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UNDERSTANDING THE IMPACTS OF POUR RATE ON SUGAR LOSSES FROM THE CHOPPER HARVESTER

A Thesis submitted by

Sombat Khawprateep, M Eng

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Abstract

Sugar loss from a mechanical harvester is the most significant of all losses in sugarcane production. The pour rate or material flow through the harvester affects the amount of cane loss and extraneous matter (EM) harvested, as well as impacts on crop production in the next season. Cane loss and EM impact on the quantity and quality of crop delivered to the mills, thus influencing the profits of cane growers, harvesting contractors and millers. The aim of this research was to investigate the effects of harvester set up and operation on sugar loss and how this was influenced by different crop nutrient practices.

Field work and data collection was conducted in the Bundaberg, Childers and Ingham districts of Queensland during the 2014–16 sugarcane growing seasons. The sites were aligned with pre-existing nutrition trials arranged in a randomised factorial design with four replicates of nitrogen application rates (0–225 N kg/ha). In the plots of interest, the physical properties of the sugarcane including crop density, stalk length and diameter and leaf percentage was measured immediately prior to harvest. The sugarcane was cut by the chopper harvester with three working fan speeds (650, 850 and 1,050 r/min) and three ground speeds (4, 5 and 6 km/h). Billet and EM samples were collected to understand the impact on billet size distribution, billet quality and loss potential. Trash samples were also collected and analysed for sugar loss. The summation of the various components allowed the full assessment of machine impacts on sugar loss, sugarcane quantity and the economic impacts on the three sectors of the sugarcane industry.

The results showed that high pour rates (driven in the trials by high N application rates) produced an increased level of EM in the cane billets supplied to the mill and reduced the fan capacity to separate trash from billets. The proportions of damaged and mutilated billets at high pour rates were also elevated due to the difficultly in separating the components by the extractor fan. Conversely, the percentage of sound billets and sugar loss were increased at the low N application as the lighter billets were ejected more easily by the cleaning system than the heavier ones. When the pour rate increased (high ground speed and the fan speed (6 km/h, 1,050 r/min, the commercial cutting setting)), the cane loss and EM were high but the billet supply bulk density decreased. Conversely, operating with the low ground and fan speeds (4 km/h, 650 r/min), the cane loss and the bulk density in the billet supply were reduced but the EM was increased, resulting in low CCS and high transportation cost that reduced the grower's income. The cutting ground speeds at 4 km/h with 850 r/min of fan speed provided the optimised cutting conditions which were a combination of increased sugar recovery without excessive transport cost. In this situation, the growers' revenue was increased around 9,700 AU$ per 1,000 t of harvested cane through better CCS and cane supply yield. Under this costing model, the harvesting contractor still achieved a balanced income even with the increased costs during harvesting and transportation. Additionally, the miller received increased returns due to the improved processing performance of the sugar recovery due to the quality of the billet supply (high CCS).

Crop parameters change very markedly between and within fields. This research has shown how these changing parameters can dramatically influence the ability of the chopper harvester to efficiently convert grower efforts on farm, to millable sugar at the refinery. The complex relationship between pour rate, ground and fan speed impacts on the profitability of the three sectors in the sugar industry – grower, contractor and miller. Continuously fine-tuning the harvester settings is important to fully optimise the system compared to the current practise of infrequent adjustment.

Certification of Thesis

This thesis is entirely the work of *Sombat Khawprateep* except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors signatures of endorsement are held at USQ.

Associate Professor Troy Jensen
Principal Supervisor

Professor Bernard Schroeder
Associate Supervisor

Professor Talal Yusaf
Associate Supervisor

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List of Associated Publications

The following articles have been published or submitted for publication from the research contained within this thesis.

Conferences

Refereed poster article

Khawprateep, S, Jensen, TA & Schroeder, BL 2015, 'Does cane yield, influenced by nitrogen fertiliser rates, affect cane loss during cutting?', in *Proceedings of Australian Society of Sugar Cane Technologists,* vol. 37, p. 19.

Jensen, TA & Khawprateep, S 2018, 'Incorporating sugar loss data with other precision agriculture layers', in *Proceedings of 3rd Agricultural engineering, agronomy and extension workshop*, 23–28 September 2018, La Réunion, p. 27.

Journal

Khawprateep, S, Jensen, TA, Schroeder, BL & Eberhard, S 2018, 'Influence of yield and other cane characteristics on cane loss and product quality', *International Sugar Journal*, vol. 120, no. 1432, viewed 3 April 2018, <https://internationalsugarjournal.com/paper/influence-of-yield-and-other-cane-characteristics-on-cane-loss-and-product-quality/>.

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Abbreviations

ANOVA	Analysis of Variance
ASMC	Australian Sugar Milling Council
BMP	Best Management Practice
BSES	Bureau of Sugar Experiment Stations
CCS	Commercial Cane Sugar
DMRT	Duncan's New Multiply Range Tests
EM	Extraneous Matter
GC	Gas Chromatography
HBP	Harvester Best Practice
HPIC	High-Performance Ion Chromatography
HPLC	High-Pressure Liquid Chromatography
IBM	International Business Machines Corporation
ICUMSA	the International Commission for Uniform Methods of Sugar Analysis
K	Potassium
N	Nitrogen
NCEA	the National Centre for Engineering in Agriculture
NIRS	Near Infrared Spectroscopy
NorrisECT	Norris Energy Crop Technology
NSW	New South Wales
NUE	Nitrogen Use Efficiency
P	Phosphorus
SPSS	Statistical Package for the Social Sciences
SRA	Sugar Research Australia
SRI	Sugar Research Institute
USA	the United States of America
USQ	University of Southern Queensland

Chapter 1 Introduction

1.1 Background

Sugarcane is one of the most important agricultural crops in Australia. Approximately 94% of Australian sugar comes from Queensland with the balance from Northern New South Wales (NSW) (ASMC 2017). The sugar industry directly employs about 16,000 people across the growing, harvesting, milling and transport sectors with around 4,500 growers supplying sugarcane to the mills. Up to 35 million tonnes of sugarcane is produced annually from about 381,000 hectares. Approximately 5 million tonnes of raw sugar were produced during the 2015 season (ASMC 2017). Australian raw sugar is sold to refineries both domestically and overseas.

Losses of sugarcane can occur at all points in the production process, from planting to cultivating and harvesting, and in the process of transport and delivery to the mills. Since all sugarcane in Australia is cut with the chopper harvesters, it is important to recognise the losses that occur from several component within the harvester itself. This includes losses from the topper, feed trains, elevator and extractor fans (Whiteing & Norris 2002). The total losses from mechanical harvesting is greater than the losses that occur during the milling process (NorrisECT 2012). Quirk (2013) indicated that about 13% of the crop was lost during green cane harvesting in NSW. Although it is apparent that the highest sugarcane loss is caused by the primary extractor system (Whiteing et al. 2001), this issue has implications for growers, harvester contractors and millers due to competing interests.

A range of in-field operations and management choices contribute to successful sugarcane production. However, some factors such as choice of cultivar, weather conditions, row spacing and soil profiles impact on cane loss and the amount of extraneous matter (EM) mixing with the cane supply during harvest (Ridge 1994a).

Forwarding speed and crop condition impact on the harvesting pour rate. Increasing pour rates can cause cane quality problems resulting from feeding and cleaning difficulties (Agnew & Sandell 2000) and entrapment of soil in the cane supply.

Additionally, excessive forward ground speeds can lead to stool damage, poor ratoon and subsequent yield decreases in later years.

Many techniques and strategies have been used to improve harvesting and reduce cane loss during the harvest operations. These include the development and use of harvesting best practice (Agnew et al. 2002; Sandell & Agnew 2002), whole crop harvesting (Inderbitzin & Beattie 2012) and cane cleaning plants (Hobson et al. 2001; NorrisECT 2013) to help improve sugar recovery during harvest. Several methods have been developed to assess these losses. They include near infrared (NIR) spectroscopy (Crees & Brotherton 1991; O'Shea et al. 2011; Mat et al. 2014) and high-pressure liquid chromatography (HPLC) used in a procedure developed by Whiteing (2013) which enabled the different soluble sugar loss components to be separated and assessed. This enable researchers, harvester contractors and other industry stakeholders to account for sugar loss within fields (Sichter et al. 2005; Whiteing 2013). However, this technique is costly to set up due to the expense of the measuring columns when compared with other colorimetric methods. The accuracy of the two techniques (HPLC and colorimetric procedures) is comparable (Campbell et al. 1999) with the possibility to test the less sugar content adhering to the trash. The two techniques detailed by Whiteing (2013) and Campbell et al. (1999) can now be applied to measure the sugar loss from the chopper harvester. Investigations into reducing cane loss due to field and crop conditions, improving billet quality for sugar recovery, along with the evaluation of cane payment systems, are now possible.

1.2 Research gaps and questions

1.2.1 Research gaps

The reviews can be identified the research gaps that lead to a subset of further gaps:

1. No research has been conducted on harvesting pour rate from varying crop conditions especially the effect of crop nutrients practice to cane and sugar loss during harvesting.
2. No research has been conducted on different ground and fan speeds operated to cut sugarcane impacted by varying crop conditions particularly the influence of crop nutrients practice. This relates to sugarcane quantity and quality.

3. No studies have been conducted on the effect of changing pour rate to economic to cane loss during harvesting influenced on the crop nutrients practice.

1.2.2 Research questions

The research question in this study is: “Do the effects of changing pour rate influenced on the crop conditions impact on sugarcane quantity and quality during harvesting including sharing industry revenue?” This research question leads to a subset of further questions:

1. How do the harvesting pour rates from the different crop conditions impact on cane and sugar loss particularly the effect of crop nutrients practice?
2. How do the effect of the varying ground and fan speeds worked in cutting sugarcane influenced by the different crop conditions impact on sugarcane quantity and quality?
3. How do the changing pour rates used in cutting sugarcane influenced by the different crop conditions impact on the sharing industry revenue (growers, harvester contractors and millers)?

1.3 Research objectives

The aim of this research was to investigate the effects of harvester set up and operation on sugar loss and its effects on productivity and Best Management Practice (BMP). Researchers have previously used a number of techniques to quantify sugarcane losses from the harvester. A standard ‘tarp test’ (Sandell & Agnew 2002) was used to measure parts of cane stalks lost during harvest. The mass balance technique (Sandell & Agnew 2002; Whiteing et al. 2004) determined cane loss by assessing crop yield when the primary extractor fan was switched off and at different fan speeds in a large scale replicated harvesting trials. A third method used electronic loss monitors (McCarthy et al. 2002; Whiteing 2004; Whiteing et al. 2004) by determining cane loss due to billets impacting the extractor blade. However, these methods did not account for all the losses such as splattered juice, shredded pulp and tiny fragments that occur in the field. To measure these ‘invisible’ cane loss during cutting, a technique for collecting and preparing trash samples in the field immediately after harvest was developed by Whiteing (2013). This was followed by colorimetric determination of the sugar content (Campbell 1999) of the extracted samples to qualify sugar loss at different extractor fan speeds. This research applied two methods to measure sugar loss adhering to trash by cleaning the extractor fan due to changing pour rates impacted by the crop condition to determine relationships between cane cleaning, cane loss and extraneous matter (EM).

The following were the specific objectives of this project:

1. To investigate the effect of the harvesting pour rate due to varying crop conditions, and studying its impact on sugar loss during harvesting.
2. To analyse the effect of different ground and fan speeds used in cutting sugarcane influenced by different crop conditions. This relates to cane quantity and quality.
3. To evaluate the economic implications of cane loss due to changing pour rate on growers, harvester contractors and millers.

1.4 Organisation of the thesis

This thesis is organised into seven chapters, and this is represented schematically in Figure 1.1.

Chapter 1 presents the background to the research and development (R&D) undertaken in this project. It includes identification of the research issue and sets out the objectives.

Chapter 2 is a literature review of published works that covers the physical properties of sugarcane, the components of the chopper harvester system, sugar cane loss as influenced by the harvester systems, harvester best practice (HBP) strategies and the techniques to evaluate cane loss.

The materials and method section is split into three separate chapters, which are detailed following.

Chapter 3 describes the physical properties of sugarcane influenced by the varying nutrient rates and the test procedure for collecting the samples from the harvester. The assessment of the results caused by crop condition at the site is presented.

Chapter 4 details the procedures to quantify and evaluate the sugar loss from the harvesting the cane at the experimental site using a chopper harvester. All residues discharged by the cleaning mechanism of the sugarcane harvester were collected and the amount of sucrose adhering was determined using the optical absorbance technique (the colorimetric method). These data add to the description of the crop conditions at the site particularly due to varying fertiliser applications rates and when the ground speed of the machine is constant.

Chapter 5 describes the varying ground and fan speed with the harvester operation, which impact on the harvested cane quantity and quality under the influence of the crop condition resulted in the nutrient rates.

Chapter 6 evaluates the implications on cane loss due to the changing pour rates to suit the crop condition caused by the nutrient applications. An economic assessment is presented and the optimum cost determined.

Chapter 7 summarises the main conclusions of this research. Further studies are also recommended.

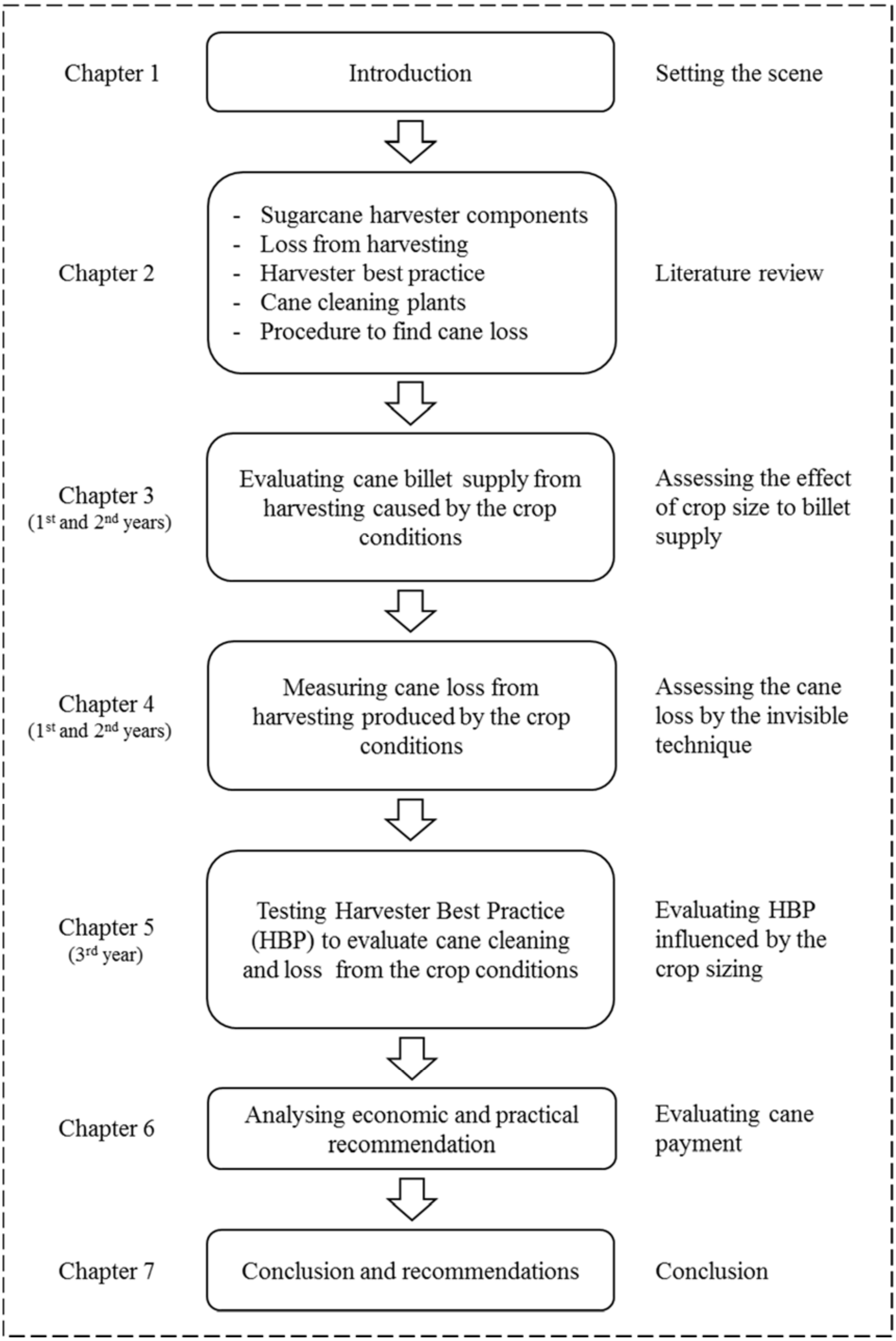


Figure 1.1 The schematic layout of this thesis

Chapter 2 Literature review

2.1 Introduction

This chapter contains a review of the literature on the sugarcane production process with particular emphasis on cane losses in the process. This includes; plant components, sugarcane harvester systems (with a focus on chopper machine), and whole crop harvesting in sugarcane. A review of sugarcane loss and cleaning from the harvester operation is also included. A relationship between extraneous matter (EM) and cane loss, harvesting best practice and sugarcane cleaning plant are reviewed. Studies of techniques to measure cane loss from harvesting are considered in this Chapter. Cane payment systems related to harvesting are also presented. Detailed literature reviews and results from experiments are revealed in this chapter.

2.2 Physical properties of the sugarcane

Sugarcane (*Saccharum spp.*) is an important agricultural crop as a source of food and biomass that enable granular sugar, ethanol and electricity generation. The components of a sugarcane plant are; stalks (87%) and trash (13%). Sugarcane trash is made up of top and green leaves (around 46%) and dry or brown leaves (around 54%) (Franco et al. 2013). All sugarcane components contain important nutrients such as nitrogen (N), phosphorus (P) and potassium (K). The ‘tops’ component of sugarcane trash contains 0.09% P, 1.24% K and 0.75% N, which offer an important source of these nutrients when returned to the field (Franco et al. 2013).

2.3 Chopper harvester systems

There are only two harvesting systems used to harvest sugarcane – a fully or partially manual system and the totally mechanised chopper harvesting system. The mechanical sugarcane harvester has been used in Australia since the early 1940’s. Sugarcane harvesting in Australia occurs between June and December each year, using the chopper harvester. Both the Case and John Deere harvester have the same basic mechanical components. The chopper harvester system (Sandell & Agnew 2002) is shown in Figure 2.1 with a description of the components given below.

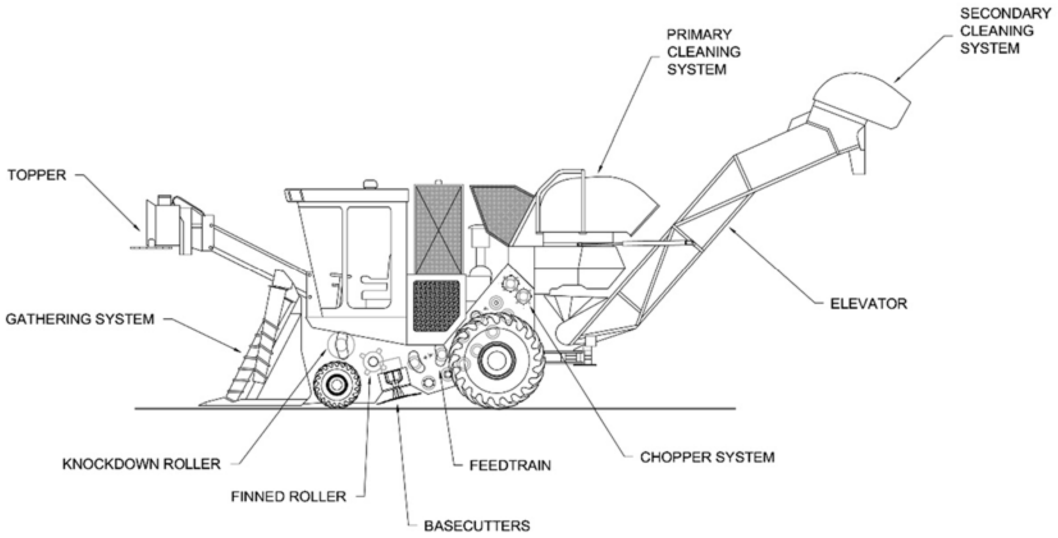


Figure 2.1 A schematic representation of the sugarcane harvester system

Topper: cuts and removes the leafy top of the cane thus reducing the amount of trash entering the harvester.

Gathering system: divides the cane and lodged cane from adjacent rows and aligns the cane in the row being cut. Gathering spirals rotate inwards to lift and align sugarcane for butt-first feeding.

Forward feed components: a knockdown roller and a finned roller fitted in front of the base cutters. The knockdown roller has the important role in the lodged and sprawled crops to encourage the gathering system to feed. The function of the finned roller is to assist the feeding of sugarcane over the base cutter.

Basecutters: cut the cane stalk at the ground level and assist the feed of the cane stalk into the feed train system.

Feedtrain system: to receive the cane stalks cut by the base cutter and deliver them to the chopper system.

Chopper system: to chop the long stalk into smaller cane billets.

Cleaning system: the primary extractor is mounted after the chopper system and attempts to separate EM from the billets by the use of a large extractor fan. Most Australian harvesters utilise a second extractor fan at the top of the elevator to repeat the process.

Elevator: the elevator transfers cane billets that have been cut and cleaned by the harvester into a haulout for transport to the mill.

2.4 Sugarcane loss and cleaning in the sugarcane production and harvest systems

Several studies have suggested that green cane harvesting has less impact on sugarcane quality than burnt cane harvesting (De Beer et al. 1995; Bell et al. 2007). However, green cane harvesting is still known to adversely affect both sugarcane quality and sugar loss (Whiteing & Norris 2002).

The reduction in cane quality is caused by both increased damage and deterioration of cane billet and the increased EM that goes to the mill (NorrisECT 2013). Damage to billets contributes to the deterioration of juice quality through the action of microorganisms. The recovery of sugar at the mill is driven by the type and amount of EM present in the delivered cane. Extraneous matter can be divided into four categories; (i) tops, side shoots and suckers (ii) weeds and grass (iii) dead cane, and (iv) dirt (Cargnello et al. 1988; Wilson & Leslie 1997). It mixes with the cane billets and adds deleterious and contaminating components to the cane supply before milling. Dirt in cane supply causes high maintenance cost due to wear in both sugar mills and harvesters, and increased fibre levels during harvesting, which reduces the recovery of commercial cane sugar (CCS) (Downs 1991). Reduction in CCS has generally been linked to the increased EM in sugarcane supply to the mills, cane damage by biological and mechanical factors and sucker growth (Crook et al. 1999). Ridge (1994a) indicated that cane loss in chopper harvester systems may also be linked to certain varietal characteristics such as initial EM levels and stalk diameter, density and brittleness. The above factors all lead to a reduction in the volume of the actual sugar which can be recovered, relative to the total sucrose delivered to the mill.

The sugarcane losses that can be directly attributed to various components of the chopper harvester are as follows: gathering system (1%), base cutters (2%), choppers (4%) and extractor system (6–9%) (Sandell & Agnew 2002; Whiteing & Norris 2002; Whiteing 2013). These losses impact directly on growers' incomes because they affect the quantity and quality of the sugarcane delivered to the mill.

A number of other factors such as field and crop conditions, harvester configuration and set-up affect sugar loss, sugar quality and the amount of EM in cane delivered to the mill. Researchers and operators have endeavoured to use various methods to solve these issues; pre and post sugarcane harvesting. These will be looked at individually.

2.4.1 Losses due to field and crop conditions

A range of in-field operations and management choices contribute to successful sugarcane production. These include planting, cultivating, harvesting and ratoon management. Factors such as choice of cultivar, weather, row spacing and soil profiles impact on cane loss and amount of soil mixing with cane billets during cutting.

However, certain cultural practices may help reduce the amount of soil in cane supplied to mills (Beattie 1991). These include:

i. Depth of planting—increased depth of the cane stool plus the hilling-up operation, supports a better anchorage for the whole plant and then reduces the problems of lodging and tipping (Beattie 1991).

ii. Row spacing—the narrow rows increase soil levels in cane supply. The effect of the narrow rows is to cause wheels of harvesters and haul-outs to move close to the stool area, which is compacted and the row profile destroyed and/or distorted. Additionally, stalks from adjacent rows are broken off and pulled into the harvester increasing the chance of dirt adhering to them (Beattie 1991; Ridge & Linedale 1993). A row spacing at least 1.8–2.0 m is recommended to suit the wheel track of harvesters and haul-outs to overcome the above-mentioned (Bell et al. 2007; Garside et al. 2009; Salter et al. 2008). These wider row spacings have reduced soil compaction and on-farm costs compared with the previous 1.5 m row spacing (Salter et al. 2008).

iii. Row profiles—crucial roles of row profiles can reduce soil in cane, pick-up loss and worn base cutter blade during harvesting. Rows should be raised (10–15 cm) with slightly rounded shoulders with a flat inter-space (Ridge & Linedale 1993).

Several other factors such as dew or dry weather, lodged cane and sugarcane varieties can cause cane quality issues at the mill (Ridge 1994b).

2.4.2 Losses from topping

The important role of the topper is to reduce the amount of EM (cane top and green leaves) from entering the harvester, allowing the extractors to work more efficiently and reducing unnecessary wear on parts such as the feed roller, chopper and primary extractor blades.

Ivin and Doyle (1989) described the "top" as the leafy material on the cane stalk above the breakpoint that is normally cut and discharged by the harvester. The harvester driver sets the topper position. The tops of cane have an average pol of 0.7 units less than the cane stalk. The fibre content of the top is about 1.2 times higher than in the cane stalk. Tops have high percentage of chlorophyll, which influences the colour of the clarified juice and the sugar recovery in the mill. Correctly setting of the topper can significantly reduce both the EM and cane loss due to better cleaning by the extractors.

Manual and automatic techniques have been developed to correctly position the topper. In one instance, a refractometer was modified for use in harvesting to measure sugar content in cane top in real time (McCarthy & Billingsley 2002). Huang et al. (2005) applied a laser scanning technique to distinguish cane tops from cane stalks. A further method used image processing with a video camera to identify cane tops (Lange & Wuestefeld 2013).

2.4.3 Losses from gathering and stool cutting

The gathering and stool cutting operation by the harvester (involving the crop dividers, the front rollers (knockdown roller and finned roller), base cutter and butt lifter) are all important in reducing cane loss.

Crop dividers have an important role in the gathering and dividing of cane stalks, particularly in lodged cane. Norris et al. (1998) indicated that shallow-angled large-diameter gathering rollers minimised stool damage and cane breakage during feeding. Minimisation of the distance between gathering rollers, base cutter and the feed train assists feeding in lodged cane. For this reason, the previous Bureau of Sugar Experiment Stations (BSES) designed and retrofitted a large single-spiral roller and lower degree angle to the gathering system of the mechanical harvester (Davis & Norris 1999). Gathering systems were studied to understand the complex relationships between the forward feeding parts and heavy lodged green cane (Davis & Norris

2002). They were normally operated close to ground level to prevent cane loss under the shoes of the gathering system. Downs (1991) indicated that spring-loaded crop lifters (crop divider lift arms) were designed to pick-up the cane without disturbance of the soil. Another approach was to use height control wheels fitted behind crop dividers to reduce ploughing and bulldozing (Lawrence & Bigg 1996). To reduce contact with the soil, the shoes on new machines (such as the CASE IH 8000 and John Deere 3520) have been made smaller to reduce soil disturbance.

Power knockdown and finned rollers (Figure 2.2) fitted in front of base cutter systems interact with the spiral rollers of gathering crop systems and push down the erect cane. Stalks can however be broken and stools removed from below ground by the pushing down action of the knockdown with extreme angle adjustment, particularly in erect cane. One approach to remedy this is to reduce the excessive knockdown angle, therefore reducing the potential for stalk and stool damage during the gathering and feeding processes while maintaining aggressive feeding of the cane (Norris et al. 1998; Davis & Norris 2002). Some reports (Downs 1991; Kroes & Harris 1996) indicated the knockdown rollers should be repositioned to reduce disturbance of stool and dirt during harvesting. Knockdown systems are important to move sugarcane into the feed train system particularly in high yielding crops (> 120 t/ha) or in badly sprawled or tangled crops when the harvesting direction is against the lie of the cane (Downs 1991).

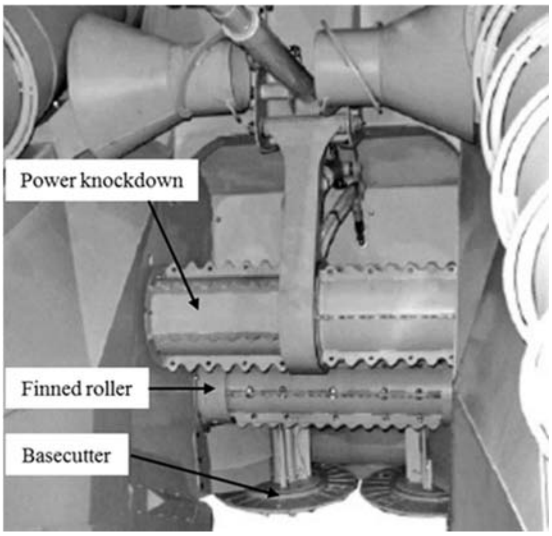


Figure 2.2 Front roller system of the sugarcane harvester (JohnDeere 2006)

Base cutter performance has an important role in reducing soil and dirt levels mixed with cane billets. The base cutters directly affect cane pick up losses and stubble damage. Basecutter angle, the speed of rotation, blade numbers with thickness and positioning (above or below ground level), all impact soil contamination (Ridge 1994a; Benson 1997, 1998; Harris 2002; Hurney et al. 2005). Benson (1997) indicated that a base cutter angle of 18° minimised soil intake, 15° picked up more soil, and 11° resulted in higher soil intake and stool damage because of the increased cutting depth. A 50% reduction in soil levels was attributed to changing the cutting angle from 11° to 18° on 20 cm hill. A base cutter rotational speed of 500–600 r/min and a forward speed of approximately 5.5 km/h was shown to help reduce stool damage. At high ground speeds, the base cutter blades were found to cut the cane stalk rather than them being damaged or broken off by the base cutter disc (Benson 1997; Kroes 1997). The configuration of the disc (Downs 1991), the blade thickness and the number of blades (Kroes 1997) all cause the cane loss and the dirt adhering to the product stream during cutting.

Pour rate is measured in tonnes per hour and is impacted by the forwarding speed and crop condition. Pour rates increased to above 100 t/h can cause the cane quality problems resulting from feeding and cleaning difficulties (Agnew & Sandell 2000). Increased pour rates result in high soil entrapment in the cane supply due to the basecutter and feed train rollers. Additionally, excessive forward ground speeds can lead to significant stool damage, poor ratoon and subsequent yield reductions in later years. The higher forward speed, resulting in increased pour rates, has also been found to result in fewer ratoon shoots (Agnew & Sandell 2000). However, many conditions impact ratooning such as size and health of the previous crop, soil type, presense of disease and weather conditions (refer to Section 2.4.1).

The feed train roller system is responsible for taking cane stalk from the base cutter and moving it to the chopper system and helps reduce the dirt in cane. The feed train consists of five rollers on the top and six on the bottom. The butt lifter rotates at 70–90 r/min and the feed rollers 125–145 r/min in the front to 160–180 r/min at the back adjacent to the chopper (Ridge & Norris 2000). The butt lifter normally rotates slower than the other rollers to encourage dirt rejection close to the ground. The different speeds of feed rollers can remove the trash adhering to the stalks transferred from the base cutter to the chopper system.

2.4.4 Different billet length impacts

Billet length is determined by the relationship of the tip speed between the chopper and feed train roller systems. The billet sizing has an impact on the cane loss and deterioration, cane cleaning and the weight in haul-out during transports to the mills all of which are explained below.

Chopper systems come in two configurations: swinging knife and rotary chopper. The swinging knife is better suited to cut on stony soils (Ridge & Norris 2000). On the other hand, the rotary chopper is more effective in cutting and cleaning green crops than the swinging knife. The rotary chopper has three configurations: over centre chop (300 mm diameter drum), offset (375 mm diameter drum) and differential drum with a large diameter over a small diameter. The blades of the offset chopper cut just before the centre line of the drums. The benefit of this system gives less compression of cane during cutting that helps reduce juice loss (Ridge & Norris 2000). In 1997, harvesters started to use wider blades (95 mm) than originally used (65 mm) to minimise the compression of cane at high feed rate. The sharp blade and blade gap setting improve cane cutting and reduce juice loss (Agnew et al. 2002). To reduce billet length, the speed of feed train rollers and chopper, numbers of blades on the chopper drum, can all be modified. If the feed train roller speeds were reduced to slowly feed the stalks into the chopper system, short billets would be cut. The chopper systems have 2, 3 and 4 blades per drum which can cut various billet sizes during harvesting to improve bin weight and transport (Davis & Norris 2001). Uniform billet length reduces bin weight due to the larger gap between uniform size. The problem of uniform billet lengths was studied by Corradini Engineering in Ingham. They improve chopper drum design to make variable billet lengths to improve the bin weight (average 380 kg/m^3 compared to 372 kg/m^3 in the standard chopper system) and minimise cane and juice loss (Davis 2007; Alcorn 2008). Different billet lengths can be produced by adjusting the relationship between the tip speed of the feed roller and chopper system (Hockings et al. 2000). Roller tip speed of approximately 60–70% of chopper speed, is suitable to produce good quality billets, reduce juice and cane loss during harvesting, with lower power requirement. The optimisation between the feed train rollers and chopper speed is crucial for minimising sugar losses during harvest. Trials conducted with the BSES chopper test rig found juice and cane loss was approximately 3.5% under ideal conditions with sharp blades, whilst blunt chopper blades caused juice losses to more than double (8.7%) (Hockings et al. 2000).

To mitigate this load density problem, there has been a move by the Australian sugar industry towards shorter billets. To make more efficient loading of cane delivery, sugar mills have encouraged higher bin weights via promotion of shorter billet length. However, with shorter billet come an increased juice loss due to the number of cuts (but little fibre loss) and there is an increased loss from biological activity (Agnew et al. 2002). Norris et al. (2000) have established that significant sucrose losses occur as part of the billeting process. The billet sizing has a significant effect on the volume of EM, cane loss and bulk density in the bin. To achive high density and good quality, short billets are usually cut in green cane or under cool or dry conditions. In contrast, with burnt cane or in hot and humid conditions, short billets should be avoided due to the risk of deterioration of chopped cane due to microbial attack (Ridge & Norris 2000). The time taken to deliver and crush causes deterioration of sugarcane billets under normal temperature conditions (Kulkarni & Warne 2004). Billet sizing and timing delay are important to growers and millers. The optimising billet sizing can improve cane loss during the cleaning of the harvester. Additionally, the decrease in timing delay can improve the good billet quality due to the reduction of microbial problems.

Other factors that relate to cane loss and EM in cane billets are chopper drum angle or blade overlap, with the chopper box angle throwing billets into extractor chamber which impact on cane loss and cleaning efficiency (Ridge & Linedale 1993). Cane loss and EM are driven by the relationship between billet length and extractor speed.

2.4.5 Losses from the extractor systems

The primary and secondary extractor fan are used to separate the leaf material and small/undersized billet from the product stream. As the fan speed increases, the cleaning ability also increases however there is the rise of ejecting good billets. As mills push to increase the bin weight, and with leaf material being much less dense than billets material, the drive is towards higher and higher fan speeds. The ability of the fans to clean is compounded by the pour rate of the material and the dwell time in the cleaning chamber. These issues will be discussed in subsequent sections.

The principal sugarcane loss is linked to the speed of the extractor with higher fan speeds resulting in greater losses. Increases in fan speed can produce high-density bin weights due to a reduction in EM entrapped with billets. Researchers (Sandell & Agnew 2002; Whiteing & Norris 2002; Sichter et al. 2005; Whiteing 2013) have sought to establish the effect of a low loss harvesting method on the delivery of potentially recoverable sugar from the field. The reports have established that significant sugarcane loss occurs as a result of the primary and secondary extractors. A survey of commercial harvesters confirmed that cane loss from the extractors could be extremely high in green cane. Other factors that have a lesser role in extractor loss include cane varieties, crop sizing, effective topping and ground speed of harvesting (Ridge & Linedale 1993).

Many researchers have focused on the study of the extractors to reduce cane loss and trash in billets, with the following concepts being tested: a paddle roller in the chamber (Burgess 1993; Ridge & Linedale 1993; Whiteing & Norris 2002), deflector and extractor blade tip clearance, type, hub as well as height (Ridge & Linedale 1993), chamber sizing (Ridge & Norris 2000), extractor hood (Lloyd 1996) and extractor speed including an electronic control system (Dick 1991; Dick & Hilton 1992; Pearce & Ridge 1992). Details are explained below;

i. The trajectory of cane from the chopper is controlled by a deflector plate fitted behind the chopper system to improve the cane loss due to cleaning by the extractor. A roller fitted within the chamber restricts cane loss and increases cane quality by reducing both airflow and scattering of cane within the trash (Burgess 1993; Ridge & Linedale 1993; Whiteing & Norris 2002).
ii. The size of the extraction chamber affects the velocity of the air movement within the space. The intake air flows through the billets that are leaving the chopper system with the lighter trash carried by the airstream, thus dividing the billets and trash during cleaning. Smaller diameter chambers (about 900 mm) require high air speed to separate cane mass while lower airspeed is required for larger diameter (1200–1350 mm) chambers. Average air velocity has been decreased from approximately 20 m/s to 12–14 m/s to improve cleaning (Ridge & Norris 2000).
iii. Lifting the extractor up provides additional height in the chamber and can improve cane cleaning through a combination of reduced cane loss and good

cleaning efficiency. Extractor blade configuration (material type and shape) can significantly influence cane loss during harvest. In high loss varieties and crops, shortening the blades of the extractor can reduce cane loss. The extractor speed can be reduced to prevent cane loss and improve blades wear rates (Ridge & Linedale 1993). Different blade numbers and configurations have also been studied, with a counter rotating fan developed by BSES (Sandell & Agnew 2002).

iv. To improve airflow in the primary extractor hood, BSES designed a new plastic hood with a larger diameter outlet and smoother shape. It improved the aerodynamic flow through and out of the extractor, thereby improving cleaning and reducing cane loss (Lloyd 1996). The anitvortex fan developed by the National Centre for Engineering in Agriculture (NCEA) at University of Southern Queensland (USQ) improved the aerodynamic of the system for cleaning cane and reducing loss. The fan cone is a plastic hemispherical cone fitted to the underside of the extractor hub.

v. Electronic systems have been developed for use in the primary extractor system to assist and measure cane loss during harvest. Agridry Rimik Pty Ltd. developed an instrument system using acoustic techniques to measure noise from cane billets hitting the primary extractor hood. The sensor fitted to the outside of the primary extractor shroud recorded impacts of billets on the sheet metal of the extractor hood (Dick & Hilton 1992; Pearce 1992). An improved and modified sensor was developed for plastic hoods where the sensor was fitted to the primary extractor hub (McCarthy et al. 2002; Whiteing 2004).

2.5 Relationship between EM and sugarcane loss

Both growers and millers recognise that the need to improve cane quality with mechanical harvesting. They are also aware of problems associated with the amount of EM in cane supply and cane loss during harvesting. High EM in harvested cane lowers the CCS directly and is reflected in lower income for the growers. Millers on the other hand are confronted with the problems associated with sugar processing. These include extraction rates, juice quality and sugar recovery and increased maintenance cost. Maximising billet quality and minimising trash and dirt in the cane supply all received attention in the rigorous machine development program mentioned above. The relationships between the amount of EM and sugarcane loss in harvesters is dependent on three main factors; field conditions, harvester pour rate and extractor speed (as discussed in Section 2.4.5).

The relationship between EM and cane loss is also dependent on the choice of cultivar and crop conditions. Cane loss is strongly correlated with stalk thickness and initial EM levels. The highest losses during harvesting usually occur with trashy, thin-stalked cultivars (Ridge & Dick 1988). With specific cultivars, losses are higher in smaller crops with thinner stalks and higher initial EM levels as is usually the case with older ratoons or if there is side shooting. Cane losses through the extractors were found to be closely related to initial EM levels, diameter and density of stalks (Ridge & Dick 1988). Harvesting in wet condition has a marked impact on cane quality. Harvesting at night or early in the morning affects cane quality due to the effect of dew on trash and dirt removal by the cleaning system. Cane losses were higher in untopped cane than topped cane (compared with the lodge and erect cane) (refer to Section 2.4.1), and more apparent in green cane harvesting than with burnt cane (Ridge & Dick 1987; Ridge & Norris 2000; Whiteing & Norris 2002).

The rise in EM associated with higher pour rates (refer to Section 2.4.3), particularly under difficult feed conditions, affects sugar quality. The EM levels were found to be affected by operational speeds, with excessive ground speed resulting in highly significant soil levels (Linedale 1997). Higher ground speeds affect the efficiency of harvesters to process the increased amount of material and impact on the ability of the extractor to separate trash, dirt and billets (Whiteing & Norris 2002; Viator et al. 2007).

Several studies have indicated that increasing the speed of the extractor results in a decreased EM in the cane, but with increased cane loss (refer to Section 2.4.5).

2.6 Harvesting best practice

As mentioned previously, field and harvesting conditions affect cane supply and the quality and quantity of raw sugar. It therefore also has the potential to improve the profitability and sustainability of the whole industry via harvesting best practice (HBP). The harvesting best practice is aimed at increasing harvested yields by reducing losses, increasing commercial cane sugar (CCS) and improving ratooning ability (Agnew et al. 2002). The low cutting pour rate and extractor fan speed balanced against time taken to harvest can produce income via reducing EM in cane supply and cane loss (Agnew & Sandell 2000).

Row spacing and soil profiles are considered to reduce the amount of soil and dirt in cane supply during cutting with the base cutter via HBP campaigns (as discussed in Section 2.4.1). Controlled traffic farming systems utilising a wider row spacing which matched the harvester and haulout equipment reduced soil compaction and cane loss (Garside et al. 2005; Salter et al. 2008). Optimising farm layout increases the efficiency of harvest time and decreases the cutting cost (Jones 2004).

The adjustment of various harvester components can reduce cane loss and EM during cutting. The optimising setting can improve EM and cane loss levels in cane supply.

2.7 Whole crop harvesting of sugarcane

To overcome the problems of sugar loss and to make better use of biomass from an energy perspective, some countries, such as Australia and Brazil, have begun or considered “whole crop” harvesting (Schmidt et al. 2012).

When this was considered in Australia, the whole crop (billets and trash) was loaded into haul-outs from the chopper harvester and transferred to the receival point for long distance transportation. At this receival point, sugarcane was then transferred to either a railway or road system or combination for transport to the mill (Schmidt et al. 2012). Due to the low bulk density, transportation of whole crops is constrained because of cane bin sizes and legislative requirements from the State Road Traffic Authority that controls traffic from farms to the mill.

2.7.1 Whole crop transportation

The critical point of the system is the low bulk density of the whole crop. Economists working for New South Wales Sugar Milling Co-Operative Ltd (trading as Sunshine Sugar) found that the most economic bulk haulage tonnage was 23.5 net tonnes cane per trip. The company therefore constructed new, lightweight aluminium multi-lift bins with a capacity of 90 m^3 (based on a bulk density of 250 kg/m^3 for a typical whole crop) wtih maximum dimensions allowed on New South Wales (NSW) roads to assist in achieving the designed weight (Doolan & Lamb 2009; Inderbitzin & Beattie 2012). This study used information from South Africa which indicated that whole crops can be economically harvested within a radius of 20 km of the mill (Meyer et al. 2011). To achieve the desired bulk density of 250 kg/m^3, harvester groups and researchers trialed numerous modifications to the cane bins and the mechanical harvesters. These included: compacted whole crop in bin (Lower Empire Vale Harvesting Co-Operative 2012), single drum chopper harvester (Barnes 2008; Barnes et al. 2009), 'Corradini' modified rotary-pinch chopper harvester (Smitch 2007), prototype hood and shredder fan (Inderbitzin & Beattie 2012) and a shredder fan with rigid chute alongside elevator (Spinaze et al. 2002). However, all methods were unsucessful.

An alternative approach to solving the density problem is the possible use of field edge trash separation (NorrisECT 2012, 2013). This technology was developed to separate the whole crop (billets and trash) on the edge of the field to increase the bulk density before the cane billets are transferred to the mill.

2.7.2 Loss from whole crop harvesting

The various components of the whole crop delivered to the mill impact on the sugar recovery process directly. The increased loading of soluble impurities and other extraneous matter (Fernandes et al. 1977) affects mill operations in two ways - directly due to reduced sugar recovery, and indirectly due to increased repair costs, the additional quantities of molasses and filter cake, and equipment attrition. Kent (2011) explained that whole crop harvesting increases cane fibre content by 5.6 units (15.8–21.4%). In addition to the reduction in pol recovery, sugar quality was reduced with filterability and colour being both negatively affected. Increased fibre levels associated with high leaf content in delivered cane is known to decrease the milling rate, juice purity and sugar production (Kent et al. 2010; Kent 2011). The weight of fibre milled for every tonne of recoverable CCS was therefore indicative of reduced cane quality and milling efficiency.

Reducing the amount of fibre milled to recovered sucrose has multiple positive aspects of mill performance including; reduced milling power demand per tonne of recovered sucrose, increased milling capacity as a result of a reduced fibre delivery rate, and reduced losses to molasses, bagasse and mud.

Whole crop harvesting is expensive due to using a lot of bin number request and light bulk density in bin. To solve the density of billet supply with trash in the bin, the researches are still ongoing.

2.8 Sugarcane cleaning plant

The cane cleaning systems are designed to remove EM from the cane supply before delivery for mill processing. The plant can be set up at many sites such as harvesting on the field and transferring stations or at the mill to reduce cane loss (Clayton & Whittemore 1971). Cargnello and Fuelling (1998) indicated that increasing the quantities of trash and soil by about 10% in cane can cause many problems in the efficiency of mill throughput, increasing processing costs and placing sugar quality at risk. Cleaning plants can therefore improve the cane supply operation prior to delivery to the mill. Mill capacity will also be improved by removal of trash and dirt from the cane supply. Although cleaning plants have two modes of action: dry cleaning and wet cleaning (Wienese & Reid 1997), some systems utilise both methods due to climate conditions and harvesting activities.

2.8.1 Dry cane cleaning systems

The dry cleaning system has been tested in many configurations. The type of cleaning system depends on the kinds of trash, the quality of cleaning requirement, and the size of the plant set up at the field or mill (Clayton & Whittemore 1971). The positive advantages of this system are: saving cost for maintenance by reducing wear; and improving mill capacity and quality of sugar processing which includes reducing sugar loss in by-product. Moreover, the large quantities of trash separated from the dry cleaning plant can be supplied as biomass to the mill or other industrial operations. The drawbacks of dry cleaning are; added equipment, capital expenditure and sugar recovery potential that is likely to be wasted (Bernhardt 1994).

Clayton and Whittemore (1971) investigated several methods of the dry cane cleaning using different types of equipment which included air blast, a notched-tooth separator, cleaning rollers beneath the conveyor, husking roll cleaners, hexagonal roll cleaners and blowers. Testing undertaken in Hawaii, USA, indicated that the use of cleaning rollers were the most efficient mechanism for cleaning tightly held high density of trash. Loose material and unburnt cane were removed easily using an air blast system during the trash separation. Although leaf trash could be removed directly by a blast of air through the cane 'mat', the immature cane could not be separated from the mature cane in this case (Cochran and Clayton (1968). Bernhardt (1994) classified dry cane cleaning according to the materials that needed separation from the cane i.e.

organic or inorganic. About 70–80% of loose trash in cane billets can be removed by the pneumatic cleaning system. The efficiency was depended however on the quantity and velocity of the air used. Unfortunately, the top which has most of their leaves cannot be separated by this system (Joyce & Edwards 1994; NorrisECT 2013). However, when the stalks were chopped into short lengths, the amount of trash detached by the air blast increased substantially. A combination of cane cleaning systems was required when cane billets contained EM such as soil and rocks. Also, the amount of leaf trash can vary significantly depending on cane varieties or cultivation factors such as weather, soil, irrigation or rainfall.

Simulation models of the pneumatic cane cleaning process to improve cane cleaning and loss have been investigated by the Sugar Research Institute (SRI). Joyce and Edwards (1994) studied the simulation of billet cleaning in a vertical wind tunnel by varying air velocity, feed velocity and injection angle on the size and power requirements of a pneumatic cleaning system. It was found that separation efficiency is related to the difference between the aerodynamic properties of the billet and leaf particles. In these simulations, the air velocity in the extraction chamber was varied between 4–24 m/s. Hobson (1995) also undertook simulation studies using a wind tunnel to investigate ways of improving cleaning efficiency. He used billet lengths of 60, 125 and 250 mm, with trash contents between 3.5 and 8.5% in cane billet mass. The material was fed into the wind tunnel at pour rate of 76 t/h at an air speed 17.3 m/s. The lower air velocities caused a small decrease in cleaning efficiency at shortened billet length, with the shorter billets improving the trash separation.

The simulated performance of a horizontal air flow cleaning system was subsequently designed and tested for cleaning cane, with the purpose of reducing cane loss. This system has the potential advantages of producing more uniform aerodynamic flow through the cane billets and reducing the problem of fan wear. A model was applied to determine the size of a cleaning system for the mill (Hobson 1997; Hobson et al. 1999; Schembri & Hobson 2000). This technology was developed for large-scale removal of trash on an industrial scale at Sunshine Sugar's Condong Mill, which could operate at a throughput of 200 t/h. The performance testing program indicated that the plant was able to achieve high levels of trash separation at cane loss less than 1% in the separated trash stream and trash content less than 1% in the cleaned billet stream (Schembri et al. 2002).

The dry cane cleaning plant was improved to increase the cane quality before crushing. Martin (2012) indicated that improved trash separation using a cleaning plant and low extractor speed on the harvester resulted in significantly enhanced sugar recovery through reduced harvesting cane losses and increased milling sugar recovery. Moreover, to reduce the problems of cane loading and transport, due to increasing trash in billets (low-density transport) from whole crop harvesting or from reducing fan speed, NorrisECT (2013) developed the edge of field mobile trash separation units.

2.8.2 Wet cane cleaning systems

Wet cleaning systems are commonly operated at mills to clean the delivered cane. Washing of whole stick harvested cane to remove soil, is mostly done in sink-float baths or by water sprayed directly onto cane. This method is unsuitable for chopped cane because of the potential for sugar loss, which has been estimated at 1.35–1.8 kg of sugar per tonne of cane billets. Sugarcane harvested in certain situations in the wet season is likely to increase trash and dirt mixed with cane billets. On average, a tonne of cane delivered to the mills contains 13% trash, but in wet conditions, this could increase to over 40% (Edwards Engineering Corporation 2014). Crop factors also have a marked effect on dirt levels in lodged cane. Burnt cane (topped and lodged stools) has higher dirt levels than for lodging alone (Hurney et al. 1984). In the United States of America (USA), Birkett and Stein (2000) investigated the washing samples of both whole stalk and billet cane. Sugar losses varying from 0.64 to 6.53 kg/t of cane and averaged 2.86 kg/t cane. The efficiency of washing varied between 0.48 and 96% (average 51.5%). An average 7.5% of cleaning water adhered to cane entering the mills. However, the water used to clean the cane supply in the washing system causes water pollutions and is difficult to treat when using a lot of water.

2.9 Important sugar quality parameters

In the Australia sugar industry, sugar content is the major parameter used to determine the payment to sugarcane growers. Sugar content is measured as commercial cane sugar (CCS) which is derived from brix, pol and fibre content in the cane delivered to the mill (BSES 2001).

2.9.1 Brix

Brix, is the amount of sucrose and soluble impurities in a solution and can be expressed as a percentage or as gram solute per 100 g solution (BSES 2001). Brix can be measured by analysing the density or refractive index (% soluble solids in sugarcane juice). If the solution contains dissolved solids other than pure sucrose, then brix only approximates the dissolved solid content.

2.9.2 Pol

Pol, a measure of the amount of sucrose in a sugar product, is defined as the concentration (in grams of solute per 100 g of solution) of a solution of pure sucrose in water, having the same optical rotation as the sample at the same temperature (Tewari & Irudayaraj 2003). More precisely, it is the value measured by direct polarization of the normal weight of a sugar product made up to a total volume of 100 ml at 20 °C clarified when necessary and read in a 200 mm long tube at 20 °C in a saccharimeter (BSES 2001).

2.9.3 Fibre

Fibre is components of dry, insoluble matter in the sugarcane (Prince 1969; BSES 2001). The percentage of fibre is directly calculated by macerating the fibrous cells and washing to remove juice. The sample is then dried and weighed to calculate the fibre volume (Watson et al. 1999). The standard industry practice to measure the sugarcane fibre is performed using either whole stalk or billet subsample methods (BSES 2001).

2.10 Techniques for sugar quality determination

The ability to measure sugar content in sugarcane is very important, particularly for assessing crop growth and development, assessing applications of precision agriculture, refining harvesting management and calculating payment options for growers. Many techniques can be used to determine sugar content in cane, such as refractometry, polarimetry and chromatography. Each method is dependent different apparatus, processes and timing, with a range of consumable and labour costs to analyse the sugar content. Additionally, some techniques are suitable for use in the laboratory verses field and some methods are inaccurate when measuring low sugar concentrations. All techniques detailed in the literature are discussed below.

2.10.1 Refractometer

As mentioned earlier, brix from sugarcane juice can be determined by using a refraction index of the juice which is related to the composition of the material in the samples. A refractometer is a laboratory or field device for measuring refractive index (refractometry). Instruments used to measure brix value are a brix spindle, brix hydrometer, density meter or refractometer. These instruments have been used for the determination of brix in juice and syrups. Automatic refractometers measure the refractive index of the sample (BSES 2001). The automatic detection of the refractive index of the sample is based on the determination of the critical angle of total reflection. However, this method requires preparation time (5–20 min) before juice samples can be measured (Mehrotra & Siesler 2003).

2.10.2 Polarimeter

A polarimeter is an optical device applied to determine sucrose content (pol value) in clear sugarcane juice. This apparatus requires clarified juice for analysis. Clarified juice samples are obtained when the raw juice is treated with lead acetate and then filtered to remove impurities (Mehrotra & Siesler 2003). The robustness of this method can be affected by the soil or other contaminants. There are, however, some health risks to those undertaking the testing and the environment impact due to the lead component. Octapol (a lead-free chemical reagent) can be used as an alternative for clarifying the juice prior to polarimetric analysis (Chullén 2014) but is more costly than the lead acetate. Juice sample preparation for testing with the polarimeter can be a time-consuming task because this process involves chemical reagents making it mostly suitable for use in the laboratory.

2.10.3 Chromatography

Chromatography is a laboratory method for separation of solutes in a mixture. Several chromatography techniques have been used to measure sugar content in solutions. In particular, sugar content can be measured using techniques such as high-performance liquid chromatography (HPLC), gas chromatography (GC) and high-performance ion chromatography (HPIC) (ICUMSA 2013). These techniques are affected by the presence of interfering compounds, requiring laborious sample preparation before analysis (Lima Filho et al. 1996). These procedures also require highly skilled analysts, expensive equipment and consumables. The process is often time-consuming, operator-dependent, and involve the use of hazardous chemicals which can only be properly applied in a laboratory (Mehrotra & Siesler 2003).

2.10.4 Biosensor

Biosensors are analytical devices used for the detection of an analysis. They are reliable instrument for sucrose analysis and are relatively convenient, fast and inexpensive. Some biosensors have been developed to determine sucrose in the sugarcane industry (Gouda et al. 2002). However, results are not as accurate as those obtained from other techniques such as HPLC when they are used to detect low sugar contents. The operation of these devices also requires a high skill level because reagents need to be added before measurement.

2.10.5 Near infrared spectroscopy (NIRS)

Near infrared spectroscopy techniques are used to detect components of materials by determining the reflectance of electromagnetic radiation in the near-infrared range of the spectrum. Spectroscopy is an established technique for determining chemical components in many agricultural products (Gómez et al. 2006) by using nondestructive quality evaluation methods. The NIRS technique has lower analytical labour and consumables costs, and an increased throughout (O'Shea et al. 2011).

This technique has been successfully used for both qualitative and quantitative measurement in the sugar industry for cane payment applications (Schäffler et al. 2003). It is capable of determining brix, pol and fibre in delivered cane. This technique is also inaccurate when determining low sugar concentrations (Whiteing 2013).

2.10.6 Colorimetric assay

Colorimetric methods have been used to measure and interpret different light absorbance coefficients of the specific sugars in plant tissue (Buysse & Merckx 1993). When specific enzymes are applied by catalysing reactions with specific sugars, the chemical assay offers greater levels of sensitivity than HPLC (Campbell et al. 1999). To detect the amount of sucrose present in samples of the plant tissue, the glucose concentration is measured before and after sucrose hydrolysis by invertase, an enzyme. The sucrose content is evaluated by looking at the difference between the glucose concentrations in the samples (Velterop & Vos 2001). The enzymatic analysis can identify sugar in plant tissue by providing an easy and economical way, when compared with HPLC, a more complex expensive technique (Campbell et al. 1999).

2.11 Cane payment system

The cane payment system in Australia is based on sugarcane quality and quantity parameters, which is an agreement between the growers and the millers and forms the basis of a contract. Sugarcane yield and quality are the major economic drivers of the sugar industry. The sugarcane yield is calculated from the weight of sugarcane stalks (on a fresh weight basis) delivered to the mill (Lawes & Lawn 2005). Commercial cane sugar is the sugar content in the cane delivered to the mill and contains the impurity effects (non-sucrose matter dissolved in sugarcane juice causing sugar loss during the refining process present as molasses) (BSES 2001). CCS is expressed as a percentage of sugarcane weight and is derived from the measurement of brix and pol in sugarcane juice, including fibre content. The standard procedure for calculating CCS as given by BSES (2001) is as follows:

$$Brix\ in\ cane = Brix\ in\ juice \times \frac{100-(Fibre\ \%\ cane + 3^{*})}{100} \qquad \text{Equation 2.1}$$

$$Pol\ in\ cane = Pol\ in\ juice \times \frac{100-(Fibre\ \%\ cane + 5^{*})}{100} \qquad \text{Equation 2.2}$$

$$CCS = Pol\ in\ cane - 0.5 \times (Brix\ in\ cane - Pol\ in\ cane) \qquad \text{Equation 2.3}$$

Where the constants indicated by the * are correction factors used to correct the brix and pol measurements in first expressed juice to more accurately represent those of the total juice in sugarcane.

2.12 Conclusions from the literature review

Several reviews of sugarcane harvesting systems have identified many issues relating to quality and quantity. This particular review has found that sugarcane cleaning and loss from the chopper harvester and activities in the field such as the crop and field conditions directly affect the Australian sugar industry. To account for cane loss during cutting, many techniques have been developed to assess harvesting efficiency. The reviewed reports on the cane cleaning plant enhanced the cane quality and increased the cane supply weight due to the effect of low fan speed in the harvester by separating the trash before loading on transport systems. Therefore, the following chapters will further investigate harvesting under the influence of the crop conditions, to evaluate cane loss and cane cleaning, for sharing revenue in the sugar industry. The cane economics will improve cane quality, and the optimisation will promote cleaning before being removed from the fields. The growers, millers and contractors will use this information and make a more equitable sharing of expenses and profits between them.

Chapter 3 Sugarcane harvesting impacted by crop condition

3.1 Introduction

This chapter focuses on the effect of fertiliser application rate on crop production and cane size, and how cane size affects the cutting action of a chopper harvester. The size of the crop influences machine performance, in particular cutting pour rates. This research details the physical properties of sugarcane due to different nitrogen (N) rates applied at the start of the crop and the impact of the cutting by the machine. The consequences of sugarcane harvesting pour rate (driven by the nutrient rates) and its impacts on harvested products are presented in this chapter. The chapter consists of the following:

- Background and literature review
- Materials and methods
- Results and discussion
- Summary and conclusion of the chapter

3.2 Background and literature review

3.2.1 The influence of N rates on sugarcane production

Fertiliser management practices are important for profitable and sustainable sugarcane production. The three main fertilisers [nitrogen (N), phosphorus (P) and potassium (K)] are important to enhance sugarcane growth. Nitrogen has a role in increasing crop production (Franco et al. 2015). Wiedenfeld (1997) indicated that increasing N rate improved growth rates due to increased stalk population, leaf area index (LAI), and resulted in increased yield and sugar production. In addition, sugarcane yield is increased by the important interaction of soil health and farm management practices such as row spacing, seed cane planting and N applications. Soil health improvement can be attributed to crop rotations (Bell & Garside 2005). Increased sucrose content and crop yield occur with increased N application rates and irrigation supply (Wiedenfeld 1995). Balanced crop production and optimised farmer profitability are possible with efficient fertiliser rates and good agronomic practices aimed at improving soil health (Nurthidayati & Basit 2015). Sugarcane root growth can be associated with the increasing N accumulation in ground residues. Nitrogen from fertiliser sources and above-ground biomass contributes to increased mineralisation of trash that, in turn, can be recovered in subsequent ratoons (Fortes et al. 2013).

The presence of excessive N can cause decreases in juice quality and sucrose content of sugarcane. This effect, however, is small compared to the increase in sugarcane growth and yield due to the application of N. Sugar yields improve as the rate of N application increases (Muchow et al. 1996; Wiedenfeld 1997). A negative impact on sugar content was observed when N application rates were high e.g. > 200 kg/ha (Wiedenfeld 1995). High N application rates can also have negative impacts on the environment, especially during extreme rainfall conditions when N is lost be run-off or leached from the soil and into the ground water. Thus, N application rates and soil health improvement are important factors in maintaining adequate crop nutrition for optimum growth when climatic conditions are favourable (Fortes et al. 2013).

3.2.2 Field and crop conditions impact on sugarcane cleaning and loss

Wet weather and conditions that favour lodging of the crop cause increases in the amount of soil entrapped with the cane to be harvested (Henkel et al. 1979; De Beer & Purchase 1999). When soil moisture content is high, soil, especially clay, can easily adhere to cane stalks and harvester parts. In Argentina, various weather factors in different seasons caused an effect on the quantity and quality of the cane supply, with varying amounts of EM. Cane harvesting during dry condition is more effective than during wet weather (De Beer & Purchase 1999) and EM levels are lower in the cane supply under these conditions.

De Beer and Purchase (1999) reported that crop condition (green or burnt, erect or lodged cane) caused the amounts of EM to also vary. Values ranged from 5–15%, with lodged cane being associated with the higher value. Lodged crop conditions also causes slower cutting rates and higher EM levels due to the topping device of harvester being ineffective. Moreover, the emergence of suckers from the lodged sugarcane will result in decreased cane quality (Crook et al. 1999; De Beer & Purchase 1999). With some varieties, deeper planting and more effective hilling-up operations helped reduce lodging (De Beer & Purchase 1999).

Both the soil profile and row spacing influence the amount of soil adhering to harvested cane during base cutter operations. Rounded soil row profiles that are about 10–15 cm high with a flat inter-row spacing, can reduce dirt and cane loss during cutting and pick up (Linedale 1994) (refer to Section 2.5.1). Flat or shallow profiles cause difficulties for base cutter systems (Linedale 1994; Patane 2014) and increased stool damage. Soil in cane supply can be reduced by setting the base cutter angle to match the low profile (Ridge & Linedale 1997). Narrow row spacings cause additional soil intake due to the off-centre cutting of base cutter in the cane row. Additionally, a row spacing that does not correspond to the wheelbase of the harvester (both tyres and tracks) causes cane loss, an increase in the amount of soil in the cane supply and decreased harvesting efficiency. Average row spacing of 1.5 m or greater is preferred (Linedale 1994; Ridge & Linedale 1997) to reduce the breakage of stalks caused by the wheel rotation (refer to Section 2.5.1). Trials in North Queensland showed that a 1.65 m row spacing can reduce cane loss (Linedale 1994) by minimising wheel traffic close to cane rows. Single and dual rows with a row spacing of 1.83 m are consistent with the wheel-spacing on harvesters and haulout machines. This reduces both the amount of soil in cane and cane loss due to wheel compaction (Ridge & Hurney 1994). With older ratoons, the amount of soil sticking to cane stalks increased because of factors such as decreased hill shape, pest damage and cane germination from the side of the row (De Beer & Purchase 1999).

In large crops, the extractor systems are ineffective in removing EM in the billet supply when excessive forward speed is used to increase pour rates. Agnew and Sandell (2000) reported that cutting at pour rates above 100 t/h causes cane quality problems resultant from feeding and cleaning difficulties. Moreover, the result of increased ground speed in high yielding crops leads to significant stool damage, poor ratoons and subsequent yield reductions, with fewer ratoon shoots (Agnew & Sandell 2000).

3.3 Materials and methods

3.3.1 Field trials

Harvesting of trials in Bundaberg and the Ingham districts in Queensland provided opportunities to investigate the quantity and quality of sugarcane influenced by varying fertiliser rates. The experimental trials were part of a Sugar Research Australia (SRA) funded project 2014/ 045 'Boosting nitrogen use efficiency (NUE) in sugarcane through temporal and spatial management options'. The field trial in Bundaberg was set up in a randomised factorial design with four replicates. It was originally established to investigate the influence of different rates of N and K on sugarcane and sugar yield (Schroeder et al. 2005). In this study, this existing trial was used to investigate the influence of varying rates of N and K on the physical properties of sugarcane and how it impacts on harvest operations. In the Ingham district, the trial was originally laid out in a randomised split-plot design with six replicates to test the impact of the varying N and farm management practices on sugarcane and sugar yield (Schroeder et al. 2005). In this study, the trial was used a resource to determine sugar loss during cutting with a sugarcane harvester. The location of the experimental plots in Bundaberg and Ingham sites are shown in Figure 3.1. Note: the trial site at Childers will be discussed in a later chapter.

Bundaberg: the trial included four rates of N (0, 75, 150 and 225 kg/ha) and four rates of K (0, 60, 120 and 180 kg/ha) applied to sugarcane cultivar KQ228. Each plot was 10 m long and 4 rows wide with a 1 m buffer between plots (Figures 3.2 and 3.3). The inter-row spacing was 1.8 m. Each plot included guard rows. The N plots for harvesting within the loss project were chosen to enable statistical analysis as a randomised complete block experiment. Selection of plots with minimal K application aimed to reduce effects of excessive K on sugar quality. The N application rates visually affected the physical properties of the sugarcane in the trial (Figure 3.4). Crop size and yield were assessed in plots that had received 75, 150 and 225 kg N/ha that were considered to be low, medium and high N rates respectively. The plots indicated by the red squares in Figure 3.2 were used to assess cutting by the chopper harvester. This meant that a minimum of five plots in each treatment were used for collection of data for the sugar loss evaluation.

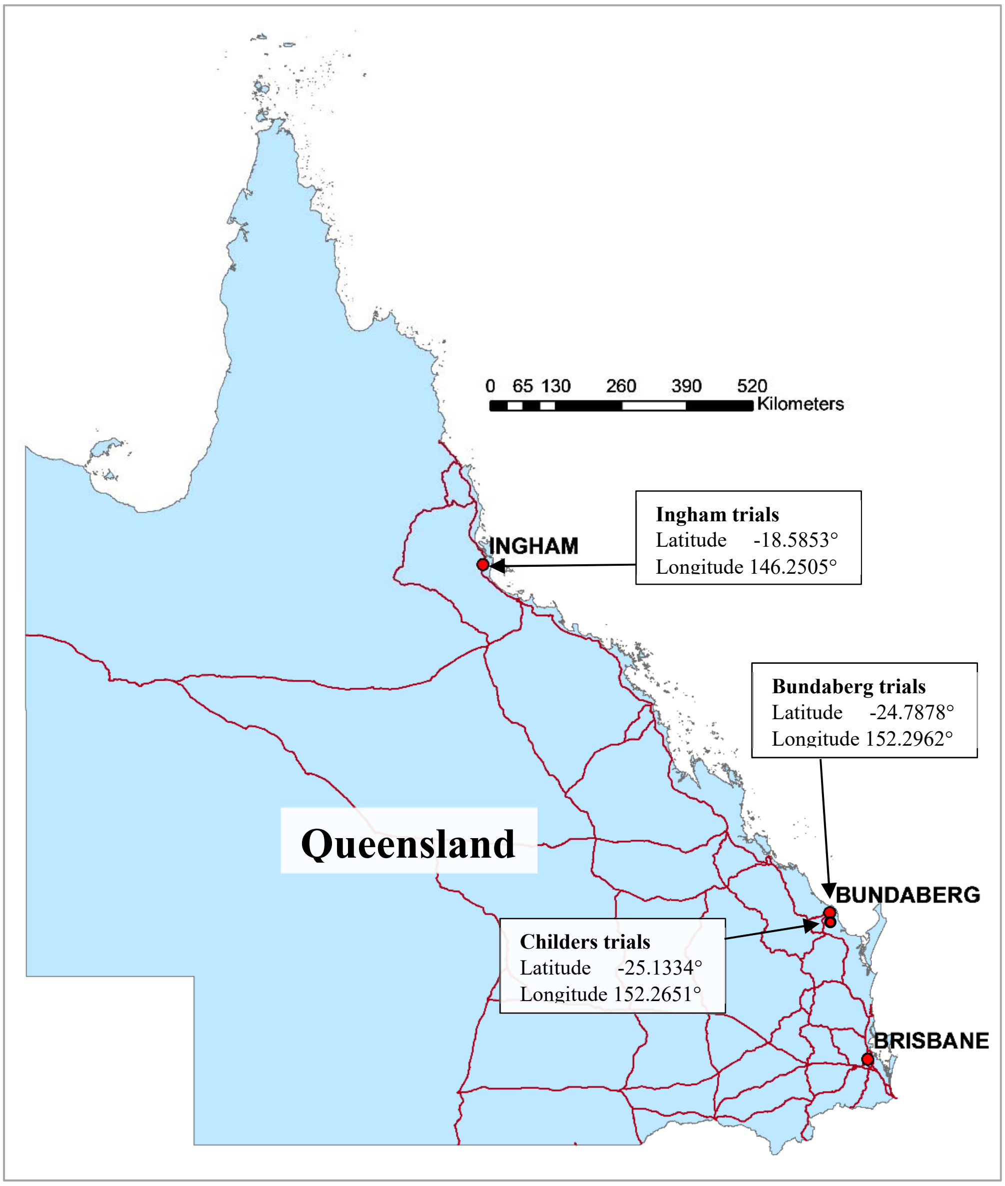
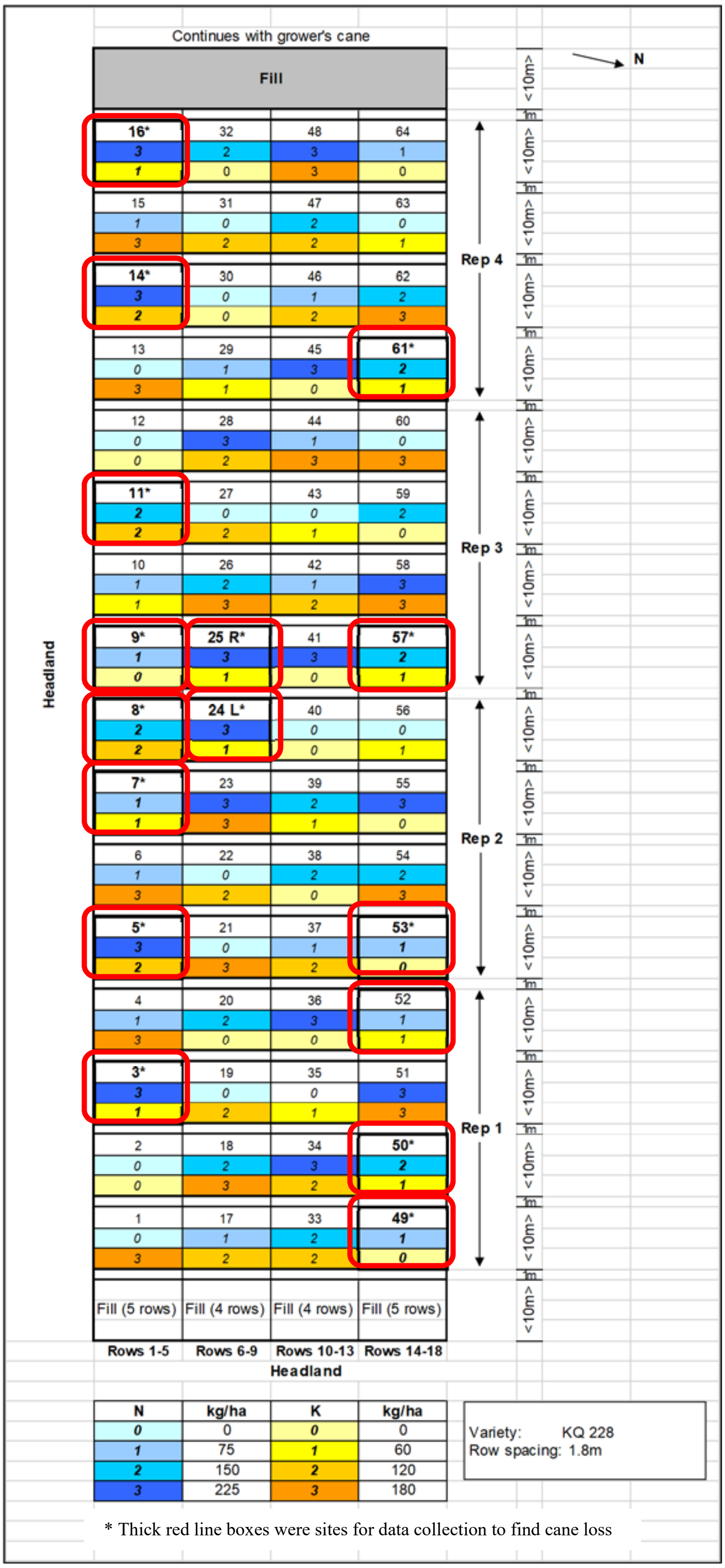


Figure 3.1 Location of the experimental sites in Bundaberg, Childers and Ingham



Continues with grower's cane

Fill

Rows 1-5	Rows 6-9	Rows 10-13	Rows 14-18	
16* 3 1	32 2 0	48 3 3	64 1 0	Rep 4
15 1 3	31 0 2	47 2 2	63 0 1	
14* 3 2	30 0 0	46 1 2	62 2 3	
13 0 3	29 1 1	45 3 0	61* 2 1	
12 0 0	28 3 2	44 1 3	60 0 3	Rep 3
11* 2 2	27 0 2	43 0 1	59 2 0	
10 1 1	26 2 3	42 1 2	58 3 3	
9* 1 0	25 R* 3 1	41 3 0	57* 2 1	
8* 2 2	24 L* 3 1	40 0 0	56 0 1	Rep 2
7* 1 1	23 3 3	39 2 1	55 3 0	
6 1 3	22 0 2	38 2 0	54 2 3	
5* 3 2	21 0 3	37 1 2	53* 1 0	
4 1 3	20 2 0	36 3 0	52 1 1	Rep 1
3* 3 1	19 0 2	35 0 1	51 3 3	
2 0 0	18 2 3	34 3 2	50* 2 1	
1 0 3	17 1 2	33 2 2	49* 1 0	
Fill (5 rows)	Fill (4 rows)	Fill (4 rows)	Fill (5 rows)	

Headland

N	kg/ha	K	kg/ha
0	0	0	0
1	75	1	60
2	150	2	120
3	225	3	180

Variety: KQ 228
Row spacing: 1.8m

* Thick red line boxes were sites for data collection to find cane loss

Figure 3.2 Experimental layout in the Bundaberg trial

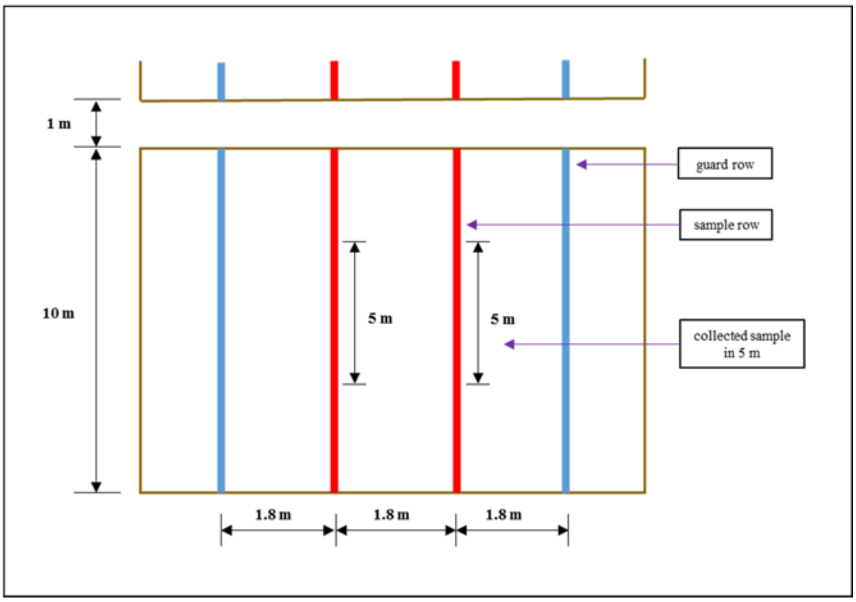


Figure 3.3 Plot layout in the Bundaberg trial

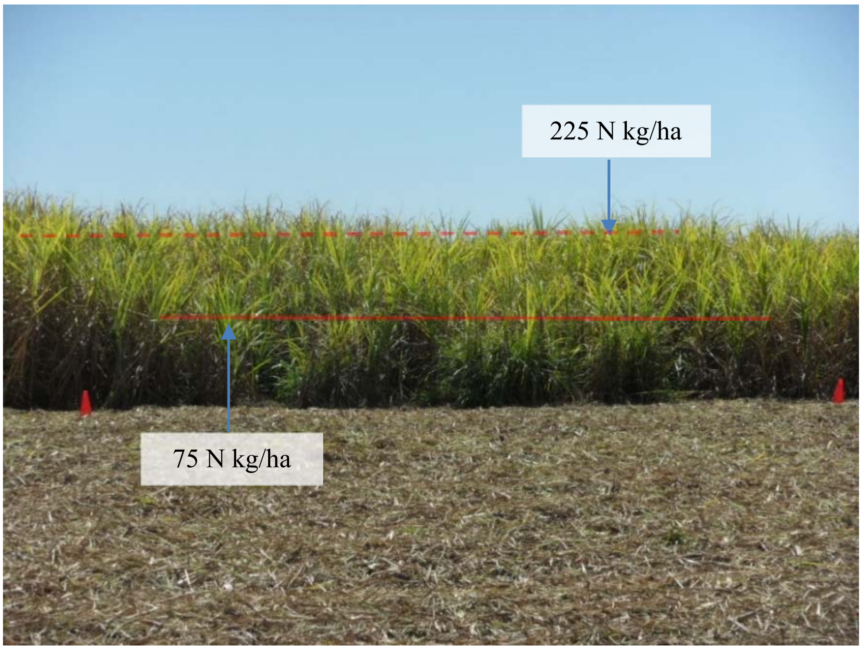
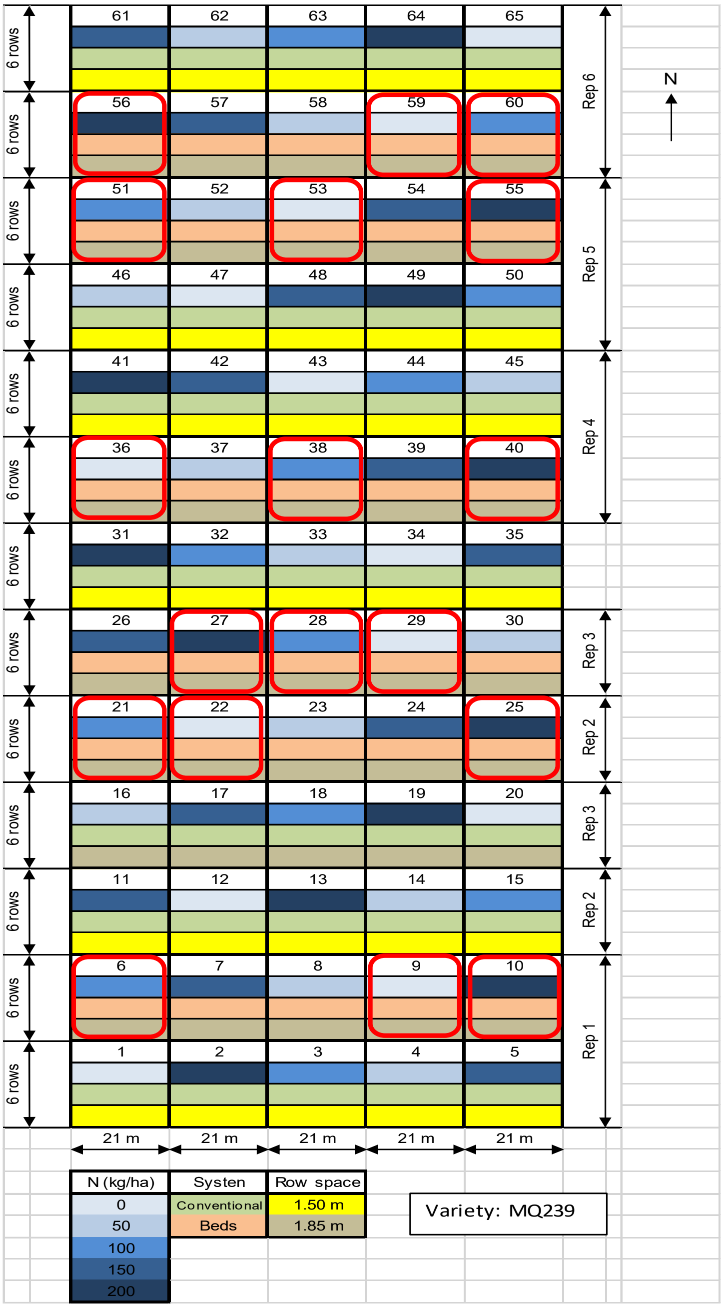


Figure 3.4 Impact of varying N application rates on crop production (Bundaberg trial)

Ingham (Macknade plots): the trial included five rates of N (0, 50, 100, 150 and 200 kg/ha) applied to sugarcane cultivar MQ239. The N rates had an obvious visual effect on the size of the sugarcane within the plots especially when 0, 100 and 200 N kg/ha (low, medium and high N rates respectively) were compared (Figure 3.7). The harvested material from each plot (cut by a chopper harvester) was used to assess the effect of N rate on billet quantity and quality. A minimum of five plots within each N treatment were used for collection of data for the sugar loss assessment.



The trial layout for the NUE trial at Ingham with blocks sampled highlighted in red.

Figure 3.5 Experimental layout in the Ingham trial

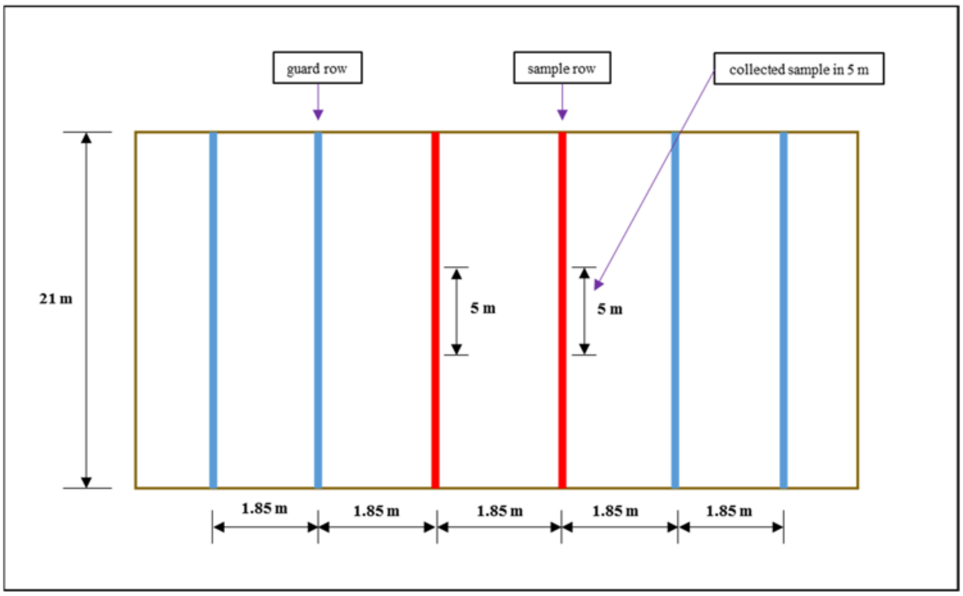


Figure 3.6 Plot layout in the Ingham trial

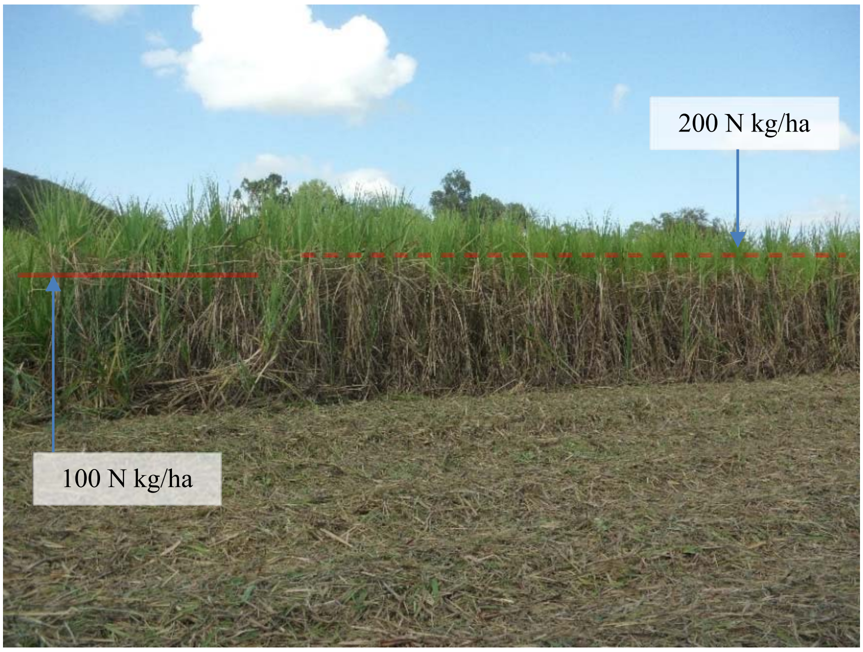


Figure 3.7 Impact of varying N application rates on crop production (Ingham trial)

3.3.2 Sugarcane harvester settings

The influence of varying N application rates on crop condition was investigated within the trial with the chopper harvester set with fixed fan and ground speeds during cutting.

3.3.2.1 Bundaberg trial

An Austoft 7000 (1996) model harvester was used to cut the sugarcane at the experiment site on September 2014. The ground speed was set at 4.5 km/h, the primary extractor fan speed at 1,150 r/min and secondary extractor fan speed at 1,450 r/min respectively. The cane topper was not used during the trial.

3.3.2.2 Ingham trail

A Cameco 2500 (1997) model was used to cut the sugarcane at the experiment site on October 2015. The harvested material was used to examine the size of the crop on billet supply and loss. The machine was set with the topper turn off, a fixed ground speed of 3.3 km/h, a primary extractor speed of 1,210 r/min and the secondary extractor speed of 1,540 r/min.

3.3.3 Harvesting test procedure

The harvesting test procedures described by De Beer et al. (1985) and Whiteing (2013) are uniformly accepted sampling methods in the Australian sugar industry. These procedures were used to determine the effect of crop conditions (caused by varying N application rates) on harvesting.

The physical properties of sugarcane as detailed by De Beer et al. (1985) were measured immediately prior to harvest. These measurements included counting all stalks in a 5 m length of two middle rows of each plot to calculate the crop density. Six stalks were then randomly selected from each trial and measured by:

- Partitioning the cane into the various components (top and green leaves, brown leaves, stalk) and weighing these to determine yield (Figures 3.8 and 3.9)
- Measuring the diameter at three locations along with stalk (top, middle and base stalk at ground level) (Figure 3.10)
- Measuring the stalk length (Figure 3.11)

Figure 3.8 Six-stalk mass measurement (Bundaberg trial)

Figure 3.9 Partitioning stalks into various components (Bundaberg trial)

Figure 3.10 Cane stalk diameter was measured at ground level (Bundaberg trial)

Figure 3.11 Cane stalk diameter and length measurement (Ingham trial)

Billet and EM samples were collected during the harvest operation (De Beer et al. 1985). This was achieved by using the harvester elevator to eject harvested material into a trailer positioned adjacent to the harvester (Figure 3.12). Each sample was collected over of period of about 3–5 seconds to collect a 20–30 kg sample and kept on a blue tarp in the trailer. The tarp also enabled each sample to be covered and kept discrete from the next sample collected in the same manner. Each samples was later seperated into cane billets, trash and dirt and then weighed (Figures 3.13 and 3.14).

Figure 3.12 Positioning the trailer under the elevator to collect sugarcane billet samples (Ingham trial)

Figure 3.13 Sorting sugarcane billet samples (Ingham trial)

Figure 3.14 Separation of sugarcane samples into billets, trash and dirt (Ingham trial)

The billets were further assessed by determining billet size and billet quality/degree of damage.

Billet size was determined by using a length metering board to measure the billet length (Figures 3.15 and 3.16). The length was classified into the following range; 0–100, 100–150, 150–200, 200–250, 250–300, 300–350, 350–400 and longer than 400 mm. Each size category was weighed. The mean length of the cane billets was calculated using the following Equation 3.1 (De Beer et al. 1985):

$$\text{Mean billet length} = \frac{50w_1 + 125w_2 + 175w_3 \text{ etc}}{\text{Total weight of sample}} \qquad \text{Equation 3.1}$$

Where w_1 = Billet length weight (0–100 mm)

w_2 = Billet length weight (100–150 mm)

w_3 = Billet length weight (150–200 mm)

Figure 3.15 Measurement of the sugarcane billet length

Figure 3.16 Classification of the sugarcane billet into various sizes

Billet quality (Figure 3.17) was assessed by separation of the billets into three quality based categories (Figure 3.17) using the methodology of De Beer et al. (1985):

- Sound billet—stalk section longer than 100 mm with no splits, small rind crack less than 40 mm long and no section of rind more than 400 mm^2 removed;
- Damaged billet—split of rind larger than 40 mm or rind section around 400-2000 mm^2 removed, all billets less than 100 mm long;
- Mutilated billet—numerous rind cracks with more than 2000 mm^2 of rind removed.

Figure 3.17 Billet qualities classified into the three groups

3.3.4 Statistical analysis

To evaluate the differences between various crop conditions, statistical analysis was used to compare the factors related to sugarcane harvesting influenced by crop conditions caused by varying rates of N applied. ANOVA tests were conducted using IBM SPSS Statistic 23 (IBM 2015) software to analyse the significance of cane quantities and qualities of the harvesting. The regression curves were examined using Microsoft Excel to study the various relationships relating to billet size and quality. The analysis conducted is detailed below:

- The physical properties of sugarcane plants prior to cutting

Sugarcane plants at the experiment plots in Bundaberg and Ingham were assessed by determining the physical properties (stalk diameter, length, weight population density and yield) and how this was impacted due to the varying N fertiliser application rates. Two-way ANOVA was performed to study the effect of varying N on crop size and components. A Duncan post-hoc test was used to study the differences of factor means by using P-value ≤ 0.05.

- Billet supply produced by harvesting

All sugarcane billet samples at the experiment plots in Bundaberg and Ingham were collected during harvesting. The samples were examined for EM mixing with sugarcane billet supply, billet size and billet quality. A one-way ANOVA was performed to determine the effect on billet production, resulting from various pour rates resultant from the different crop sizes associated with varying N application rates. Duncan's new multiple range test (DMRT) was used to test for significance in billet samples by using P-value ≤ 0.05.

3.4 Results and discussions

The results of the assessment of sugarcane yield and billet quantities and qualities are presented and discussed below.

3.4.1 The physical properties of sugarcane plants prior to cutting

The results of the physical properties measured in Bundy and Ingham are shown in Table 3.1. Significant difference were indicated for all means when P-value ≤ 0.05. The highest N rates produced the highest yields in both the Bundaberg and Ingham trials (P-value ≤ 0.05). This finding aligns with other studies (Wiedenfeld 1995; Muchow et al. 1996; Wiedenfeld 1997). The other measured physical stalk properties (stalk length, diameter and weight) were also found to be the highest at the highest N rate (P-value ≤ 0.05), as were stalk population (P-value ≤ 0.05). The latter is consistent with results presented by Bell and Garside (2005). The weights of the sugarcane components at both sites indicated that stalks, tops and trash are 78–85%, 10–15% and 2.5–12% of the total weight respectively. These weights varied according to the amount of N applied (P-value ≤ 0.05). At both sites, the percentage of tops and trash were the highest with the lowest amount of N applied (P-value ≤ 0.05). Conversely, the highest proportion of cane stalk resulted from the highest N rate (P-value ≤ 0.05). These results align with other studies (Bell et al. 2004; Bell & Garside 2005).

Table 3.1 Physical properties of sugarcane as influenced by varying N rates.

Site	N rate (kg/ha)	Crop Yield (t/ha)	Stalk Length (m)	Diameter Stalk (mm)	Stalk Weight (kg)	Stalks/m^2	Cane Weight (%)		
							Stalk	Top	Brown Leaves
Bundaberg	75	43.90^{a}	1.39^{a}	22.36^{ab}	0.55^{a}	13.13^{a}	78.48^{ab}	10.28^{a}	11.24^{bc}
	150	86.49^{c}	1.96^{b}	21.92^{ab}	0.75^{b}	17.40^{b}	77.90^{a}	10.12^{a}	11.98^{c}
	225	91.00^{c}	2.12^{b}	24.51^{c}	0.94^{cd}	18.44^{b}	80.70^{bc}	11.08^{a}	8.22^{b}
Ingham *	0	62.54^{b}	3.02^{c}	21.57^{a}	0.92^{c}	11.66^{a}	81.84^{cd}	14.54^{b}	3.62^{a}
	100	82.97^{c}	3.41^{d}	23.66^{bc}	1.07^{de}	13.43^{a}	83.94^{d}	13.60^{b}	2.46^{a}
	200	91.98^{c}	3.66^{d}	24.70^{c}	1.17^{e}	13.67^{a}	83.35^{cd}	13.55^{b}	3.10^{a}

* Legume improved soil-nutrient content in the first crop before nitrogen rates applied
Means with the same column followed by the same letter are not significantly different (P-value ≤ 0.05)

The high N rate (225 N kg at Bundaberg trial) increased the sugarcane yield about 91.00 t/ha (2.47 N kg/t cane). Conversely, the low N rate (75 N kg) produced the lower crop yield (43.90 t/ha, 1.71 N kg/t cane). The varying of N applications between the high and low nutrient rates (150 N kg of the nutrient difference) caused a difference in crop production of around 47 t/ha (different 0.76 N kg/t cane). There was however no difference (P-value ≤ 0.05) between the high and medium N rates in sugarcane yield even though there was a difference of 75 kg N/ha in the application rates. The Ingham results were a repeat of the Bundaberg results. The high and low nutrient rates caused a difference in crop yields of approximately 30 t/ha. When comparing between the high and medium N rates, the crop productions were not different (P-value ≤ 0.05) but the high N rate was increased usage (100 N kg/ha). In addition, the medium N rate was compared with the low N rate. The varying nutrient rates caused a difference in crop yields of approximately 20 t/ha. The impact of these varying nutrition levels resulted in varying harvesting pour rates when the ground speeds of the sugarcane harvester are constant during cutting. This will be further discussed in Section 3.4.2.

The relationships between the different stalk parameters (length, diameter and weight) due to the different N rates were investigated by regression analysis. The results are shown in Figures 3.18 and 3.19. The linear relationships between stalk diameter and stalk length, and stalk weight and stalk length for the Bundaberg trial (Figures 3.18a and 3.18c respectively) indicated high regression ($R^2 > 0.80$). The relationship between stalk weight and stalk diameter due to N applied was less robust with a regression coefficient (R^2) of about 0.6 (Figure 3.18b). At the Ingham trial, the regression (Figure 3.19a) was relatively high between stalk diameter and stalk length with an R^2 value of 0.73. However, the relationship between the other stalk parameters shown in Figure 3.19b (weight versus diameter) and Figure 3.19c (weight versus length) had lower R^2 values (0.42 and 0.45 respectively) due to the impact residual N from a previous fallow legume crop and the ensuing lacks of response to applied N.

Findings discussed here, agree with works of other researchers. The relationships between the stalk parameters resulted from varying the N rates (Wiedenfeld 1995; Muchow et al. 1996; Wiedenfeld 1997). Therefore, the crop yield and sizing were different when applied by varying nutrient levels. This range of plant parameters in turn resulted in different pour rates during harvesting due to yield differences (Jones 2004; *Harvesting best practice manual* 2014). In addition, the size of the crop and density of stalks within row has a marked impact on harvester performance during the cutting (Jensen et al. 2010).

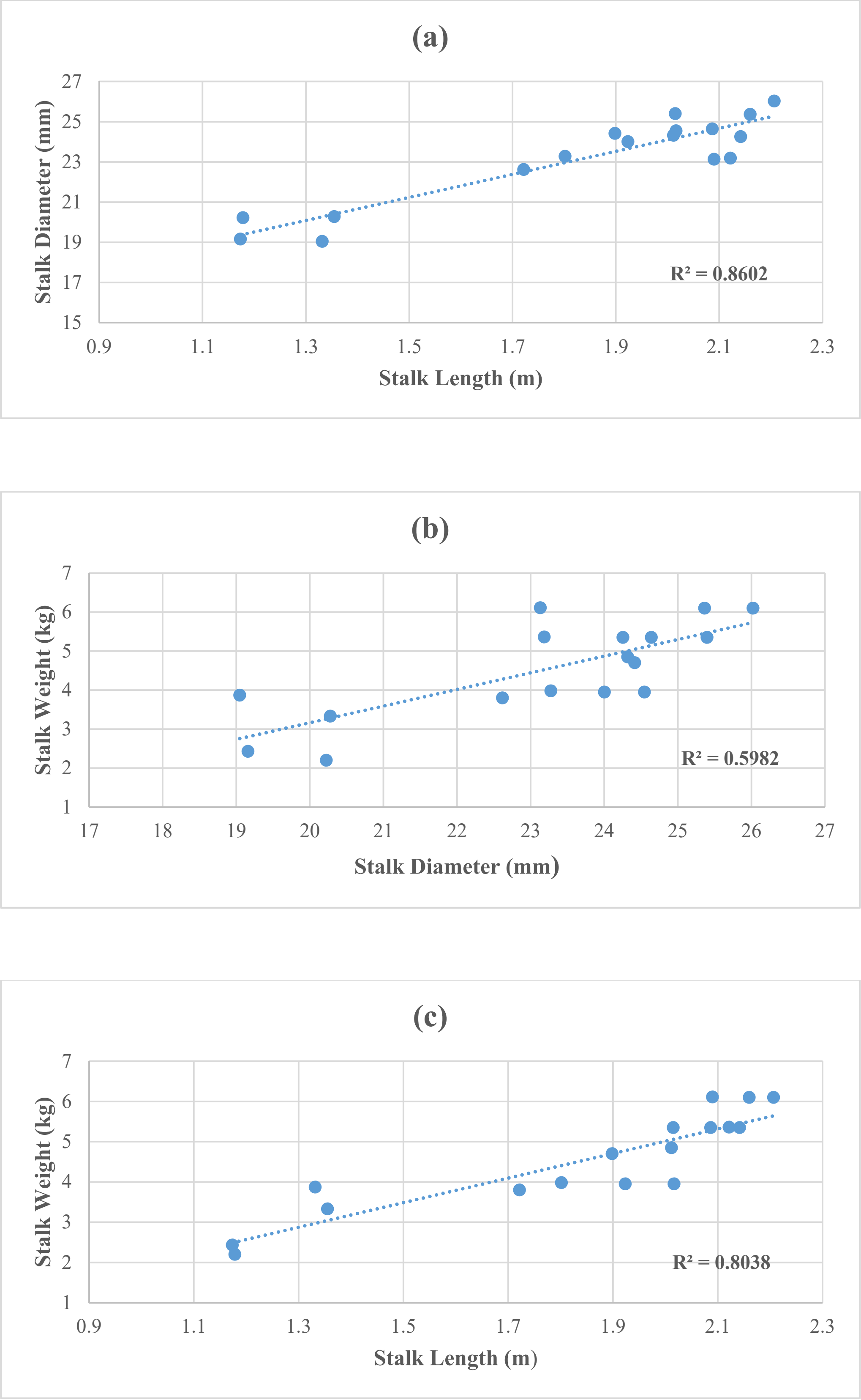


Figure 3.18 Relationships between different stalk parameters as influenced by varying N rates at Bundaberg trial
(a) Diameter and length
(b) Weight and diameter
(c) Weight and length

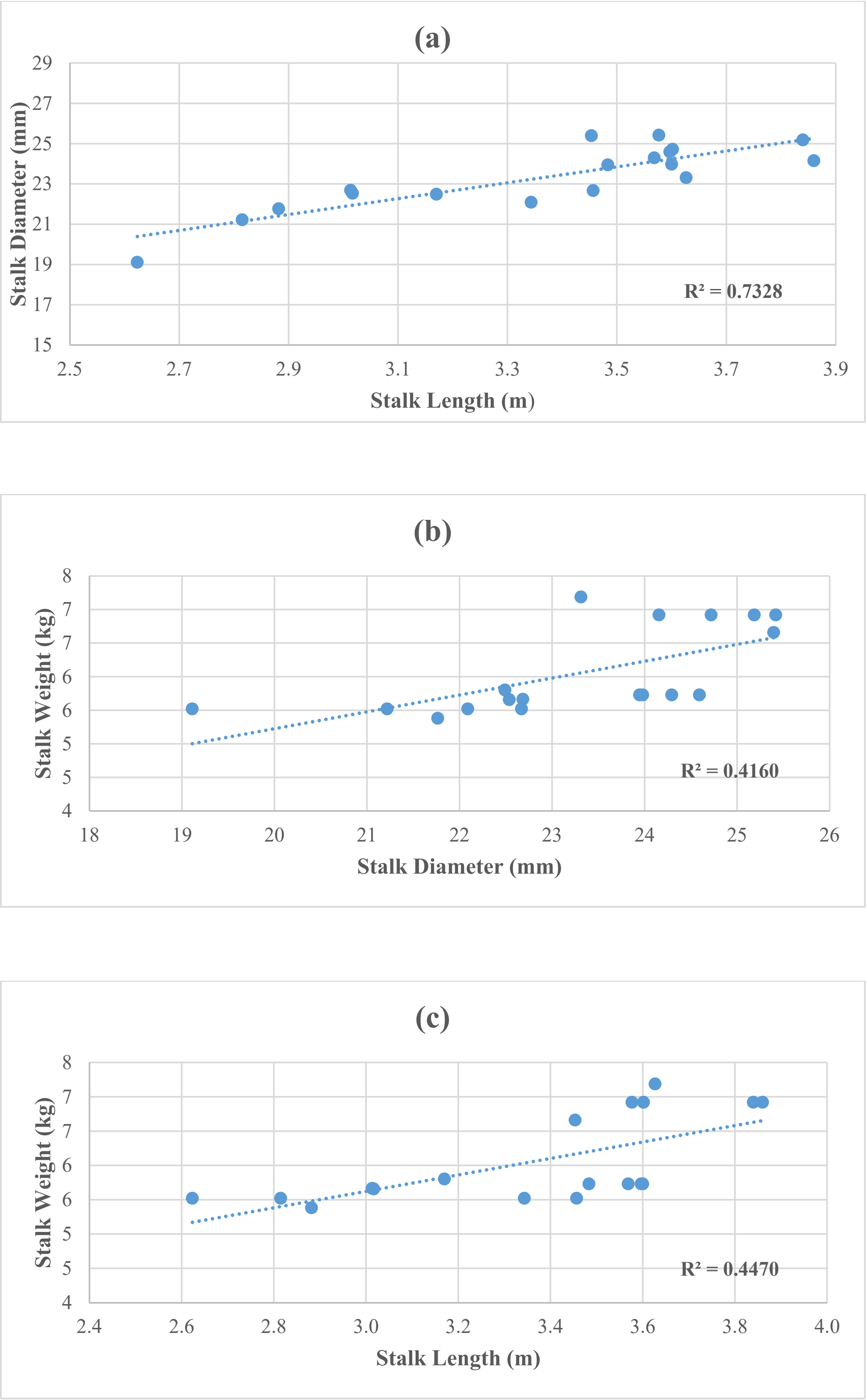
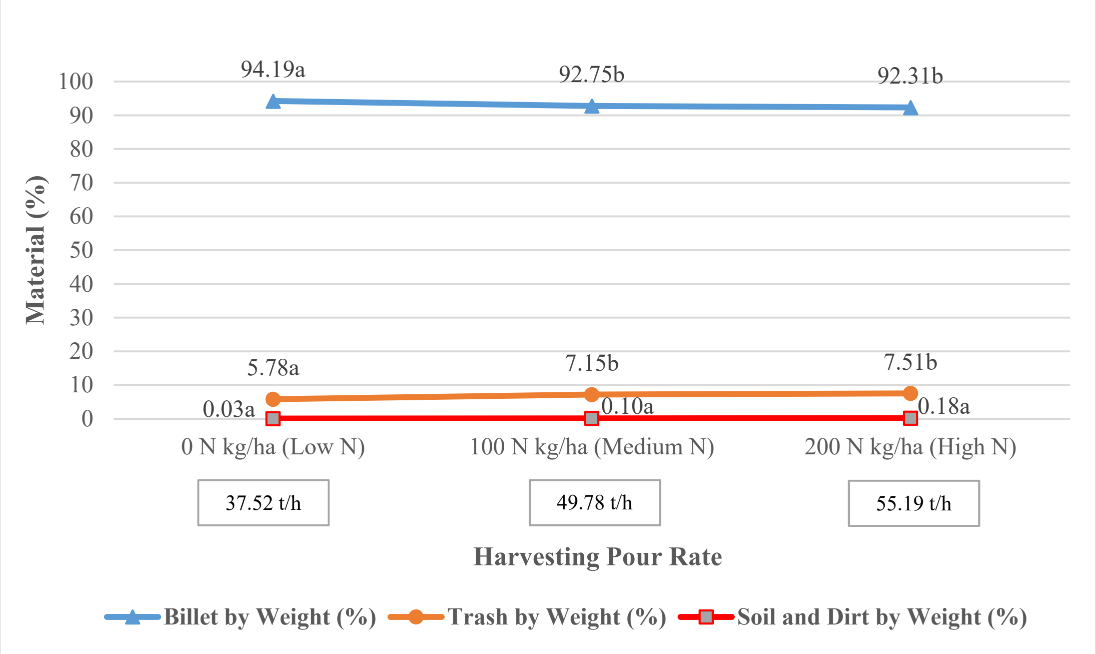


Figure 3.19 Relationships between different stalk parameters as influenced by varying N rates in the Ingham trial (a) Diameter and length (b) Weight and diameter (c) Weight and length

3.4.2 Billet supply produced by harvesting

3.4.2.1 Extraneous matter entrapment

All sugarcane billet cut with a chopper harvester contain some EM. The billet samples collected from harvesting of the Ingham trial were examined to classify this material into three categories: billets, trash and dirt. The various proportion of billets produced during harvesting, under a range of pour rates driven by varying N application rates, showed that the highest cutting pour rate was achieved from the highest rate of applied N. The percentage of billets decreased as the rate of N applied increased, there was a corresponding increase in the percentage of EM (trash, soil and dirt) which is shown in Figure 3.20. The pour rate affected the percentage of billets and trash by weight, but soil and dirt levels were not significantly different (P-value ≤ 0.05).



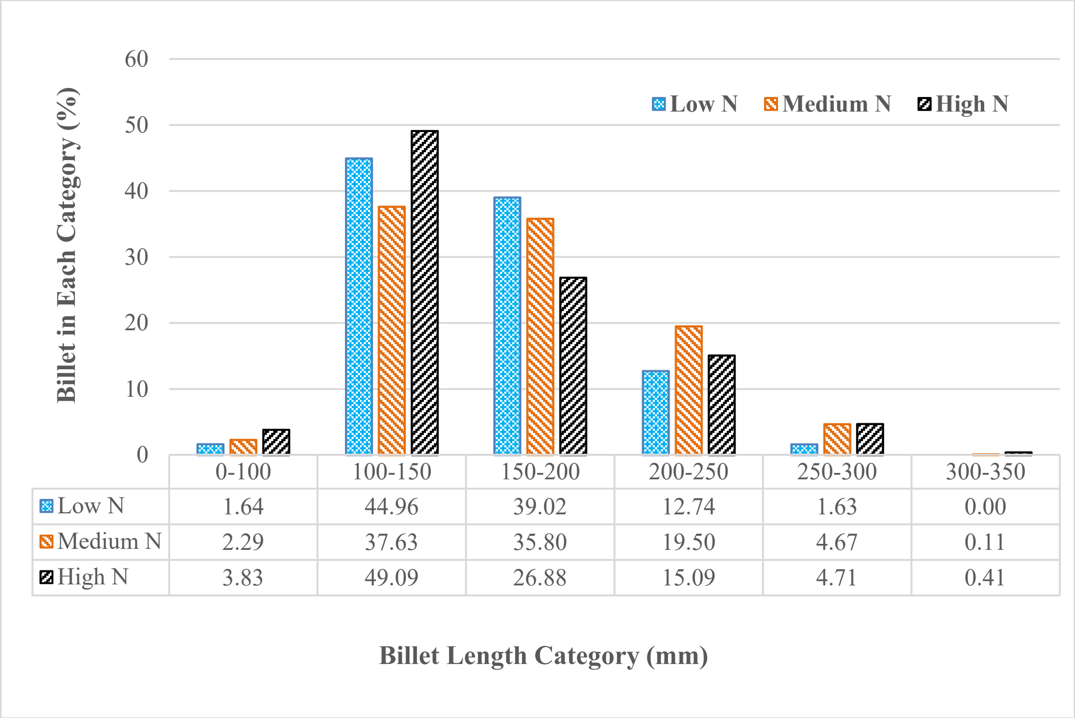
Means with the same line and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 3.20 Cane sample classification from Ingham trial

The differing N rates resulted in a range of the stalk physical properties (stalks per unit area, billet size and stalk weight) and cane yields (t/ha) (Table 3.1). With the harvester operating at a constant ground speed (and set fan speed), the pour rate was indirectly driven by the N applied. As pour rate increased, the ability of the extractor fan to efficiently differentiate trash from billets decreased. These findings were consistent with past investigations (Agnew & Sandell 2000; Whiteing & Norris 2002; Whiteing 2013; *Harvesting best practice manual* 2014).

3.4.2.2 Billet size

Mean billet length distributions, resultant from the various pour rates caused by different crop sizes due to different N rates applied, are shown in Figure 3.21. A one-way ANOVA performed on the data showed that the differences were not statistically significant (P-value ≤ 0.05) although trends were evident. Billet lengths were predominantly separated into two classes: 100–150 mm and 150–200 mm, of which the 100–150 mm class contained 43.9% of the total billets. At the high pour rate (driven by the high N application rate), the highest percentage of billets (49.09%) was in this range. The low pour rate (driven by the low N application rate) resulted in the percentages of billets in the two ranges (100–150 and 150–200 mm) being higher than the percentages associated with the medium pour rate and medium N application rate. The highest percentage of billets in the 0–100 mm range occurred at the high pour rate. In contrast, the lowest percentage of billet in this range was associated with the low pour rate driven by the low N application rate. Different N rates produce sugarcane stalks with different physical properties (refer to Section 3.4.1) and affect the EM mixed with the billets produced during harvesting at a constant ground speed (refer to Section 3.4.2.1). When assessing billet length from harvested cane, light short billets (low bulk density) were easier to discharge during the cleaning process of the extractor. This resulted in very few of these smaller billets being assessed and is consistent with data presented by Ridge and Dick (1988) and Whiteing and Norris (2002).



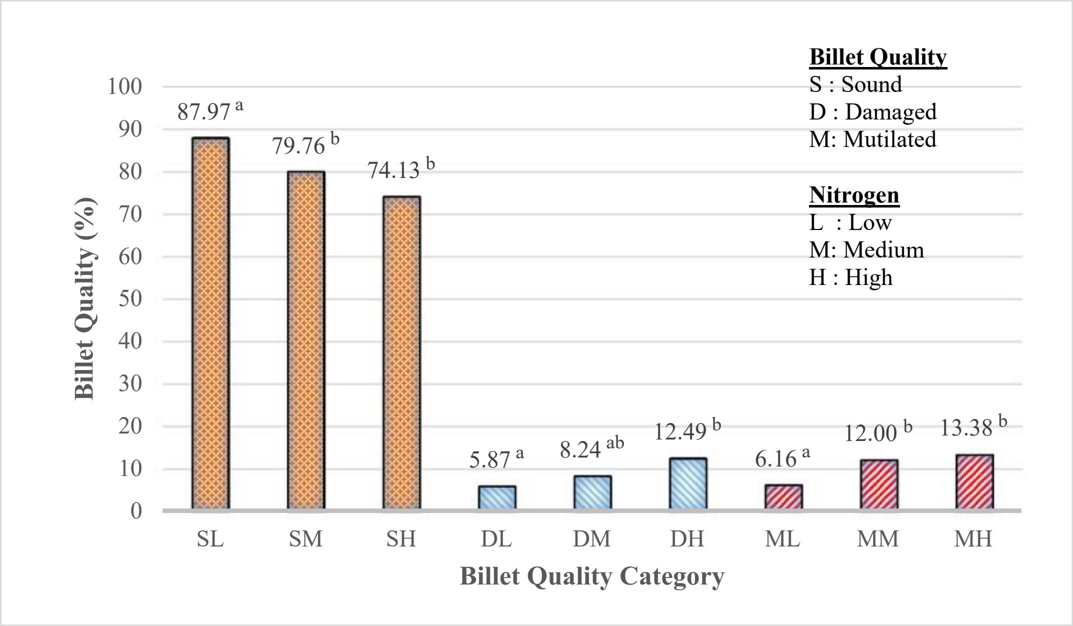
	0-100	100-150	150-200	200-250	250-300	300-350
▨ Low N	1.64	44.96	39.02	12.74	1.63	0.00
▨ Medium N	2.29	37.63	35.80	19.50	4.67	0.11
▨ High N	3.83	49.09	26.88	15.09	4.71	0.41

Figure 3.21 Billet lengths separated into classes due to the different pour rates driven by varying N rates (Ingham trial)

3.4.2.3 Billet quality

The billet samples from the Ingham trial plots were sorted into three categories (sound, damaged and mutilated billets) following the convention of De Beer et al. (1985). The percentage of damaged and mutilated billets increased when the higher N rate was applied (Figure 3.20). The increased N application rate improved the stalk length and diameter resulting in increased crop yield (Bell & Garside 2005; Franco et al. 2015). The light billets (damaged and mutilated types in the low N plots) were preferentially ejected by the cleaning system compared to the heavy billets. These results align with those reported by Ridge and Dick (1988). The highest proportion of sound billets in the billet supply occurred at the lowest N application rate (Figure 3.22). Conversely, larger and heavier billets associated with the higher N application rates and higher pour rates were mixed with trash and were more difficult to separate by the cleaning system (Figure 3.20). These findings are in agreement with other researchers (Norris & Ridge 1998; Agnew et al. 2002; Jones 2004; *The sugarcane advisors information kit* 2013).

After cleaning the cane billets, the proportion of the sound billets, which was influenced by the low N rate, increased in the billet supply. Conversely, the high bulk density of billet, influenced by the high N rate, resulted in the increase of billet quality percentage (damaged and mutilated billets) in the billet supply.



Means with the same column and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 3.22 Quality of billets from a chopper harvester due to different pour rates influenced by the varying N application rates (Ingham trial)

From the data of Table 3.1 and the results in Subsection 3.4.2.1–3, the high N rates (225 kg at Bundaberg and 200 kg at Ingham) delivered increased harvested crop yields (91.00 and 91.98 t/ha respectively). With a fixed the ground speed at harvest, the high N rate caused high pour rate which in turn resulted in high EM (Figure 3.20) leading to the low quality cane. Conversely, the low N rates (75 kg at Bundaberg and zero N at Ingham,) led to lower sugarcane production (43.90 t/ha and 62.50 t/ha of crop yield respectively), in turn led to the low pour rate but gave the high sound billet (87.97%) (Figure 3.22). However, the small pieces with the low bulk density were ejected by the extractor system during the cleaning. The analysis detailed in Chapter 4 will further investigate sugarcane loss during harvesting of lower crop yields related with the lower N application rates by evaluation of sugar loss adhering to trash ejected by the cleaning system.

3.5 Conclusion

Different N fertiliser application rates that resulted in different pour rates, led to varying sugarcane physical properties such as length, diameter and weight of stalk, crop density and yield. The physical properties of sugarcane in turn caused three ranges of harvesting pour rates. Additionally, crop size and row density affect the machine separation performance. High N application rates resulted in an increase in the cutting pour rate due to the crop size and stalk population in the row when the ground speed of the harvester was a fixed. When the pour rate increased due to increased yield due to high N applied, EM (7.69%) adhering to cane billets also increased, as did the proportion of billets with a mean length in the range 100–150 mm. The highest proportion of sound billets (87.97%) occurred at low N application rates. Conversely, the highest proportion of damaged and mutilated billets during harvesting occurred in cane that had received a high N fertiliser application. The increased proportion of sound billets with the lowest N application rate suggested that the small pieces with low bulk density were ejected by the extractor system during the cleaning.

Not only do soil-nutrient practices impact on crop yield, they also affect the physical properties of sugarcane. When the harvester's ground speed is kept constant with high fan speed, the small and light pieces of stalk are easily blown by the fan system and cause high cane loss. Additionally, when the pour rate is increased by increased N application rates, the EM will increase and contribute to low cane quality. These results confirm that cane losses are occurring during harvesting processes in the Australian sugar industry and the world. The investigations reported in Chapter 4 will aim to confirm loss of cane during harvesting of lower yields associated with lower N application rates and report on the evaluation of sugar loss on trash.

Chapter 4 Assessing sugar loss from sugarcane harvesting

4.1 Introduction

This chapter focuses on sugar loss due to cutting with a chopper machine. In the fields sampled, the different N rates impacted on the physical properties of sugarcane, especially crop size and density. When the harvester operates, the extractor systems clean the billets and discharge the trash back onto the field. Some billet fragments are however ejected by the extractor system with the trash and other EM. Cane loss is often determined using the visible method of separating these components, but this is difficult and time consuming. Sugar losses that occur during cutting are largely invisible. A colorimetric technique (Campbell et al. 1999; Velterop & Vos 2001) and a method of collecting samples from the material discharged from the harvester (Whiteing 2013) were used to evaluate the amount of sugar loss during the harvest of sugarcane trials with a chopper harvester. This chapter covers the following:

- Background and literature review
- Methodology and experimental set-up
- Results and discussion
- Conclusion

4.2 Background and literature review

4.2.1 Techniques to measure cane loss from harvesters on fields

Cane loss is very difficult to measure accurately. Many methods have been developed to measure cane loss in many countries, but the accuracy of results is questionable (Whiteing 2013). The various methods detailed in the literature are discussed below.

4.2.1.1 The tarp test

A standard 'tarp test' (Sandell & Agnew 2002) is a cane loss measurement method to quantify cane loss during harvest. The tarp test is a quick and easy method of measuring cane loss in fields by determining the visible cane loss within a defined area to predict the loss on a larger scale. The tarp test involves placing a tarp adjacent to the row being cut, collecting the material ejected by the primary extractor and then sorting and weighing the cane fragments in the sample. This method has been found to seriously underestimate cane loss due to the disintegration of billets as they pass through the extractor blades and disintegrate, making them impossible to find in the trash sample (Sandell & Agnew 2002; Sichter et al. 2005). This method can only measure the weight of the cane fragment that are recovered from the tarp. The accuracy of this method is not high due to the variability of cane loss across the field and the inability to find very small pieces. The 'tarp test' is often used as a quick estimate of cane loss due to its easy of implementation. This method is reasonably accurate when losses are less than eight tonnes per hectare, however when losses increase, the amount of discarded cane found on the tarp decreases as actual cane loss increases (Sandell & Agnew 2002).

4.2.1.2 Mass balance cane loss

The mass balance loss method involves determining the difference in weight of harvested cane with no extractor fans operating and varying the fan speeds. This method (Sandell & Agnew 2002) is expensive and time-consuming, and the accuracy not fully known or understood. This method necessitates larger-scale harvesting trials for testing cane loss. It is time-consuming and labour-intensive because of the need to retrieve and sort the lost cane by hand. In using this method, blocks of apparent uniform cane are selected for data collection. When the in-field yield is variable between trial plots, the results of the investigation are not likely to accurate due to the unstable pour rate through the cleaning system (Sandell & Agnew 2002; Whiteing et al. 2004).

4.2.1.3 Electronic loss monitors

Electronic systems have been developed by Agridry Rimik Pty Ltd and NCEA (refer to Section 2.5.5) to measure cane loss by detecting the sound from billets hitting the primary hood or fan blades during harvest. However, some components of the sugarcane stalk such as splattered juice, shredded pulp and tiny fragments cannot be detected by this technique (Whiteing & Norris 2002).

4.2.1.4 The tarp test combined with a loss assessment method

This procedure improved on the limitations of the standard tarp test (Sandell & Agnew 2002) by combining with the HPLC technique (refer to Section 2.9.3) to measures sugar lost in harvest residue (Whiteing 2013). Other techniques are unable to measure sugar loss due to juice being lost in the form of splatter when the billets hit with the extractor fan blades during cleaning. Tarps are positioned to collect all trash ejected from one pass of the harvester. This material is homogenised with a mulcher. The sample is stored and later taken to the laboratory for analysis (Sichter et al. 2005; Whiteing 2013). The HPLC method is a method of chemical analysis to identify and quantify each component in a mixture (Whiteing 2013). Pulverised billets deposited in the sugarcane field during harvest are not always visible as whole or piece of billets. They are often in the form of small fragments and juice mixed into the trash blanket. This technique combines polarimetry and HPLC methods to evaluate the volume of sugar loss. The relationship between polarimetry values and those obtained from HPLC is useful (Whiteing 2013) because polarimetry is cheaper and quicker than when measuring the samples.

4.2.2 Sugarcane quality measurement at the mill

4.2.2.1 Brix measurement

Brix is a measure of the percentage of total solids in a solvent. Two devices are commonly used to evaluate brix volume. Firstly, a hydrometer or spindle is used to determine brix and estimated sucrose in a liquid by floatation. Secondly, a refractometer (refer to Section 2.9.1) uses the refractive index of light to determine sucrose in a solvent (BSES 2001). Refractometers are common in the sugarcane industry and can be used in the field or laboratory to evaluate cane quality and hence a means of determining cane payment. Handheld or portable refractometer is best used in the field. However, they are not as precise as a laboratory device that can accurately control the temperature at 20 °C before measurement, thus avoiding the need for temperature corrections (Crees & Brotherton 1991). In addition, pure water cleans the jacket surrounding the prisms in the laboratory devise. This allows equilibrium in the atmosphere within the instrument to be reached and maintained during the observation period of the refractive index.

Factors that influence the accuracy of brix volume measurement include (BSES 2001).

- Temperature which affects the density of the solution thereby changing the bending of light with an affect on the refractive index.
- Changes in the wavelength of radiation causing anomalous dispersion in the refractive index.
- Atmospheric pressure causing changes in the refractive index.

4.2.2.2 Polarization measurement

A polarimeter is used to measure the amount of sucrose in sugarcane juice by analysing and evaluating optical properties. When plane polarized light is passed through a sugar solution, its direction changes and this change is measured by the angle of rotation that occurs (BSES 2001). This is accurate only for pure sucrose solutions. Therefore, the contamination in juice is cleared with clarifying and decolorizing agents before testing is possible with this method. This procedure was described in Sections 2.9.2 and 2.10.2.

4.2.2.3 pH in cane supply

Sucrose inversion (splitting the disaccharide to monosaccharide) is one of the major problems in sugar supply system. As sugar reduces from sucrose to glucose, the acid of sugar juice raises due to sucrose degradation (Cole & Bugbee 1976). When the sucrose degrades, hydrogen ions in juice increase resulting in a lowering of the pH. Measuring pH is a method by which the levels of acid and alkali in the liquid can be determined and used to monitor the total reducing sugar. As the amount of reducing sugar increases, sucrose decreases. This provides the ability to assess raw materials and control the sugarcane quality in sugarcane processing in sugar mills (Panpae et al. 2008).

4.2.3 Evaluating sugar by enzymatic assay

Colorimetric methods have been used to measure and interpret different light absorbance coefficients of the specific sugars in plant tissue (Buysse & Merckx 1993). When specific enzymes are applied to make the catalysed reactions with particular sugars, the chemical assay offers greater levels of sensitivity than HPLC (Campbell, Hansen & Wilson 1999). To detect the amount of sucrose present in samples of the plant tissue, the glucose concentration is measured before and after sucrose hydrolysis by invertase. The sucrose content is calculated by assessing the sucrose and glucose concentrations in samples (Velterop & Vos 2001). The enzymatic analysis can identify sugar in plant tissue by providing an easy and economical way compared to the HPLC technique (Campbell, Hansen & Wilson 1999).

4.3 Materials and methods

4.3.1 Field trials

Sugar loss during harvesting was investigated at field trials in Bundaberg and Ingham. Details of the trials are provided in Chapter 3.

4.3.2 Material collection and processing

4.3.2.1 Samples collected during harvest

All the trash on the ground adjacent to the harvested row was cleared with garden rakes to prepare the harvested row prior to cutting and sample collection. Two blue tarps (size 3.65 m × 4.87 m) were placed adjacent to a harvest row (short sides against the row) at the trial site to receive the small billet fragments, trash (and juice) blown from the cleaning system of the chopper machine (Figures 4.1 and 4.2). The trash on the tarp was rolled into a ‘sausage’ alongside the harvested row. The ‘sausage’ was subsampled by collecting the centre section (approximately 1/3 of the volume) for further analysis (Figure 4.3). All the trash collected on the tarp was weighed to determine the total amount per unit area (Figure 4.4).

Figure 4.1 Two blue tarps were positioned alongside the harvested row to collect the residue from the harvester (Bundaberg trial)

Figure 4.2 Trash is discharged from the harvester onto the blue tarps (Bundaberg trial)

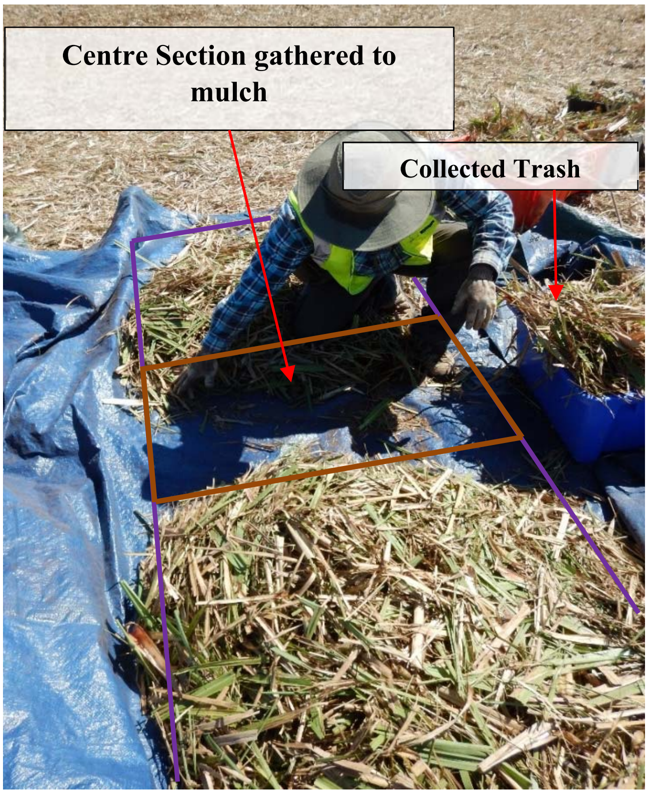


Figure 4.3 Subsampling of trash 'sausage' for mulching (Bundaberg trial)

Figure 4.4 Weighing a trash sample (Bundaberg trial)

The sample collected from the centre section of the 'sausage' (approximated 5 kg) was processed with a petrol-powered mulcher: Viking GB480 6 kW at the Bundaberg site (Figure 4.5) and an ECHO Bear Cat, SC3305 11 kW at the Ingham site. Both mulchers were hammer-mill type units where the material was impacted by flails to reduce particle size until it could escape the 35 mm diameter aperture screen (plate). The mulched samples were homogenised by hand-mixing the sample (Figure 4.6). A subsample (300–500 g) was collected in a plastic bag (Sichter et al. 2005; Whiteing 2013). The samples were placed immediately in a freezer (-25 °C) for storage prior to analysis in a laboratory (Brokensha 1979). Each sample was processed within one hour to retard the sucrose inversion (Whiteing 2013).

Figure 4.5 Mulching a trash sample (Ingham trial)

Figure 4.6 Homogenising the mulched sample (Ingham trial)

4.3.2.2 Measuring sugar content

The mulched samples from the trial sites were analysed in a laboratory at the University of Southern Queensland (USQ) to determine the amount of sugar adhering to sugarcane trash. In this process, distilled water was added to each trash sample and blended to mobilise the sugar coatings on the leaf material and to disperse any small billet components that may be presented. The method utilized was based on the 'whiteing' method (Whiteing, 2013) but made use of additional equipment present in the laboratory. This procedure is divided into six steps shown diagrammatically in Figure 4.7.

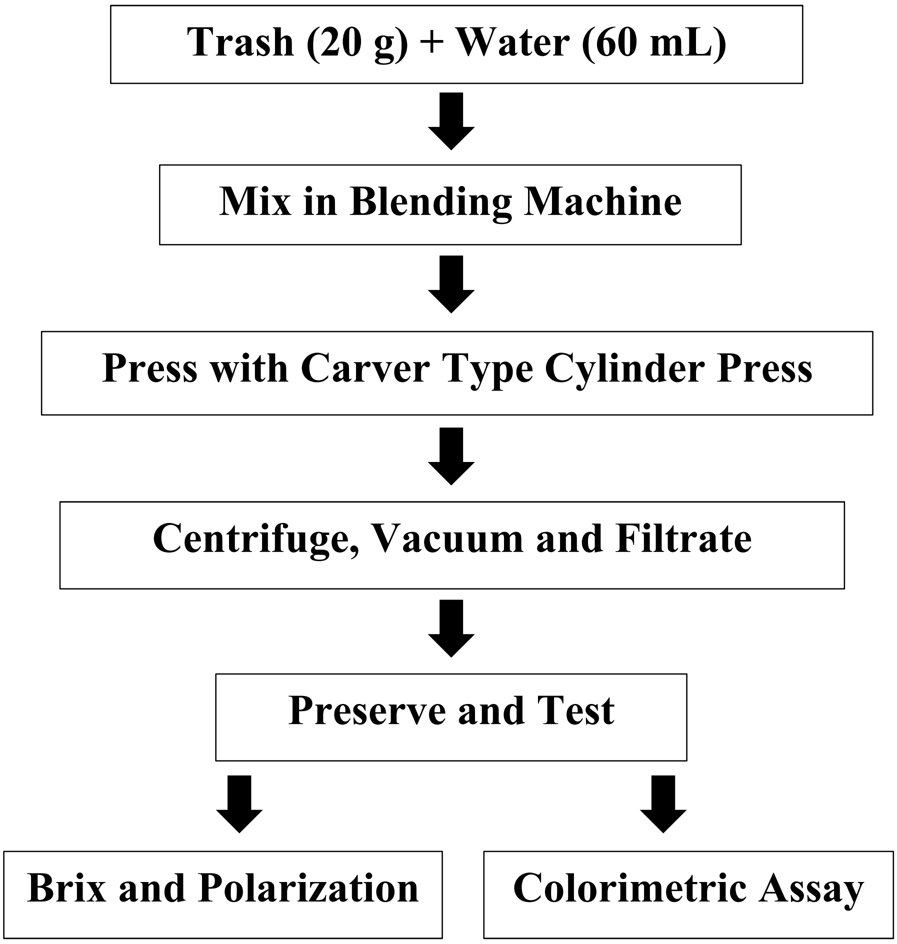


Figure 4.7 Sugar extraction from sugarcane trash sample

1. A 20 g trash sample was added to 60 mL of distilled water in a receptacle of a commercial blender (Breville model BBL300) (Figure 4.8). The blender, which spins at 13,000 r/min, was operated for 5 min. The blending action was then paused to dislodge any material clinging to the sides of the vessel. This process as repeated three times per sample to ensure homogeneity (Whiteing 2013).
2. The paste from the blender was put into the juice extraction cylinder and pressure applied using a hydraulic press (Carver Press, model 3856) (Figure 4.9) to force the liquid from the sample (at 90 kN force applied for 2 min)

(Birkett 1998; Whiteing 2013). A leachate sample was collected using a syringe.

3. As the leachate contained small particle mixed, the liquid sample was shaken with a rotatory shaker (at 30 r/min, 2 min) (Figure 4.10 a) to blend all material. The liquid sample tubes were then spun in a centrifuge (Spintron model GT-20) at 3,500 r/min, 5 min (Figure 4.10 b) to separate the liquid from the small particle (Birkett 1998). The supernatant was then filtered using a glass fibre filter no. GA55 and a vacuum pump (Figure 4.10 c) to remove the very small particles in the juice before testing with the colorimetric method.
4. The liquid sample was stored at a temperature of -25 °C to retard the sugar reduction (Brokensha 1979) until analysis could be undertaken. The liquid samples were defrosted in a water bath (Figure 4.10d) at 20 °C to protect against sucrose degradation. Brix volume was determined in the liquid sample (ICUMSA 2013).

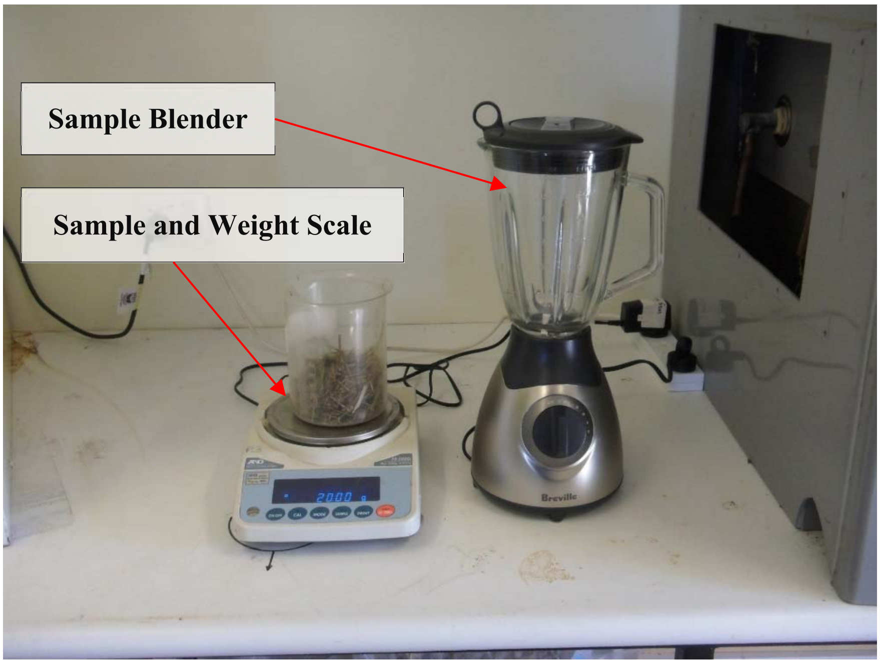


Figure 4.8 Weighing samples and the blender used for processing

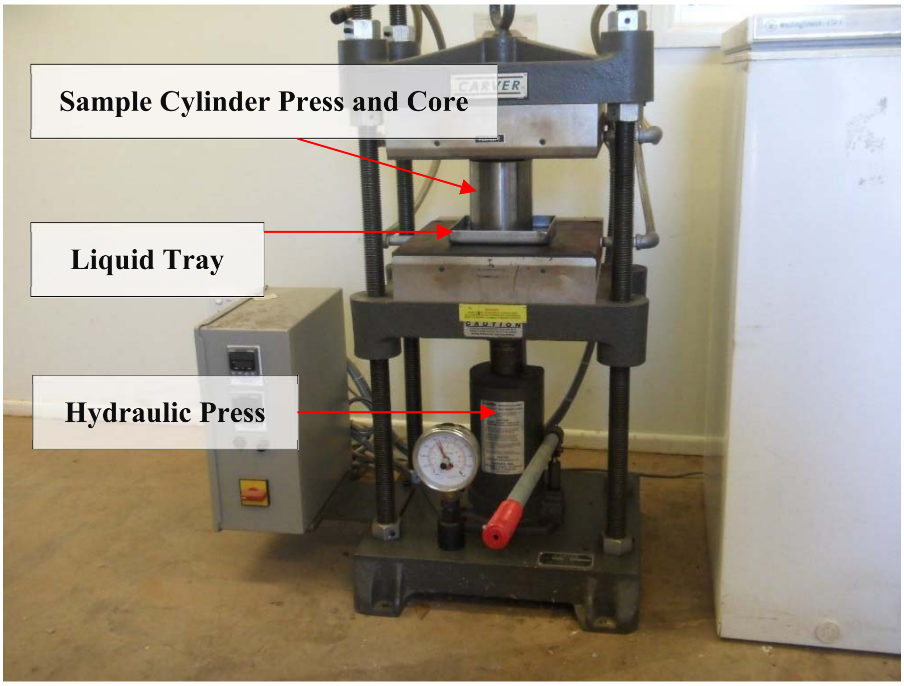


Figure 4.9 The 'carver' hydraulic press used to extract the leachate from the trash paste obtained from the blender

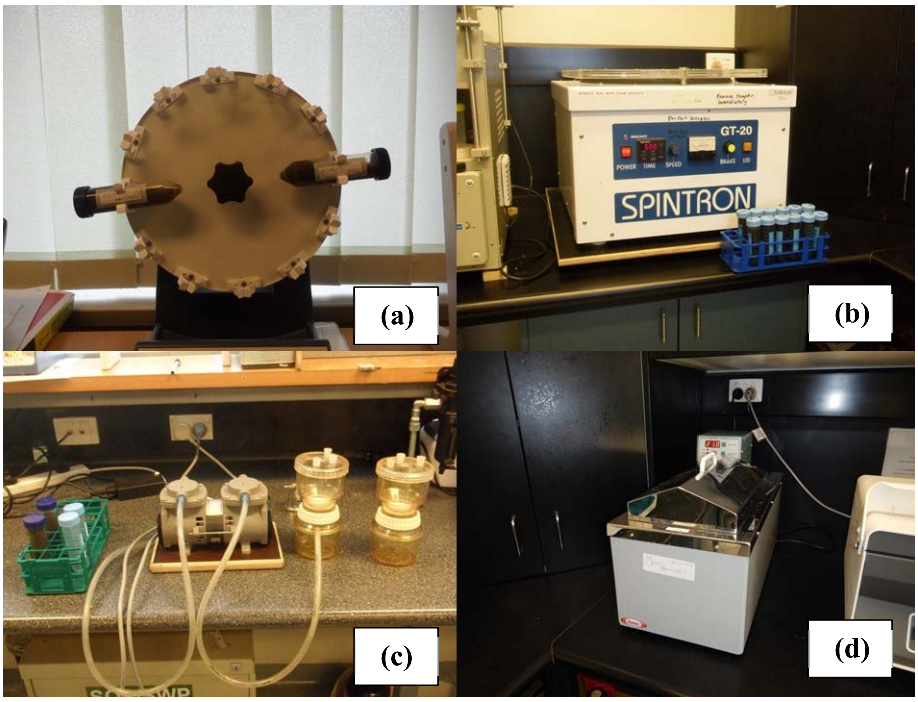


Figure 4.10 Filtration of small particle

(a) Rotator (b) Centrifuge (c) Vacuum filtration device (d) Water bath

4.3.3 Sugar loss adhering to trash measured by colorimetric technique

A colorimetric method was used to test the liquid samples which were extracted from the trash samples collected from the Bundaberg and Ingham trials. Glucose and sucrose colorimetric assay kit MAK013 from Sigma-Aldrich (2015) was utilised to evaluate the liquid samples associated with the colorimetric technique (Campbell *et al*. 1999). The procedure followed the instructions of the assay kit from Sigma-Aldrich, USA, which are detailed in Figure 4.11.

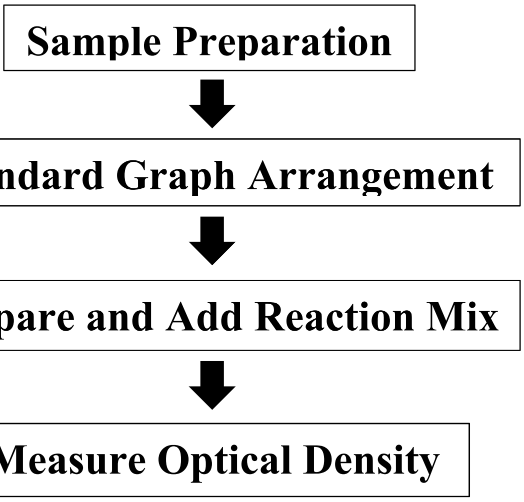


Figure 4.11 The procedures for colorimetric assay (Sigma-Aldrich 2015)

The steps taken included:

1. The juice samples were diluted with the distilled water to ensure the concentration was in the range for detecting by the assay kit and colorimetric machine. The degree of dilution was calculated by using the sugar loss report of Whiteing (2013) and the colorimetric detection guidelines by Sigma-Aldrich (2015) following Equation 4.1:

$$M_1V_1 = M_2V_2$$ Equation 4.1

Where M_1 = Sugar weight before dilution
M_2 = Sugar weight after dilution
V_1 = Volume before dilution
V_2 = Volume after dilution

The sample solution was diluted 10 µL of juice sample in 990 µL of distilled water by using the pipettes to prepare the samples for testing with chemical from the assay kit.

2. The standard solution was prepared to test all samples to find the amount of glucose and sucrose in the samples by following the instruction of the assay kit. The concentration range between 0–10 nmole by adding 2 nmole increments where used to make a standard graph for measuring the amount of glucose in the samples. The standard samples were detected at wave range 570 nm (Sigma-Aldrich 2015). Data was analysed using Microsoft Excel to make the regression line to calculate sugar loss from the liquid samples during the harvesting.
3. 15 µL of the diluted solution was mixed with 35 µL of the assay buffer into the microtiter plate (a flat plate with multiple 'wells' used as small test tubes) to bring the total volume up to 50 µL. The diluted samples mixed with reagents of the colorimetric assay kit in 96-well plates (Figures 4.12, 4.13 and 4.14) by following the production information (Sigma-Aldrich 2015). After mixing all reagents, the samples were incubated (Figure 4.15) for 30 min at 37 °C in order for the reaction to take place.
4. The samples were tested by a colorimetric/fluorometric instrument (FLUOstar Omega model) (BMG LABTECH Pty 2017) (Figure 4.15) which was adjusted a wave range 570 nm (Sigma-Aldrich 2015) to detect glucose and sucrose levels by following the instruction of the assay kit.
5. The glucose and sucrose concentrations of the samples were calculated from a calibration equation which was generated from a standard graph.

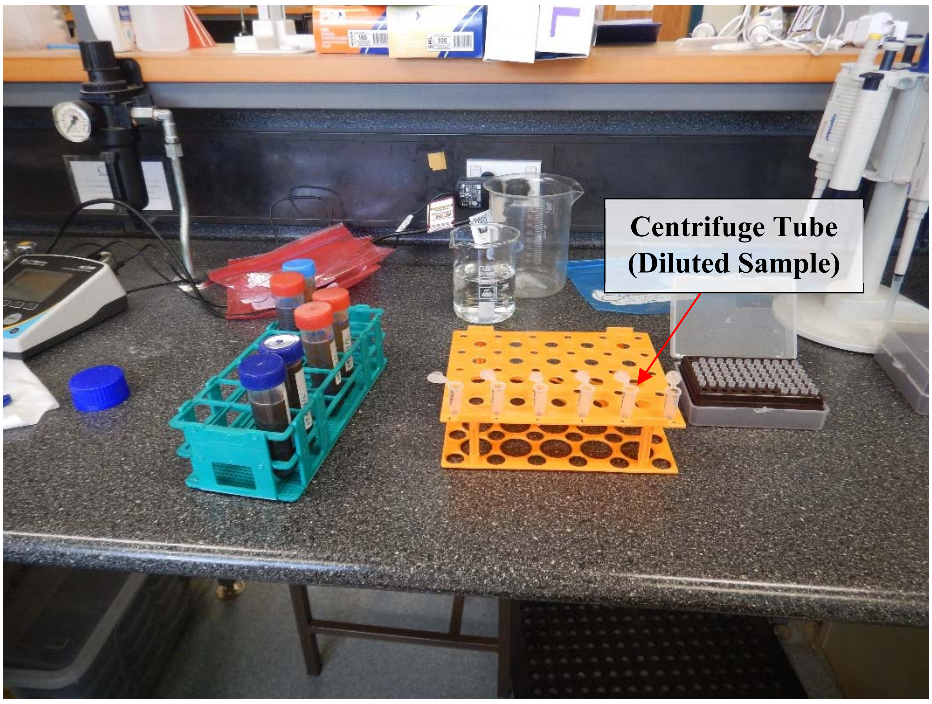


Figure 4.12 Liquid samples were diluted prior to the test

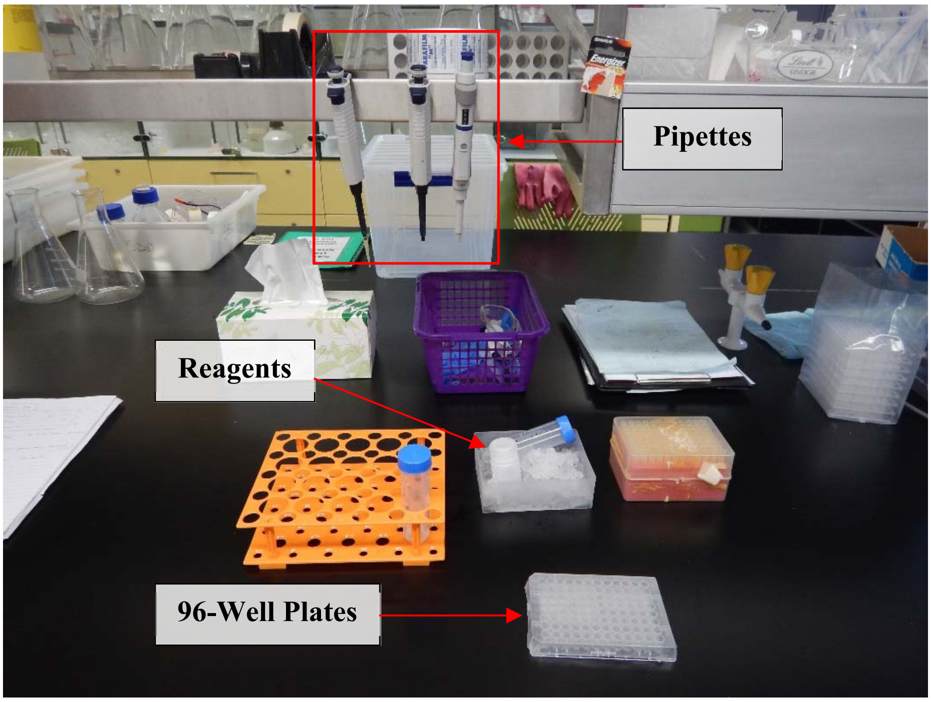


Figure 4.13 Liquid samples mixed with reagents in the 96-well plates

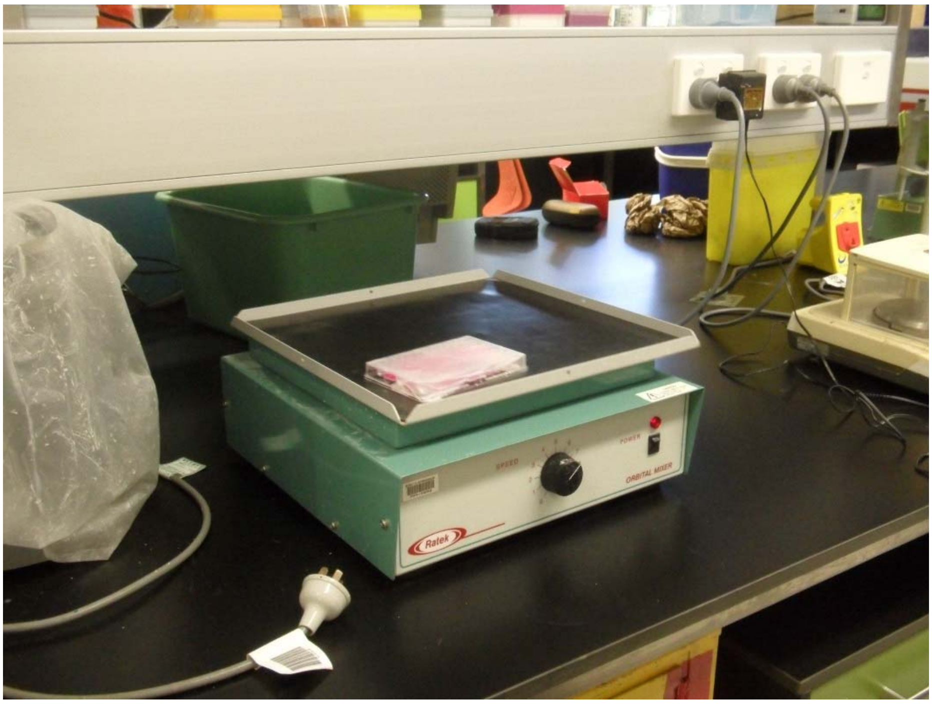


Figure 4.14 Mixing and shaking solvents in the 96-well plates

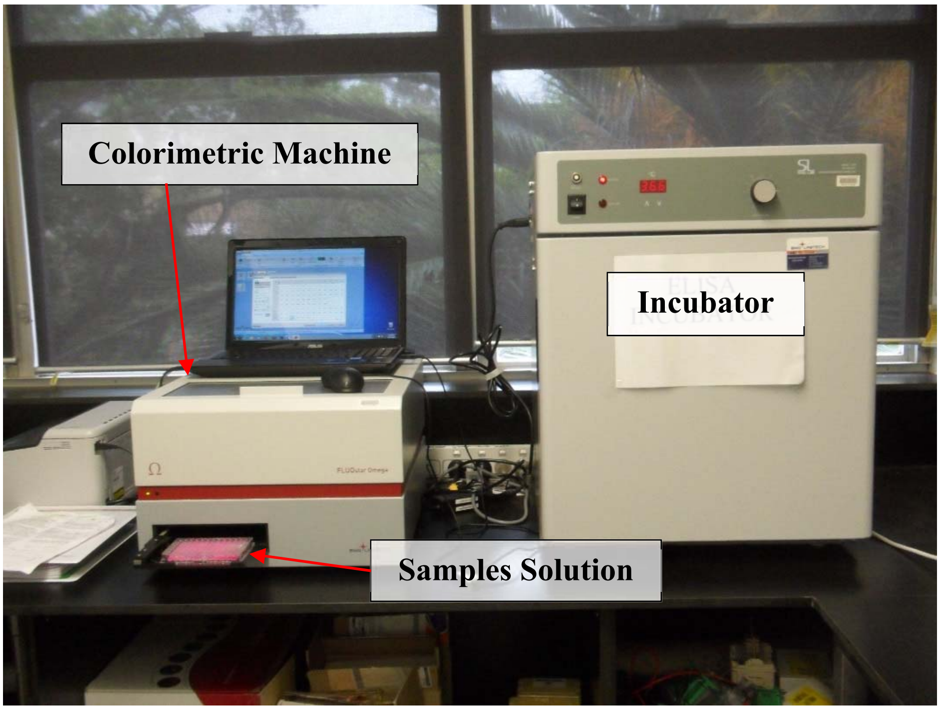


Figure 4.15 Colorimetric/Fluorometric machine (FLUOstar Omega) and Incubator

4.3.4 Brix, pol (polarization) and pH procedures

The liquid samples, which were tested with the colorimetric technique, were also run through the standard procedure of ICUMSA (2013) to measure the sucrose degradation and find the relationship between brix, pol and sugar loss from the samples.

4.3.4.1 Measuring brix and pol in the liquid samples

The procedures detailed in the standard no. GS 5/7–28 of ICUMSA (2013) were used to determine brix and pol in liquid samples from harvesting activities. All samples were measured at the SRA laboratory in Bundaberg. 250 mL of each sample was used to measure the brix and pol volume with the automatic refractometer (Bellingham & Stanley, Model RFM 310 Refractometer) and polarimeter (Schmidt Haensch, Model Polartronic NIR W2) at temperature 20 °C. The volume of pol and brix from the samples was used to compare the colorimetric results detailed in Section 4.3.3.

4.3.4.2 pH measuring in the liquid samples

The pH was measured by a Eutech Instruments Model PC 2700 (Figure 4.16), following the ICUMSA (2013) standard by using the procedure no. GS 1/2/3/4/7/8/9–23 for the detection of an amount of pH in the juice samples.

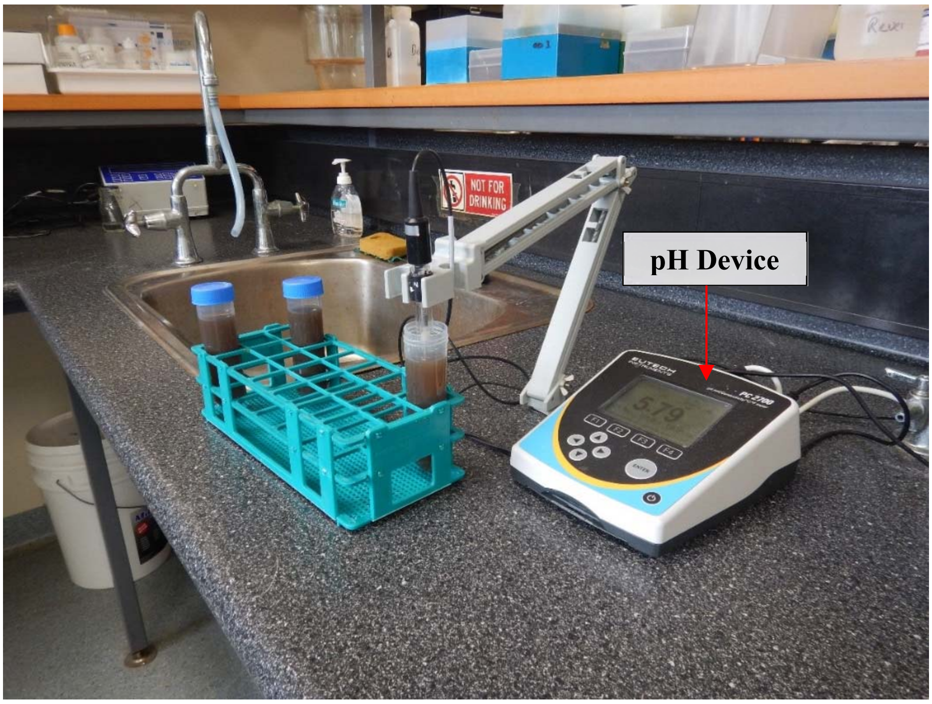


Figure 4.16 A pH meter used in the laboratory

4.3.5 Statistical analysis

The statistical analysis that was used to analyse the data from the trash and juice samples collected from Bundaberg (2014) and Ingham (2015) using IBM SPSS Statistics version 23 and Microsoft Excel, is detailed below.

- Sugar loss, brix, pol and pH from samples

A two-way ANOVA was performed to study the sugar loss effect of harvesting by using parameter at P-value ≤ 0.05. A DMRT was analysed to compare means of sugar loss and trash discharged by the cleaning system from samples of Bundaberg and Ingham trials.

Two-way ANOVA was used to assess the effect of varying N rates on the brix content of sugarcane trash discharged from the primary extractor systems by using parameter at P-value ≤ 0.05. The DMRT enabled a comparison of the means of brix value in liquid samples of Bundaberg and Ingham trials.

The brix and pol data associated with the liquid samples from the Ingham trial were analysed using a one-way ANOVA (P-value ≤ 0.05) to assess the effect of cutting pour rate on the brix and pol adhering to trash samples discharged from the primary extractor fan of the harvester. The DMRT post hoc test was performed to study the differences between the independent variables.

Two-Way ANOVA was analysed to study the significant effect of harvesting and experimental sites to consider pH of all juice samples before testing the amount of sugar with the colorimetric method. The parameter was used at P-value ≤ 0.05.

- The relationship of brix, pol and sugar loss impacted from harvesting

A one-way ANOVA was used to determine the relationships between brix, pol and sugar loss as influenced by cutting with a chopper harvester. The data included brix, pol and sugar losses adhering to the trash samples blown from the primary extractor fan. The analysis was performed to study the significance of the independent variables of N effects on the dependent variables of brix, pol and sugar loss by using parameter at P-value ≤ 0.05. The DMRT post hoc test was performed to study the differences between the independent variables. A simple regression was performed to analyse the relationships using Microsoft Excel.

The results are presented in the following section.

4.4 Results and discussions

4.4.1 Sugar loss evaluation by colorimetric assay

Production of a standard curve enabled simultaneous determination of the sugar content in the samples from each site. This decreased the error by reducing variations in room temperature and humidity during the test. The results are presented in Sections 4.4.1.1 and 4.4.1.2.

4.4.1.1 Standard solution to calculate sugar loss for samples from Bundaberg trial

Standard glucose samples were analysed to provide data for the standard curve to evaluate the sugar content in the samples when tested with the colorimetric device. The straight line equation was determined with Microsoft Excel. The results for the standard calibration are shown in Figure 4.17. The equation of the calibration line is shown in Equation 4.2.

$$y = 6.3456x + 0.2017 \qquad \text{Equation 4.2}$$

Where y = Standard Glucose (nmole)

x = Absorbance @ 570 nm

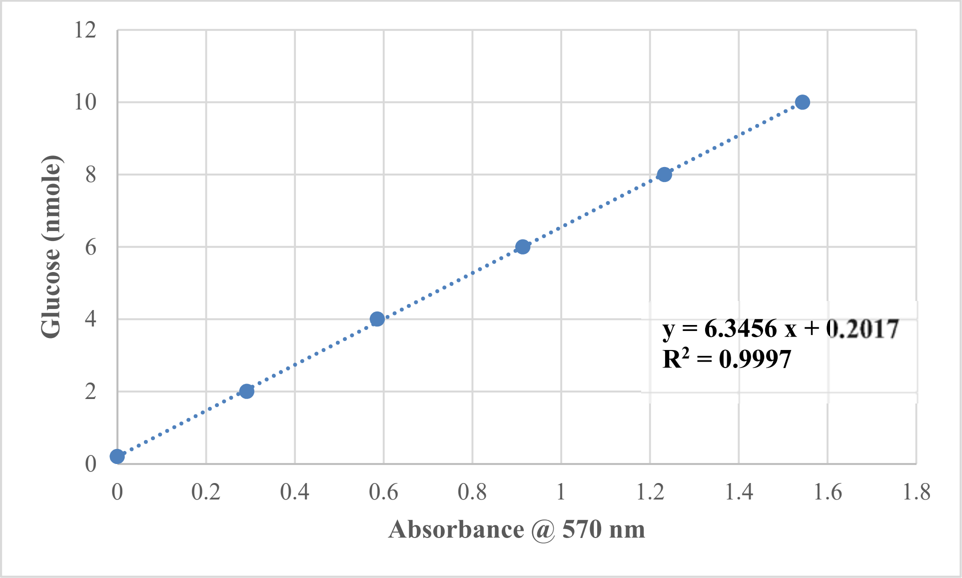


Figure 4.17 Standard curve used for the colorimetric assays of the Bundaberg samples

The light absorbance from all samples detected by the colorimetric device was calculated to evaluate the sugar content with the Equation 4.2 following the method of Sigma-Aldrich (2015). The sugar content results are shown in Table 4.1 and explained in Section 4.4.1.3.

4.4.1.2 Standard solution to measure sugar loss for samples from Ingham trial

Standard glucose samples were also used to construct a standard curve for calculating the sugar content in the samples from Ingham under the laboratory temperature and humidity conditions. The standard line was determined with Microsoft Excel. The results for the standard calibration are shown in Figure 4.18. The equation of the calibration line is shown in Equation 4.3.

$$y = 7.1483x - 2.0066 \qquad \text{Equation 4.3}$$

Where y = Standard Glucose (nmole)

x = Absorbance @ 570 nm

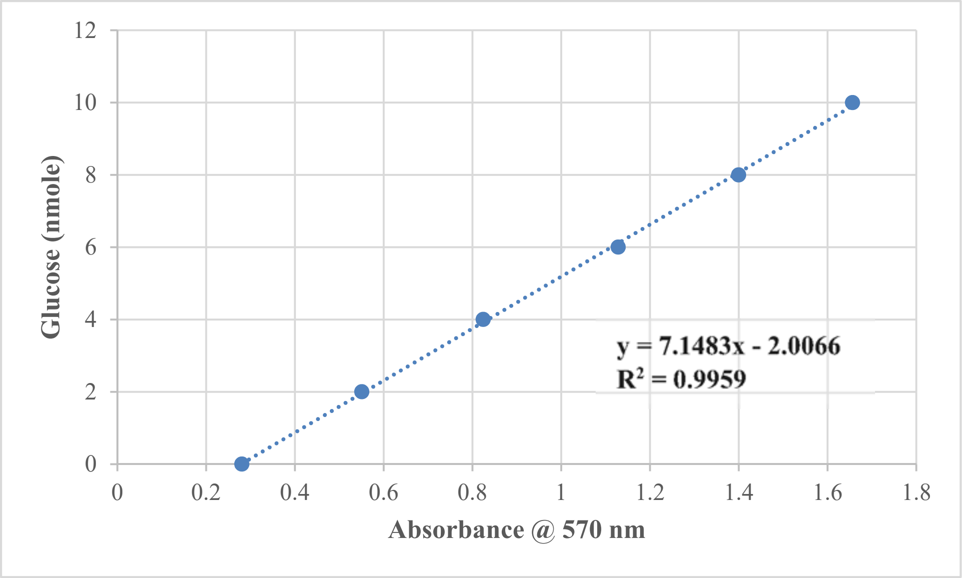


Figure 4.18 Standard curve used for the colorimetric assays of the Ingham samples

The light absorbance from all samples detected by the colorimetric device were calculated to evaluate the sugar content with the Equation 4.3. The sugar content results are shown in Table 4.1 and explained in Section 4.4.1.3.

4.4.1.3 Total sugar loss adhering to samples of Bundaberg and Ingham

Equations 4.2 and 4.3 were used to calculate the amount of glucose and sucrose in all samples from absorbance results detected by the colorimetric method, using the procedures of Sigma-Aldrich (2015). Glucose, added the twice volumes due to the sucrose inversion in sugarcane (Wikipedia 2017), was determined by the colorimetric method. Total sugar was increased by adding the amount of glucose due to sugar inversion. All data was evaluated to find total sugar loss in the field due to differences in yield resulting from varying N rates (Table 4.1).

Total sugar loss was the highest from plots that had received low N application rates at both the Bundaberg and Ingham sites (Table 4.1) when cutting with the chopper machine (P-value ≤ 0.05). In Bundaberg, the total sugar loss of 0.50 g occurred from plots that had received the low N rate (75 kg/ha). The same trend was observed at the Ingham site with the highest sugar loss (0.51 g) from plots that had received zero N applied (P-value ≤ 0.05). Although there was some evidence of differences in the amounts of trash expelled from the chopper harvester, they were not always significant (Table 4.1). When analysing the trash blown from the cleaning system, the sugar losses (t/ha) were not significantly different (P-value ≤ 0.05).

Table 4.1 Sugar loss adhering to trash ejected from the primary extractor system.

Site	N Rates (kg/ha)	Trash 20 g			Trash on field (t/ha)	Sugar loss (t/ha)
		Sucrose loss (g)	Glucose loss (g)	Total Sugar loss (g)		
Bundaberg	75	0.24 ^{bc}	0.26 ^{c}	0.50 ^{b}	17.48 ^{a}	0.43 ^{a}
	150	0.21 ^{b}	0.23 ^{bc}	0.44 ^{ab}	15.80 ^{a}	0.35 ^{a}
	225	0.08 ^{a}	0.27 ^{c}	0.35 ^{a}	21.49 ^{b}	0.38 ^{a}
Ingham	0	0.37 ^{d}	0.14 ^{ab}	0.51 ^{b}	17.95 ^{ab}	0.45 ^{a}
	100	0.37 ^{d}	0.06 ^{a}	0.43 ^{ab}	18.12 ^{ab}	0.39 ^{a}
	200	0.32 ^{cd}	0.03 ^{a}	0.35 ^{a}	18.45 ^{ab}	0.33 ^{a}

Means with the same column followed by the same letter are not significantly different (P-value ≤ 0.05)

Compared to the Ingham results, there were elevated glucose levels at the Bundaberg. This maybe have been caused by the extended storage duration of these samples due to delays in equipment availability, which promoted sucrose degradation. Although there are slight differences in the sugar fractions, the total sugar values are accurate.

When considering the sugar loss adhering to the trash, the highest sugar losses occurred at the low N rates at both sites. The low bulk density billets, caused by the low N rates, were ejected more easily with the trash during cleaning (Ridge & Dick 1988; *Harvesting best practice manual* 2014) than the normal heavier billets. In addition, sugar loss per area were calculated with the trash. The sugar loss (t/ha) was relatively constant across the N treatments despite the amount of the trash being higher at the high N rate. Nitrogen application rate is therefore an important factor when cane and sugar losses are considered at constant harvesting ground speed. The N levels produce crop sizes and yields which lead to changing pour rates and losses during harvesting. For example, the sugar loss of around 0.33 t/ha (Table 4.1) resulted from harvesting the high N rates (200 kg/ha) plots at Ingham trial. The monetary value of sugar loss during harvesting of the high N application plots was calculated at 152 AU$/ha (Note: sugar price at 460 AU$/t (QSL 2017) varied within year). The monetary value of sugar loss at the medium N rate was about 180 AU$/ha. Conversely, the effect of the low N rate at Ingham caused a sugar loss of 0.45 t/ha equating to the monetary value about 207 AU$/ha. These results indicate that there will be an income reduction with the lower N rate (the low crop nutrient practise). Therefore, the crop production will be concerned especially the optimum of the N application rates. When considering the crop yield influenced by the varying N application rates (Table 3.1, Chapter 3) and sugar loss occurring during harvesting (Table 4.1), the N rates between 100–150 kg/ha, as tested on the Bundaberg and Ingham trials, can improve the optimal crop size to reduce the sugar losses in trash ejected by the harvesting.

4.4.2 Sugar loss occurring on harvesting with chopper harvester influenced N rates

The sugar yield and sugar loss data from the two trials are presented in Table 4.2. Although there were significant sugar yield responses to applied N, sugar losses from the tarp test were not significantly different from each other. However, sugar losses expressed as a percentage of the sugar yield at the low N rates were significantly higher (P-value ≤ 0.05) than the percentage losses calculated for the higher N rates (Table 4.2): 7.09% at 75 N kg/ha at Bundaberg and 4.95% at 0 N kg/ha at the Ingham site.

Table 4.2 The amount of sugar loss discharged from the primary extractor system at Bundaberg and Ingham trials.

Site	N rate (kg/ha)	Sugar yield (t/ha)	Tarp sugar loss (t/ha)	Sugar loss as percentage of sugar yield (%)
Bundaberg	75	6.84 ^{a}	0.43 ^{a}	7.09 ^{c}
	150	13.92 ^{c}	0.35 ^{a}	2.55 ^{a}
	225	14.25 ^{c}	0.38 ^{a}	2.67 ^{a}
Ingham	0	9.44 ^{b}	0.45 ^{a}	4.95 ^{b}
	100	13.18 ^{c}	0.39 ^{a}	3.07 ^{a}
	200	13.62 ^{c}	0.33 ^{a}	2.48 ^{a}

Means with the same column followed by the same letter are not significantly different (P-value $\leq$ 0.05)

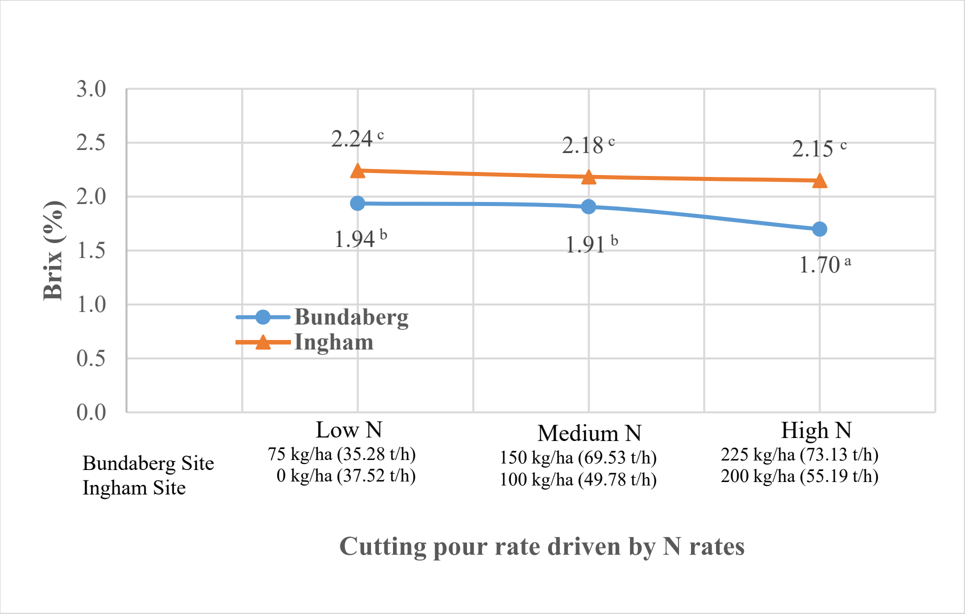
Sugar loss relative to the total sugar was the highest at the low N rates at both sites. This reflected similar trends in sugar losses shown in Table 4.1. With the quantification of the discharge of EM from the extractor system at commercial speed, small billet size (low mass as affected by reduced length and diameter) and sugar loss are both important contributors to overall harvesting losses (Ridge & Dick 1987; Ridge & Dick 1988; Whiteing & Norris 2002; *Harvesting best practice manual* 2014). As N application rates (Bundaberg trial) increased from 75 N kg/ha to 225 N kg/ha, sugar loss as a percentage of sugar yield decreased from 7.09% (0.43 t/ha) to 2.67% (0.30 t/ha). The average sugar loss was around 0.37 t/ha. When considering the sugar loss occurring across the entire Australian sugarcane growing area (381,000 ha) (ASMC 2017), will result in 141,000 tonnes of sugar being lost during harvesting by varying pour rates impacted by the crop nutrient practise. The loss of sugar is considerable for the whole of Australia. Thus, the optimal crop nutrient levels can improve the crop production as the optimum target yield to reduce sugar losses in trash during harvesting.

4.4.3 Brix, pol and pH in the juice of trash samples

4.4.3.1 Brix in liquid samples of Bundaberg and Ingham trials

The average brix results of trash juice samples, ejected by the extractor system from two sites, were highest at the low N application and generally decreased with increasing N application rate (Figure 4.19). Samples from the Bundaberg trial indicated that the brix associated with the high N rate was significantly lower than the brix values for the lower N rates (P-value ≤ 0.05). Although the brix values from the Ingham site showed some downward trend the differences were not significant (P-value ≤ 0.05) across the three N rates.

When considering the brix results from both sites (Figure 4.19), brix values at the low N applications were the highest. This corresponded to the higher relative sugar loss at the low N rates described in Section 4.4.1.3 with sugar was adhering to the trash during the cleaning. This again confirms the previous conclusion that light bulk density billets from low N plots can be more easily blown from the harvester by the primary extractor fans. Thus, the brix values are linked to the sugar loss in the trash samples (BSES 2001; ICUMSA 2013). It is therefore possible that brix values determined on trash samples (as influenced by N application rates in this case) can be used to evaluate the sugar loss during the harvesting (Whiteing 2013).

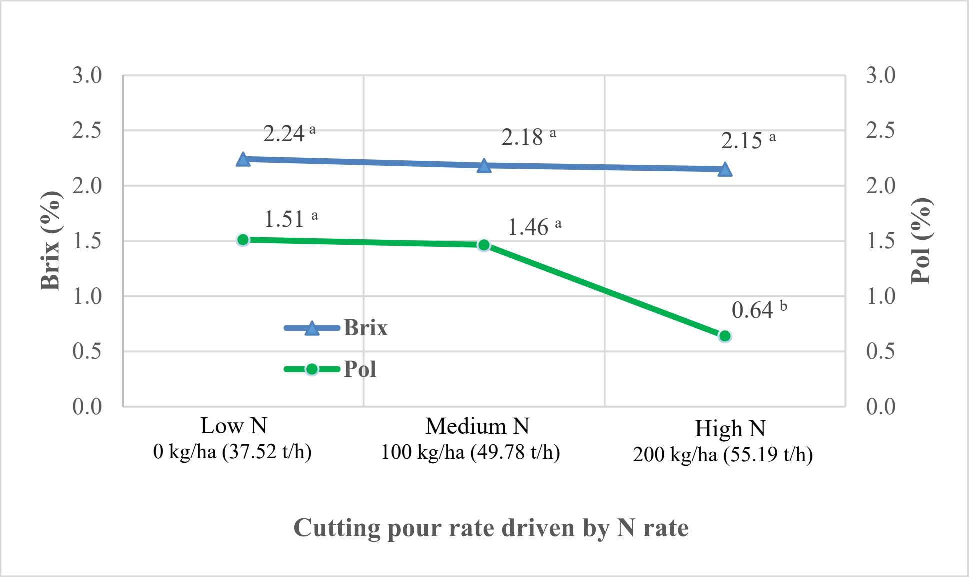


Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 4.19 Brix from the trash samples blown by the primary extractor system

4.4.3.2 Brix and pol in liquid samples of Ingham trial

The average brix of the samples was the highest (2.24%) at zero N applied (Figure 4.20). Although the values seemed to decrease as the N application rate increased, the differences were not significant (P-value ≤ 0.05). However, the pol values (1.51% and 1.46%) at the low and medium N rates were significantly higher than the mean pol value at the high N rate (P-value ≤ 0.05). This means that the percentage of pol was lower at the high N rate, with the balance of the brix in the juice being higher amounts of non-sucrose.



Means with the same line and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 4.20 Brix and pol of the trash samples discharged from the primary extractor system at Ingham trial

When considering the brix and pol values from Ingham trial, the brix values remained approximately constant across the N treatments. The pol of the juice extracted from the trash at the low N rate was high and decreased as N was applied. The size of the sugarcane crop due to the rate of N applied affected the amount of trash that was ejected during the cleaning process in the harvester. The brix and pol results from the trash samples (BSES 2001) can possibly be used to evaluate sugar loss during the harvesting as the results of Whiteing (2013).

4.4.3.3 pH in liquid samples

Average pH of the samples from the Bundaberg and Ingham are shown in Table 4.3. The results indicated that there was no statistical differences (P-value ≤ 0.05).

Table 4.3 pH of juice associated with the trash samples collected after harvest of the Bundaberg and Ingham trials.

Site	**Bundaberg**			**Ingham**		
N rate (kg/ha)	**75**	**150**	**225**	**0**	**100**	**200**
pH (Mean ± SD)	5.58 ± 0.12 ᵃ	5.50 ± 0.15 ᵃ	5.48 ± 0.14 ᵃ	5.49 ± 0.06 ᵃ	5.48 ± 0.06 ᵃ	5.54 ± 0.04 ᵃ

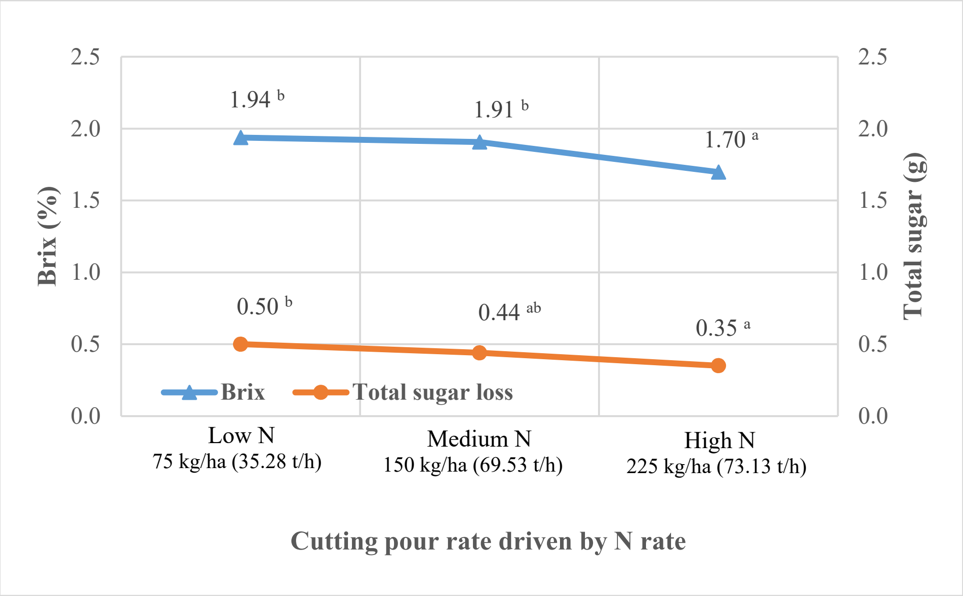
Means with the same row followed by the same letter are not significantly different (P-value ≤ 0.05)

The pH of a sample can be used to determine whether the sugar contents in the liquid samples have been degraded before measurement of the sucrose levels using a colorimetric procedure. This is an easy way of minimising the risk of unnecessary consumable and labour costs when using the colorimetric technique. From the measurement of pH value in the juice samples, the average value of pH values ranged from 5.48 ± 0.14 to 5.58 ± 0.12. This indicated that the pH of the juice samples was in the normal range and had not deteriorated due to temperature and microorganism effects (Panpae et al. 2008).

4.4.4 The relationship of brix, pol and sugar loss impacts from harvesting

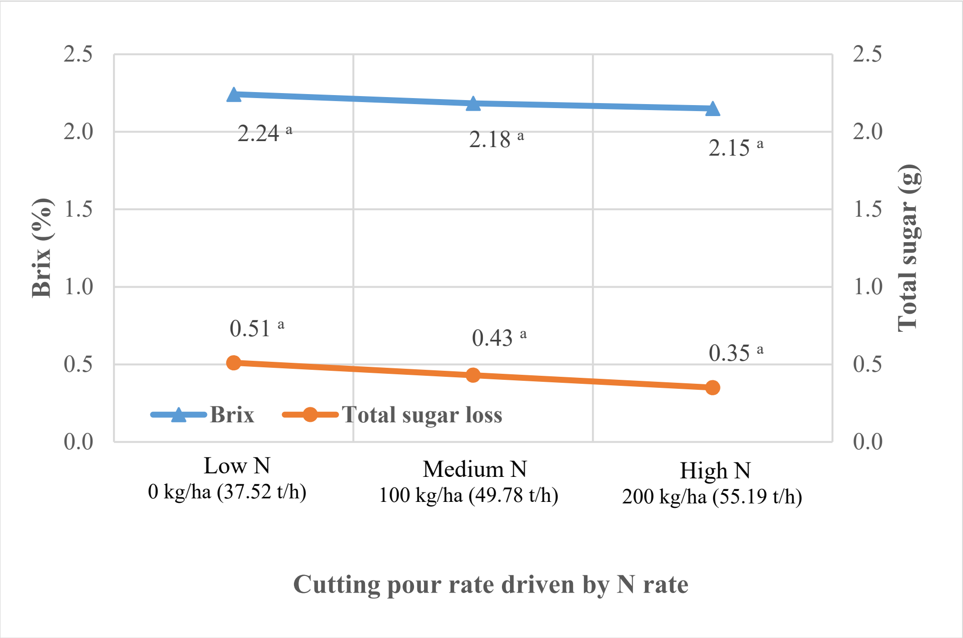
The brix and total sugar loss values associated with samples collected from the Bundaberg trial decreased as the N rate increased (Figure 4.21). Although the brix and total sugar losses associated with the samples collected from the Ingham site also decreased as the N rate increased the difference were not statistically different (P-value ≤ 0.05) (Figures 4.22 and 4.23).

The relationships between total sugar loss and brix and pol values for both sites are presented in Figures 4.24, 4.25 and 4.26. When the loss increases, the brix and pol values also increase. However as indicated in Figures 4.24 and 4.25, the relationship between brix and sugar loss were not significant. It is hypothesised that some materials adhering to the trash samples during the cutting dissolved in the juice (Thai & Doherty 2011) and caused varying brix values. In addition, the sucrose degradation in the samples could have been impacted by changing temperatures and storage times. Therefore, the various brix values from the samples were inconsistent with the sugar content results (Kawahigashi et al. 2013). However, when some of the outlying data (red outline) was removed from Figure 4.24, the correlation coefficient improved to $R^2 = 0.35$. This indicates that the credibility of the brix method may be reduced when used to compare brix to sugar content values under varying circumstances during the harvesting (Kawahigashi et al. 2013). The total sugar loss values plotted against pol values from the Ingham trial indicated an improved $R^2 = 0.80$). This result was in accordance with other research findings (BSES 2001; ICUMSA 2013; Whiteing 2013). When considering the relationship between the pol and sugar loss, the pol method provides a useful measure the sugar content adhering to the trash samples.



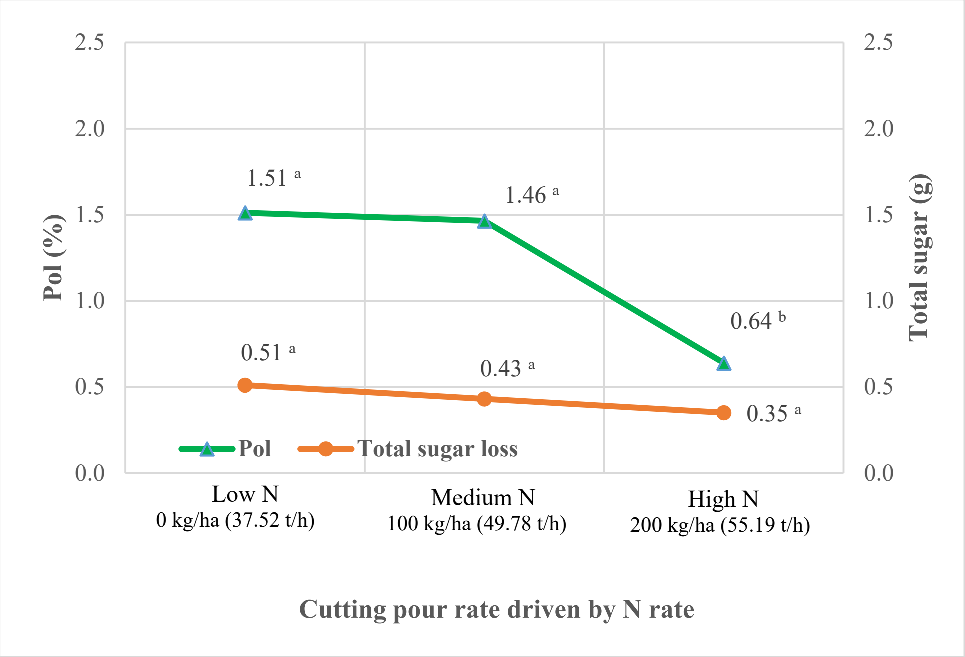
Means with the same line and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 4.21 The relationship between brix and total sugar loss on trash samples from a range of pour rates at the Bundaberg site



Means with the same line and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 4.22 The relationship between brix and total sugar loss on trash samples from a range of pour rates at the Ingham site



Means with the same line and sign followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 4.23 The relationship between pol and total sugar loss on trash samples from a range of pour rates at the Ingham site

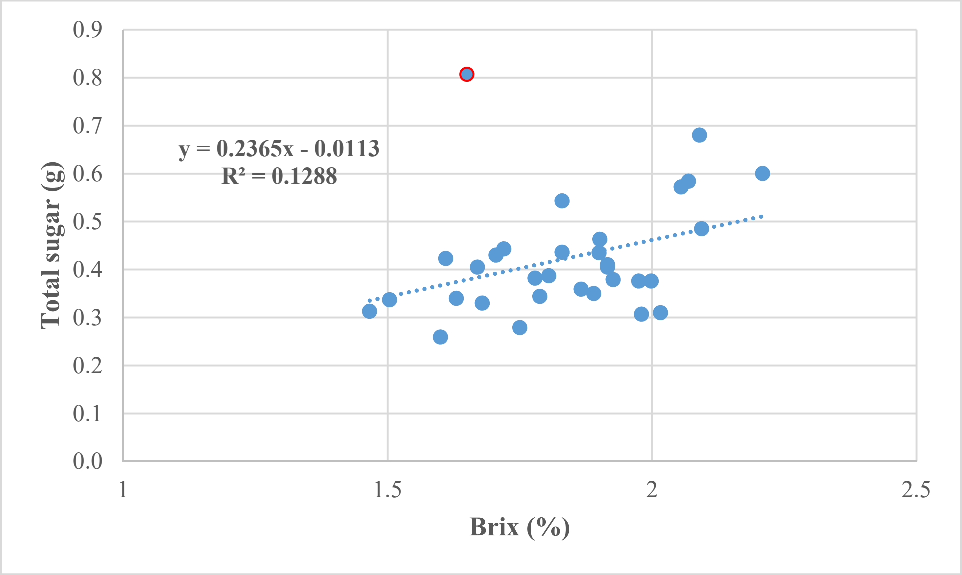


Figure 4.24 The relationship between brix and total sugar loss on trash samples from a range of pour rates at the Bundaberg site

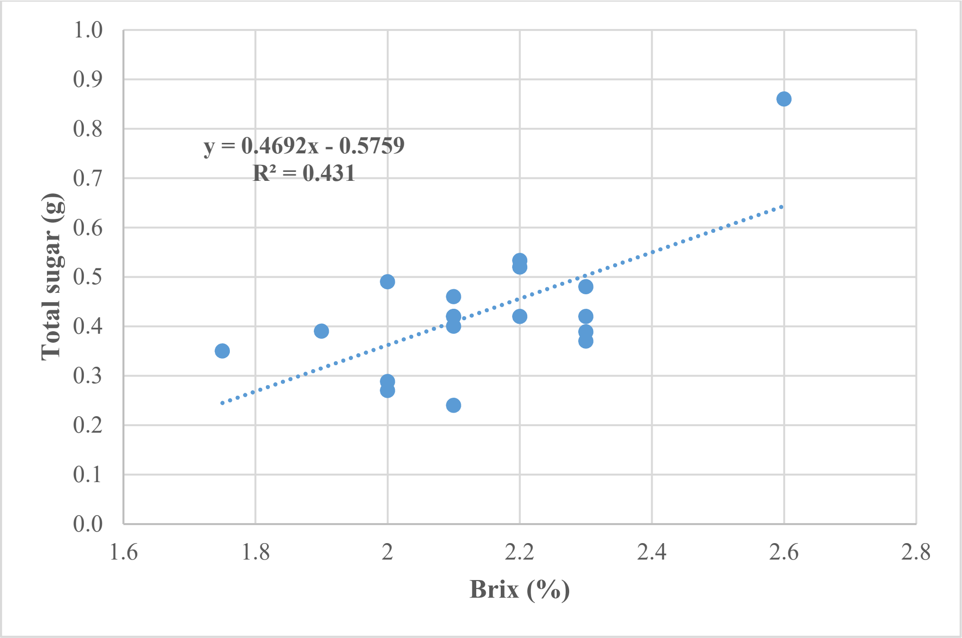


Figure 4.25 The relationship between brix and total sugar loss on trash samples from the Ingham site

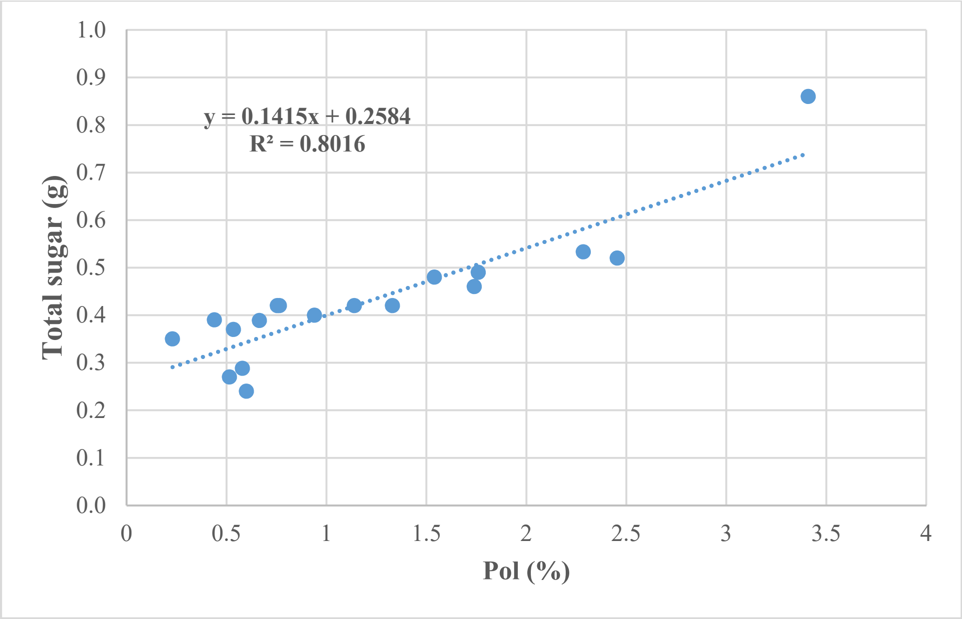


Figure 4.26 The relationship between pol and total sugar loss on trash samples from the Ingham site

The different N rates resulted in a range of pour rates which, in turn, impacted on the brix and pol values in the samples from the Bundaberg and Ingham sites. Both the brix and pol values increased at the lower pour rate (a corresponding low N rate) treatment at the two sites. This result was related to the increase in sugar loss due to juice adhering to EM that was discharged from the primary fan during the cleaning process. Accordingly, when sugar loss increases by cutting with the harvester, the brix and pol values rise also. However, the brix values can be variable due to a range of circumstance. A large number of samples may be necessary to establish a suitable relationship for predictive purposes (Kawahigashi et al. 2013). Thus, the pol method is therefore for more appropriate to test sugar losses from trash samples collected under variable harvesting conditions on commercial fields. Additionally, it was found that appropriate N rates that improve crop yield also support harvester performance during cutting and help reduce cane and sugar losses (Whiteing et al. 2001; *Harvesting best practice manual* 2014).

4.5 Conclusion

Sugar loss from the harvester was impacted by the crop condition, which in these trials was directly related to the N fertiliser application rates. In this chapter, sugar loss was examined under varying pour rates due to varying rates of N applied in two trials at two sites in Bundaberg and Ingham. The procedures to evaluate the samples in the field during cutting were based on the techniques of Whiteing (2013) that covered collection and calculation of sugar loss. The colorimetric method was used to measure the invisible sugar loss in the juice samples. Additionally, the pH value of the samples were tested to evaluate the deterioration of samples before measuring the amount of sugar with the colorimetric assay. The brix and pol values were used to determine the extent of sugar loss from the harvesting cane of different sizes.

The results from both sites indicated the low N rates (75 kg N/ha and 0 kg N/ha in the Bundaberg and Ingham trials respectively) affected the pour rates that were influenced by crop size. High sugar losses were indicated by increasing brix and pol values associated with trash samples expelled during cleaning by the primary extractor system. However, the larger crop sizes that were related to the high N applications rates resulted in decreased losses from the chopper harvester when the ground speed was constant. The results indicated that appropriate N fertiliser applications are important in improving crop size and helping to reduce cane and sugar losses associated with small crops and lighter billets during harvesting. The level of N application (100 N kg/ha at Ingham trial and 150 N kg at Bundaberg trial) can improve the crop production as the optimum target yield to reduce sugar losses in trash during harvesting. Another important consideration is to match the extractor fan speed and ground speed of the harvester to match the material (pour rate) presented to the machine.

Chapter 5 Influence of harvesting pour rate on billet supply and losses

5.1 Introduction

The impacts of sugar loss and cane quality under varying crop size conditions were discussed in chapter 3 and 4. This chapter focuses on the experimental work performed to study cane loss and quality of the sugarcane supply from the harvester, using the sugar loss assessment measuring technique developed by Whiteing (2013) and the colorimetric measurement technique (Buysse & Merckx 1993; Campbell et al. 1999). This chapter covers the following topics that relate to harvesting best practice:

- Background and literature review
- Materials and methods
- Results and discussion
- Conclusion

5.2 Background and literature review

5.2.1 Sugar industry improvement via harvesting best practice

Harvesting best practice (HBP) relates to the overall process, from a system management perspective that aims to reduce cane loss and EM in harvested cane from pre-harvest to post-harvest. There are three classes of factors affecting harvesting performance: farm factors (e.g. row profiles, soil types), harvester factors (e.g. topping, gathering, feeding chopping, cleaning) and farming system factors (e.g. pour rate, group size) (refer to Section 2.5). Many strategies have focused on the improvement and operation of the sugarcane harvester to reduce sugar loss and EM in cane billets. Harvesting best practice guidelines have been developed and improved to enable operators to make informed decisions about adjustments to their harvesters. Adopting HBP with particular attention to extractor speed, pour rate, feed train roller and chopper speed synchronisation, base cutter height setting, row profiles, row length and cane production can increase industry profitability for both millers and growers (refer to Section 2.6). Harvesting best practice not only increases the amount of whole cane delivered to the mills, but also the possibility of reduced environmental impacts associated with sugar juice entering watercourses causing de-oxygenation (Sandell & Agnew 2002; Jones 2004).

Traditionally, the chopper harvesters are fitted with hydraulic pressure gauges to monitor the base cutter and chopper systems as well as the primary extractor. This instrumentation assists operators to check cane loss and EM via hydraulic pressure and extractor speed and can adjust cutting speed, ground levelling and optimise fan speed to produce good quality cane (Agnew & Sandell 2000; Ridge & Norris 2000). In order to collect data from harvesters during operation, data loggers are installed to record elevator operations, base cutter and chopper pressure, primary extractor and ground speed, top roller opening position and time. These measurements assist in determining harvester capacity, which can be displayed to operators, to control all functions of harvesters to produce well-cleaned cane. Such an electronic system is able to collect comprehensive and accurate data that has led to yield mapping (Esquivel et al. 2007; Bella et al. 2009; Jensen et al. 2010). This information can contribute to improved yields and harvesting efficiency.

5.2.2 Effects of cane cleaning

5.2.2.1 Field factors

One of the main drivers of sugarcane quality and quantity is the field condition, that impacts on the mechanical harvester. Trash in cane supply increases when the cane is lodged and during wet conditions (Whiteing et al. 2001). Lodged and sprawled cane is more difficult to gather during harvesting resulting in increased trash and dirt loads. Sugarcane varieties with high leaf fibre lead to high EM that also affects the quality of the cane supply. These aforementioned aspects of harvesting are detailed in Section 2.4.1 and 3.4.2.

5.2.2.2 Harvesting pour rate

The ground speed of the chopper harvester and the crop size, impact on pour rate during harvesting. Trash and dirt levels in the cane are high when pour rate increases due to high harvesting speed (refer to section 3.2.2). As machine pour rates increase, the extractor system becomes overloaded and is unable to remove trash from the cane supply as effectively as it does at lower pour rates (Ridge & Norris 2000). High EM levels impact on cane supply delivered to mills. It is well-documented that trash and dirt in the cane supply (Whiteing et al. 2001; Whiting 2004) have the following impacts:

- reduce bulk density in bin which increases transport costs;
- reduce mill crushing capacity due to high fibre levels;
- decrease CCS and extraction efficiency; and
- have negative impacts on sugar quality

5.2.2.3 Extractor speed and cane loss

During harvesting, cane loss mainly occurs from the sugarcane harvesters during pick-up and gathering, at the base cutter and in the chopper and extractor systems (Whiteing & Norris 2002). The cleaning system of the harvester causes the main loss during cutting. When fan speed increases to reduce EM in cane supply, the cane loss increases (Sandell & Agnew 2002; NorrisECT 2013). This was detailed in section 2.4.5.

5.2.3 Improving harvest efficiency

Harvester efficiency is an important factor that drives profit for all growers and decreases sugar loss during cutting. Sugarcane field management therefore contributes to this overall process (Agnew et al. 2002).

a) Farm layout: Improving farm layout increases the productive time for harvesters and reduces the time spent turning on headlands. Wide headlands support fast and smooth turning of harvesters and haul-outs.
b) Row spacing and profile: Row spacing improves ratooning by minimising soil compaction and reduces stool damage from harvester and haul-out wheels. Additionally, row profile or hill-up reduces cane loss and dirt entrapment in cane supply when cut by the basecutter (refer to section 2.4.1).
c) Cane varieties and practices: Choice of cane varieties can improve harvest capacity. Lodged cane increases cane loss and dirt in cane supply (refer to section 2.4.1). Conversely, high-yielding erect cane and good practices such as better hilling up and nitrogen application, can increase harvesting efficiency.
d) Harvest planning: Scheduling of harvest allows for crops to be harvested at peak CCS.
e) Harvester setup and operating: Harvester maintenance particularly the condition of the base cutter and chopper blades has an important impact on

stool damage and cane loss from sharp or blunt blades including blade gap timing. Optimising extractor speed can also improve cane quality and supply.

f) Harvesting at wet conditions: Wet conditions cause harvesting difficulties and soil compaction effects. Good drainage improves soil traffic ability and minimises compaction at harvest in wet weather (refer to section 2.4.1).

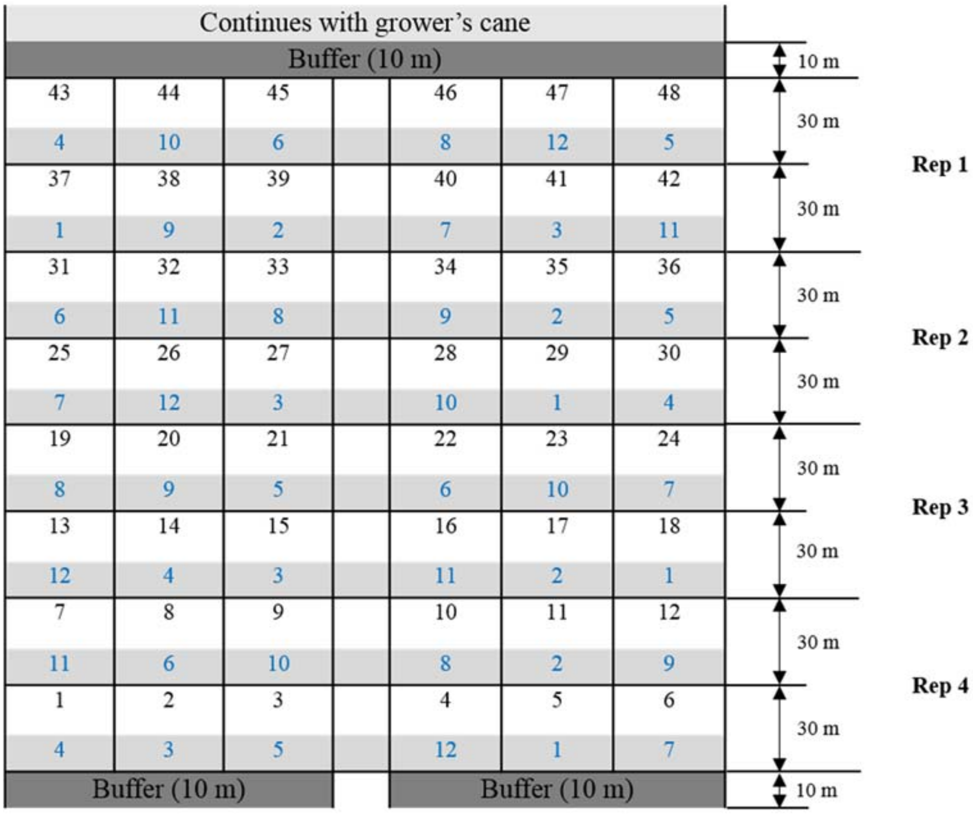
g) A sufficient bin supply: This reduces the time lost during harvesting operating.

5.3 Materials and methods

The methods used to collect data from the experimental fields followed those described by De Beer et al. (1985) and Whiteing (2013). All procedures are explained below.

5.3.1 Field crop conditions

This investigation used a pre-existing field trial located in Bundaberg, which was part of a SRA–funded project 2014/045 ‘Boosting nitrogen use efficiency in sugarcane through temporal and spatial management’. The trial aimed to study yield responses to different fertiliser formulations aimed at supplying N to the crop through temporal strategies. The application rates were based on the current N guide lines (SIX EASY STEPS). Sugarcane variety (Q183) was planted in a 1.83 m row-spacing layout in September 2015 (plant cane) and received the different N applications over a three to four-month period. The details of treatments and plots are shown in Figure 5.1. The quality determination of this work used these plots to investigate the pour rate effects on sugar loss during harvesting.



43 4	44 10	45 6	46 8	47 12	48 5	
37 1	38 9	39 2	40 7	41 3	42 11	Rep 1
31 6	32 11	33 8	34 9	35 2	36 5	
25 7	26 12	27 3	28 10	29 1	30 4	Rep 2
19 8	20 9	21 5	22 6	23 10	24 7	
13 12	14 4	15 3	16 11	17 2	18 1	Rep 3
7 11	8 6	9 10	10 8	11 2	12 9	
1 4	2 3	3 5	4 12	5 1	6 7	Rep 4

Treatment No.	Treatments
1	120 kg N/ha (Urea) 40, 40, 40, 0
2	120 kg N/ha (Urea) 40, 40, 20, 20
3	160 kg N/ha (Urea) 40, 80, 20, 20
4	160 kg N/ha (Urea) 40, 80, 40, 0
5	160 kg N/ha (Entec) 40, 120, 0, 0
6	120 kg N/ha (Urea) 40, 80, 0, 0
7	160 kg N/ha (Urea) 40, 120, 0, 0
8	120 kg N/ha (Entec) 40, 80, 0, 0
9	160 kg N/ha (Agromaster) 40, 120, 0, 0
10	120 kg N/ha (Agromaster) 40, 80, 0, 0
11	160 kg N/ha (Urea) 40, 40, 40, 40
12	Control

Soil type: Red clay loam
Plots: 6 rows × 30 m × 1.83 m
Variety: Q183
Cane planted: 09/09/2015

Block No.
Treatment No.

Figure 5.1 The field trials at Bundaberg 2016

5.3.2 Chopper harvester and speed controllers

An Austoft model 7000/1996 (electric option) harvester was used to harvest the cane. The harvester had a modified chopper [381 mm (15 inch) diameter differential chopper drum with four knives (width of 65 mm) and extractor system (a vertical primary extractor (anti-vortex type) fitted with four standard blades] to improve the cleaning operation. The speeds of primary extractor fan were driven and controlled by a hydraulic system that was controlled by a variable displacement piston pump and a fixed displacement motor (closed circuit system) (Figure 5.2).

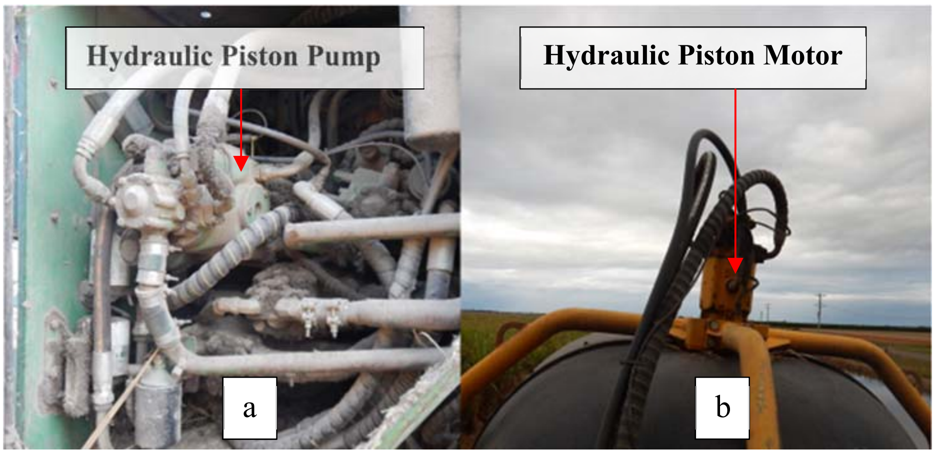


Figure 5.2 Hydraulic system driven the primary extractor system

(a) Variable displacement piston pump (b) Fixed displacement piston motor

The harvester was preinstalled with instruments to monitor cleaning and ground speed. A cane loss monitor (www.agridrydryers.com) measured the speeds of the primary fan (Figure 5.3). A sensor was fitted on a vertical arm of the primary extractor system to detect the speeds and revolutions and transfer the data to the in-cab monitor. The ground speeds were detected with a global navigation satellite system (GNSS) via an AutoFarm RTK guidance device (www.novariant.com) (Figure 5.4). The forward speeds were controlled from the harvester cabin using the operator controls.

Figure 5.3 The cane loss monitor measuring the primary fan speed levels

Figure 5.4 The AutoFarm monitor controlling the ground speeds during the cutting

5.3.3 Harvesting test procedures

The procedures used to measure sugarcane qualities and quantities including sugar loss during harvesting are detailed below.

5.3.3.1 Plot physical properties

Physical properties of sugarcane: (refer to section 3.3.3)

1) Stalk population densities were determined by counting the number of mature stalks in a 5 m linear section in each of the 2 middle rows of each plot.
2) The yields were calculated by weighing all the cane stalks from the 2 x 5 m sections of row (Figure 5.5 and 5.6).
3) Six stalks were randomly selected from the harvested material for further evaluation:
    - Stalk weight (partitioned into tops, brown leaves and stalks) was recorded from a Wedderburn Model DS-531 balance (Figure 5.7)
    - Stalk diameters at multiple locations (node and internode at top, middle and bottom of each stalk) was measured using calibrated vernier callipers.
    - Stalk lengths measured using a tape measure.

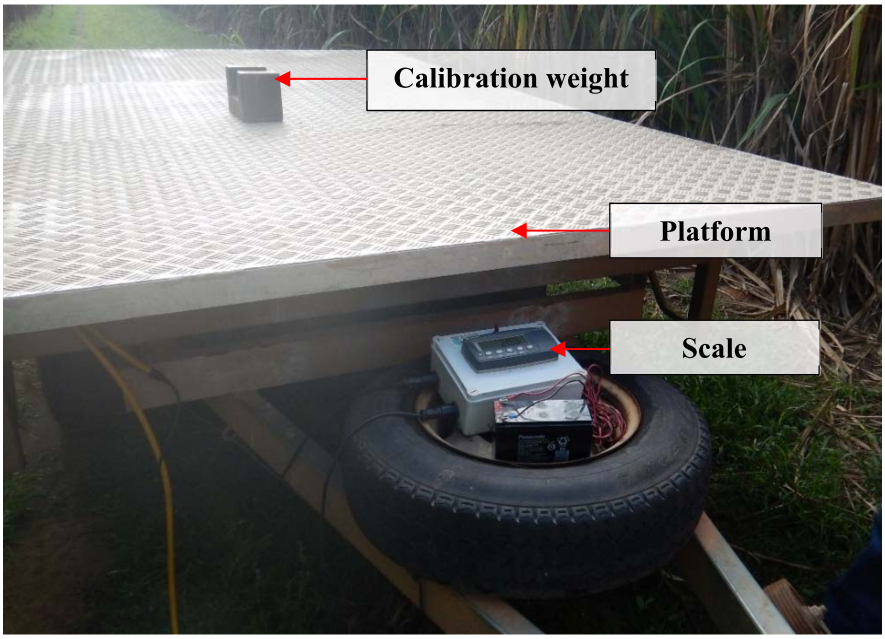


Figure 5.5 Scale was calibrated before measuring cane samples

Figure 5.6 Weighing cane from plot to determine yield (2016)

Figure 5.7 Weighed sugarcane top and brown leaves (2016)

Sugarcane qualities:

The six stalks sample from each plot were shredded to evaluate sugarcane qualities that included brix, pol and fibre of the cane, measured by a hydraulic press method (Birkett 1998; BSES 2001). The instrument that was used to test the quality samples was located at SRA Bundaberg.

5.3.3.2 Harvester setup

1) **Primary extractor speed calibration**

The primary extractor fan was calibrated to ensure that the fan speed was properly set before cutting. Firstly, the free-running fan was set at three speeds [850, 1,000 and 1,260 (full speed) r/min]. The harvester ground speed was then set at 6 km/h during the calibration phase. The calibration equation then enabled the fan speed to be set for the harvesting tests.

Setting fan speed after the calibration and ground speed adjustment

The ground and fan speeds were adjusted to enable harvesting impacts to be determined at three speeds. Calibrated data were used to set the working speed of the primary extractor for the in-field testing. Fan speeds were adjusted to the 3 working speeds of 650, 850 and 1,050 r/min recommended by other reports (Whiteing & Norris 2002; NorrisECT 2012, 2013). Sugarcane billet quality and quantity and sugar losses were determined for each of the fan speeds with ground speeds set at 4, 5 and 6 km/h.

Harvesting under varying pour rates and fan speeds

In this investigation, the topper and secondary extractor system were not used during harvesting across the range of fan and ground speeds. The same sampling method as detailed in section 3.3.3 was used for this trial.

1) **Billet supply from harvesting**

The chopper machine was tested in the sugarcane trials by controlling the factors of forward and fan speeds during operation. Sugarcane billet subsamples were collected from the elevator into a trailer (Figure 5.8). Billet samples of between 20–25 kg per sample were collected to measure the parameters indicated below using the procedures of De Beer et al. (1985):

- Billet subsamples were uniformly packed into a plastic box of known dimension (450 mm × 385 mm × 670 mm) and weighed in order to calculate density (Figure 5.9).
- The samples were classified into billets, trash and dirt by weight (Figure 5.10 and 5.11).
- Billet size distribution was determined using the following length intervals: 0–100, 100–150, 150–200, 200–250, 250–300, 300–350, 350–400 and > 400 mm (Figure 5.12). Each size category was weighed. The mean lengths for the billets were calculated according to De Beer et al. (1985). Explanations are provided in section 3.3.3.
- Billet qualities were classified into three groups (Figure 5.13) based on the assessment methodology detailed by De Beer et al. (1985). The detailed explanation is provided in section 3.3.3.

Figure 5.8 Sugarcane billet samples collected in the trailer (2016)

Figure 5.9 Billet sample were weighed to calculate the bulk density

Figure 5.10 Sorting the billet sample (2016)

Figure 5.11 Classification of material (2016):

(a) Billet (b) Trash (c) Soil and dirt

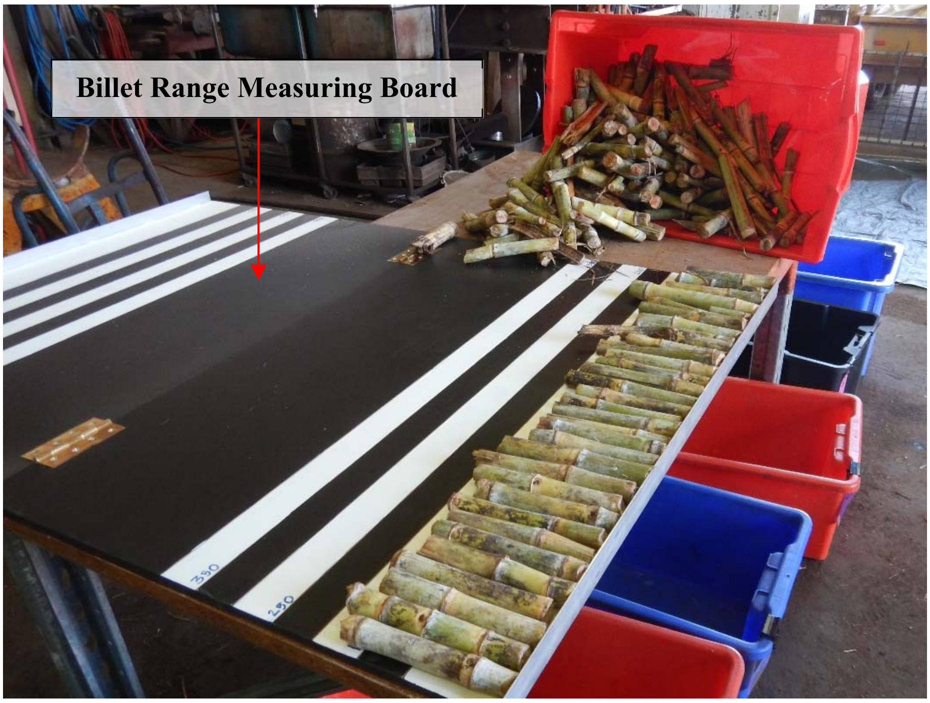


Figure 5.12 Billet length measured on a classification board (2016)

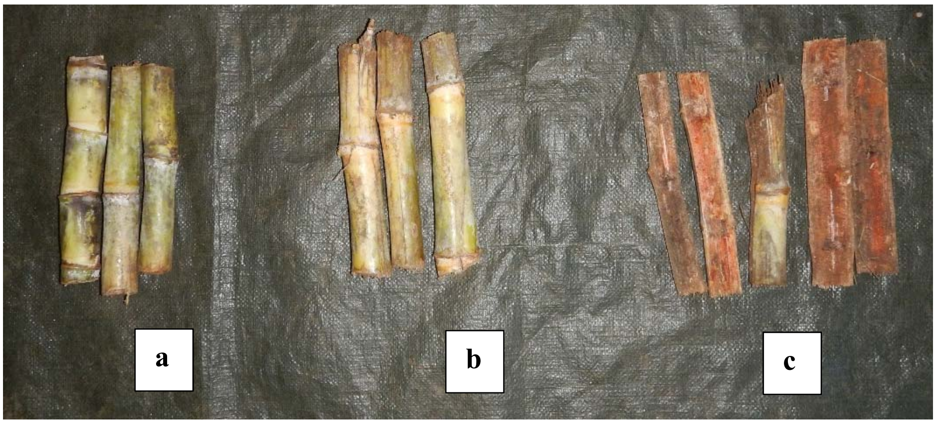


Figure 5.13 Billet qualities classified into three categories (2016): (a) Sound billet (b) Damaged billet (c) Mutilated billet

2) Cane billet qualities during harvesting

A sample of approximately 2 kg was collected from the trailer and shredded for testing at the SRA Bundaberg laboratory. The shredded material was tested using the same hydraulic press method (Birkett 1998; BSES 2001) for brix, pol and fibre.

3) Sugar loss caused by the varying pour rates and fan speeds

- The sugarcane trash from each plot was collected from the blue tarps during cleaning by the primary extractor system. This enabled the impact of ground and cleaning speed of the chopper machine to be determined. All procedures were explained in section 4.3.2.1 (Figure 5.14, 5.15, 5.16, 5.17 and 5.18).
- The samples of shredded trash were preserved at -25 °C and prepared for analysis to determine the amount of sugar adhering to the trash surfaces in a laboratory. Details are provided in section 4.3.2.2.

Figure 5.14 Blue tarp located adjacent to the harvested row (2016)

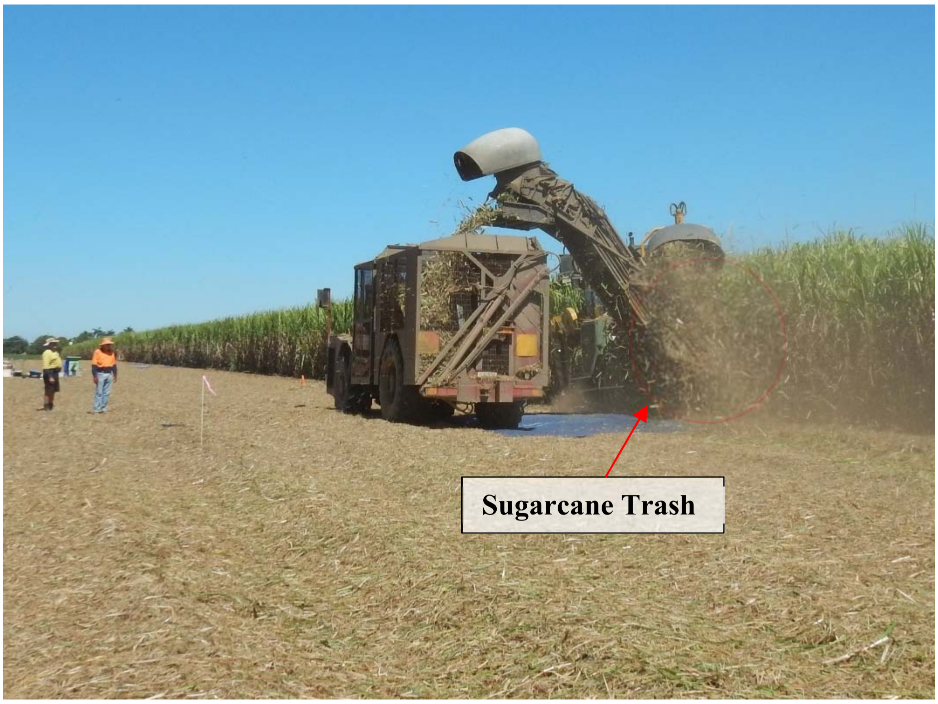


Figure 5.15 Residues blown onto the blue tarp (2016)

Figure 5.16 Trash on the tarp was collected for weighing (2016)

Figure 5.17 Weighing the trash sample (2016)

Figure 5.18 Trash was shredded using a mulcher (Viking, GB480 6 kW) (2016)

- The shredded residue samples were also used to measure the moisture content due to varying fan speeds. The moisture content was determined in samples by weighing the sample before and after drying in an oven (www.steridium.com) set at a temperature of 105 °C, for 4 h (*Official methods of analysis of AOAC International* 1996) (Figure 5.19).

Figure 5.19 Determining the moisture content of the trash samples

5.3.4 Commercial harvesting operations

Data collected as part of a Sugar Research Australia (SRA) funded project 2014/028 ‘Product and profit—Delivering precision to users of precision agriculture in the Australian sugar industry—Yield monitoring’ was utilised for analysis. The procedures were as follows:

- Blocks of sugarcane in the Childers area south of Bundaberg were used to collect data during harvesting by a contractor at commercial speeds.
- A data logger was set up on the harvester to record the cutting pour rates and ground speeds during actual harvest events.
- Cane loss as determined from the field trial in Bundaberg 2016, was used to calculate the loss of income from the various pour rates relevant to the commercial harvesting in the Childers blocks.
- All data were analysed with the yield monitor.

5.3.5 Statistical analysis

The relationships of sugarcane quality and quantities from the effects of pour rate and cane cleaning were tested using statistical analysis (IBM SPSS Statistics 23) (IBM

2015). Microsoft Excel was used to analyse all data of cane qualities and quantities that related to the cutting by the chopper harvester.

- Crop sizing influenced by the varying N rates

Sugarcane physical parameters affected by varying N application rates were investigated by using a one-way ANOVA method to analyse the data (P-value ≤ 0.05). A Duncan post-hoc test was performed to study the differences of factor means.

- Billet quantities and qualities impacted by harvesting speed
  - Bulk density and billet supply components

A two-way ANOVA was performed to study the effect of the different ground speeds and the varying fan speeds. The analysis was performed to study the significance of the effect of the independent variables of ground speed and cleaning fan speed, on the dependent variables of the bulk density and the component (billet, trash and dirt) of billet supply parameter at P-value ≤ 0.05. A Duncan post-hoc test (DMRT) was performed to study the differences between the independent variables.

  - Sugarcane billet length distribution

Two-way ANOVA was performed on the billet length data as influenced by ground speed and fan speed (P-value ≤ 0.05). The procedure was performed using a post-hoc test for multiple comparisons with a DMRT.

  - Sugarcane billet quality

Two-way ANOVA was used to determine the effect of the various ground and fan speeds on billet quality especially in terms of assessing the occurrence of sound, damaged or mutilated billets (P-value ≤ 0.05). A Duncan post-hoc test was performed to establish the extent of differences in these quality parameters.

  - Sugarcane billet supply quality (mill delivery)

The billet samples influenced by the different ground and fan speeds were used to measure product qualities (brix, pol and fibre % cane) during delivery to the mill. Two-way ANOVA was used to analyse the impacts of ground speeds and primary extractor speed on these chemical parameters (P-value ≤ 0.05). The procedure was performed using a post-hoc test for multiple comparisons with a DMRT.

- Sugarcane loss when cut with varying fan and ground speeds

The sugarcane trash samples collected from the harvester operated at various ground and fan speeds during harvesting were used to measure the sugar loss. Two-way ANOVA was used to analyse these impacts at P-value ≤ 0.05. A Duncan post-hoc test was used to determine the differences between the independent variables.

5.4 Results and discussions

5.4.1 Crop sizing influenced by the varying N rates

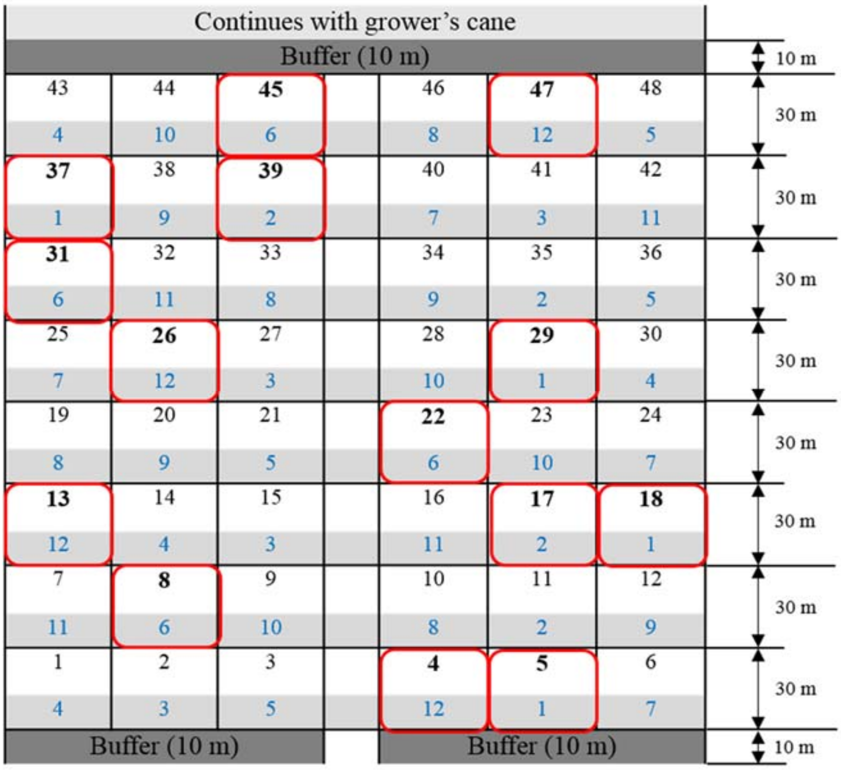
Sugarcane physical properties affected from the variable N rates were examined and compared by evaluating the differences of factor means. The results are shown in Table 5.1. Although the means of the various physical and chemical properties of the sugarcane harvested from the Bundaberg trial showed some differences, they were generally not statistically significant (P-value ≤ 0.05). The exceptions were the means of the percentage of brown leaves and the pol in juice (Table 5.1).

Table 5.1 Physical and chemical properties of sugarcane (Bundaberg trial 2016).

Treatment	Yield (t/ha)	Cane Stalk			Cane weight (%)			Pol in Juice (%)	Brix in Juice (%)	Fibre in Cane (%)
		Crop Density (Stalks/ m)	Diameter (mm)	Length (cm)	Stalk	Top	Brown Leaves			
1	103.57 ^{a}	11.30 ^{a}	25.64 ^{a}	221.58 ^{a}	72.09 ^{a}	15.79 ^{a}	12.12 ^{ab}	83.13 ^{ab}	21.62 ^{a}	13.38 ^{a}
2	103.00 ^{a}	11.96 ^{a}	24.44 ^{a}	219.7 ^{a}	70.36 ^{a}	16.44 ^{a}	13.20 ^{ab}	84.53 ^{ab}	21.93 ^{a}	13.04 ^{a}
3	109.97 ^{a}	11.18 ^{a}	25.76 ^{a}	240.00 ^{a}	73.39 ^{a}	15.90 ^{a}	10.71 ^{ab}	84.00 ^{a}	21.83 ^{a}	13.40 ^{a}
4	112.85 ^{a}	11.50 ^{a}	25.36 ^{a}	234.00 ^{a}	69.30 ^{a}	16.77 ^{a}	13.94 ^{a}	82.50 ^{ab}	21.61 ^{a}	13.55 ^{a}
6	104.58 ^{a}	11.20 ^{a}	25.17 ^{a}	232.92 ^{a}	70.86 ^{a}	18.19 ^{a}	10.95 ^{ab}	84.27 ^{a}	21.81 ^{a}	13.62 ^{a}
7	110.76 ^{a}	11.13 ^{a}	25.13 ^{a}	218.42 ^{a}	58.87 ^{a}	15.43 ^{a}	25.70 ^{ab}	83.98 ^{b}	22.01 ^{a}	13.06 ^{a}
11	110.26 ^{a}	11.53 ^{a}	25.39 ^{a}	229.08 ^{a}	68.85 ^{a}	15.03 ^{a}	16.12 ^{b}	85.94 ^{ab}	22.17 ^{a}	13.37 ^{a}
12	109.83 ^{a}	11.43 ^{a}	25.19 ^{a}	230.96 ^{a}	69.62 ^{a}	15.55 ^{a}	14.84 ^{ab}	85.27 ^{ab}	22.19 ^{a}	13.36 ^{a}

Means with the same column followed by the same letter are not significantly different (P-value ≤ 0.05)

The lack of significant responses is probably due to the trial being a plant crop with little chance of presenting marked yield differences due to fertiliser N treatments. Due to this lack of variability, all samples (across the N treatments) can be used to evaluate the effects of fan and ground speeds on cane quality and quantity, and sugar losses during harvesting. Plots for this investigation were chosen on a random basis (shown by the red squares in Figure 5.20).



Continues with grower's cane

Buffer (10 m) — 10 m

43 4	44 10	**45** 6	46 8	**47** 12	48 5	30 m
37 1	38 9	**39** 2	40 7	41 3	42 11	30 m
31 6	32 11	33 8	34 9	35 2	36 5	30 m
25 7	**26** 12	27 3	28 10	**29** 1	30 4	30 m
19 8	20 9	21 5	**22** 6	23 10	24 7	30 m
13 12	14 4	15 3	16 11	**17** 2	**18** 1	30 m
7 11	**8** 6	9 10	10 8	11 2	12 9	30 m
1 4	2 3	3 5	**4** 12	**5** 1	6 7	30 m

Buffer (10 m) Buffer (10 m) — 10 m

Treatment No.	Treatments
1	120 kg N/ha (Urea) 40, 40, 40, 0
2	120 kg N/ha (Urea) 40, 40, 20, 20
3	160 kg N/ha (Urea) 40, 80, 20, 20
4	160 kg N/ha (Urea) 40, 80, 40, 0
5	160 kg N/ha (Entec) 40, 120, 0, 0
6	120 kg N/ha (Urea) 40, 80, 0, 0
7	160 kg N/ha (Urea) 40, 120, 0, 0
8	120 kg N/ha (Entec) 40, 80, 0, 0
9	160 kg N/ha (Agromaster) 40, 120, 0, 0
10	120 kg N/ha (Agromaster) 40, 80, 0, 0
11	160 kg N/ha (Urea) 40, 40, 40, 40
12	Control

Soil type: Red clay loam
Plots: 6 rows × 30 m × 1.83 m
Variety: Q183
Cane planted: 09/09/2015

Block No.
Treatment No.

Figure 5.20 Field trials at Bundaberg 2016

5.4.2 Fan speed calibration

The results of the evaluation of the primary extractor speed were set with free operating speeds of 850, 1,000 and 1,260 (full fan speed) r/min. Free operating (no-load) speeds were measured, as was the working fan speed during cutting to determine the relationship for use when samples were collected from the trial. The regression line of the fan speeds is indicated in Figure 5.21.

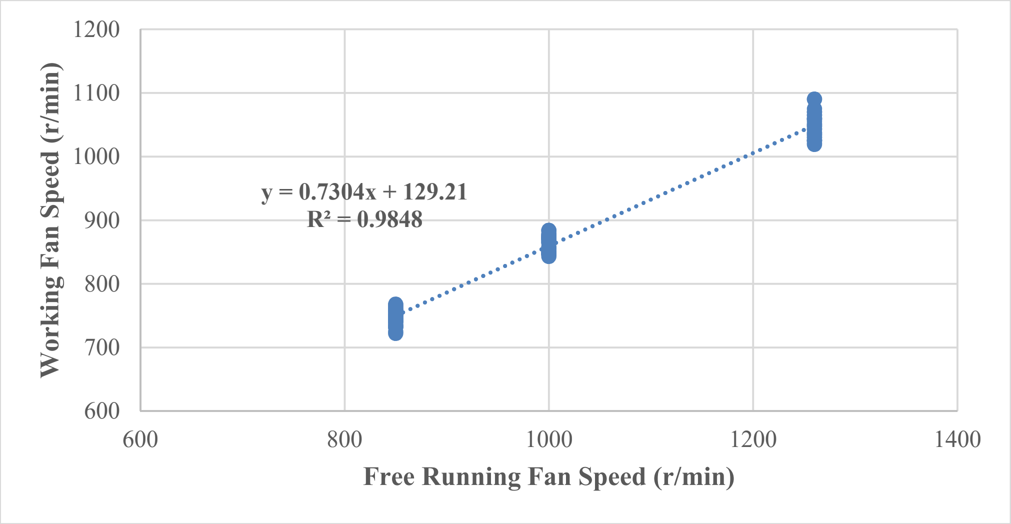


Figure 5.21 Fan speed calibration

Using the linear regression line from an equation 5.1 (Figure 5.21), the primary extractor system was set according to the values shown in Table 5.2.

$$Y = 0.7304X + 129.21 \qquad \text{Equation 5.1}$$

Where Y = Working fan speed (r/min)

X = Free fan speed (r/min)

In order to achieve the desired speeds of 650, 850 and 1050 r/min (recommended by NorrisECT (2013)), free running speeds of 715, 990 and 1260 r/min were selected.

Table 5.2 The primary extractor speeds were adjusted before cutting the Bundaberg trials 2016.

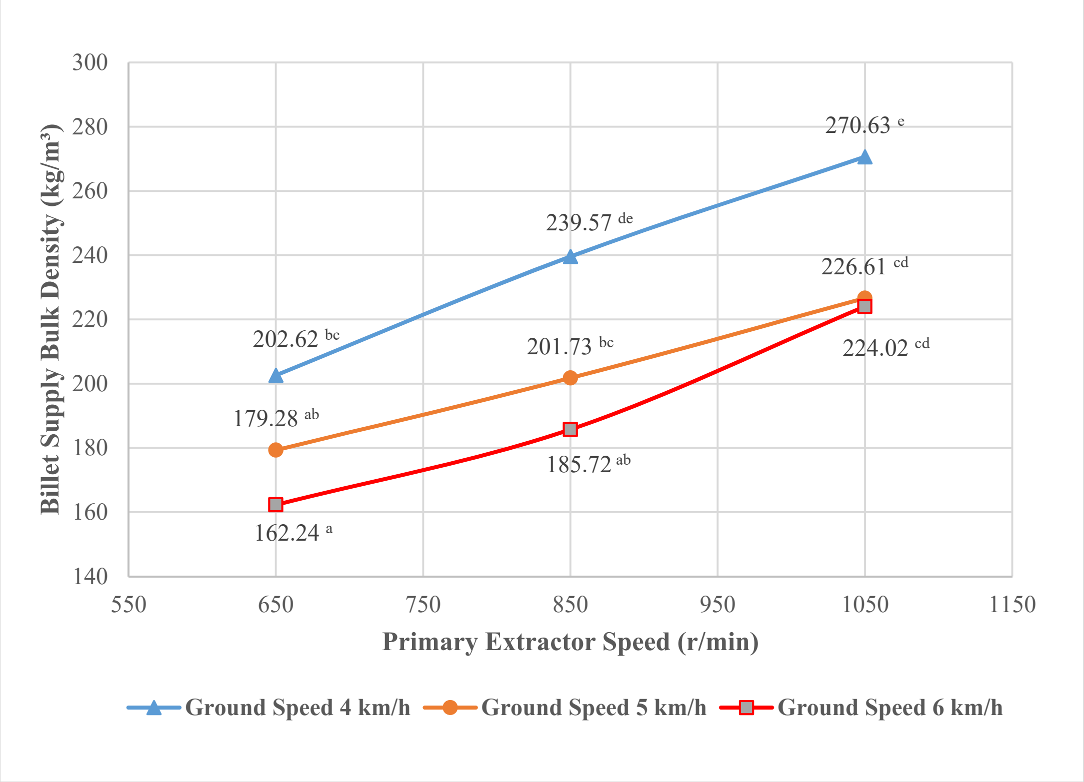
Primary extractor system	Loaded fan speed (r/min)	Unloaded fan speed (r/min)	SD (r/min)
	650	715	± 12.43
	850	990	± 12.63
	1050	1260	± 19.78

5.4.3 Billet quantities and qualities impacted by harvesting speed

5.4.3.1 Bulk density and billet supply components

The billet samples were measured to analyse the effect of varying fan and ground speeds to the bulk density and billet supply components. The results are shown in Figure 5.22 and 5.23. The analysis gave the following results:

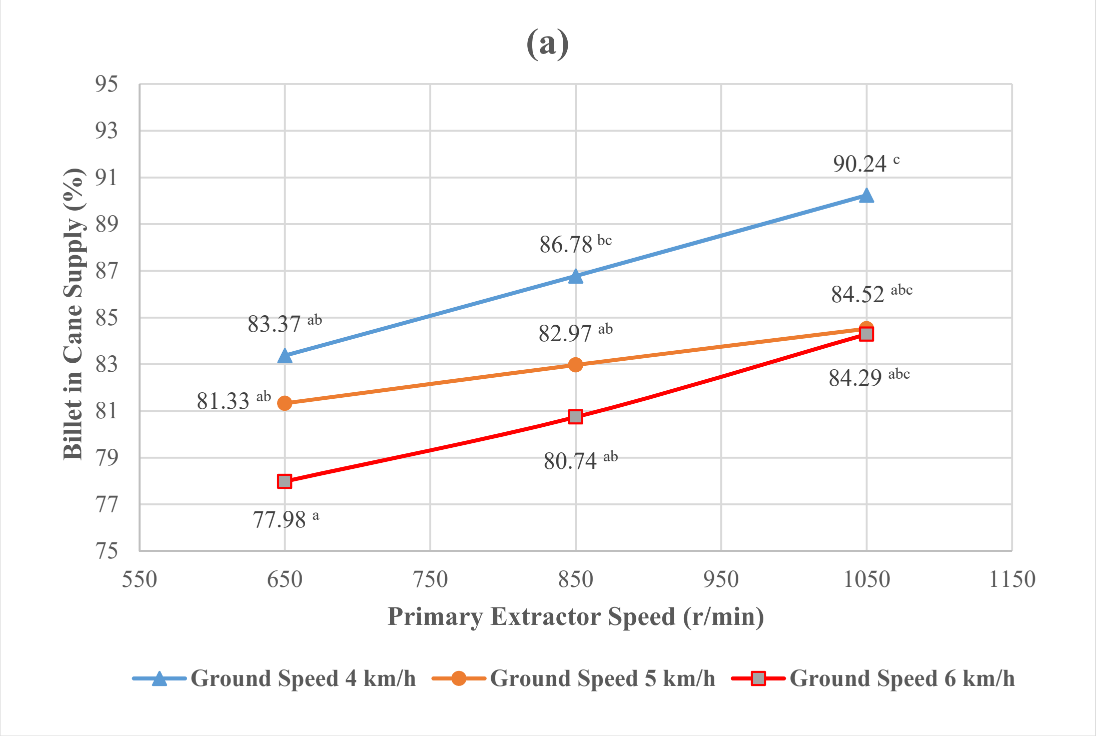
- From Figure 5.22, the bulk density of the cane billet supply increased with increasing fan speeds and slower ground speeds. The ground and fan speeds of the harvester (4 km/h and 1,050 r/min respectively) produced the highest bulk density at 270.6 kg/m^3 (P-value ≤ 0.05). Conversely, the lowest bulk density occurred with the ground speed at 6 km/h and the fan speed at 650 r/min, was 162.2 kg/m^3 (P-value ≤ 0.05).



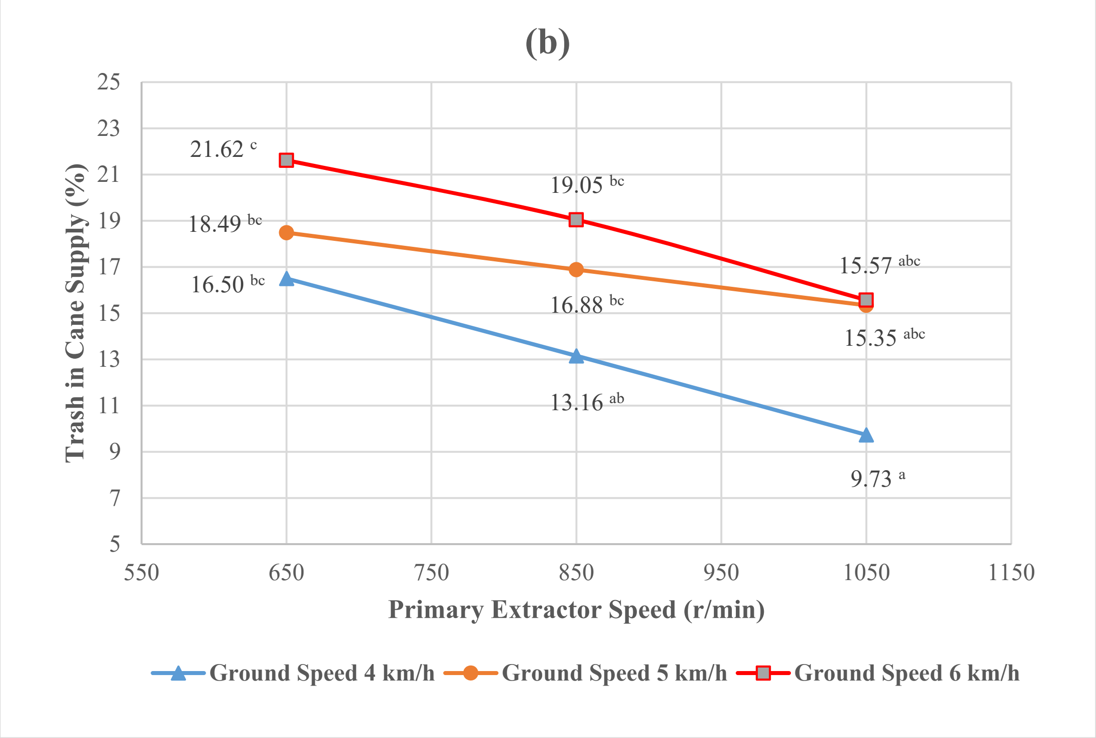
Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.22 Bulk density of billet supply affected by the primary extractor and ground speeds

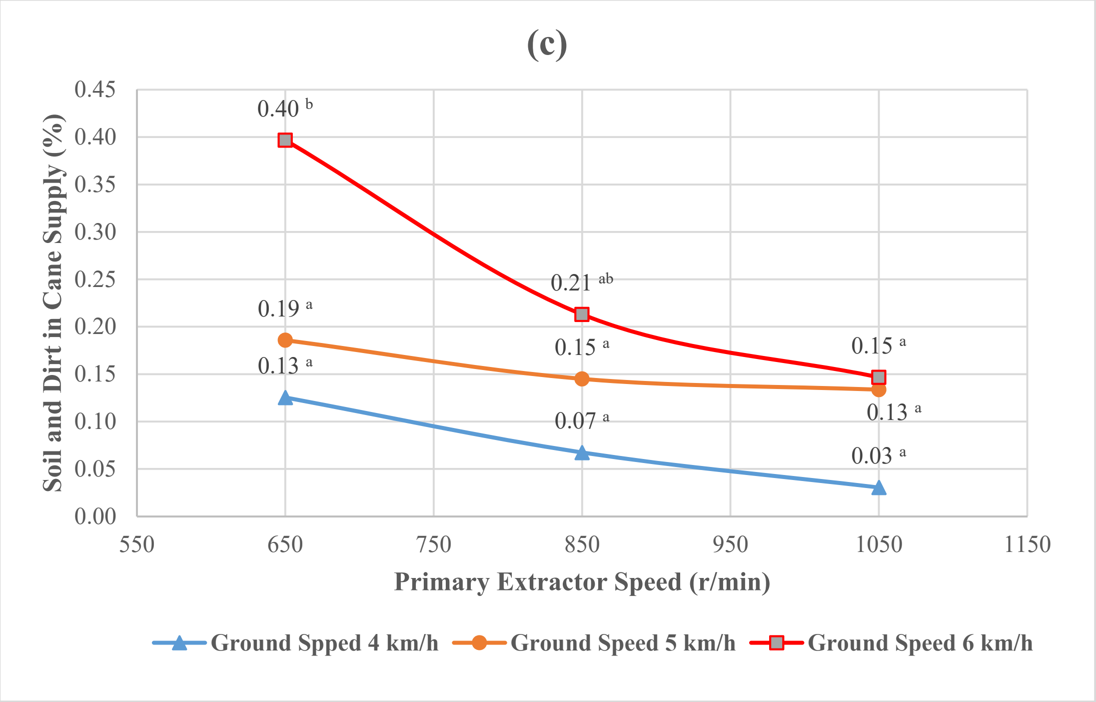
- The highest percentage of billets in the cane supply (90.2%) (Figure 5.23a) was achieved by adjusting the fan and ground speeds at 1,050 r/min and 4 km/h respectively (P-value ≤ 0.05). On the other hand, the lowest billet percentage was a result of fan and ground speeds at 650 r/min and 6 km/h (P-value ≤ 0.05).
- The EM of the cane supply is shown in Figure 5.23b and 5.23c. The percentage of trash and soil / dirt in the billet supply decreased with higher fan and lower ground speeds. The lowest percentage of trash (9.73%) was obtained with high fan speed at 1,050 r/min and the low ground speed at 4 km/h (P-value ≤ 0.05) (Figure 5.23b). Additionally, the lowest percentage of soil and dirt material (0.03%) occurred at the same speeds (P-value ≤ 0.05). Conversely, the highest percentage of EM (trash 21.62% and soil with dirt 0.40%) resulted from low fan speed and the high ground speeds (650 r/min and 6 km/h respectively) (P-value ≤ 0.05) shown in Figure 5.23b and 5.23c.



Means followed by the same letter are not significantly different (P-value ≤ 0.05)



Means followed by the same letter are not significantly different (P-value ≤ 0.05)



Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.23 Billet supply influenced by the primary extractor and ground speeds (a) % billet by weight (b) % trash by weight (c) % soil and dirt by weight

These results show that the components making up the cane supply (billet, trash and soil and dirt) cut by the harvester, are strongly influenced by the primary extractor and ground speed settings. The bulk density of cane increases under the lower pour rates from decreased ground speed and is in agreement with the other research related to HBP (Norris & Ridge 1998; Agnew et al. 2002; Whiteing 2013; *Harvesting best practice manual* 2014). Additionally, high fan speed can reduce the amount of EM in the billet supply during harvesting (Figure 5.23b and 5.23c). These results are also in agreement with information from other studies (Pearce & Ridge 1992; Whiteing 2004; Inderbitzin 2012; *Harvesting best practice manual* 2014).

5.4.3.2 Sugarcane billet length distribution

Billet length distribution was measured to study the impact of various fan and ground speeds to the billet size. The results are shown in Table 5.3 and Figure 5.24. The analysis highlighted the following results:

- The overall percentage of billets in the category 0–100 mm was 1.88 ± 1.68 but was not significant (P-value ≤ 0.05). The percentage of billet size between 0 and 100 mm long was highest (4.10 ± 4.87%) when the ground speed was 4 km/h with a fan speed of 850 r/min.
- The overall percentage of billets in the range 100–150 mm was 2.54 ± 1.36. The highest percentage of this range was 4.38 ± 1.92 at the ground speed 4 km/h and the fan speed of 850 r/min (significant at P-value ≤ 0.05).
- The highest percentage of billets in the range 150–200 occurred at a ground speed of 4 km/h and a fan speed of 1050 r/min) with a value of 96.16 ± 1.58 (significant at P-value ≤ 0.05). This is the percentage in all lengths.
- The highest percentage of billets (9.38 ± 6.72%, significant at P-value ≤ 0.05) in the range 200–250 mm occurred at a ground speed of 4 km/h and the primary extractor speed of 650 r/min.
- Very few billets fell in the range 250–300 mm.

The majority of the billets occurred in the category of 150–200 mm with an average occurrence of 92.92%. Restricted distribution of stalk lengths results in billets of approximate uniform size and reduced bulk density of the billet supply (Ridge & Dick 1988; *Harvesting best practice manual* 2014). Such material is easier to clean with the extractor system and results in decreased loss problems (refer to section 3.4.2.2 and section 4.4.2).

Table 5.3 The billet length category due to the range of ground and primary extractor speeds.

Ground Speed (km/h)	**Fan Speed (r/min)**	**Billet Category (%)**				
		0–100 mm	**100–150 mm**	**150–200 mm**	**200–250 mm**	**250–300 mm**
4	**650**	1.62 ± 0.29 ^{a}	3.24 ± 0.72 ^{ab}	85.76 ± 6.30 ^{a}	9.38 ± 6.72 ^{b}	–
	850	4.10 ± 4.87 ^{a}	4.38 ± 1.92 ^{b}	89.08 ± 4.82 ^{ab}	2.24 ± 1.97 ^{a}	0.21 ± 0.36 ^{a}
	1050	1.08 ± 0.20 ^{a}	1.50 ± 0.90 ^{a}	96.16 ± 1.58 ^{c}	1.26 ± 0.77 ^{a}	–
5	**650**	0.97 ± 0.33 ^{a}	2.34 ± 1.52 ^{ab}	96.14 ± 0.83 ^{c}	0.55 ± 0.96 ^{a}	–
	850	1.99 ± 0.75 ^{a}	2.85 ± 1.31 ^{ab}	93.47 ± 1.03 ^{bc}	1.68 ± 1.60 ^{a}	–
	1050	1.90 ± 0.73 ^{a}	2.04 ± 0.85 ^{a}	92.09 ± 2.67 ^{bc}	2.86 ± 1.36 ^{a}	1.12 ± 1.15 ^{b}
6	**650**	1.38 ± 0.28 ^{a}	2.25 ± 0.73 ^{ab}	95.83 ± 0.41 ^{c}	0.53 ± 0.66 ^{a}	–
	850	2.25 ± 1.18 ^{a}	1.06 ± 0.28 ^{a}	93.79 ± 0.91 ^{bc}	2.90 ± 2.15 ^{a}	–
	1050	1.66 ± 0.10 ^{a}	3.20 ± 1.21 ^{ab}	93.95 ± 1.04 ^{bc}	1.20 ± 0.38 ^{a}	–

Means with the same column followed by the same letter are not significantly different (P-value $\leq$ 0.05)

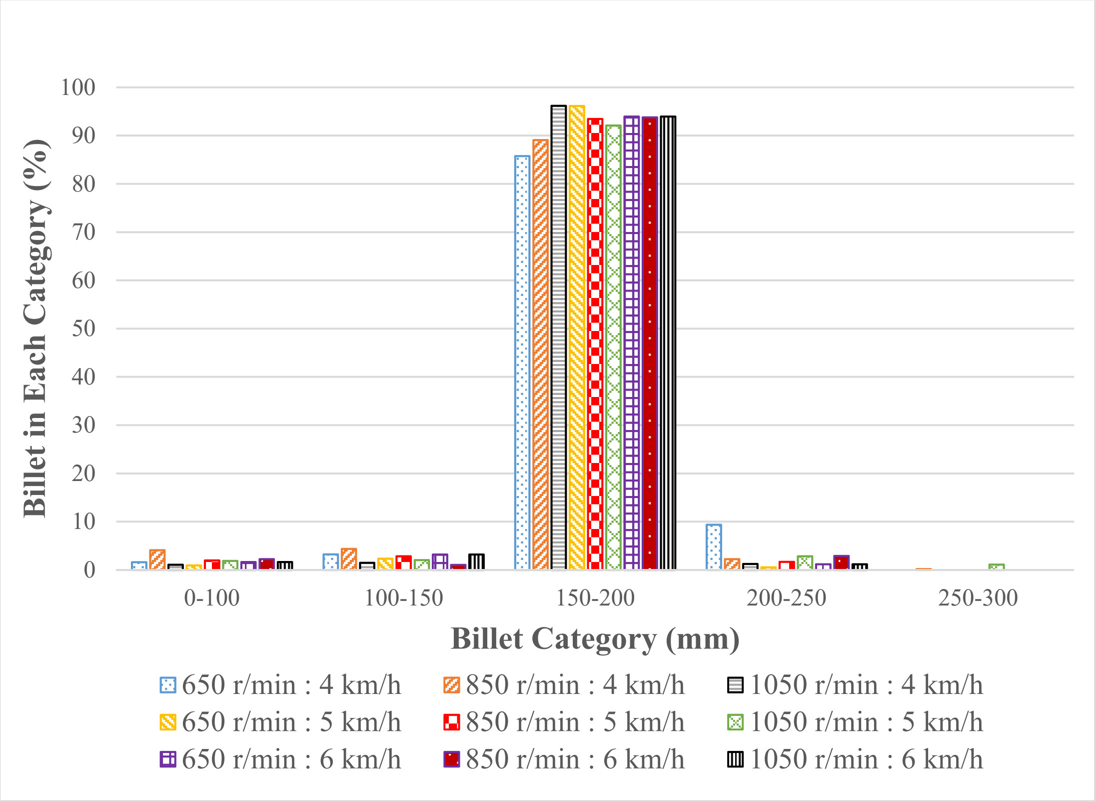


Figure 5.24 Billet lengths from the harvester influenced between the primary extractor and ground speeds

5.4.3.3 Sugarcane billet quality

The billet samples were classified into three quality-based categories using the procedure of De Beer et al. (1985). The descriptive statistics results and Duncan's new multiple range tests (DMRT) are shown in Table 5.4 and Figure 5.25. The data indicated that:

- Sound billets presented as the highest percentage (87.67 ± 1.37%) at a ground speed 4 km/h and the primary extractor speed at 1050 r/min (P-value ≤ 0.05). The overall average percentage of sound billets across all ground and fan speeds was 84.57 ± 5.33.
- The highest perecentage of damaged (13.25 ± 4.82%) occurred at a ground speed of 4 km/h and a fan speed of 850 r/min (P-value ≤ 0.05). The lowest perecentage of damaged billets (5.56 ± 3.05%) occurred at a fan speed of 850 r/min and a ground speed of 5 km/h (P-value ≤ 0.05).

- The highest percentage of mutilated billets (10.72 ± 3.11%) occurred at the fan speed of 850 r/min and operating at 4 km/h (P-value ≤ 0.05).

Table 5.4 The billet quality due to the range of the ground and primary extractor speeds.

Ground Speed (km/h)	**Fan Speed (r/min)**	**Billet Quality (%)**		
		Sound Billet	**Damaged Billet**	**Mutilated Billet**
4	**650**	84.86 ± 4.85 ^{bc}	9.42 ± 0.83 ^{ab}	5.72 ± 3.99 ^{a}
	850	76.05 ± 6.56 ^{a}	13.25 ± 4.82 ^{b}	10.70 ± 3.11 ^{b}
	1050	87.67 ± 1.37 ^{bc}	5.85 ± 1.48 ^{a}	6.48 ± 0.59 ^{ab}
5	**650**	86.02 ± 1.16 ^{bc}	8.52 ± 0.95 ^{a}	5.46 ± 1.21 ^{a}
	850	87.00 ± 7.09 ^{c}	5.56 ± 3.05 ^{a}	7.44 ± 1.69 ^{ab}
	1050	82.59 ± 3.78 ^{abc}	8.07 ± 1.87 ^{a}	9.34 ± 3.38 ^{ab}
6	**650**	87.18 ± 2.85 ^{bc}	7.42 ± 2.90 ^{a}	5.41 ± 0.95 ^{a}
	850	85.40 ± 2.85 ^{bc}	7.50 ± 2.14 ^{a}	7.10 ± 2.92 ^{ab}
	1050	80.25 ± 2.48 ^{ab}	10.46 ± 2.21 ^{ab}	9.29 ± 1.65 ^{ab}

Means with the same column followed by the same letter are not significantly different (P-value ≤ 0.05)

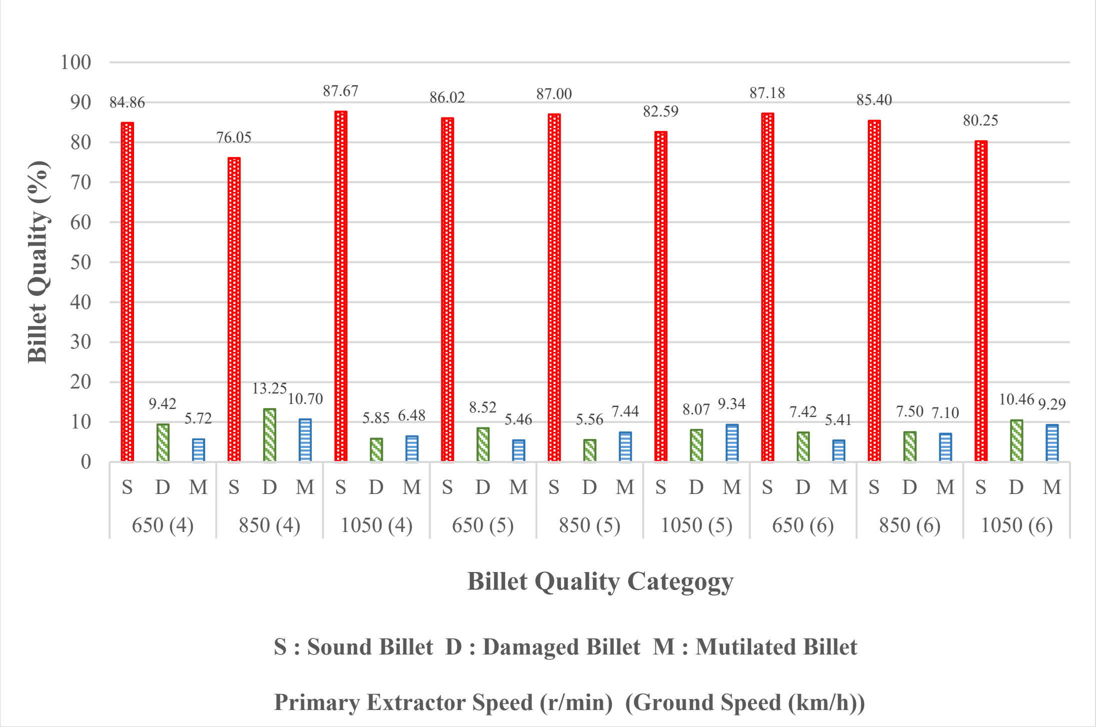


Figure 5.25 Billet quality impacted by the primary extractor and ground speeds

The relatively consistent billet length (section 5.4.3.2) and billet quality (sound, damaged and mutilated billets) across all treatments suggest that the feed train roller speeds are consistent with the chopper speed system (Norris et al. 2000). Consistency between the feed rollers speeds and the chopper systems ensure that billets of similar length with reduced damage and tension in the cane bundle (Norris & David 2001). Uniform billet length and hence bulk density enable the extractor fans to eject trash more easily than with billets of varying sizes, thus reducing cane loss (section 3.4.2.2 and 3.4.2.3). These results are similar to those presented in other reports/publications (Ridge & Dick 1988; *Harvesting best practice manual* 2014).

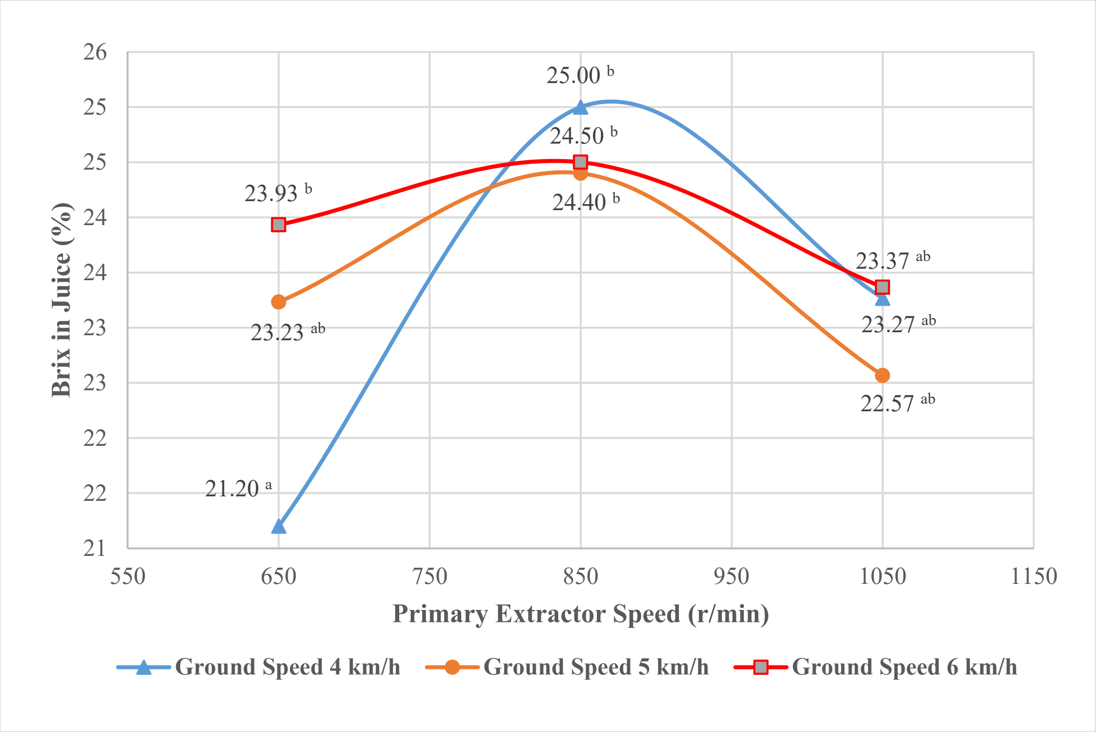
5.4.3.4 Sugarcane billet supply quality (mill delivery)

The billet samples influenced by the different ground and fan speeds were used to determine quality parameters (brix, pol and fibre % cane) during delivery to the mill. The results are displayed in Figure 5.26, 5.27 and 5.28 and show that:

- In Figure 5.26, the results brix in juice varied between 21.20 and 25.00%. The minimum value (21.20%) occurred at a ground speed of 4 km/h and at fan speed of 650 r/min (P-value ≤ 0.05). The maximum value was 25.00% occurred at ground and fan speeds of 4 km/h and 850 r/min respectively (P-value ≤ 0.05), although the intermediate values indicated some variability, they were not significant different (P-value ≤ 0.05).

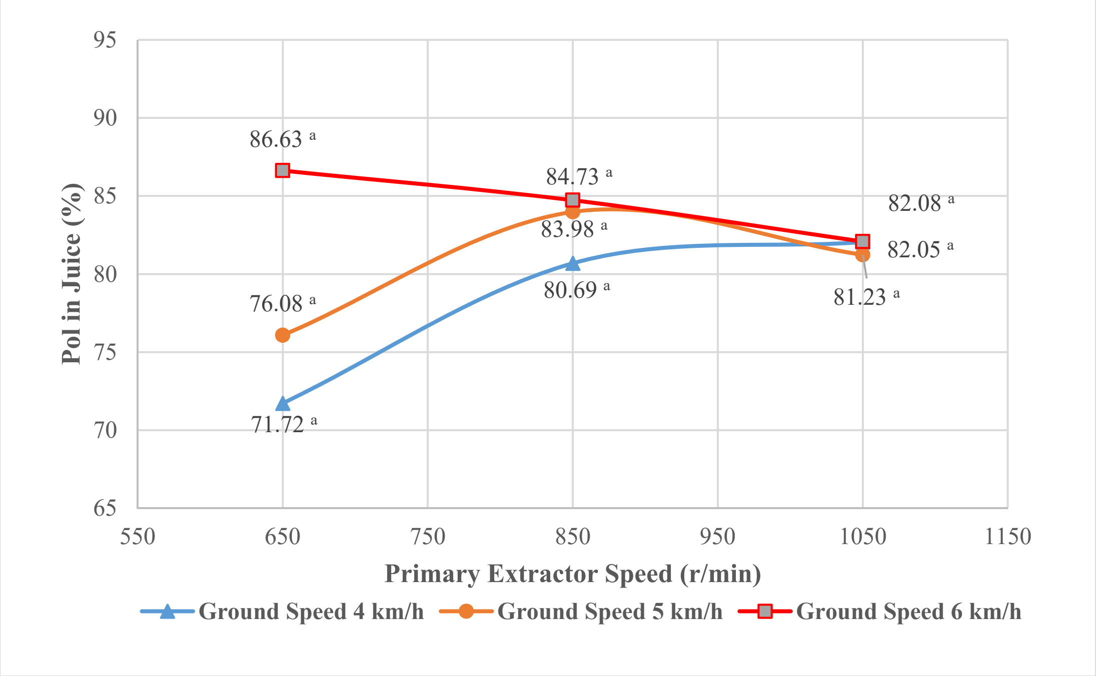
- The pol results of cane billet supply ranged between 71.72 and 86.63%. The highest value of pol was 86.63% at a ground speed of 6 km/h and an operating fan speed of 650 r/min. The lowest value was 71.72% at ground and fan speeds of 4 km/h and 650 r/min respectively (P-value ≤ 0.05). However, there was no significant difference in pol in juice (%) (P-value ≤ 0.05) due to ground and fan speeds changes (Figure 5.27). The results in Figure 5.27 were similar to the brix results shown in Figure 5.26.
- The fibre % cane increased with low fan speeds and high ground speeds. The fibre % cane (22.67%) was the highest value at a ground speed of 6 km/h and the fan speed 650 r/min (P-value ≤ 0.05). The lowest value for fibre % cane was 16.51% at the ground speed 4 km/h and the fan speed 1,050 r/min (P-value ≤ 0.05) (Figure 5.28).

Harvesting with a range of primary extractor fan and ground speeds impacted on the quantities and qualities of billets supplied. The effect on the quantity of billets is explained in section 5.4.3.1. The pour rate increased with high ground speed during cutting but this resulted in high EM in the billet supply. The increasing EM impacted the fibre % cane when the ground speed was 6 km/h (Figure 5.28). Additionally, low fan speed levels increased the fibre % cane especially with low ground speeds. These result agree with those prsented by others (Ridge & Linedale 1997; Norris & Ridge 1998; NorrisECT 2013; *Harvesting best practice manual* 2014).



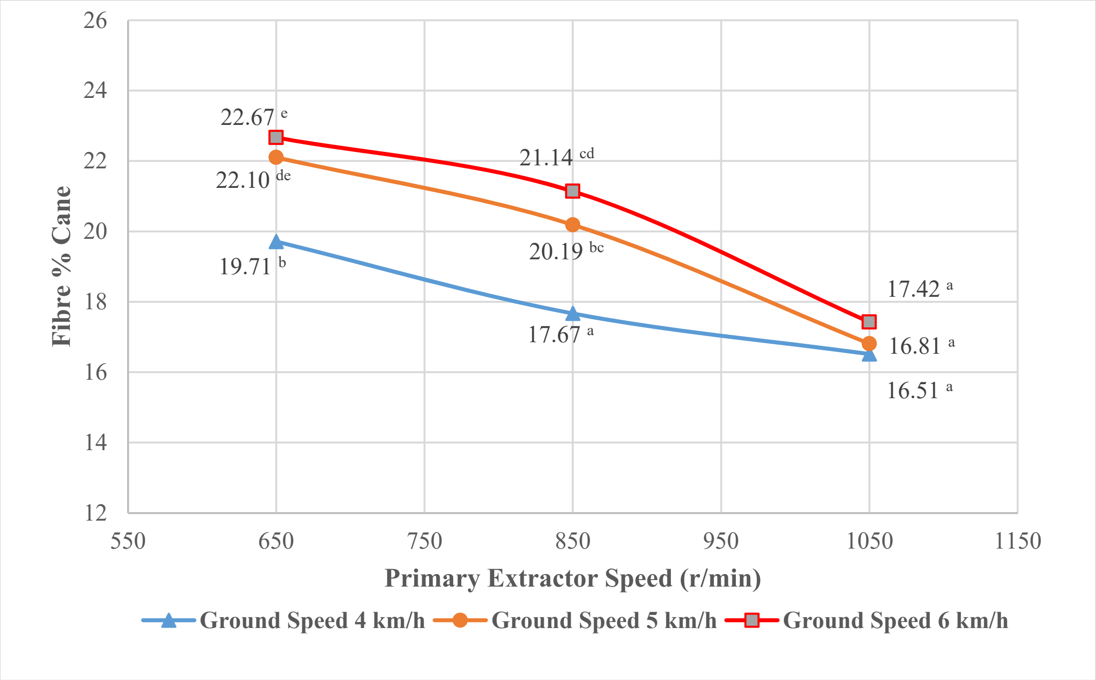
Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.26 Brix of billets influenced by the primary extractor and ground speeds



Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.27 Pol of billets influenced by the primary extractor and ground speeds



Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.28 Fibre of billets influenced by the primary extractor and ground speeds

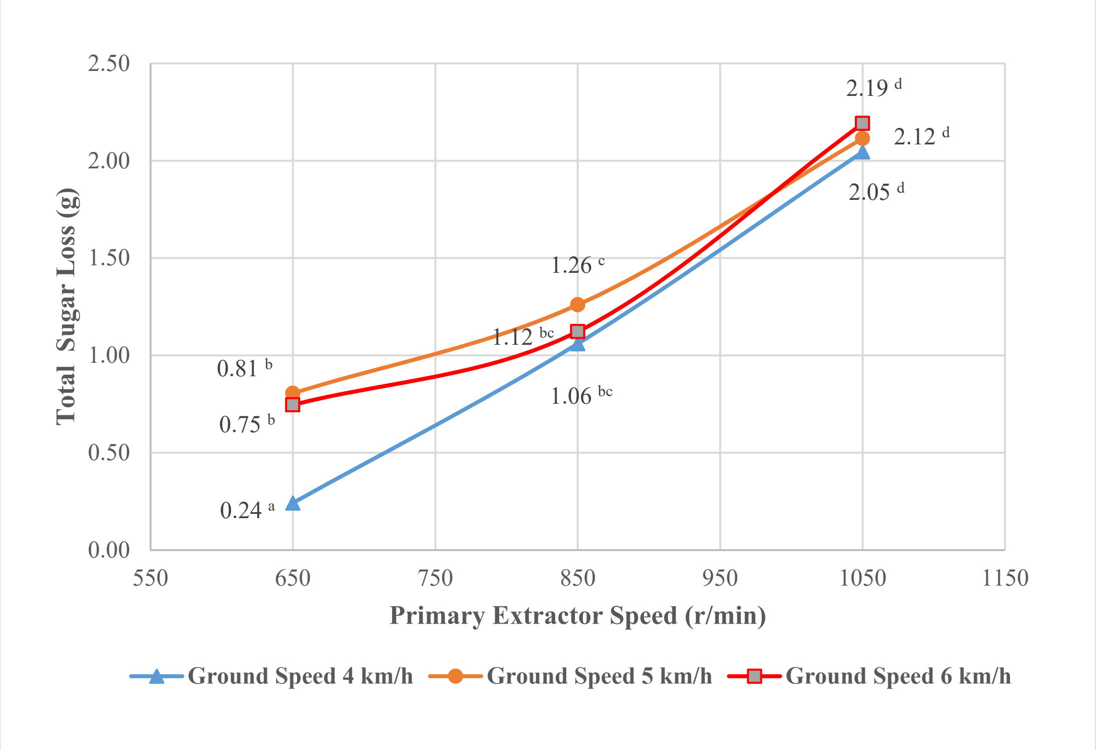
5.4.4 Sugarcane loss when cut with varying fan and ground speeds

The sugarcane trash samples collected from the harvester operated at various ground and fan speeds during harvesting were used to measure the sugar loss. The descriptive statistics and results of Duncan's new multiple range test (DMRT) are shown in Figure 5.29, 5.30 and 5.31. In summary:

- The sugar loss associated with different ground and fan speeds is shown in Figure 5.29. Total sugar loss increased when ground and fan speeds were high (P-value ≤ 0.05). The sugar loss was the highest at 2.19 g from 20 g trash when ground speed 6 km/h and the primary extractor speed 1,050 r/min were used but not significant with other levels (P-value ≤ 0.05). Conversely, the least sugar loss [0.24 g, significant at (P-value ≤ 0.05)] occurred when the harvester was operated at the lowest ground speed (4 km/h) and lowest fan speed (650 r/min).

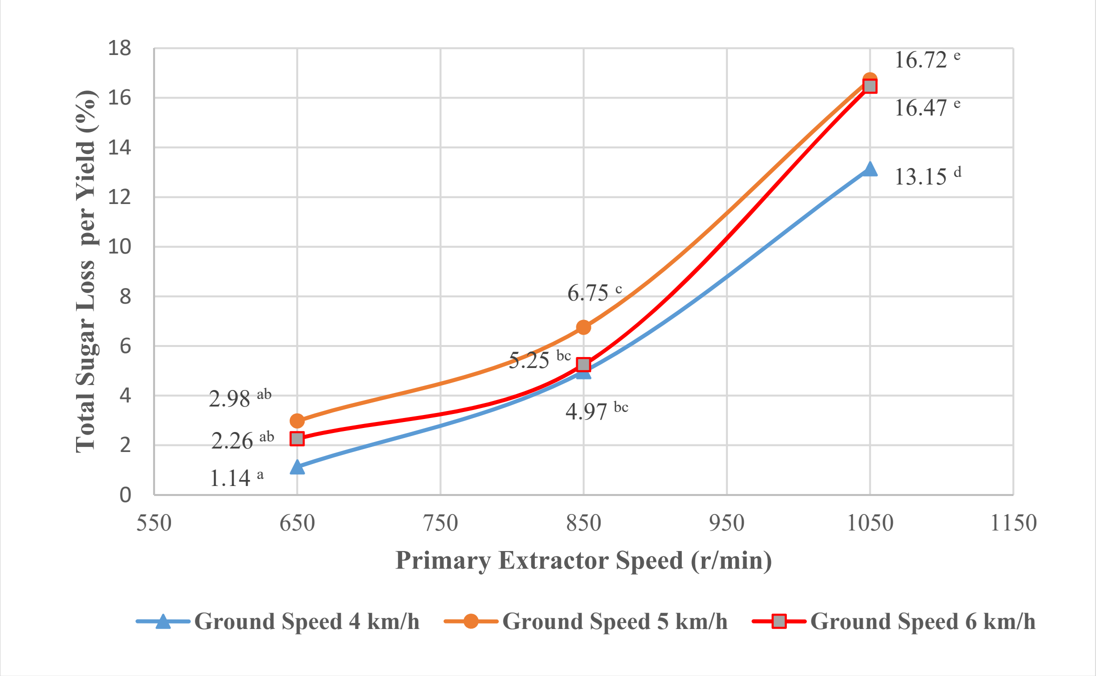
- The percentage of sugar loss from the crop was the highest when the ground speed was either 5 or 6 km/h and the fan speed was 1,050 r/min (Figure 5.30). This was not significantly higher than the percentage sugar loss at a lower ground speed (4 km/h) with the fan speed maintained at 1,050 r/min (P-value $\leq$ 0.05) Percentage of sugar loss at the moderate fan speed (850 r/min) at the various ground speed were not significantly different from one another (P-value $\leq$ 0.05). Significant differences (P-value $\leq$ 0.05) occurred at the low fan speed. Percentage of sugar loss was 1.14% at a ground speed of 4 km/h and a fan speed of 650 r/min.
- Moisture content (%db) of the harvested material measured during harvesting increased with the high fan and ground speed levels (Figure 5.31) with the highest values occurring at 6 km/h and 1,050 r/min respectively (P-value $\leq$ 0.05). The percentage of moisture content decreased when the low fan and ground speeds were applied (650 r/min, 4 km/h) (P-value $\leq$ 0.05).
- There is a linear relationship between sugar loss and moisture content (%) with a correlation coefficient (R^2) of 0.55 (Figure 5.32).

Fan and ground speeds during harvesting, affect the ratio of materials in the billet supply (Whiteing et al. 2001). This study used the methodologies developed by Whiteing (2013). High fan and ground speeds during harvesting caused an increase in sugar loss and the amount of sugar adhering to the trash discharged from the primary extractor (Whiteing 2004; NorrisECT 2013). The total sugar loss is a combination of the sugar juice contained within the lost billet pieces and the juice adhering to the trash; which was determined when the trash was homogenised by shredding with the mulcher during the sampling process. Moisture content (%db) and sugar loss in the residue were found to be correlated (Figure 5.32) under varying fan and ground speed levels.



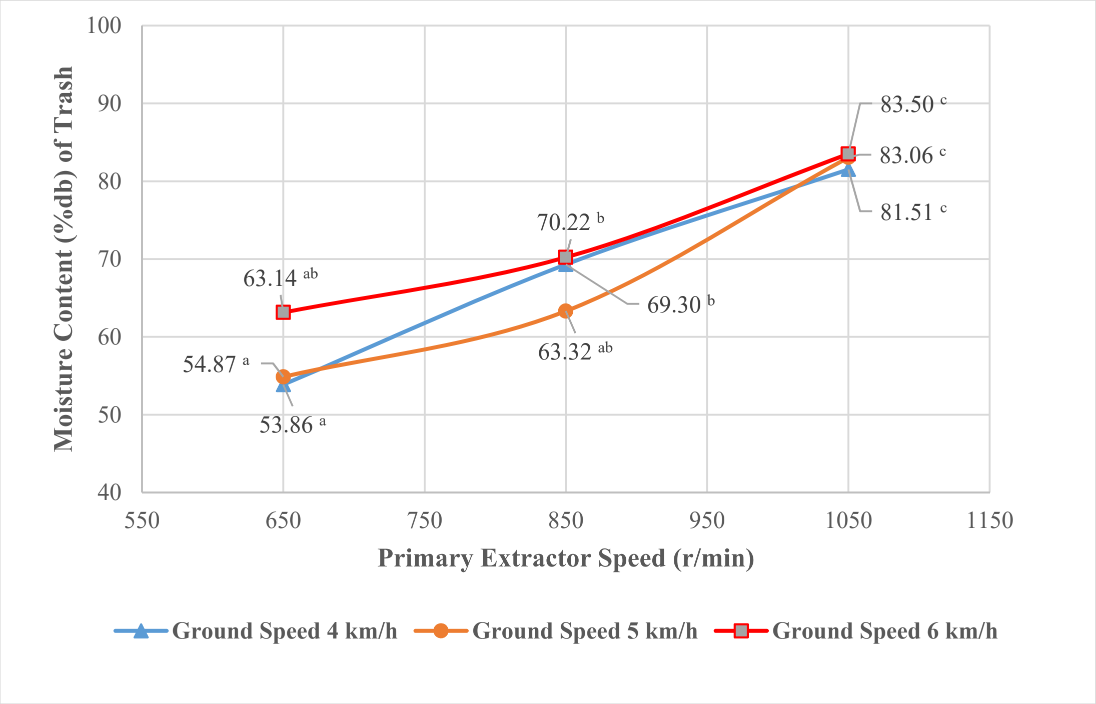
Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.29 Total sugar loss influenced by the primary extractor and ground speeds



Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.30 Total sugar yield lost under the speed effects of the fan and ground speeds



Means followed by the same letter are not significantly different (P-value ≤ 0.05)

Figure 5.31 Moisture content of trash influenced by fan and ground speeds

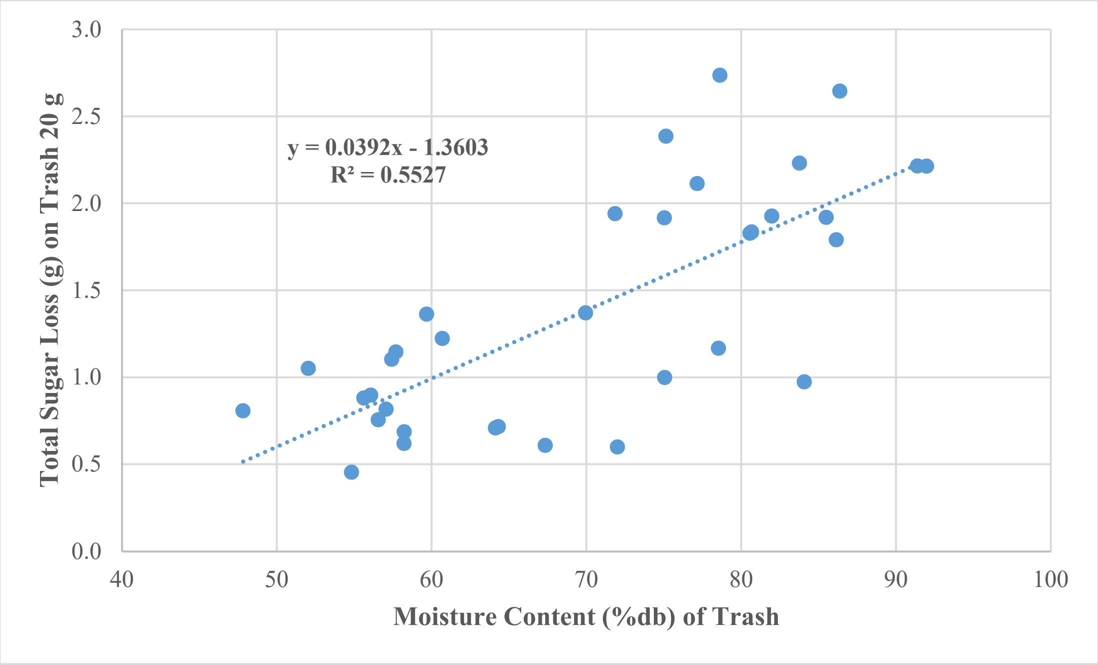


Figure 5.32 The relationship between sugar loss and moisture content during harvesting by varying primary fan speeds

5.4.5 Sugar loss implications for commercial cane harvesting

Chapter 3 details the impact of harvester pour rate on the physical properties on the material harvested and Chapter 4 then goes on to quantify and evaluate the sugar loss caused by the changing pour rate. In this chapter, the primary drivers of pour rate, those being ground and fan speed, are investigated in a trail situation. In this section, the understandings derived from the previous chapters has been applied to commercial harvesting situations, to investigate whole of industry implications.

As commercial cutting practices generally only using high fan speeds, selected data from the trials detailed in previous chapters, was extracted that aligned closely with commercial operational settings. Results from Bundaberg in 2016 (fan speeds 1,050 r/min – common fan speed for commercial cutting) with varying ground speeds (4, 5 and 6 km/h) were used to study the impacts of various pour rates on the commercial harvesting operation. The cost of leaving various levels of sugar behind in the field was evaluated using pour rate data, a sugar price of 460 AU$/t (QSL 2017) and CCS values (calculated from brix, pol and fibre values in Table 5.1) using equations 2.1, 2.2 and 2.3. These losses were calculated for cane loss due to high fan speed (1,050 r/min) with varying ground speeds for different pour rates (Figure 5.33). As the collected data related only to the high fan speed with various ground speeds, the dataset was limited to 18 samples. Due to time and resource constraints during the harvesting test, additional data could not be collected. The physical restriction of small plot sizes detailed in the earlier chapters meant that with the constant stopping and starting of the harvester, high pour rates (>120 t/ha) were never achieved. Therefore, datasets from other studies (Whiteing et al. 2001; Whiteing & Norris 2002) were interrogated and additional data points added to the study. This data provided an additional 4 data points, which are shown as red dots on Figure 5.33. When considering the relationship between pour rates and dollar loss, the fitted curve in Figure 5.33 was found to be exponential and in agreement with information reported by other researchers (Whiteing et al. 2001; Sandell & Agnew 2002; Whiteing & Norris 2002).

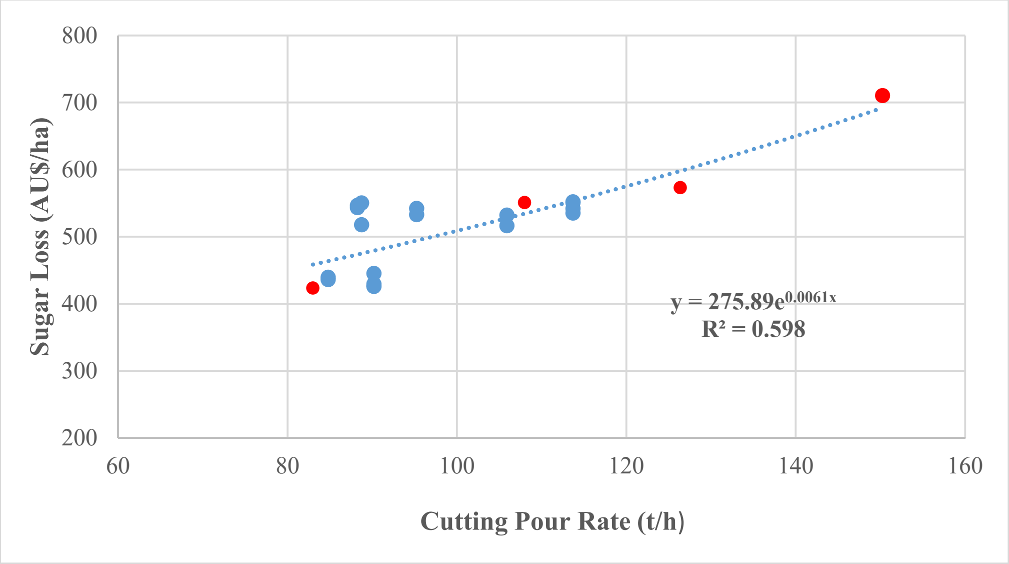


Figure 5.33 The relationship between cutting pour rate and income loss from the commercial harvesting

To investigate the implications of this relationship on harvesting in a commercial situation, yield monitor data were sourced from an SRA-funded project 2014/028 ‘Product and profit—Delivering precision to users of precision agriculture in the Australian sugar industry—Yield monitoring’. These data were from a block of sugarcane (6.1 ha with 1.8 m row-spacing) in the Childers district in south east Queensland (refer to chapter 3, Figure 3.1) which was cut with a chopper harvester (John Deere, model 3520/2015) on 22 November 2016. The harvester was set up with a prototype yield monitoring system, the details of which were explained in Jensen et al. (2013). The underlying yield map was generated using the yield monitor protocol of Bramley and Jensen (2014), which involved a process to remove erroneous data on the edges of the field. The data were krieged using the Vesper program (Minasny et al. 2005).

The resultant maps (Figure 5.34–5.37) were displayed with ArcGIS 10.3.1 (Environmental System Research Institute 2017). Speed data from the differential global positioning system (GPS) (Figure 5.34), were combined with the row width to produce the cutting pour rate (Figure 5.36) and calculate the crop yield (Figure 5.35). In order to investigate cane loss spatially across the field, the cutting pour rate combined with the income loss function from Figure 5.33 were then applied to the pour rate map (Figure 5.36) to predict sugar loss (due to changing pour rates) across an entire field. The results were then used to display the data as an income loss map (Figure 5.37) due to varying quantities of sugar being left behind in the field.

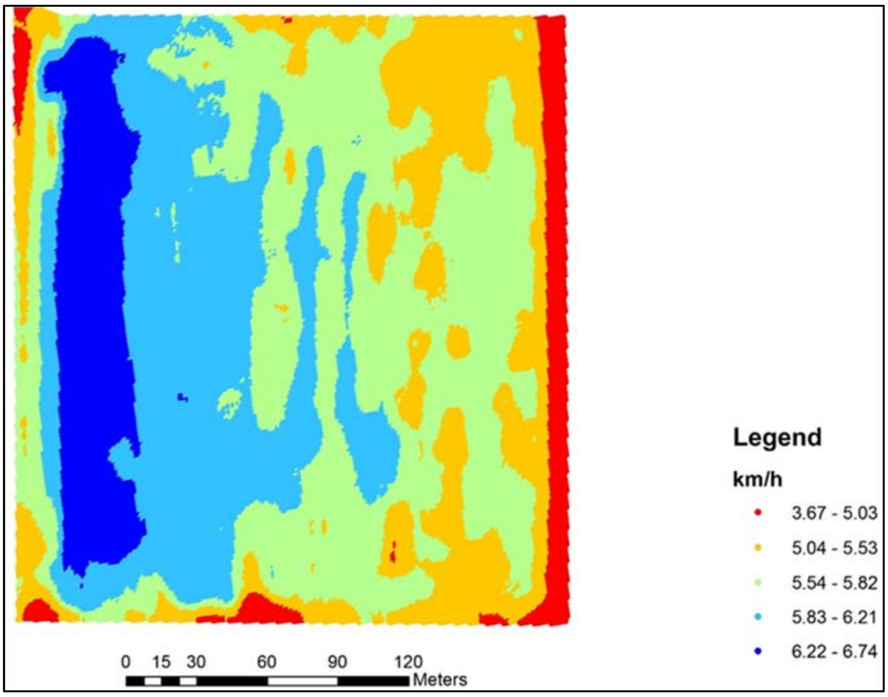


Figure 5.34 Harvester ground speed across the study area

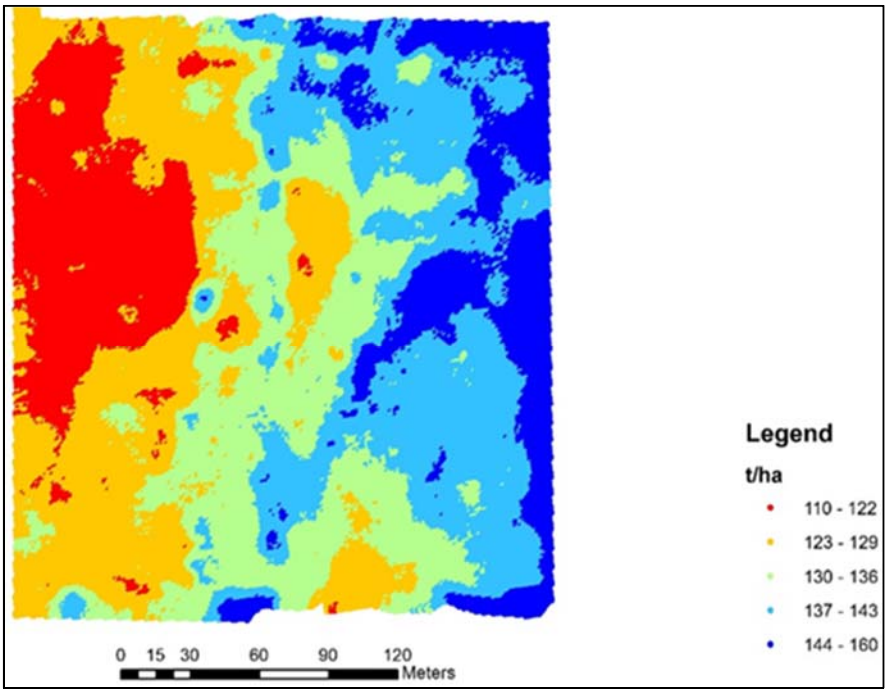


Figure 5.35 Sugarcane yield as calculated from the study area

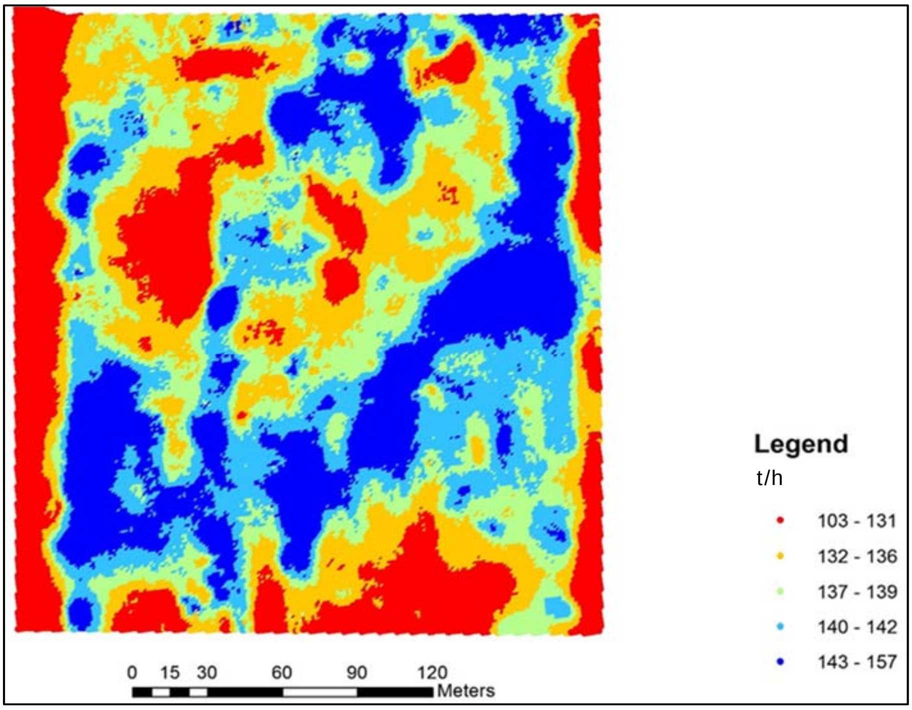


Figure 5.36 Harvesting pour rate associated with the study area

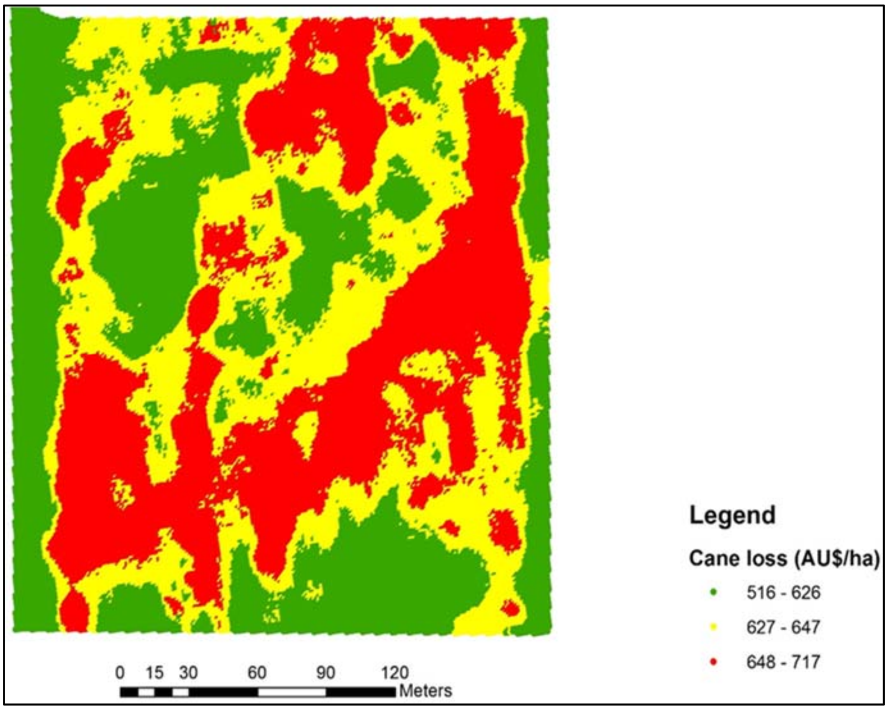


Figure 5.37 Income loss due associated with cane losses determined for the study area

When considering the yield map ((Figure 5.35), yields ranged from low (< 122 t/ha) on the left side to high (> 144 t/ha) on the right side. The harvester ground speed map (Figure 5.34) indicated that the harvester operator was trying to maximise machine throughput (or alternatively pour rate) by moving faster in the lower yielding areas. The exception to this statement is near the edges of the field where infrastructure prevented higher speeds. The harvesting pour rate is shown in Figure 5.36 with the values ranging between 103 t/h and 157 t/h. The loss of income across the field (Figure 5.37) shows the impact of high pour rate on sugar loss. The sugar loss aligned with the harvester throughput ranged from 1.08 t/ha – 1.52 t/ha. The resultant economic losses in this particular block ranged from 500 AU$/ha to 700 AU$/ha approximately (Note: sugar price at 460 AU$/t (QSL 2017) varies with years).

This initial analysis, although only based on data from one field and a rudimentary relationship between sugar loss and pour rate, showed that there are a considerable range of pour rates practiced in commercially cut cane. The trial work, detailed in chapter 3, 4 and 5 together with other works from the literature, revealed that changing pour rates produced the potential for considerable sugar loss. To fully utilise the effort and expense that goes into growing sugarcane and to minimise sugar loss, harvesters should be optimised by continual changing of machine settings to reflect seasonal and in-field conditions and crop yields. The current situation is that the fan speed is set at the start of the harvesting season by the commercial harvester operator and unless a major issue occurs, is usually not modified. The data presented in this chapter suggests that the current approach may cause considerable sugar loss and is something that should be changed according to the conditions as the harvester progresses down the field, almost on a second by second basis. For this to occur, electronic monitoring would be required. To further investigate this relationship, an economic analysis is conducted in the next chapter to determine that the approach is economically feasible.

5.5 Conclusion

Desired cane supply is characterised by good billet quality and relatively low EM. In this study it was found that the various pour rates and fan speeds affected the amount of trash and soil mixed with the billet supply during cleaning with the extractor system, from samples collected during the 2015–2016 trials. The billet length distribution showed that 92% of the billets were in the category 150–200 mm. The assessment of the billet quality indicated that on average 84% were sound, 8% were damaged and

7% were mutilated. When EM increased, the bulk density of the billet supply decreased particularly with high ground speed (pour rate) and low fan speed. When the fibre percentage of cane in the billet samples were analysed, the fibre increased with increasing pour rate and decreasing fan speeds. The brix values corresponded to the pol values when ground and fan speeds were changed. Sugar loss, as influenced by ground and fan speeds during harvesting, was assessed by collecting the trash discharged from the primary fan system. Sugar loss increased at high ground and fan speeds and vice versa. The relationship between the moisture content (%db) and the sugar lost in the trash samples when all speed factors were considered, resulted in a correlation coefficient (R^2) of 0.55. The income lost from commercial harvesting and aspects of yield was approximately 500–700 AU$/ha (based on the assumptions within the study).

Harvesting with varying ground and fan speeds affects the quantities and qualities of the billet supply. High cane loss and EM in the billet supply is one of the main challenges faced by the sugarcane industry in Australia. This challenge affects the income of all three sectors (growers, harvester contractors and millers). Cane losses result in reduced revenue for growers. Additionally, high EM causes low CCS and high transportation cost that decrease the profit of the grower. In addition, increasing EM influences sugar mill performance by reducing the crushing efficiency and loss of sugar in the bagasse. These results influence the miller’s cost and profits. Optimising the cutting pour rate and reducing cane losses and EM are in the interest of growers and harvester contractors. An economic assessment of cane and sugar losses is therefore provided in Chapter 6 to illustrate the economic benefit of curbing losses during sugarcane harvesting.

Chapter 6 Economic analysis and practical recommendations

6.1 Introduction

This chapter focuses on the economic analysis and practical recommendations for sugarcane production to reduce sugar loss and improve yield outcomes during harvest. Data derived from the chapter 3, 4 and 5 were combined with information from sugar mills to analyse and apportion costs between the various segments of the industry, those being sugarcane growers, contractors and millers. This chapter covers the following topics concerning the cane payment system:

- Background and literature review
- Materials and methods
- Results and discussion
- Conclusion

6.2 Background and literature review

6.2.1 Sharing industry revenue under HBP campaigns

The general sugar value chain was detailed in section 5.2.1 and comprises planting, harvesting, cane transportation, mill processing and marketing (storage, shipping and selling sectors) (Higgins et al. 2007). When considering the HBP strategies, each of the three sectors (growers, contractors and millers) have different economic drivers for their profitability (NorrisECT 2013).

- Grower sector: primary drivers are to minimise the cost of harvesting. Payment to contractors is generally made on a per tonne cane cut basis.
- Contractor or harvesting sector: the main driver for harvesting contractors is to maximise cane output, as the harvesting charge out rate is based on the amount of cane cut per day with this being maximised to receive the highest income.
- Miller sector: the mill capacity and efficiency are normally dependent on the cane quality and the quantity of cane supplied. The CCS payment system is used to balance the cane quality delivered by the growers.

The sugar industry requires the coordination of drivers of all three sectors to maximise production and maintain profitability. However, individual sectors have optimised in isolation, resulting in reduced incomes for all groups of the sugar industry (NorrisECT 2013).

Economic forces and other incentives have caused the harvesting group to move towards shorter billets, resulting in high cleaning losses and excess stool damage, resulting in a lower quality of billets supplied to the mill (refer to section 2.5). Many strategies have been targeted at improving harvesting operations. Lowering ground speed has successfully reduced EM in the cane supply. The optimum harvester settings can improve cane cleaning and loss. Impact of the primary extractor speed (refer to section 2.4.5), the chopper system (refer to section 2.4.4) and the gathering and base cutter system (refer to section 2.4.3) have been discussed previously. Additionally, the transport system related with the HBP has been investigated to improve the cane payment system (Sandell & Prestwidge 2004).

The drive towards harvesting best practice has attempted to increase incomes for all sectors, with strategies and campaigns to increase/optimumise bulk densities, reduce fibre % cane/soil/dirt and reduce cane loss. The grower and miller can receive higher income through better CCS, increased cane supply/yield (due to reduced losses) and improved ratoon ability (refer to section 2.6). Before a new payment system can be applied, a new costing model is required for the harvesting contractor. Under the influence of HBP benefits, the cost incurred for the labour cost of harvesting needs to be shared (Antony et al. 2003) so that there is a sharing of costs among all three sectors to fulfil the HBP strategy.

6.2.2 Sugarcane billet transportation

Billet supply in Australia is delivered to the mill by three modes of transportation from the field (Pernase & Pekol 2012):

- Direct delivery from the field to the mill by rail wagon.
- Direct delivery from the field to the mill by the road.
- Combined road and rail.

The cane transportation utilises two methods: rail and road. Delivery by road is divided into three distances; 1) less than 5 km from the mill using 8 t cane capacity with semi-trailers, 2) up to 12 km using 12 t cane capacity with semi-trailers and 3) exceeding 20 t cane transferred by the haulage vehicles (De Beer et al. 1993). For railway transportation, the mill controls the trains and the bins for delivery. The railway is used to transport approximately 88% of the Australian sugarcane supply from the farm to the mill, with the average bin weight between 4 and 15 t of cane (Pernase & Pekol 2012). In field, trailer sizes range from about 4 to 8 t for transferring cane billets from the farm to the loading zones within an approximate 1 km radius. Mills are geographically 'near' farms with an average distance of about 25 km (Higgins et al. 2007), with more distant locations becoming less economical, due to transport costs.

6.2.3 Cane payment for sugar industry

Cane payment in Australia has traditionally been based on a formula originally designed to share net proceeds from sugar sales between the millers and the growers according to their approximate relative capital investments. Recovery of sugar is defined in the term of commercial cane sugar (CCS). The average recovery of CCS during the milling process is usually at 90% efficiency (Canegrowers 2017). The apportionment of proceeds are split with two-thirds going to the growers and one-thirds to the millers, for basic production. This efficiency level for sugar processing was developed into the cane payment formula in 1916 (Equation 6.1) (*The Australian sugar industry-basics of growing cane to payment* 2017).

$$P_c = P_s \times (90 / 100) \times (CCS - 4) / 100 \qquad \text{Equation 6.1}$$

Where P_c = price of cane

P_s = price of sugar

From 1916 to 1949, the formula was adjusted by the incorporation of a constant in the formula (Equation 6.1) to improve the cane payment. Up until 1994, the constant value was set at 32.8 cents. Subsequently, the value was modified in 2000 by using a value of 57.8 cents, and the new formula became equation 6.2 (*The Australian sugar industry-basics of growing cane to payment* 2017).

$$P_c = [\ P_s \times (90 / 100) \times (CCS - 4) / 100\ ] + 0.578 \qquad \text{Equation 6.2}$$

Where P_c = price of cane

P_s = price of sugar

Under the *SUGAR INDUSTRY Act 1999*, each mill is to specify cane payment activities as part of the cane processing and cane supply contract. The cane price can be different from the equation 6.2 and can be unrelated to the sugar cost by agreement between the millers and growers (*The Australian sugar industry-basics of growing cane to payment* 2017).

6.3 Materials and methods

The sugarcane value chain is a large complex structure extending from the farm to the market. This chapter is focused on the harvesting implications. Due to varying cane quality from the harvester, CCS evaluation by the mill laboratory is used to penalise growers for poor management decisions. The method used to determine the most appropriate cost sharing is presented below.

6.3.1 Materials

The activity costs used in this analysis are based on data from interviews with persons associated with the harvesting groups in the Bundaberg district. In addition, some data relative to the calculation of the cane payment have been extracted from industry websites, reports and publications.

6.3.2 Methods

The calculations were performed with Microsoft Excel to find the economic balance by using the information from chapter 5, interviews with sugarcane harvester operators and appropriate websites (Table 6.1). The assumptions made for this assessment include; crop yield of 110 t/ha with 1.83 m row spacing and cut by the chopper harvester, with the billet supply being transferred by the powerhaul (9 t capacity) from the farm to the delivery site (assumed distance of 1 km). The cane payment was evaluated by assuming the cane harvested was 1,000 t. The model (using a spreadsheet application) was run for multiple scenarios of harvester ground speed (4, 5 and 6 km/h) and primary fan speeds (650, 850 and 1050 r/min). All details in Table 6.1 were analysed based on the sample values presented below:

- CCS from the cane billet by HBP strategies.
- Cane and sugar prices.
- Cane loss due to harvesting on the field.
- Harvester operating and labour costs.
- Billet supply transportation cost.

Table 6.1 Data used in the cost analysis for the sugarcane harvesting and transportation.

Item	Value	Unit	Source
Sugarcane harvester (John Deere Model CH 570, Engine 251 kW (337 hp)	673,000*	AU$	Interview (Vanderfield Pty 2017)
Powerhaul (Agricon Equipment Model ACE transporter, Engine 186 kW (250 hp), loading 14 t	450,000*	AU$	Interview (McDonald Murphy Machinery Pty 2017b)
Economic life of sugarcane harvester	5	year	Interview (McDonald Murphy Machinery Pty 2017b)
Economic life of powerhaul	3	year	Interview (McDonald Murphy Machinery Pty 2017b)
Used sugarcane harvester price at 5 years of age (Average price at 5,000 h)	317,000*	AU$	Evaluation of website access (*New & used sugarcane harvesters for sale in Australia* 2017; McDonald Murphy Machinery Pty 2017a)
Annual usage in a cutting season and transportation	800	h/year	Interview (McDonald Murphy Machinery Pty 2017b), Evaluation from website access (*New & used sugarcane harvesters for sale in Australia* 2017; McDonald Murphy Machinery Pty 2017a)
Registration costs and concessions for the farm machinery	179*	AU$/year/unit	Website access (*Registration costs* 2017)
Insurance and housing rate	1	% per year	Website access (Edwards 2017)
Interest rate (a typical lease in 3 years for machinery)	7	% per year	Interview (Vanderfield Pty 2017)
Repair and maintenance rate	20	% per year	Website access (Edwards 2017)
Wage rate for cane haulage	19.21	AU$/h/person	Website access (*Pay guide - Sugar industry award* 2016)

* GST including (Goods and Services Tax)

Table 6.1 (Continuous) Data used in the cost analysis for the sugarcane harvesting and transportation.

Item	Value	Unit	Source
Wage rate for cane harvesting	19.88	AU$/h/person	Website access (*Pay guide - Sugar industry award* 2016)
Wage rate for contract	22.86	AU$/h	Website access (*Pay guide - Sugar industry award* 2016)
Fuel cost (Diesel)	1.18*	AU$/litre	Website access (Caltex Pty 2017)
Repair and maintenance rate	10	% per year	Website access (Edwards 2017)
Fuel consumption factor for diesel engine power (hp)	0.16676	–	Website access (Edwards 2017)
Lubrication factor for fuel consumption cost	0.15	–	Website access (Edwards 2017)
Labour factor	1.1	–	Website access (Edwards 2017)
Consumable parts for harvesting (base cutter blade, chopper blade, *etc.*)	0.40*	AU$/t	Interview (Vanderfield Pty 2017)
Price of sugar (export price)	459.91	AU$/t	Website access (QSL 2017)
Railway bin volume	19.45	m^3	Physical measurements
Powerhaul bin volume	24.77	m^3	Physical measurements

* GST including (Goods and Services Tax)

6.4 Results and discussions

6.4.1 Impact of billet supply on sugarcane harvest economics

All data that was evaluated, including the assumed values, are shown in Table 6.1 and the summarised results presented in Table 6.2. These summarised results, were calculated with a range of fan and ground speeds, as discussed in Chapter 5, with the calculations detailed in Appendix B1, Tables B1-B4. All settings influenced the billet supply, and improved the sugarcane economics. The highest CCS value was 8.73% at a fan speed of 1,050 r/min and a ground speed of 4 km/h. This result influenced the growers income via maximising the cane price (20.16 AU$/t). However, there is substantial cane loss problems when compared with the majority other speed (except for the 1,050 r/min and 6 km/h). Billet weights in the rail bins and powerhaul at the low ground speed (4 km/h) and the high fan speed (1,050 r/min) were high (5.26 and 6.70 t respectively). Conversely, the billet loading weights in the rail bins and powerhauls were low (3.15 and 4.02 respectively) at the low fan speed (650 r/min) and low ground speed (6 km/h).

Table 6.2 Cane billet supply and loading information due to changing the primary extractor and ground speeds.

Ground Speed (km/h)	**4**			**5**			**6**		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
CCS (%)	5.08	8.65	8.73	5.78	8.29	8.40	7.82	8.15	8.47
Cane loss (t/ha)	1.95	17.58	26.62	6.89	11.92	17.27	6.01	11.10	27.54
Cane price (AU$/t)	5.048	19.825	20.156	7.946	18.335	18.790	16.390	17.756	19.080
Cane loss per crop yield (%)	1.80	9.80	24.63	6.37	11.02	15.98	5.56	10.27	25.48
Billet in rail bin (t)	3.94	4.66	5.26	3.49	3.92	4.41	3.15	3.61	4.35
Billet in powerhaul (t)	5.02	5.93	6.70	4.44	4.99	5.61	4.02	4.60	5.55

The different speeds during cutting influenced the quantity and quality of the harvested sugarcane. At the low ground speed and the high fan speed, the billet supply quality was improved as shown by the high CCS value via the brix, pol and fibre in billet supply. The results correspond with the results of other research (Ivin & Doyle 1989; Kent et al. 2010; Thai & Doherty 2011). When CCS values increase, the growers receive higher revenues. Additionally, the billet supply due to higher speeds increased the density in the bin during transportation (Inderbitzin & Beattie 2012), thus decreasing the number of trips and bins needed to deliver the billet supply to the mill. Reducing the number of trips saves transportation costs (Prestwidge et al. 2006). However, when operated at the high fan speed and high ground speed, the cane loss increases during harvesting (Norris & Ridge 1998). The high pour rate decreases the grower's income due to high cane loss and low billet qualities via the low CCS and increasing trip numbers for transportation (Freebairn 2003; Sandell & Prestwidge 2004; Pollock 2013). All results shown in Table 6.2 are consistent with other research outcomes (Agnew et al. 2002; Jones 2004; NorrisECT 2013).

6.4.2 Economic costs of the various scenarios

The integrated models were investigated to check the net increase in profit for all scenarios. The focus of the analysis was on the economic variability of each scenario. The cost analysis was used to calculate the harvesting costs influenced by the different ground and fan speeds and the billet supply transportation from the farm to the delivery site (assumed distance of 1 km). The information from Table 6.1 and 6.2 were applied to analyse the economic costs of operating the sugarcane harvester and powerhaul with further details available in Appendix B2, Tables B5–B8.

6.4.2.1 Harvesting and transportation costs

The harvesting and transportation costs were evaluated by reviewing ownership costs and the impact of the varying ground and fan speeds shown in Figure 6.1. The harvester cost was the lowest (3.31 AU$/t) when a high ground speed (6 km/h) was used. The high fan speeds (1,050 r/min) resulted in the lowest cost of delivery (about 2.80 AU$/t) at ground speeds of 4 and 6 km/h. The lowest total price of the cutting and transportation was 6.10 AU$/t at high ground and fan speeds (6 km/h, 1,050 r/min). However, the highest harvesting costs were 4.74 AU$/t when operated at the low ground speed (4 km/h). The transportation cost was the highest value (3.42 AU$/t) at a ground speed of 5 km/h and a fan speed of 650 r/min. The total prices were the highest value (8.08 AU$/t) at ground and fan speeds of 4 km/h and 650 r/min respectively).

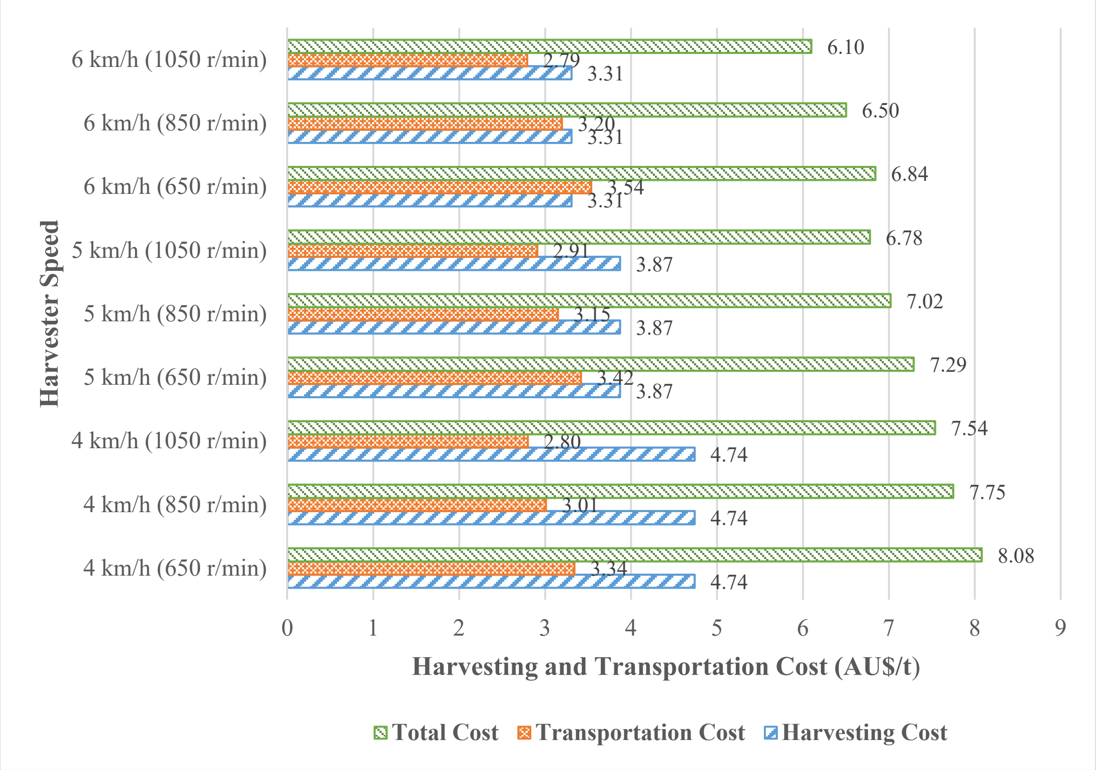


Figure 6.1 Harvesting and transportation costs influenced by the primary extractor and ground speeds

The harvesting and transportation economic cost varied due to the different ground and fan speeds. The harvesting costs reduced when using high ground speed as the pour rate increased (Sandell & Prestwidge 2004). However, when operated at the low ground speed (the low pour rate), the harvesting capacity decreased (Whiting 2004). The operation costs increased due to the prices of labour and fuel consumption (Sandell & Prestwidge 2004). The results shown in Figure 6.1 were comparable to those reported by others (Norris & Ridge 1998; Sandell & Prestwidge 2004).

Primary extractor fans operated at high speed causes a decrease in EM in the billet supply (Whiteing et al. 2001). When considering the economic aspects of the transportation from the field to the delivery site, EM in the transportation bin was reduced. Thus, the billet supply weight increased (Inderbitzin 2012; Inderbitzin &

Beattie 2012). The transportation cost was improved by reducing the loading time, and the bin and trip numbers (Prestwidge et al. 2006; Inderbitzin & Beattie 2012). Conversely, when low fan speed is used, EM increases and weight in the bins is reduced (Inderbitzin & Beattie 2012). The increase transportation rates are presented in Figure 6.1.

When considering the total costs influenced by the ground and fan speeds (Figure 6.1), the lowest ground and fan speeds (4 km/h, 650 r/min) produced high operating costs due to the low pour rate and light weight billet supply in the cane bin. Conversely, lower costs resulted from the highest ground speed (6 km/h) due to higher cutting pour rate. The highest fan speed at 1,050 r/min that discharged high EM in the cane billet supply increased the weight in the bins and reduced the trip numbers. However, high ground and fan speeds caused the cane loss as reported in Chapter 5, Section 5.4.4. These results correspond with the those reported by others (Sandell & Prestwidge 2004; Inderbitzin & Beattie 2012). These results support the HBP campaign which is achieved by reducing ground speed (cutting pour rate) and allowing the reduction in the fan speed to decrease EM and cane loss, to benefit the sugarcane industry when operating chopper harvesters (Agnew & Sandell 2000; Agnew et al. 2002).

6.4.2.2 Harvesting cost comparisons

Labour cost data (22.86 AU$) (*Pay guide - Sugar industry award* 2016) was used in combination with a machinery cost analysis (*Guide to machinery costs and contract rates* 2009) to determine the economic costs of harvesting. When the economic costs of ownership was compared to contract costs (Figure 6.2), the contract cost was the highest value (9.65 AU$/t) at the lowest ground and fan speeds. Conversely, the lowest price (7.18 AU$/t) occurred at the high ground and fan speeds (6 km/h, 1,050 r/min). When the ownership and contract rates were considered by comparing each of the speeds to the high speeds (6 km/h, 1,050 r/min) (Figure 6.3), the operating costs varied with ground and fan speeds during the cutting. The operating cost was high at low ground speed and low fan speed. For example, the low ground and fan speeds (4 km/h, 650 r/min) was 2.47 AU$/t lower than that of the highest ground and fan speeds (Figure 6.3). All results corresponds with section 6.4.2.1.

This information may encourage growers to negotiate harvesting costs with contractors by showing that both parties can obtain greater revenue by adopting these practises.

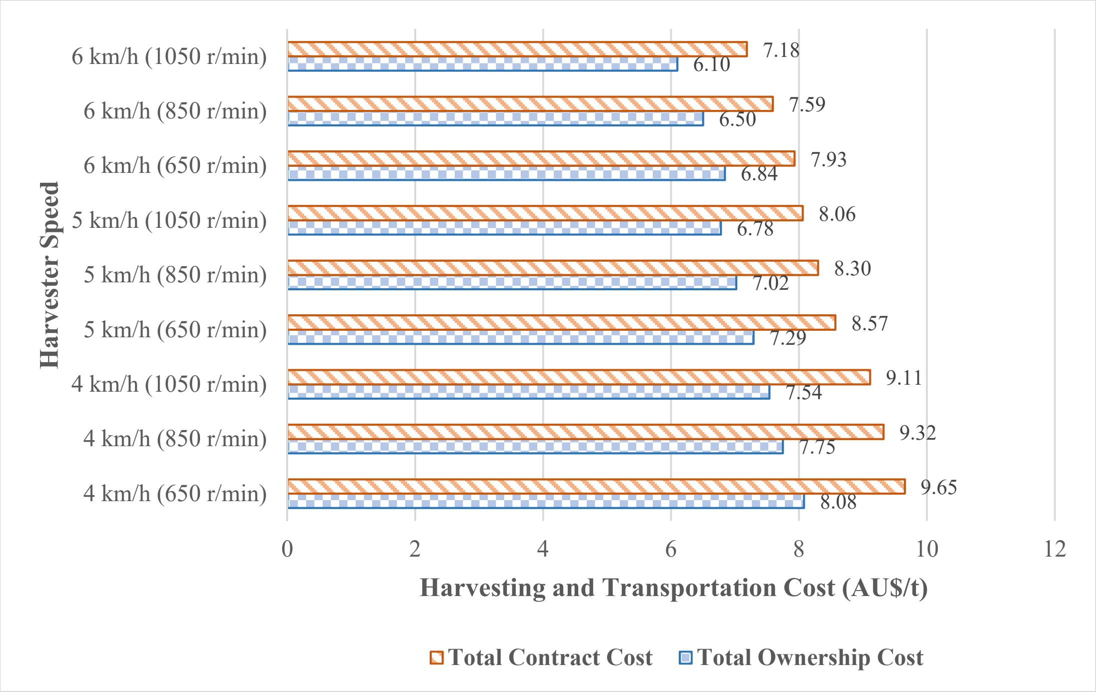


Figure 6.2 Harvest costs influenced by primary extractor and ground speeds

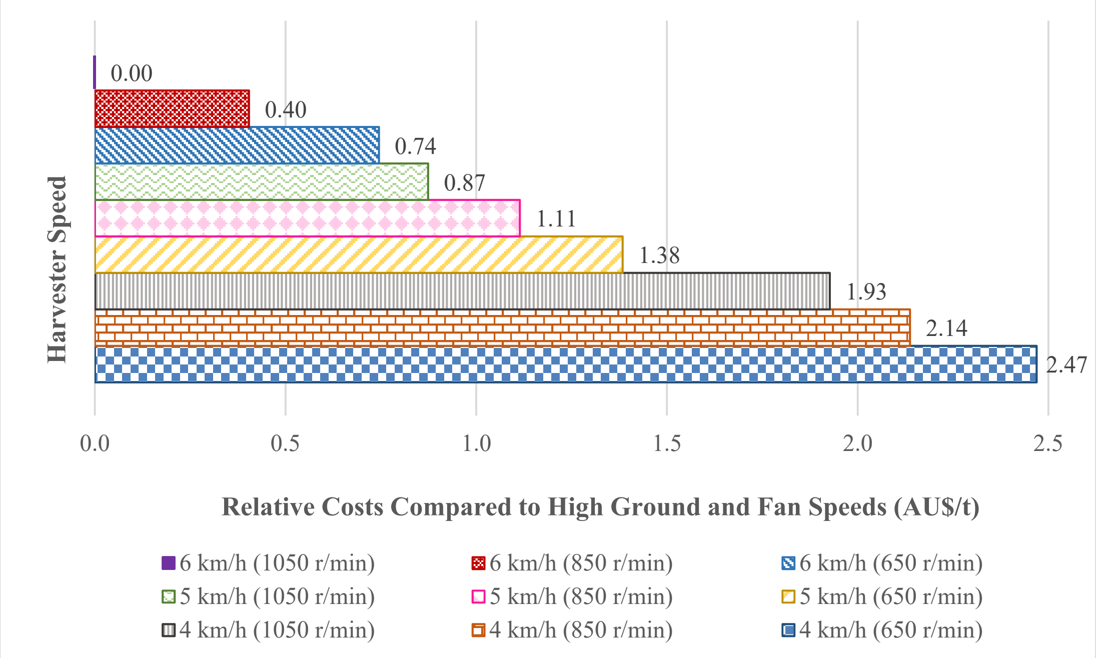


Figure 6.3 Relative costs of the contract rates compared to the high speeds of primary extractor and ground systems

6.4.3 Cost benefit for the various scenarios

The profits for the various scenarios of ground and fan speeds were calculated by using the cane losses and cane prices from Table 6.2, and the contract costs from Figure 6.2. The cane payment was analysed by assuming the cane harvested was 1,000 t. The cane payment at the ground speed 4 km/h and fan speed 850 r/min produced the highest return (9745.51 AU$) to the grower as shown in Table 6.3. Conversely, the lowest ground and fan speed (4 km/h, 650 r/min) resulted in a loss to growers (-4519.16 AU$). The cane loss was the highest (254.8 t) at the ground and fan speeds of 6 km/h, 1,050 r/min. The lowest loss (18 t) occurred at the lowest ground and fan speeds (4 km/h, 650 r/min).

Table 6.3 The cane payments due to a range of primary extractor and ground speeds.

Ground Speed (km/hr)	**4**			**5**			**6**		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
Crop yield (t)	1000	1000	1000	1000	1000	1000	1000	1000	1000
Cane loss (t)	18.0	98.0	246.3	63.7	110.2	159.8	55.6	102.7	254.8
Cane harvested (t)	982.0	902.0	753.7	936.3	889.8	840.2	944.4	897.3	745.2
Cane harvested price (AU$)	4957.14	17882.15	15191.58	7439.84	16314.48	15787.36	15478.72	15932.46	14218.42
Contract cost (AU$)	9476.30	8406.64	6866.21	8024.09	7385.34	6772.01	7489.09	6810.51	5350.54
Balance cost (AU$)	**-4519.16**	**9745.51**	**8325.37**	**-584.25**	**8929.14**	**9015.35**	**7989.62**	**9121.95**	**8867.88**

The cane payment calculated in Table 6.3 was calculated using cane loss, cane quality (CCS) and the cane price. It also included the effects of the contract rates. When the fan speed was high, cane loss was also high but with reduced EM. High ground speed resulted in high pour rates, but with increased cane and EM losses (Norris & Ridge 1998; NorrisECT 2013). Conversely, low ground and fan speeds resulted in less cane loss but caused higher EM and CCS losses in the billet supply (Kent et al. 2010; Thai & Doherty 2011) and transportation impacts (Inderbitzin & Beattie 2012). The effects of cutting with low speeds (4 km/h, 650 r/min) reduced cane quality (cane price) but increased harvesting time and transportation costs (contract price). Optimal harvester operations resulting from appropriate setting of ground and fan speeds has the ability to improve the grower's revenue. Harvester settings of 4 km/h and 850 r/min (Table 6.3) result in a balance of increasing CCS of the billet supply and reducing cane loss and transportation costs. These results are in agreement with other researchers (Norris & Ridge 1998; Agnew et al. 2002; Muscat & Agnew 2004; *Harvesting best practice manual* 2014).

6.5 Conclusion

The effects of varying ground and fan speeds in a chopper harvester impacts on both cane quality and cane quantity. Calculation of cane payment for the various scenarios enabled economic assessment based on CCS, cane loss and transportation costs during the harvester operating. The optimal speed (i.e. ground and fan speeds of 4 km/h and 850 r/min respectively) produced the highest income of about 9,700 AU$ per 1,000 t of sugarcane cut.

The sharing of costs of the harvesting and transportation between the grower and the harvester contractor is essential to optimise profit through improved quantity and quality of billet supply during cutting and delivery to the mill. This type of approach will not only be of benefit to the Australian sugar industry but also to other sugar-producing countries where chopper harvesters are used.

Chapter 7 Conclusions and recommendations

The quality and quantity of sugarcane crops can vary significantly on-farm due to various factors, including different nutrient management strategies and harvester configurations. As such, there is a strong need to improve harvester operation for different crop conditions in the sugarcane industry. The problems of cane loss in field and EM adhering to the cane supply during harvesting impacts the revenue of both growers and millers. This thesis aimed at investigating the most suitable framework for dealing with the problems associated with crop conditions during cutting with a chopper harvester. The primary goal of this study was to investigate the effect of harvester pour rate, under the impact of the varying crop conditions, and evaluate the resulting sugar loss. Problems can be reduced by operating within the HBP guidelines. These details were addressed in Chapters 3 to 6. This last chapter presents a summary of the major findings of the research and offers conclusion and recommendations for future research.

7.1 Summary of findings

This thesis has provided new knowledge that nutrition and other drivers influence the physical properties of the cane that is presented to the harvester. This variation is on a scale much finer than is currently considered in commercial harvesting. Insights on the collection and preparation of samples for determining sugar loss which adhering to trash discharged from the extractor systems impacted by crop size can be justified by colorimetric assay. Harvesting best practice guidelines were used to investigate billet supply and sugar loss from field trials. Cane among the various parties in the sugarcane industry.

Chapter 3 discussed crop size as impacted by different N rates. Crop variability directly affects the billet supply when harvesting with a fixed ground speed during cutting. The major findings of this chapter were as follows:

1. Pour rates driven by crop size can affect the amounts of EM in the billet supply. High crop yields produce an increased amount of the trash in the billet supply when the ground speed is constant. The higher the pour rates, the lower the capacity of the extractor fan to remove the trash.

2. Nitrogen applied to sugarcane can produce crops of difference size. Low N application rates results in small cane (diameter, length and weight). The light bulk density of this cane means that billets can be blown out easier than the heavy ones cleaning with the extractor system is in operation. This results in higher bulk density of the cane billet supply from the harvester. The billet size therefore affects the transport bulk density.
3. The proportion of sound quality billets increases in the billet supply due to the lower bulk density in cane caused by the low N rate. The damaged and mutilated billets (the light weight billets) can be more easily removed than the heavier billets.
4. The optimum N application rates (crop nutrients practise) can improve crop size to reduce cane loss and increase billet supply quality during harvesting.

Chapter 4 discussed the method used to measure sugar loss due to the effect of varying pour rates that were achieved by nutritional differences and its impact on crop size. The procedure for collecting the trash samples from the trials during cutting and the subsequent colorimetric assay were used to measure the 'invisible losses' due to sugar juice adhering to the EM. The major findings of this chapter covered losses due to the various pour rates influenced by the N application rates (crop nutrients practise):

1. Sugar loss increased when cutting the low yielding crop (light bulk density) caused by the low N application rate. The colorimetric technique was a suitable method to confirm the losses reported in Chapter 3.
2. The suitable N rates are important in improving crop size and helping to reduce cane and sugar losses associated with small crops and light bulk density of billets during harvesting, as is overcoming other constraints such as compaction, available water, weed pressure etc. that causes similar crop physical properties.
3. The relationship between total sugar loss and pol from the trash discharged from the cleaning system, produced a correlation coefficient of $R^2 = 0.80$.

Chapter 5 investigated cane loss due to the impact of varying fan and ground speeds. The key findings were:

1. The percentage of sound billets increased with low ground speed and high fan speed. The EM reduced under the same circumstances. The pour rate

influenced by the ground and the extractor speeds caused the loss in cane quality.

2. The moisture content in the trash blown from the primary fan speed increased with high fan speed due to the billets hitting with the extractor fan and coating the trash with juice. The moisture / sugar loss relationship developed has the potential to be used to predict the cane loss.

Chapter 6 investigated the economic drivers of the cane payment system across the various sectors of the industry. The results present an option for sharing the sugar revenue between the three sectors, those being cane grower, harvesting contractor and miller. The following are the major findings:

1. Low ground and fan speeds influenced by low cutting pour rate increased the labour cost for harvesting and transportation. Conversely, with high ground and fan speeds comes improved cane quality delivered to the mill, but with higher cane loss.
2. Optimising the ground and fan speeds can balance costs by improving the cane loss, cane quality and transportation.

7.2 Conclusions

Based on the outcomes of this research, it has been shown that the size of a sugarcane crop, as affected by the amount applied N, affects cane loss and the quality of the cane supply during cutting with a mechanical harvester.

The application of varying N rates impacted on the physical properties of the sugarcane (the crop condition). When the ground speed for the cutting is fixed, the pour rate is driven by the crop size. The bulk density of the crop impacts on the degree of cane loss, especially in billets under low pour rate situations caused by the low N application rates.

Due to the invisible losses associated with billet fragments (juice splatter, small pieces, *etc.*) disappearing through the extractor fans, the colorimetric assay was used to measure the sugar content adhering to the trash samples. This method was an economic alternative to other more expensive approaches due to the relatively low operating cost. It was however found to be sufficiently sensitive to detect losses in line with other more expensive techniques. The sugar loss increased in the samples from higher pour rate plots that had received low N applications.

Varying ground and fan speeds were used to determine losses in harvesting trials. The technique of collecting samples from sugarcane plots in combination with the colorimetric method was used to evaluate cane and quality losses. The cane loss increased when the harvester was operated at high ground and fan speeds. An increase in EM mixed with the billet supply occurred at the low fan speed and high pour rates during the harvesting.

Cane payment was calculated to share revenue in a balanced way among the grower, contractor and miller. The grower's income can be increased by using optimised ground and fan speeds. The optimised speeds improved the quality and quantity of sugarcane billet supply during harvesting and transportation.

Finally, based on the findings of the above study, this thesis has also provided the basic calculations to assess the impacts of invisible loss and cane payment due to the crop conditions on the harvest. The harvesting losses can cost the Australia sugarcane industry about 470 million AU$ a year occurred at high ground and fan speeds (6 km/h, 1,050 r/min). Such losses are also an issue in other countries (such as Brazil, Thailand, and India) as they move towards mechanised harvesting. Not only does N application affect crop condition, it also affects cane supply quality due to high EM in the billet supply. This, in turn, impacts on the grower's income via CCS and the sugar mill efficiency during the processing. From the experimental work conducted in this research, the impacts of N on crop physical properties was also assessed. Although such change were evident in every row, harvest fan and ground speeds are not adjusted accordingly.

7.3 Recommendations for future works

This thesis has successfully achieved all of the objectives outlined in chapter 1. Due to issues around seasonality of the sugarcane with limited harvest season, limited availability of crop experiments, limited accessibility of the laboratory facilities, this proof of concept study was not progressed as far as originally hoped. However, through the experience gained from this study, the following are recommendations for future research:

- Most of the results reported in this thesis were based on experimental work carried out in one harvest season. Hence, further research work needs to be done over a range of crop conditions.

- Varying crop size as influenced by N application rate suggests that a diversity of stalk samples needs further study. The physical properties of different sized crops is impacted by the many factors including soil nutrients and sugarcane varieties. Apart from further work in relation to choice of fertilisers and varieties, the effects of soil compaction and different soil types need to be investigated. It is recommended that optimising fertiliser rate for suitable crop sizes for mechanical harvesting be investigated. The interaction between sugarcane varieties and nutrient management in each area also needs to be investigated to increase crop size and improve billet supply when harvesting. The effect of soil compaction and soil types also needs attention, particularly in relation to the size of the crop and harvesting during subsequent seasons.
- Billet size is influenced by nutrients and impacts cane loss during harvest. If the billet length increases, it impacts the bulk density in the bin and the EM in the billet supplied to the mill. Thus, it is recommended that optimal length of billets be investigated to improve cane transportation.
- This study has quantified the variation in sugar content adhering to trash samples collected during harvesting. As freezer space is often limited, it is difficult to store many samples prior to analysis. Thus, the use of dried samples should also be investigated to improve sample preservation when large numbers of samples are collected in the field.
- Currently, it is difficult to identify cane loss and billet quality to provide feedback directly to operators during cutting. If the operator receives the information quickly, it will be helpful in selecting suitable machine parameters to cut the cane with reduced cane loss. Further development of sensors and devices to detect cane loss within the primary extractor system is also necessary.
- The hydraulic power drive controls the fan speeds during the cleaning of the billet supply. Low primary extractor speed can improve cane loss. When the fan speed decreases, the energy supply driving the fan system reduces. Thus, in the future, it is recommended that fuel consumption data be supplied with the power requirement to drive the fan speed. Electronic fuel consumption data to document inefficient block layouts and poor cane quality may be useful to

refine the cane payment formula and/or the contract payment rates between the cane grower and the contractor.

- The ground and fan speeds are currently set at the start of harvesting. It is difficult to continuously change these settings as the crop size changes in the row during harvesting. All speeds need to be continuously adjusted during harvest to achieve optimal harvest pour rate. Thus, electronic controller systems need to be develop to allow automatic adjustments as the pour rates due to crop yield varies.
- Changes in physical properties of sugarcane and impacts on cleaning also need to be considered. Due to the limited scope for further cleaning by the extractor system during the harvesting, field-edge trash separation should be investigated to improve cleaning of the billet supply as influenced by the crop condition (soil nutrient effects).

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Appendix A

A.1 Statistical analysis of chapter 4 (sugar loss)

This appendix (A.1) explained the statistical analysis of the sugar loss per sugar yield (%) from chapter 4 by measuring the sugar loss from the Bundaberg and Ingham trials. The operation by the chopper harvester was fixed the ground speed to cut the sugar cane influenced the various N rates. The results shown in Table A1 are the summary statistics of the sugar loss for the varying N rates (which represents pour rates). The ANOVA results are shown in Table A2 and the mean comparisons by using the DMRT are shown in Table A3.

Table A1 The descriptive statistics of the sugar loss per sugar yield during the cutting with the chopper harvester at Bundaberg and Ingham sites influenced the varying N rates.

Dependent Variable: Sugar loss per sugar yield (%)

Site	N rate	Mean	Std. Deviation	N
Bundaberg	75 kg/ha	7.0906	3.05988	10
	150 kg/ha	2.5533	1.02696	10
	225 kg/ha	2.6709	0.77826	12
	Total	4.0153	2.77115	32
Ingham	0 kg/ha	4.9550	2.11012	6
	100 kg/ha	3.0683	1.05190	6
	200 kg/ha	2.4783	0.84682	6
	Total	3.5006	1.73991	18
Total	75 kg/ha	7.0906	3.05988	10
	150 kg/ha	2.5533	1.02696	10
	225 kg/ha	2.6709	0.77826	12
	0 kg/ha	4.9550	2.11012	6
	100 kg/ha	3.0683	1.05190	6
	200 kg/ha	2.4783	0.84682	6
	Total	3.8300	2.44354	50

Table A2 Two-Way ANOVA of the sugar loss per sugar yield during the cutting with the chopper harvester at Bundaberg and Ingham sites influenced the varying N rates (P-value ≤ 0.05).

Dependent Variable: Sugar loss per sugar yield (%)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	160.772[a]	5	32.154	10.734	.000	.550
Intercept	664.583	1	664.583	221.862	.000	.835
Site	.000	0	.	.	.	.000
N rate	157.720	4	39.430	13.163	.000	.545
Site * N rate	.000	0	.	.	.	.000
Error	131.801	44	2.995			
Total	1026.015	50				
Corrected Total	292.573	49				

a. $R^2 = 0.550$ (Adjusted $R^2 = 0.498$)

Table A3 Mean comparison of the sugar loss per sugar yield during the cutting with the chopper harvester at Bundaberg and Ingham sites influenced the varying N rates (P-value ≤ 0.05).

Method	N rate	N	Subset		
			1	2	3
DMRT	200 kg/ha (Ingham)	6	2.4783		
	150 kg/ha (Bundaberg)	10	2.5533		
	225 kg/ha (Bundaberg)	12	2.6709		
	100 kg/ha (Ingham)	6	3.0683		
	0 kg/ha (Ingham)	6		4.9550	
	75 kg/ha (Bundaberg)	10			7.0906
	Sig.		.550	1.000	1.000

A.2 Statistical analysis of chapter 5 (sugar loss)

This appendix (A.2) presented the statistical analysis of the sugar loss per sugar yield (%) from chapter 5, by measuring the sugar loss from the Bundaberg site that investigated the effect of the various ground and primary extractor fan speeds. The results shown in Table A4 are the summary statistics of the sugar loss for the varying ground and fan speeds. The ANOVA results are shown in Table A5 and the mean comparisons by using the DMRT are shown in Table A6.

Table A4 The descriptive Statistics of the sugar loss per sugar yield during cutting with the chopper harvester at Bundaberg site influenced by the varying ground and fan speeds.

Dependent Variable: Sugar loss per sugar yield (%)

Ground Speed	Fan Speed	Mean	Std. Deviation	N
G 4 km/h	F 650 rpm at 4 km/h	1.1433	0.49354	6
	F 850 rpm at 4 km/h	4.9733	2.26836	6
	F 1050 rpm at 4 km/h	13.1483	5.05464	6
	Total	6.4216	6.06242	18
G 5 km/h	F 650 rpm at 5 km/h	2.9820	0.74344	6
	F 850 rpm at 5 km/h	6.7483	2.37020	6
	F 1050 rpm at 5 km/h	16.7230	3.42151	6
	Total	8.8178	6.39192	18
G 6 km/h	F 650 rpm at 6 km/h	2.2600	1.04433	6
	F 850 rpm at 6 km/h	5.2533	1.94787	6
	F 1050 rpm at 6 km/h	16.4733	4.48650	6
	Total	7.9955	6.85040	18
Total	F 650 rpm at 4 km/h	1.1433	0.49354	6
	F 850 rpm at 4 km/h	4.9733	2.26836	6
	F 1050 rpm at 4 km/h	13.1483	5.05464	6
	F 650 rpm at 5 km/h	2.9820	0.74344	6
	F 850 rpm at 5 km/h	6.7483	2.37020	6
	F 1050 rpm at 5 km/h	16.7230	3.42151	6
	F 650 rpm at 6 km/h	2.2600	1.04433	6
	F 850 rpm at 6 km/h	5.2533	1.94787	6
	F 1050 rpm at 6 km/h	16.4733	4.48650	6
	Total	7.7450	6.33055	54

Table A5 Two-Way ANOVA of the sugar loss per sugar yield during cutting with the chopper harvester at Bundaberg site influenced by the varying ground and fan speeds (P-value ≤ 0.05).

Dependent Variable: Sugar loss per sugar yield (%)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1754.877[a]	8	219.360	26.741	.000	.826
Intercept	3739.807	1	3739.807	455.894	.000	.910
Ground Speed	.000	0	.	.	.	.000
Fan Speed	1747.992	6	291.332	35.514	.000	.826
Ground Speed * Fan Speed	.000	0	.	.	.	.000
Error	369.146	45	8.203			
Total	5863.830	54				
Corrected Total	2124.023	53				

a. $R^2 = 0.826$ (Adjusted $R^2 = 0.795$)

Table A6 Mean comparison of the sugar loss per sugar yield during cutting with the chopper harvester at Bundaberg site influenced by the varying ground and fan speeds (P-value ≤ 0.05).

Method	Speed	N	Subset				
			1	2	3	4	5
DMRT	F 650 rpm at 4 km/h	6	1.1433				
	F 650 rpm at 6 km/h	6	2.2600	2.2600			
	F 650 rpm at 5 km/h	6	2.9820	2.9820			
	F 850 rpm at 4 km/h	6		4.9733	4.9733		
	F 850 rpm at 6 km/h	6		5.2533	5.2533		
	F 850 rpm at 5 km/h	6			6.7483		
	F 1050 rpm at 4 km/h	6				13.1483	
	F 1050 rpm at 6 km/h	6					16.4733
	F 1050 rpm at 5 km/h	6					16.7230
	Sig.		.300	.094	.368	.080	.877

Appendix B

B.1 The cane qualities and quantities influenced by the different primary fan and ground speeds

This appendix (B.1) explained the cane qualities and quantities influenced by harvesting by operating the varying ground and fan speeds. The results affected the CCS value (Table B1), the sugarcane loss (Table B2), the cane price (Table B3) and loading for transportation (Table B4) including the harvester and powerhaul costs. All results influenced the cane payment by calculating in chapter 6.

Table B1 Cane qualities from the harvesting influenced by the varying primary fan and ground speeds.

Ground Speed (km/h)	**4**			**5**			**6**		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
Brix in Juice (%) *	21.20	25.00	23.27	23.23	24.40	22.57	23.93	24.50	23.37
Pol in Juice (%) *	71.72	80.69	82.05	76.08	83.98	81.23	86.63	84.73	82.08
Fibre of Cane (%) *	19.71	17.67	16.51	22.10	20.19	16.18	22.67	21.14	17.42
Brix in Cane (%)	16.39	19.83	18.73	17.40	18.74	18.24	17.79	18.59	18.60
Pol in Cane (%)	54.00	66.46	64.40	55.46	66.74	64.03	62.66	62.58	63.68
Pol or Sucrose (%)	8.85	13.18	12.06	9.65	12.48	11.68	11.15	11.63	11.84
Impurity (%)	7.54	6.65	6.67	7.75	6.27	6.56	6.64	6.95	6.76
CCS (%)	5.08	8.65	8.73	5.78	8.29	8.40	7.82	8.15	8.47

*Data derived from Figure 5.29-5.31

Table B2 Total cane loss on the fields affected by the different primary fan and ground speeds.

Ground Speed (km/h)	4			5			6		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
Sugar loss (g)[*]	0.24	1.06	2.05	0.81	1.26	2.12	0.75	1.12	2.19
Trash (t/ha)	15.75	19.34	25.36	17.12	18.40	15.91	15.75	19.17	24.45
Sugar loss (t/ha)	0.19	1.03	2.59	0.67	1.16	1.68	0.59	1.08	2.68
Cane loss (t/ha)**	1.95	10.59	26.62	6.89	11.92	17.27	6.01	11.10	27.54
Cane loss per yield (%)	1.80	9.80	24.63	6.37	11.02	15.98	5.56	10.27	25.48

[*] Sugar adhering to trash 20 g from Figure 5.29.

Cane loss calculated by the sugarcane formula: **Sugar yield (t/ha) = CCS% × Cane yield (t/ha)/100
CCS and crop yield results (average value 9.73% and 108.10 t/ha) were used to calculate from Table 5.1.

Table B3 Sugarcane price affected by the different primary fan and ground speeds.

Ground Speed (km/h)	4			5			6		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
Cane Price before Cutting (AU$/t)[*]	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30
Cane Price after Cutting (AU$/t)[**]	5.048	19.825	20.156	7.946	18.335	18.790	16.390	17.756	19.080

[*] CCS (average value 9.73%) were used to calculate from Table 5.1.

**CCS were used to calculate from Table B1.

.

Table B4 The billet weight on the train bin and powerhaul bin impacted by the varying primary fan and ground speeds.

Ground Speed (km/h)	**4**			**5**			**6**		
Fan Speed (r/min)	**650**	**850**	**1050**	**650**	**850**	**1050**	**650**	**850**	**1050**
Bulk Density (kg/m^3)	202.62	239.57	270.57	179.28	201.73	226.61	162.24	185.72	224.02
Billet in railway bin (t)	3.94	4.66	5.26	3.49	3.92	4.41	3.15	3.61	4.35
Billet in powerhaul (t)	5.02	5.93	6.70	4.44	4.99	5.61	4.02	4.60	5.55

B.2 The harvesting cost analysis

The harvesting cost analysis was calculated by presenting the sugarcane harvester and the contractor costs (Table B5), including the transporter cost shown in Table B6, B7 and B8. All results were used to make the sharing of the cost revenue in chapter 6.

Table B5 The harvester and contractor cost influenced by varying ground speeds.

Information for the harvester	**4 km/h**	**5 km/h**	**6 km/h**	**Unit**
A. Purchase price	673,000.00	673,000.00	673,000.00	AU$
B. Trade-in price	317,000.00	317,000.00	317,000.00	AU$
C. Economic life	5.00	5.00	5.00	year
D. Interest rate	7.00	7.00	7.00	%
E. Insurance and housing rate	1.00	1.00	1.00	%
F. Registration and concession for farm machinery	179.00	179.00	179.00	AU$/year
G. Annual use (h/year)	800.00	800.00	800.00	h/year
H. Field capacity (t/h)	73.20	91.50	109.30	t/h
J. Engine horsepower (HP)	337.00	337.00	337.00	HP
K. Fuel consumption factor for diesel engine (Litre factor)	0.17	0.17	0.17	_
L. Fuel cost	1.18	1.18	1.18	AU$/Litre
M. Lubrication factor	0.15	0.15	0.15	_
N. Repair and maintenance factor	20.00	20.00	20.00	%
O. Engine overhaul repair	10,000.00	10,000.00	10,000.00	h
P. Labour cost for harvesting	19.88	19.88	19.88	AU$/h
Q. Labour cost for cane haulage	19.21	19.21	19.21	AU$/h
R. Labour factor	1.10	1.10	1.10	_
S. Consumable cost	0.40	0.40	0.40	AU$/t
Fixed costs				
a. Purchase price = A	673,000.00	673,000.00	673,000.00	AU$
b. Trade-in price = B	317,000.00	317,000.00	317,000.00	AU$
c. Average investment = (a + b) / 2	495,000.00	495,000.00	495,000.00	AU$
d. Depreciation = (a-b) / C	71,200.00	71,200.00	71,200.00	AU$/year
e. Interest cost = (D/100) x c	34,650.00	34,650.00	34,650.00	AU$/year
f. Insurance and housing cost = (E/100) x c	4,950.00	4,950.00	4,950.00	AU$/year
g. RTA = (F)	179.00	179.00	179.00	AU$/year
h. Total fixed costs (per year) = d + e + f + g	110,979.00	110,979.00	110,979.00	AU$/year
i. Total fixed costs (per h) = (d + e + f + g) / G	138.72	138.72	138.72	AU$/h
j. Total fixed costs (per t) = (d + e + f + g) / (G x H)	1.90	1.52	1.27	AU$/t
Variable costs				
I. Repair and maintenance (price / h) = (((100 + N) /100) x a) / O	80.76	80.76	80.76	AU$/h
II. Fuel consumption (price / h) = K x J x L	66.31	66.31	66.31	AU$/h
III. Lubrication consumption (price / h) = M x II	9.95	9.95	9.95	AU$/h
IV. Labour cost for harvesting = R x P	21.87	21.87	21.87	AU$/h
V. Consumable cost = S x H	29.28	36.60	43.72	AU$/h
VI. Total variable costs (per year) = (I + II + III + IV + V) x G	166,535.08	172,391.00	178,087.08	AU$/year
VII. Total variable costs (per h) = I + II + III + IV + V	208.17	215.49	222.61	AU$/h
VIII. Total variable costs (per t) = (I + II + III + IV + V) / H	2.84	2.36	2.04	AU$/t
Total costs				
1. Total costs (per year) = h + VI	277,514.08	283,370.08	289,066.08	AU$/year
2. Total costs (per h) = i + VII	346.89	354.21	361.33	AU$/h
3. Total costs (per t) = j + VIII	4.74	3.87	3.31	AU$/t
Contractor rate				
Total costs (per h) from 2.				
AA. Job costs sub-total (AU$/h) = 2. + 22.86 AU$	369.75	377.07	384.19	AU$/h
BB. Contingency margin (AU$/h) = 5% of AA	18.49	18.85	19.21	AU$/h
CC. Profit margin (AU$/h) = 20% of AA	73.95	75.41	76.21	AU$/h
DD. Margin sub-total (AU$/h) = BB + CC	92.44	94.27	96.05	AU$/h
EE. Hourly contract rate (AU$/h) = AA + DD	462.19	471.34	480.24	AU$/h
FF. Harvesting pour rate (t/h) = H	73.20	91.50	109.30	t/h
HH. Contract rate (AU$/t) = EE / FF	6.31	5.15	4.39	AU$/t

Table B6 The powerhaul cost influenced by the varying ground speeds.

Information for the powerhaul	**4 km/h (650 r/min)**	**4 km/h (850 r/min)**	**4 km/h (1050 r/min)**	**5 km/h (650 r/min)**	**5 km/h (850 r/min)**	**5 km/h (1050 r/min)**	**6 km/h (650 r/min)**	**6 km/h (850 r/min)**	**6 km/h (1050 r/min)**	**Unit**
A. Purchase price	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	AU$
B. Trade-in price	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	AU$
C. Economic life	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	km
D. Interest rate	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	%
E. Insurance and housing rate	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	%
F. Registration and concession for farm machinery	179.00	179.00	179.00	179.00	179.00	179.00	179.00	179.00	179.00	AU$/year
G. Annual use (h/year)	800.00	800.00	800.00	800.00	800.00	800.00	800.00	800.00	800.00	h/year
H. Field capacity (t/h)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	t/h
J. Engine horsepower (HP)	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	HP
K. Fuel consumption factor for diesel engine (Litre factor)	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	_
L. Fuel cost	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	AU$/Litre
M. Lubrication factor	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	_
N. Repair and maintenance factor	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	%
O. Engine overhaul repair	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	h
P. Labour cost for harvesting	19.88	19.88	19.88	19.88	19.88	19.88	19.88	19.88	19.88	AU$/h
Q. Labour cost for cane haulage	19.21	19.21	19.21	19.21	19.21	19.21	19.21	19.21	19.21	AU$/h
R. Labour factor	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	_
S. Annual Usage	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00	25,000.00	km
OO. Crop yield (data from Chapter 5)	108.10	108.10	108.10	108.10	108.10	108.10	108.10	108.10	108.10	t/ha
AA. If working 800 h/year, distance (Table B7, AA)	13,625.31	12,760.85	12,134.01	15,736.17	15,164.72	14,583.79	17,338.59	16,740.87	15,876.03	km/year
BB. Transportation factor (Table B7, Z)	0.06	0.06	0.07	0.05	0.05	0.05	0.05	0.05	0.05	h/km

Table B6 (Continuous) The powerhaul cost influenced by the varying fan and ground speeds.

Information for the powerhaul	**4 km/h (650 r/min)**	**4 km/h (850 r/min)**	**4 km/h (1050 r/min)**	**5 km/h (650 r/min)**	**5 km/h (850 r/min)**	**5 km/h (1050 r/min)**	**6 km/h (650 r/min)**	**6 km/h (850 r/min)**	**6 km/h (1050 r/min)**	**Unit**
CC. All total distance for loading and transport (km) (Table B7, U)	48.78	42.17	37.98	54.41	49.04	44.25	59.50	52.71	44.67	km
DD. All time (h) (Table B7, Y)	2.86	2.64	2.50	2.77	2.59	2.43	2.75	2.52	2.25	h
Fixed costs										
a. Purchase price = A	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	300,000.00	AU$
b. Trade-in price = B	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	120,000.00	AU$
c. Average investment = (a + b) / 2	210,000.00	210,000.00	210,000.00	210,000.00	210,000.00	210,000.00	210,000.00	210,000.00	210,000.00	AU$
d. Depreciation = (a-b) / C	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	AU$/km
e. Interest cost = ((D/100) x c) / S	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	AU$/km
f. Insurance and housing cost = ((E/100) x c) / S	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	AU$/km
g. RTA = (F)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	AU$/km
h. Total fixed costs (per km) = (d + e + f + g) / S	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	AU$/km
Variable costs										
I. Repair and maintenance (price / km) = (((100 + N) /100) x a) / C	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	AU$/km
II. Fuel consumption (price / km) = ((K x J) x L) x BB	2.89	3.08	3.24	2.50	2.60	2.70	2.27	2.35	2.48	AU$/km
III. Lubrication consumption (price / km) = M x II	0.43	0.46	0.49	0.38	0.39	0.40	0.34	0.35	0.37	AU$/km
IV. Labour cost for harvesting (price / km) = ((R x Q) x G) / AA	1.24	1.32	1.39	1.07	1.11	1.16	0.97	1.01	1.06	AU$/km
V. Total variable costs (per h) = I + II + III + IV	6.00	6.31	6.56	5.39	5.54	5.70	5.03	5.15	5.36	AU$/km
Total costs										
1. Total costs (per km) = h + V	7.40	7.71	7.96	6.79	6.94	7.10	6.42	6.55	6.75	AU$/km
2. Total costs (per t) = (1. x CC) / OO	3.34	3.01	2.80	3.42	3.15	2.91	3.54	3.20	2.79	AU$/t

Table B7 The powerhaul operating impacted from the varying fan and ground speeds.

Information	4 km/h (650 r/min)	4 km/h (850 r/min)	4 km/h (1050 r/min)	5 km/h (650 r/min)	5 km/h (850 r/min)	5 km/h (1050 r/min)	6 km/h (650 r/min)	6 km/h (850 r/min)	6 km/h (1050 r/min)	Unit
A. Crop yield (Data from Chapter 5)	108.10	108.10	108.10	108.10	108.10	108.10	108.10	108.10	108.10	t/ha
B. Row spacing (Data from Chapter 5)	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	m
C. Ground speed of harvester operating (Data from Chapter 5)	4	4	4	5	5	5	6	6	6	km/h
D. Bin loading (Table B4)	5.02	5.93	6.70	4.44	4.99	5.61	4.02	4.60	5.55	t/bin
E. Distance from field to paddock (assuming) (Higgins et al. 2007)	1	1	1	1	1	1	1	1	1	km
F. Powerhaul speed on road	30	30	30	30	30	30	30	30	30	km/h
G. Loading on paddock	5	5	5	5	5	5	5	5	5	min
Calculation										
I. Row length = (((40 / B) + 1) x 40) x 6.25	5,714.48	5,714.48	5,714.48	5,714.48	5,714.48	5,714.48	5,714.48	5,714.48	5,714.48	m/ha
J. Crop yield per meter = A / I	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	t/m
K. Harvesting pour rate = (J x C) x 1000	75.67	75.67	75.67	94.58	94.58	94.58	113.50	113.50	113.50	t/h
L. Time for total loading on field (h/bin) = (1 / K) x D	0.07	0.08	0.09	0.05	0.05	0.06	0.04	0.04	0.05	h/min
M. Time for total loading on field (min / bin) = L x 60	3.98	4.70	5.31	2.82	3.17	3.56	2.13	2.43	2.93	min/bin
N. Number of bin per crop yield = A / D	21.53	18.23	16.13	24.35	21.66	19.27	26.89	23.50	19.48	bin
O. Time of total loading = M x N	85.72	85.72	85.72	68.57	68.57	68.57	57.14	57.14	57.14	min/ha
P. Total distance from field to paddock (return) = (E x 2) x N	43.07	36.46	32.27	48.69	43.33	38.54	53.78	47.00	38.95	km
Q. Time on road to transport (h) = (1 / F) x P	1.44	1.22	1.08	1.62	1.44	1.28	1.79	1.57	1.30	h
R. Time for road on road to transport (min) = Q x 60	86.14	72.92	64.54	97.39	86.65	77.08	107.56	94.00	77.91	min

Table B7 (Continuous) The powerhaul operating impacted from the varying fan and ground speeds.

Information	4 km/h (650 r/min)	4 km/h (850 r/min)	4 km/h (1050 r/min)	5 km/h (650 r/min)	5 km/h (850 r/min)	5 km/h (1050 r/min)	6 km/h (650 r/min)	6 km/h (850 r/min)	6 km/h (1050 r/min)	Unit
T. Time for road and loading at paddock (h) = R / 60	1.44	1.22	1.08	1.62	1.44	1.28	1.79	1.57	1.30	h
U. All total distance (km) = (L / 1000) + P	48.78	42.17	37.98	54.41	49.04	44.25	59.50	52.71	44.67	km
V. All time (min) = O + R	171.85	158.63	150.25	165.96	155.23	145.65	164.71	151.14	135.05	min
Y. All time (h) = V / 60	2.86	2.64	2.50	2.77	2.59	2.43	2.75	2.52	2.25	h
Z. Transportation factor (h/km) = Y / U	0.06	0.06	0.07	0.05	0.05	0.05	0.05	0.05	0.05	h/km
AA. If working 800 h/year, distance (km) = (U / Y) x 800	13,625.31	12,760.85	12,134.01	15,736.17	15,164.72	14,583.79	17,338.59	16,740.87	15,876.03	km/year

Table B8 Harvesting and transportation costs impacted from the varying fan and ground speeds.

Information	4 km/h (650 r/min)	4 km/h (850 r/min)	4 km/h (1050 r/min)	5 km/h (650 r/min)	5 km/h (850 r/min)	5 km/h (1050 r/min)	6 km/h (650 r/min)	6 km/h (850 r/min)	6 km/h (1050 r/min)	Unit
A. Harvesting cost (derived from B5, 3)	4.74	4.74	4.74	3.87	3.87	3.87	3.31	3.31	3.31	AU$/t
B. Transportation cost (derived from B6, 2)	3.34	3.01	2.80	3.42	3.15	2.91	3.54	3.20	2.79	AU$/t
C. Total cost = A + B	8.08	7.75	7.54	7.29	7.02	6.78	6.84	6.50	6.10	AU$/t