climate forecasting indices to guide N fertiliser management. Climate forecasting indices are being used to provide wheat growers with crop growth and yield forecasts so that they can adjust in-season N fertiliser application rates rather than predicting the amount of N fertiliser to apply. The ability of the June to August Oceanic Niño Index to predict N fertiliser requirements for ratoon sugarcane crops significantly advances the application of climate forecasting indices for N fertiliser management in agricultural crops.

6.4. Objective 4: To assess nitrogen fertiliser recovery and nitrogen use efficiency of successive ratoon sugarcane crops grown on the Bulgun soil series

The fate of N fertiliser not recovered by the sugarcane crop, immobilised in soil N pools and/or lost from the sugarcane production system, is of significant importance for the economic and environmental sustainability of the Wet Tropics sugar industry. Small-plot N fertiliser rate response experiments conducted in ratoon sugarcane crops grown on the Bulgun series soil between 2011 and 2014 were used to investigate the i) total N and fertiliser N recoveries of successive ratoon sugarcane crops, ii) fertiliser nitrogen use efficiency of ratoon sugarcane crops, and iii) impact of improving fertiliser nitrogen use efficiency on grower and industry profitability. The total amount of N recovered decreased as the crop cycle progressed, indicating older ratoons are less efficient at recovering N. The amount of fertiliser N recovered in the aboveground crop components was comparable to previous research conducted in the Wet Tropics but differences were observed between successive ratoon crops. The third ratoon crops recovered less N, in total, than the first and second ratoon crops, but were more reliant on fertiliser N whereas the majority of N recovered by the first ratoon crops was supplied by soil N sources. This significantly improves the understanding of N recovery by sugarcane crops as previous research has not investigated N recovery of successive ratoon sugarcane crops. These results are specific to a single poorly-drained alluvial soil type (Bulgun series soil) within the Wet Tropics region. However, it is likely that these results will also be relevant to other poorly-drained alluvial soils with similar soil organic carbon (%) and physical characteristics and positions in the landscape to the Bulgun series soil. The results also indicate the SIX EASY STEPS N fertiliser guidelines for ratoon sugarcane crops grown on the Bulgun series soil need to be reviewed.

Improving fertiliser N-use efficiency is of environmental importance given the current operating environment of the Wet Tropics sugar industry. Reducing N fertiliser rates below the SIX EASY STEPS N guidelines (Schroeder et al., 2007b) to sugarcane ratoon crops grown on Bulgun soils, every year, will improve fertiliser N-use efficiency. However, reducing the amount of N fertiliser applied every year, especially in years experiencing favourable growing conditions, will adversely affect grower and industry marginal economic returns due to a reduction in cane yields. Any proposed improvements in fertiliser N-use efficiency should also be economically effective. Reducing N fertiliser rates in wet years is likely to have a positive impact on NUE and be economically effective. Chapter 4 indicated N fertiliser requirements are lower in wet years for sugarcane ratoon crops grown on Bulgun series soils. The challenge will be ensuring the crop is able to acquire fertiliser N in wet years.

6.5. Future Work

This thesis has highlighted the importance of managing the impact of climate variability on N fertiliser requirements in the Wet Tropics region. Reducing N rates below SIX EASY STEPS N guidelines will improve fertiliser N-use efficiency but reduce grower and industry profitability. Future research needs to focus on identifying sustainable N management practices, which improve fertiliser nitrogen use efficiency to protect the environment and are economically effective to ensure the longevity of the Wet Tropics sugar industry. Opportunities to improve N fertiliser management in the Wet Tropics warranting further research that have been identified in this thesis are discussed in the following.

The impact of spring-summer rainfall on N fertiliser requirements was investigated for a single soil type, the Bulgun series soil in the Wet Tropics region. It is recommended that the impact of spring-summer rainfall on N fertiliser requirements be investigated for other major sugarcane growing soil types occurring throughout the Wet Tropics. Understanding the relationship between spring-summer rainfall and N fertiliser requirements for a wide range of soil types is required before revising the SIX EASY STEPS N management guidelines for the Wet Tropics region.

It was outside the scope of this thesis to investigate the economic and environmental benefit of reducing N fertiliser rates in wet years to ratoon sugarcane crops grown on the Bulgun series soil. As seasonal climate forecasts only provide probabilistic information about future climatic conditions, there will always be some uncertainty regarding the accuracy of climate forecasts. Future research should focus on quantifying the economic and environmental benefit of using the June to August Oceanic Niño Index to predict N fertiliser requirements. Given that the simulation study supported a reduction in N fertiliser rates in wet years future research should also investigate the impact of changing the frequency of N fertiliser inputs and/or use of enhanced efficiency N fertiliser products in wet years.

The SIX EASY STEPS N management guidelines do not differentiate N fertiliser requirements between ratoon crop classes. The fact that older ratoons recovered less N in total but were more reliant on fertiliser N than younger ratoons indicates the SIX EASY STEPS N management guidelines for ratoon sugarcane crops grown on the Bulgun series soil need to be reviewed. However more research is required to quantify the $AgronEff_{Fert}$ and N recovery of successive ratoon sugarcane crops grown on a diverse range of soil types occurring throughout the Wet Tropics. If older ratoons are consistently less efficient in recovering N and more reliant on N fertiliser for the major soil types, then the SIX EASY STEPS N guidelines can be revised to differentiate between ratoon crop classes. Further research should also focus on understanding the $AgronEff_{Fert}$ and N recovery of successive ratoon sugarcane crops grown on other soil types in regions outside the Wet Tropics.

The N mineralised from soil organic matter pools was extremely valuable in meeting the N requirements of first ratoon crops. The SIX EASY STEPS N management guidelines acknowledges the contribution of N mineralised from soil organic matter in meeting crop N requirements by considering the N mineralisation potential of a soil, based on the soil organic carbon (%) content, when determining fertiliser N requirements. As young ratoons were more efficient in recovering soil N it may be possible to reduce the amount of N fertiliser applied to young ratoons. However, the amount and rate of N mineralised from soil organic matter pools needs to be better understood before fine-tuning N fertiliser guidelines, especially for first ratoon sugarcane crops.

This thesis significantly advances the application of climate forecasting indices for N fertiliser management in agricultural crops and improves the understanding of N recovery by ratoon sugarcane crops. For ratoon sugarcane crops grown on Bulgun series soil, fertiliser nitrogen use efficiency can be improved by reducing N fertiliser application rates in wet years and differentiating N fertiliser requirements between ratoon crop classes. The knowledge generated in this thesis will contribute towards the development of N fertiliser management practices that will ensure both the economic and environmental sustainability of the Wet Tropics sugar industry.

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Appendix 1

Initial soil nitrate (NO_3^{2-}) and ammonium (NH_4^+) nitrogen values for 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil profile depths used to parameterise APSIM-Sugar

N rate (kg N/ha)	Mean soil ammonium N (NH_4^+ kg/ha) values				
	0-20cm	20-40cm	40-60cm	60-80cm	80-100cm
0	35.000	32.905	30.81	30.433	30.055
30	9.560	7.270	4.98	3.823	2.665
60	24.815	21.188	17.56	17.248	16.935
75	24.590	20.980	17.37	15.718	14.065
90	36.225	33.018	29.81	29.538	29.265
105	36.225	32.308	28.39	29.625	30.86
120	40.005	38.293	36.58	35.998	35.415
135	13.770	12.243	10.715	9.953	9.19
150	16.105	13.503	10.9	10.645	10.39
180	10.230	7.058	3.885	3.788	3.69
210	8.685	5.753	2.82	2.685	2.55
240	25.415	24.495	23.575	22.190	20.805
N rate (kg N/ha)	**Mean soil nitrate N (NO_3^{2-} kg/ha) values**				
	0-20cm	20-40cm	40-60cm	60-80cm	80-100cm
0	8.605	5.985	3.365	3.693	4.02
30	4.605	4.025	3.445	3.378	3.31
60	6.845	5.158	3.47	3.490	3.51
75	5.78	4.733	3.685	3.578	3.47
90	7.505	5.493	3.48	3.545	3.61
105	7.74	5.555	3.37	4.418	5.465
120	4.67	4.160	3.65	3.653	3.655
135	8.305	6.013	3.72	4.125	4.53
150	7.105	5.458	3.81	3.688	3.565
180	5.805	4.700	3.595	3.585	3.575
210	5.45	4.578	3.705	3.705	3.705
240	7.43	5.505	3.58	4.948	6.315

Appendix 2

Mean organic carbon (%) values for 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil depths used to parameterise APSIM-Sugar

N rate	Organic Carbon (total %)				
(kg N/ha)	0-20	20-40	40-60	60-80	80-100
0	2.720	1.865	1.010	0.770	0.530
30	2.380	1.518	0.655	0.490	0.325
60	2.395	1.630	0.865	0.585	0.305
75	2.790	1.960	1.130	0.748	0.365
90	2.655	1.828	1.000	0.680	0.360
105	2.635	1.855	1.075	0.745	0.415
120	2.395	1.643	0.890	0.663	0.435
135	2.225	1.375	0.525	0.468	0.410
150	2.380	1.520	0.660	0.483	0.305
180	2.670	1.713	0.755	0.523	0.290
210	2.065	1.403	0.740	0.465	0.190
240	2.215	1.705	1.195	0.725	0.255

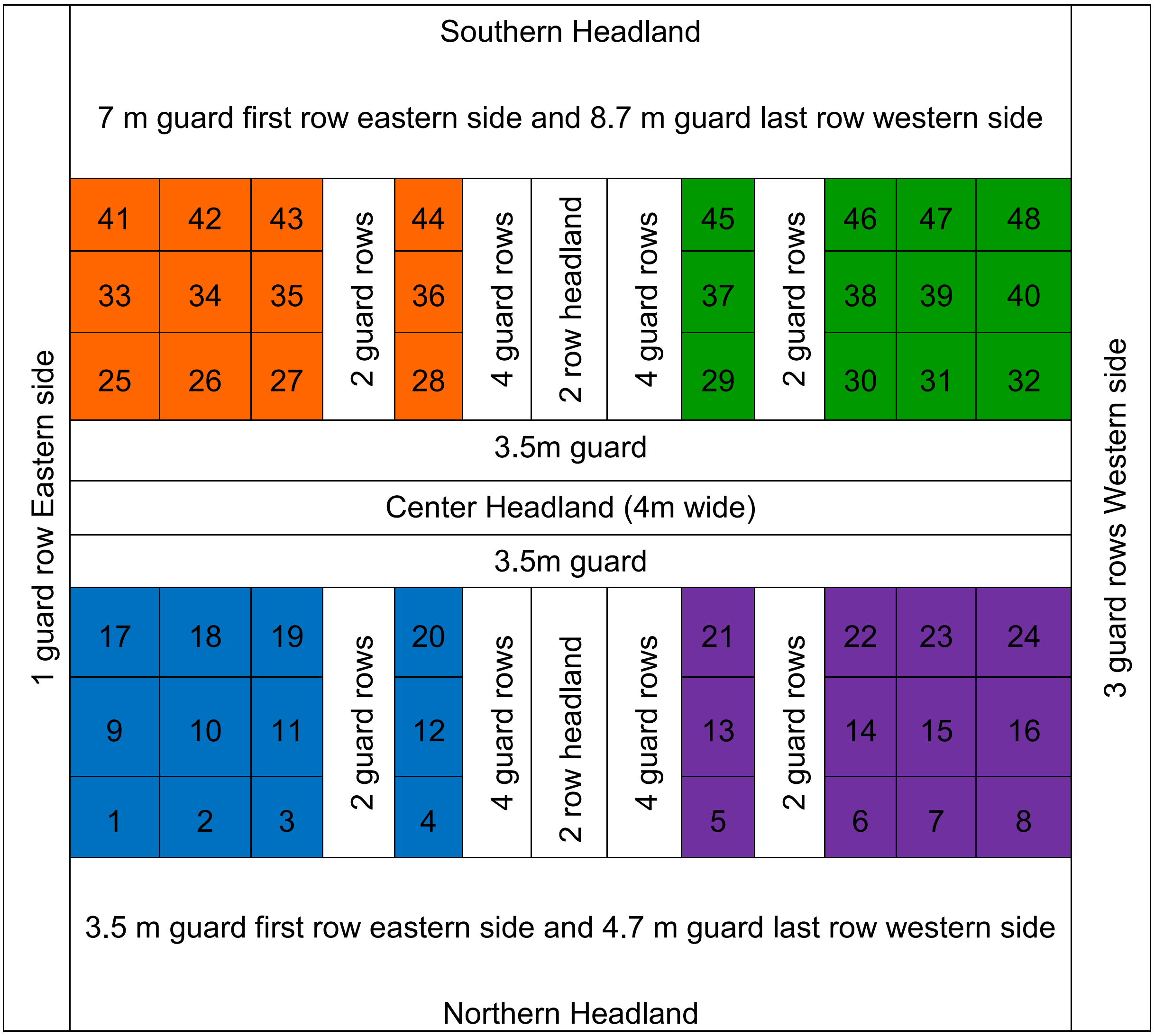
Appendix 3

Soil bulk density and volumetric water content values for 0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm soil depths used to parameterise APSIM-Sugar

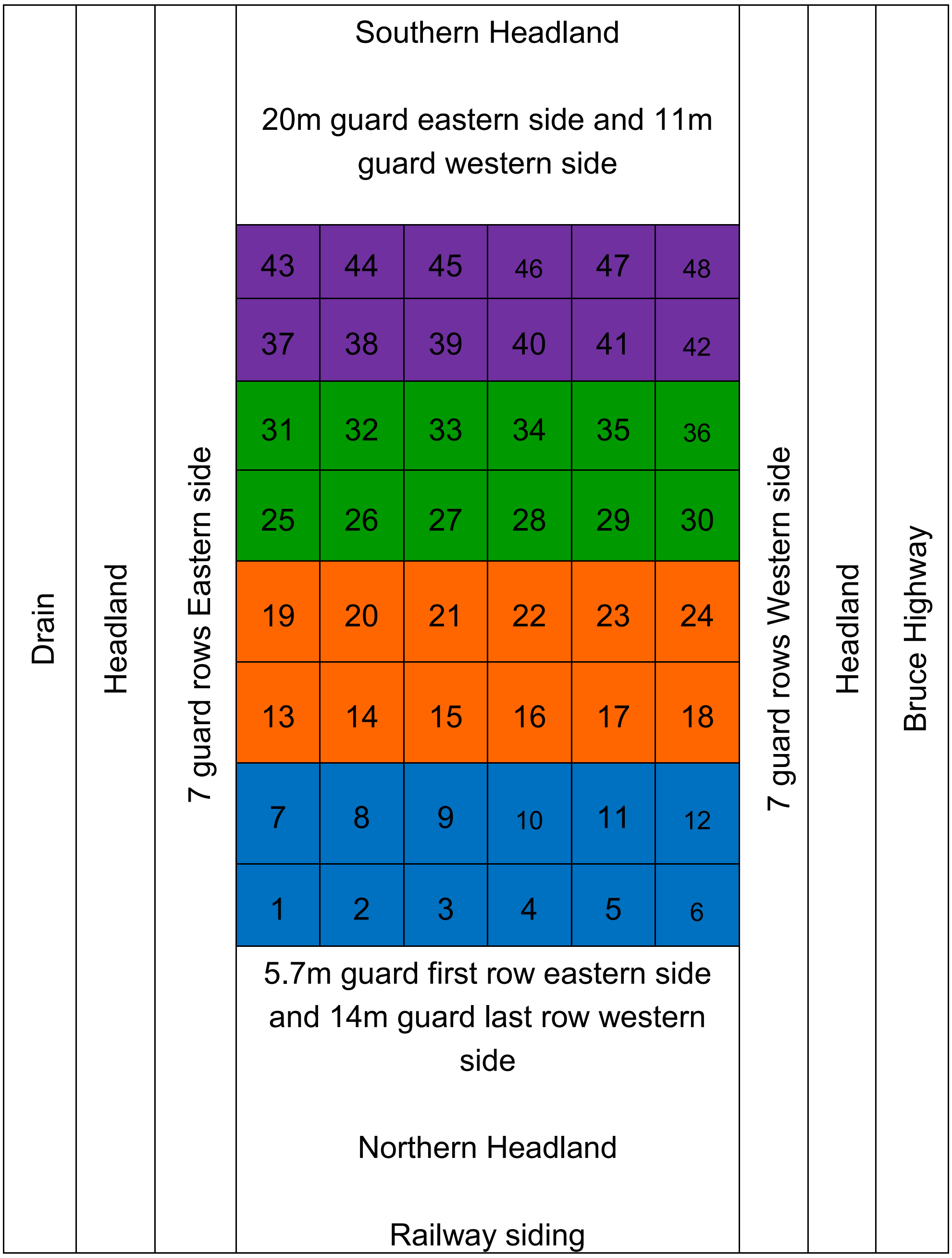
Soil depth (cm)	Bulk Density (g/cm^3)	Wilting Point (cm^3/cm^3)	Field Capacity (cm^3/cm^3)	Saturated Water Content (cm^3/cm^3)
0-20	1.18	0.294	0.367	0.475
20-40	1.31	0.276	0.346	0.463
40-60	1.46	0.306	0.386	0.447
60-80	1.40	0.343	0.409	0.470
80-100	1.44	0.344	0.421	0.468
100-120	1.49	0.323	0.407	0.455

Appendix 4

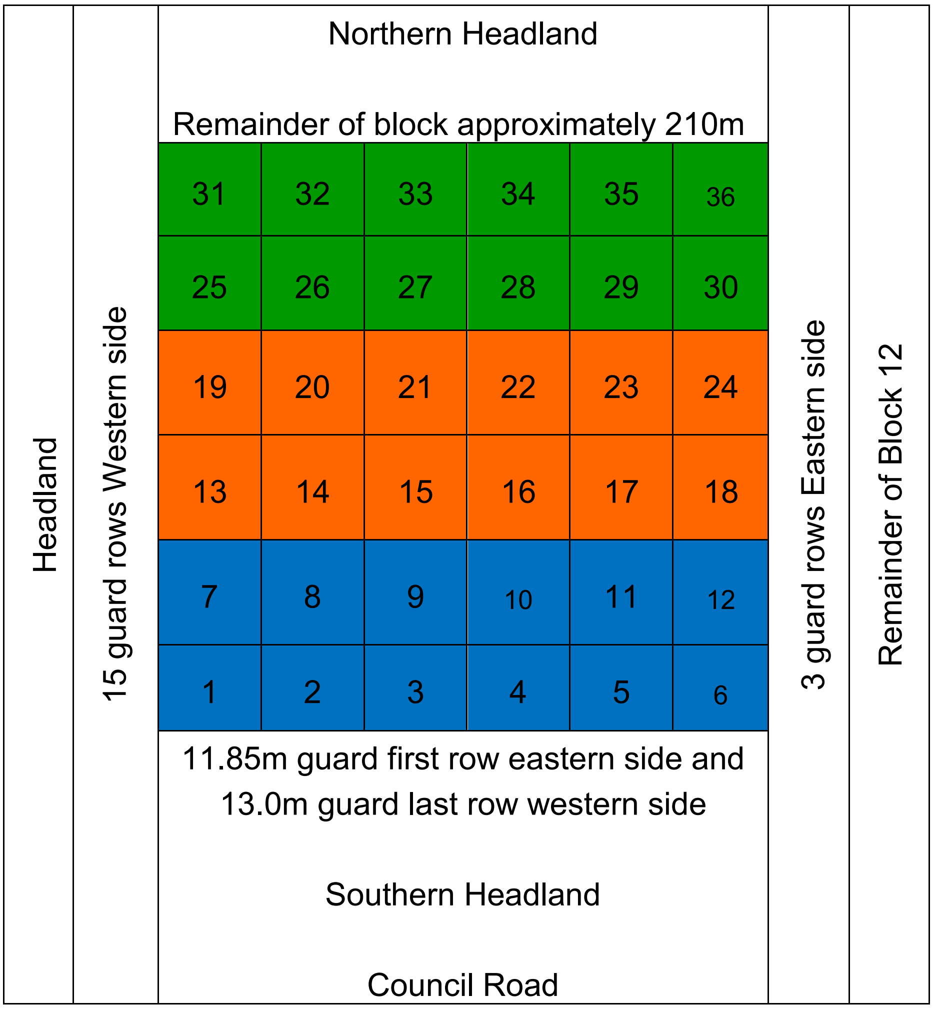
Small-plot N fertiliser rate field experiment designs



Appendix 4.1. Experimental design of trial site T1 showing plot locations (labelled numerically) and replication (colour coded).



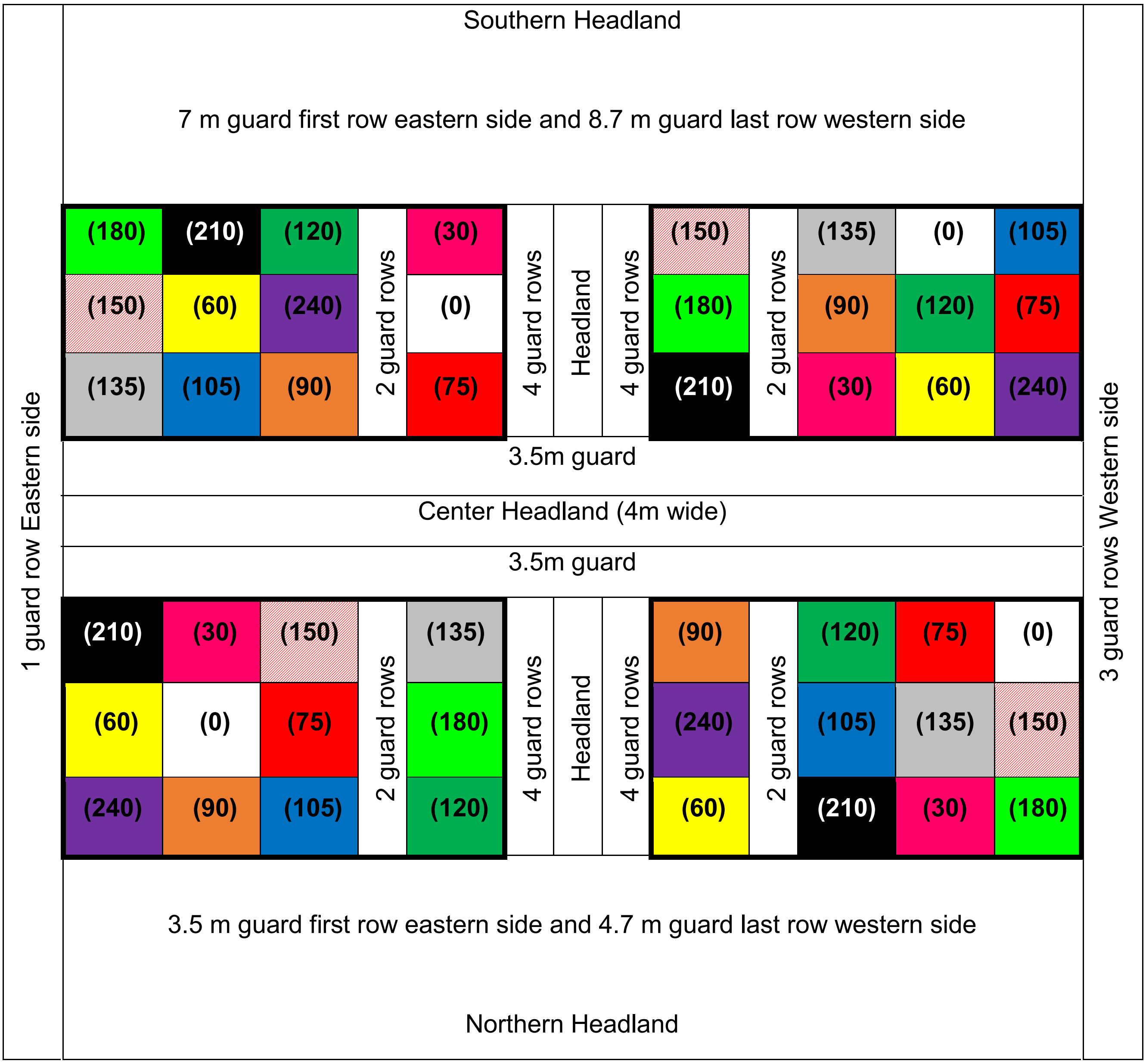
Appendix 4.2. Experimental design of trial site T2 showing plot locations (labelled numerically) and replication (colour coded).



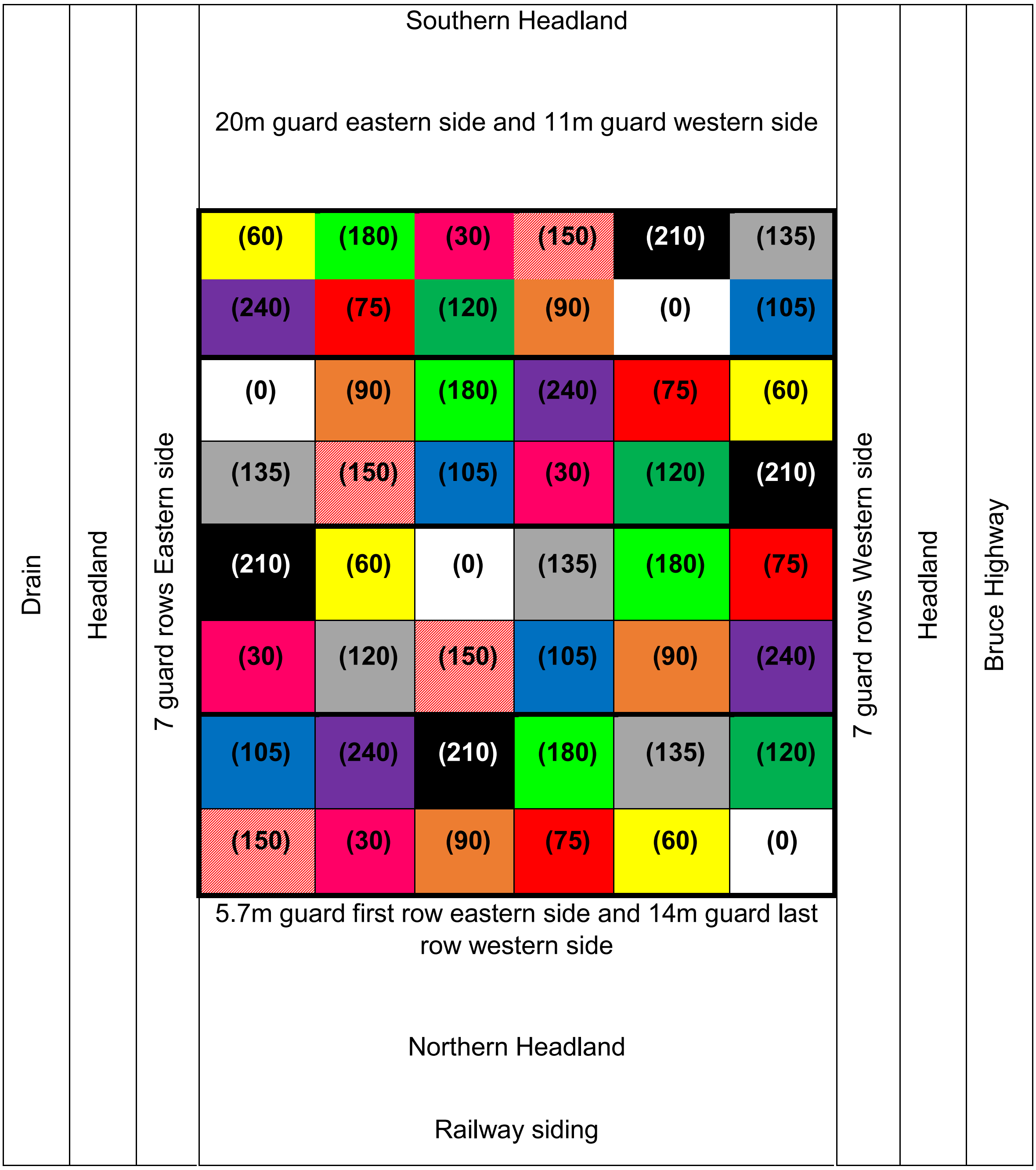
Appendix 4.3. Experimental design of trial site T3 showing plot locations (labelled numerically) and replication (colour coded).

Appendix 5

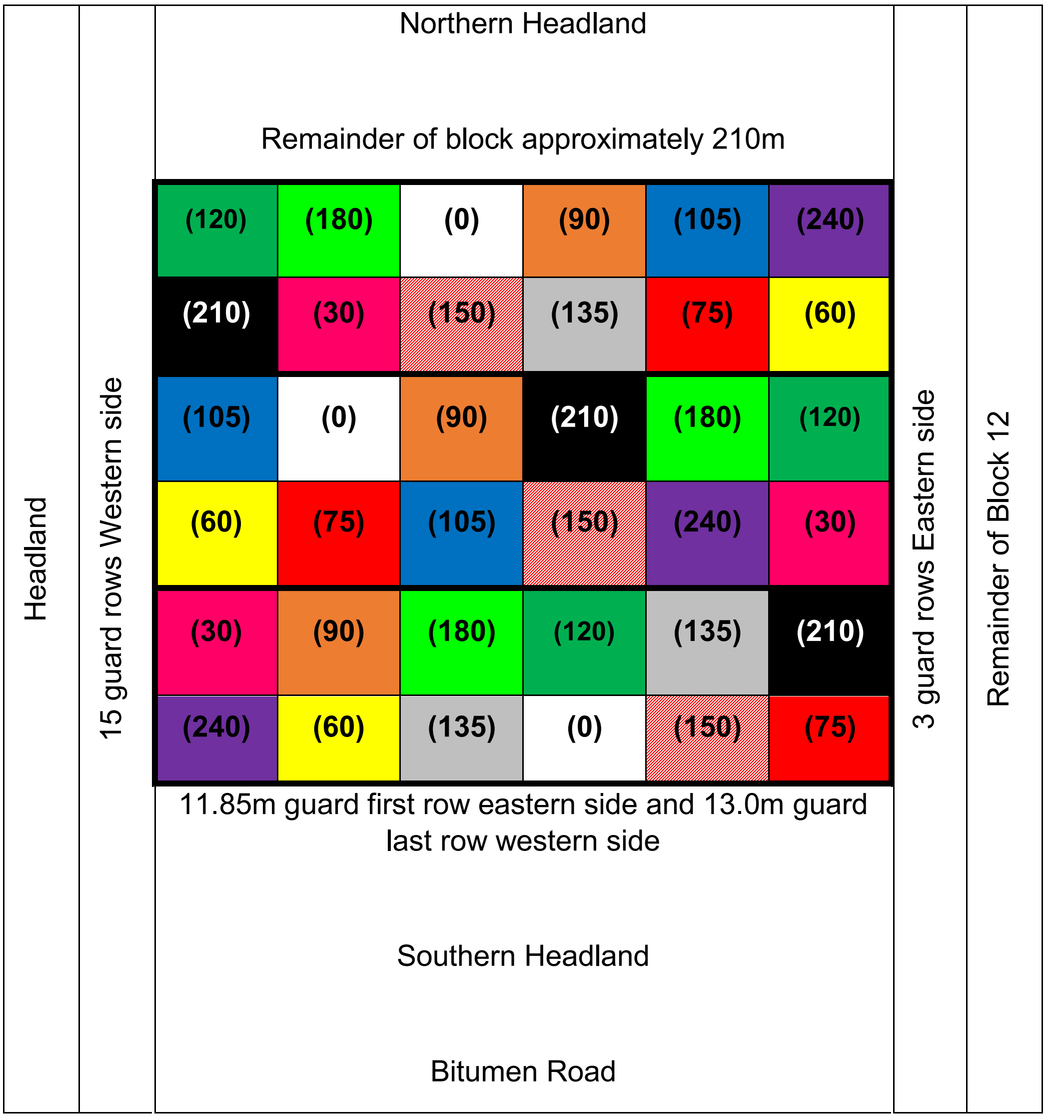
Small-plot N fertiliser rate field experiment treatment layouts



Appendix 5.1. Experimental layout of trial site T1 showing the N treatment (kg N/ha) applied to each plot. Plots have been colour coded according to the N fertiliser rate applied (kg N/ha is reported in brackets).



Appendix 5.2. Experimental layout of trial site T2 showing the N treatment (kg N/ha) applied to each plot. Plots have been colour coded according to the N fertiliser rate applied (kg N/ha is reported in brackets).



Appendix 5.3. Experimental layout of trial site T3 showing the N treatment (kg N/ha) applied to each plot. Plots have been colour coded according to the N fertiliser rate applied (kg N/ha is reported in brackets).