ESTIMATING TRAFFIC INDUCED SUGARCANE LOSSES FOR VARIOUS HARVESTING, LOADING AND INFIELD TRANSPORT OPERATIONS IN SOUTH AFRICA

PB Tweddle

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Bioresources Engineering
School of Engineering
University of KwaZulu-Natal
Pietermaritzburg
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Supervisor: Professor PWL Lyne
Co-supervisor: Dr GL Lagerwall

DECLARATION

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Supervisor: ………………………....................................... Date: ....

Professor PWL Lyne

Co-Supervisor: ………………………....................................... Date: ....

Doctor GL Lagerwall

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ABSTRACT

Infield traffic has been understood to cause adverse field conditions for crop growth. Literature containing traffic induced yield responses for sugarcane was reviewed and synthesised to better estimate the impact of infield traffic on sugarcane yields. Approximately 128 sugarcane yield responses to infield traffic treatments from local and international trials were collated and analysed. The impact of soil compaction effects on soil properties were not considered as there is a substantial body of knowledge on this topic. The results confirm that traffic on a sugarcane row is more detrimental than inter-row traffic. Soil water content at the time of infield traffic and infield traffic load intensity are further critical factors affecting soil compaction and sugarcane yield. Further aggregation of the data by soil textural groups was found to establish yield response trends useful for modelling of infield traffic scenarios, but were not statistically significant.

Infield traffic paths of equipment movements were surveyed and mapped for a range of typical harvesting systems found commercially in the South African sugarcane industry. The maps were analysed to proportion the field area by row traffic, inter-row traffic and remaining non traffic areas for each machine component used infield. Yield losses based on vehicle traffic impacts were assigned to each corresponding component as determined from the results of the literature synthesis. The traffic induced yield loss was apportioned to the areas trafficked to determine a field based yield loss estimate for each of the harvesting and extraction systems and a corresponding economic impact reported. The ranking of system costs, reported off a mechanisation costing base, altered when the additional field traffic induced yield loss components were added, particularly when yield losses were compounded across multiple ratoons within a cropping cycle. Systems operating with low impact vehicles, of low traffic extent combined with controlled traffic practices resulted in the lowest yield losses on a field basis and also resulted in the lowest overall cost. Controlled traffic practices reduce the impact of heavy infield equipment on yields.

The significance of this work is that the yield losses due to infield traffic can now be attributed to systems to allow for improved costing analyses and system comparisons to be conducted. It is proposed that this new contribution be incorporated into standard mechanisation costing methodologies to allow for such crop yield losses to be accounted for.

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1. INTRODUCTION

Soil compaction is recognised as a factor that can limit crop yield potential (Srivastava, 1984; Braunack *et al.*, 1993; Robotham, 2003; Tullberg *et al.*, 2003; Braunack *et al.*, 2006). Much research has been conducted to investigate or model soil physical responses to compaction (Yang, 1977; Torres and Rodrigues, 1995; Braunack and Peatey, 1999; Van Antwerpen *et al.*, 2000; Marx *et al.*, 2006). These trials generally show a negative impact of soil compaction on soil physical, chemical and biological attributes that may, but do not necessarily, lead to yield reductions. At the 2001 International Society of Sugar Cane Technologists (ISSCT) Agricultural Engineering Workshop, Meyer *et al.* (2001) noted the need for research to determine relationships between row spacing, mechanisation, soil compaction and cane stool damage in both agronomic and economic terms. The links between compaction and yield response have not been clearly established and much effort has been spent on detailed and specialised soil measurements to determine thresholds of when yield impacts are likely to occur. Such results are generally not practical for farming operations management or extension advisory services. Other studies have specifically investigated differences between traffic on the inter-row resulting in inter-row soil compaction and traffic on the crop row resulting in cane stool damage (Swinford and Boevey, 1984; Torres *et al.*, 1990; Braunack, 1995; McGarry *et al.*, 1997; Braunack and Hurney, 2000; De Paula and Molin, 2013). Amongst a wide range of treatments and responses, the impact of traffic on the sugarcane row was typically found to be significantly more severe compared to inter-row traffic. These outcomes have led to the promotion of alternative agronomic practices, harvesting systems and infield management practices (Pankhurst *et al.*, 2003; Robotham, 2003; Tullberg *et al.*, 2003; Garside *et al.*, 2005; Braunack and McGarry, 2006; Lecler and Tweddle, 2010; Torres *et al.*, 2010; Kingwell and Fuchsbichler, 2011).

In the South African context, field trial research into the impact of compaction and stool damage has been conducted that similarly has produced variable results over wide range of treatment conditions. The difficulty in quantifying the magnitude of reductions in crop yield to infield traffic has led to general recommendations for control traffic systems and better management practices to be adopted (Van Antwerpen, 2007). The widespread use of non-slewing loaders that cannot comply with control traffic principles and the lack of cost effective alternative loading options have, until recently, made the adoption of control traffic difficult to achieve. Such uncertainty of translating variable research findings of infield traffic into economic terms, the associated risks that would accompany a full system change and the subsequent reintroduction of small slewing loaders into the local market has stimulated interest in such research again. In addition, anecdotal evidence presented at a farmer's day in the Eston area in 2009 showed a distinct divergence in crop production and farming profitability between a top performing grower and others in the same area. One of the distinctions made was that this grower had remained on a particular loading operation compared to his peers who had all changed to higher impact loading system and had all experienced subsequent diminishing crop performance results (Pearce, 2009a; Pearce, 2009b). Other anecdotal examples exists in the Northern Irrigated areas of the Southern African sugar industry, where interviews with farmers that had adopted controlled traffic practices, consistently reported of the benefits of higher yields and longer ratoons that far outweighed the costs associated with adoption (Van Antwerpen *et al.*, 2013). There are also examples of growers elsewhere in the industry reverting from conventional cut and windrow systems to traditional cut and stack operations despite higher operational costs on the concerns that crop production has been adversely affected over time.

This work investigates the overarching direct relationships that infield traffic has on yield thus circumventing the complexities of detailed soil compaction and complex soil interactions. This is a fresh and unique investigation based on a meta-analysis study of past research conducted across the world that links infield traffic to yield loss directly. Analysis of these relationships on higher and detailed levels were used to develop useful trends and also allow for economic impact comparisons to be estimated between systems. It is the first time compaction information has been presented in this way where the impact has been quantified for systems. Researchers have been trying to present this without success. This has now been achieved. This work shows that that current machinery costing techniques are not adequate and that the system has to be accounted for. This work will change many practices which are currently considered the most economical.

Collating and synthesising the current body of literature for yield response trends would provide a basis from which harvesting best practices could be made and to guide where possible future changes to infield harvesting and loading systems in the industry may be required. In a typical commercial harvesting and extraction operation, infield traffic cannot be eliminated, but rather controlled during the process of removing a high yielding crop such as sugarcane from the field. Yield losses are expected to vary depending on the systems used and management thereof and how controlled or uncontrolled the traffic is infield. Uncontrolled traffic is defined as the practice where infield vehicles are at liberty to travel anywhere in the field without restriction in a random pattern and thereby indiscriminately traffic both cropped (row) and non-cropped (inter-row) areas within the field.

The hypothesis for this study is that there will be large differences in yield losses between the various systems typically used in South Africa, with the highest losses being attributed to systems containing the largest amount of uncontrolled traffic occurring infield.

The purpose of this dissertation is:

a) To review the typical complement of equipment and systems used infield for sugarcane harvesting and extraction operations within the South African industry.
b) To review techniques, practices and systems that are being developed and promoted locally and internationally to minimise the impact of infield traffic.
c) To collate and synthesise, from local and international literature, the impact that infield traffic has on the sugarcane plant and on crop yield.
d) To determine, through field investigations, the extent and severity of infield traffic by profiling a range of sugarcane harvesting and extraction systems typically found in the South African sugarcane industry.
e) To conduct overall cost comparisons between typical systems used in the South African sugarcane industry taking the cost of mechanisation and the cost of associated yield loss estimates into account.

Chapter 2 contains a background to the sugar industry and a summary of various harvesting and loading systems typically found in South Africa. Chapter 3 contains a review of various row and vehicle spacing configurations and systems developed to minimise the impact of infield vehicle traffic. Chapter 4 contains a summary of experiments relating sugarcane yield response to traffic with distinctions made between soil compaction and stool damage. The synthesis of yield responses to infield traffic is contained in Chapter 5. The methodology used to gather the field data and analyse it to determine the extent of field traffic is contained in Chapter 6. Maps showing the extent of infield traffic for a range of sugarcane harvesting and extraction systems and corresponding results from field data analyses are contained in Chapter 7. The mechanical field performances of equipment and the various systems are presented in Chapter 8. Chapter 9 contains the accumulation of economic cost components used to develop a holistic overall system cost comparison between systems. Discussions, conclusions and recommendations for future work are contained in Chapter 10.

2. OVERVIEW OF HARVESTING AND LOADING SYSTEMS USED IN SUGARCANE PRODUCTION IN SOUTH AFRICA

The South African sugar industry is comprised of approximately 22 000 sugarcane growers and 14 sugar mills (Figure 2.1) producing approximately 2.1 million tons of sugar per season. Direct income of over R 12 billion is generated from sugar sales to local and international markets. Direct employment within the sugar industry provides for approximately 79 000 jobs. Indirect employment is estimated at 350 000 jobs (Anon, 2016a). The total area under sugarcane production in South Africa is approximately 370 000 hectares. The average production of a large scale grower in the industry is 12 000 tons per annum and 160 tons per annum for small scale growers (Anon, 2016a). The industry average cane crop production is approximately 64 tons per hectare of harvested cane (Anon, 2016a).

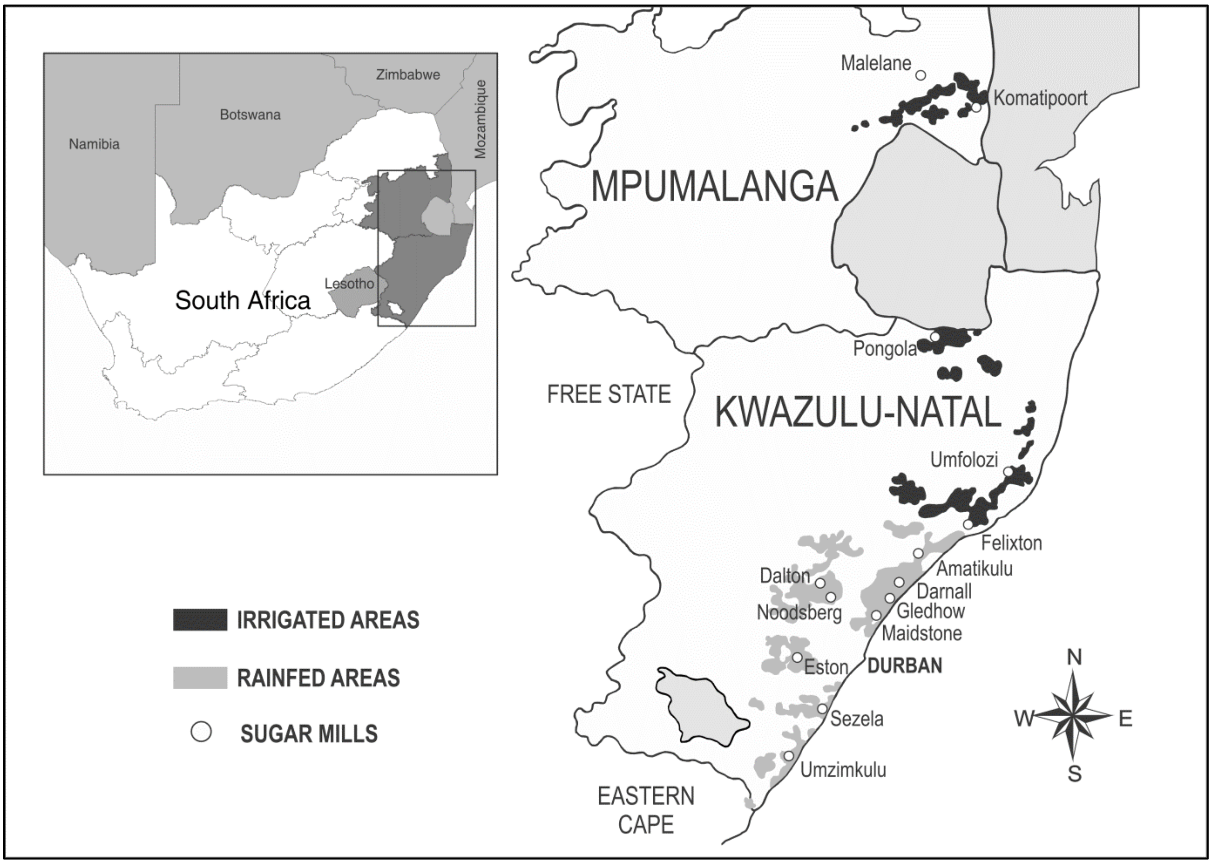

Figure 2.1 Map of the South African sugar industry showing the distribution of sugarcane growing areas (distinguishing between rain-fed and irrigated areas) and mill locations (after Anon, 2005)

Sugarcane is a perennial crop with typically between six and eight harvesting cycles (termed ratoons) before being re-established. The average sugarcane crop cycle in South Africa varies from 12 to 24 months, depending on the bioclimatic region in which it is grown. Sugarcane row spacing in South Africa typically range between 0.9 meter (m) to 1.5 m.

A variety of harvesting systems are employed in the South African sugarcane industry (Figure 2.2). The choice of system depends on factors, such as labour cost and availability, growing conditions and topography (Meyer *et al.*, 2005).

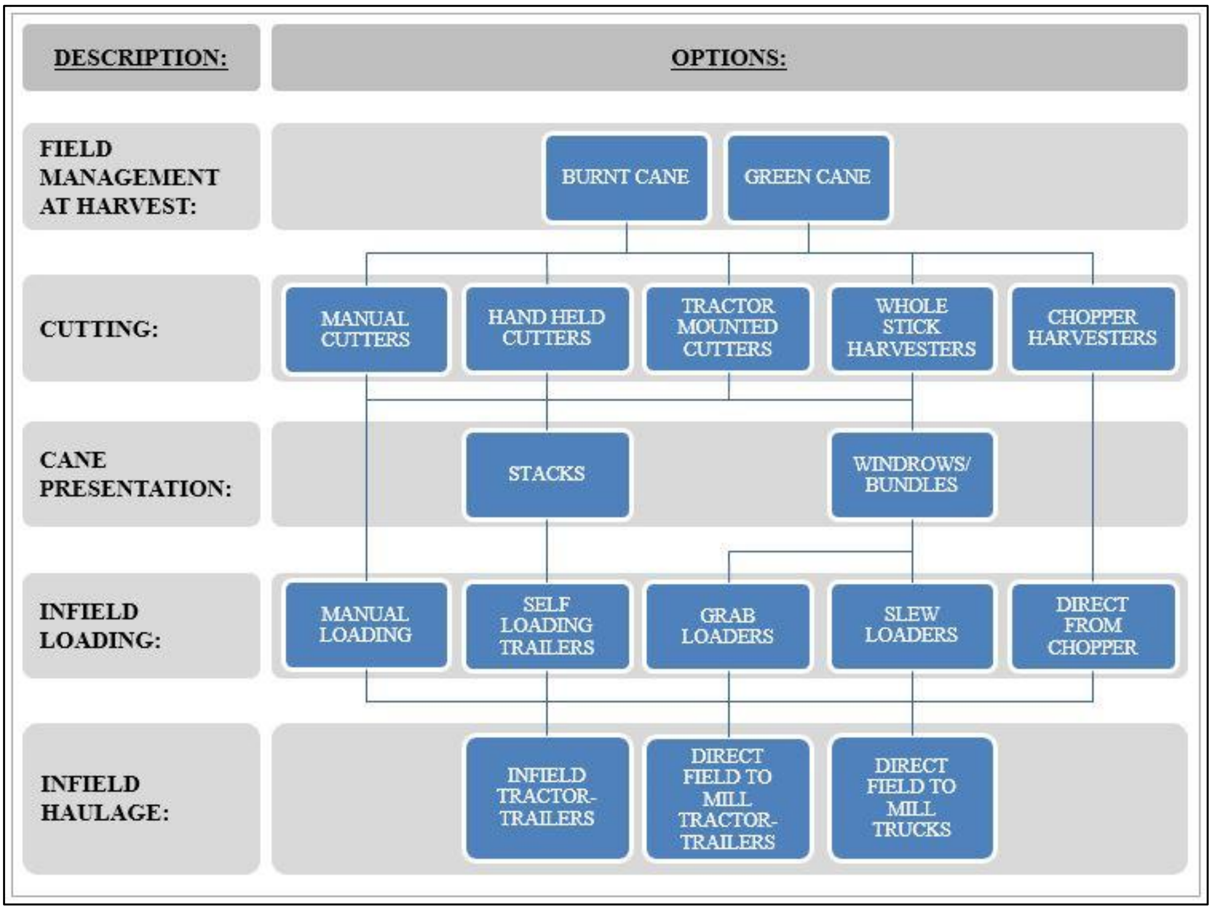

Figure 2.2 Infield harvesting and haulage options (after Braithwaite, 2013)

The results of a survey conducted during the 2003/04 season to determine the distributions of harvesting systems used in the South African sugar industry are listed in Table 2.1. The most prevalent system practiced is to burn the cane, manually cut and place the cane into windrows and then to mechanically load the cane from the windrows into extraction vehicles.

Table 2.1 Harvesting systems used in South Africa (after Meyer, 2005)

System	Fraction of crop (%)	Total (%)
Harvested green	6.1	100
Harvested burnt	93.9	
Mechanical harvest	2.2	100
Manual cut and load	1.3	
Manual cut and stack	30.0	
Manual cut and windrow, mechanically loaded	66.4	

2.1 Cane Cutting

In South Africa, the majority of cane is hand cut. This typically occurs between April and December. Burning is practiced to enable easier manual harvesting (Meyer, 2005). In the process of manual harvesting, the cane from three to six cane rows is merged into a continuous windrow for mechanical loading or placed into stacks for bundle loading (Meyer *et al.*, 2001). Manual cutting and windrowing of burnt cane is shown in Figure 2.3.

Figure 2.3 Manual cutting of burnt cane

Meyer and Fenwick (2003) concluded that the harvesting of burnt cane using manual labour is approximately 20 % more efficient than manually cutting green cane (Table 2.2). The labour productivity for a cut and stack system is approximately 60 % to 65 % of that for the cut and bundle and approximately 50 % of the continuous windrowing system, respectively (Meyer and Fenwick, 2003). It is noted that cutter productivity for the cut and windrow system shown in Table 2.2 may have been enhanced compared to the other systems due to higher cane yields in that system.

Table 2.2 Manual cutter performances in southern Africa (Meyer and Fenwick, 2003)

Harvesting system	**Average cane yield (tons/ha)**	**Cutter output (tons/day)**	**Cutters per 1000 tons**
Cut and stack (green)	72.50	3.45	1.79
Cut and stack (burnt)	69.60	4.20	1.44
Cut and bundle (green)	73.94	5.58	1.07
Cut and bundle (burnt)	69.93	6.56	1.08
Cut and windrow (burnt)	92.87	8.01	0.99

Trends in employment in South Africa have shown a decrease of about 1 % of the labour force per annum for employment within the sugarcane industry between 1973 and 2003. This is less than the broader agricultural sector over the same time period (Murray and van Walbeek, 2007). In response to labour legislation and escalating costs, Murray and van Walbeek (2007) and Murray (2009) surveyed the downsizing of labour forces, reduction of working hours and an increase in training to improve worker productivity. Farmers were found to be streamlining labour intensive operations and investigating mechanical alternatives to manual operations.

Various intermediate systems between manual cutting and chopper harvesters have been developed, but few have been successfully adopted on a large commercial scale (Meyer *et al.*, 2005). Examples include harvesting aids (Langton *et al.*, 2006), self-propelled semi-mechanical cutters (Langton *et al.*, 2008) and a wide range of tractor mounted mechanical whole stick harvesters as reviewed by Meyer (1996a).

2.2 Mechanical Harvesting

Most chopper harvesters harvest a single row, or two closely spaced rows, per pass. Whole stalks entering the harvester are cut into smaller pieces, termed "billets", and conveyed into adjacent infield haulage vehicles travelling alongside the harvester as shown in Figure 2.4. These operations result in two wheel passes from the harvester and two or more passes by the haulage vehicle per row being harvested. The number of passes by the haulage vehicle depends on the crop yield, field length and loading capacity of the haulage vehicle. Such traffic may cause crop yield losses, especially when harvesting under wet conditions and when considering the weight of harvesters (up to 20 tons) and infield equipment (Braunack *et al.*, 2006; Braunack and McGarry, 2006). Harvester pour rates may affect infield extraction equipment requirements. Pour rates of 60 tons per hour for green cane and 100 tons per hour for burnt cane are achievable, depending on field condition and ancillary support systems (De Beer *et al.*, 1993; Meyer, 1999).

Figure 2.4 A chopper harvester and an accompanying tractor trailer to receive cane billets

Environmental and social drivers combined with the prospect of an additional revenue stream through biomass harvesting of cane is likely to increase the adoption of green cane harvesting. Such a practice will require either a change of extraction systems or the amount of infield traffic for field recovery of the cane and leaves. Biomass recovery techniques and systems are constantly being researched and reviewed (Mendoza *et al.*, 2002; Hassuani *et al.*, 2005; Meyer *et al.*, 2012; Rees *et al.*, 2014; Smithers, 2014). These range from manual cane/biomass separation followed by separate recovery of cane and biomass infield to fully mechanised systems, such as chopper harvesters, where the whole crop is harvested and separated at the mill or at a nearby separation plant. These inevitably result in higher amounts of infield traffic. Chopper harvester speed and productivity is reduced when green cane is harvested. Meyer *et al.* (2005) indicated that when harvester fans were switched off, the higher trash content reduced truck payloads by as much as 38 %. This would in turn result in an increase in field trips of a similar magnitude to recover the infield biomass.

2.3 Infield Loading

Manual loading, which provides the cleanest cane of all loading methods, may be employed where small fields, wet conditions and steep terrains are encountered (Meyer *et al.*, 2001). The low productivity and cost of manual extraction of cane is offset by the scale of operation, inability to access the field or field damage caused by alternative mechanical means.

Self-loading trailer systems are designed for the loading of infield stacks. The stacks are cable winched onto a trailer that is parked adjacent to it (Figure 2.5).

Figure 2.5 A double stack self-loading trailer with one stack loaded

Single, double stack, side and rear loading variations are practiced. Typical stack sizes range from 3 tons to 6 tons. The advantage of these systems is that loading occurs independently of other operations. The system typically has lower infield traffic as both the loading and haulage operations are handled by the same vehicle. Stacks are often strategically placed at the field edge to help eliminate infield traffic. A disadvantage may be that lower payloads require a higher number of infield trips and larger fleets of vehicles to achieve sufficient throughput. Meyer *et al.* (2001) report on an example from Zimbabwe, where a fleet of 42 tractor and self-loading trailer combinations conveyed stacks from field to trans-loading zones weighing on average 5.25 tons. A typical single stack self-loading trailer is capable of conveying 20 000 tons per annum when well utilized and can operate on slopes of up to 25 % (De Beer, 1989). This low cost and simple system is well suited for smaller scale commercial operations (De Beer *et al.*, 1993).

Mechanical loaders provide high capacity loading capabilities and usually require high capital investment. High fixed costs are offset through the full and efficient use of these machines (Anon, 2016b). Tractor mounted slew, self-propelled slew and non-slew loader variations are used. Slew type loaders have a grab mounted on a rotating boom that is able to swivel independently of the vehicle as shown in Figure 2.6.

Figure 2.6 A slewing loader fitted with a front mounted push-piler

The non-slewing loaders have a boom that can be raised and lowered on the vehicle, but not rotated relative to the vehicle. Their grab position is determined by the position, movement and orientation of the vehicle itself (Figure 2.7).

Figure 2.7 A non-slewing loader which is most commonly used in the South African sugarcane industry

A non-slew loader is theoretically capable of loading approximately 80 000 tons per annum on a double shift operation. High capacity self-propelled grab loaders have been measured to load an average of 147 000 tons per annum using two 9 hour shift operations (Meyer *et al.*, 2001). A seasonal average loading rate of 43 tons per hour was reported for a fleet of 11 slewing loaders operating in Swaziland (De Beer, 1989). Slewing loaders can operate on slopes of up to 20 %, whereas non-slew loaders can typically operate on slopes of up to 40 % due to their greater stability and manoeuvrability (De Beer, 1989). De Beer (1989) suggested that non-slew loaders may cause more field and cane stool damage compared to larger slew machines, especially under wet field conditions. The advantages of the non-slew loaders are their relatively lower capital cost, rigid construction, lower weight, high manoeuvrability, high productivity and versatility for use infield or for zone loading operations.

2.4 Infield Haulage

Haulage systems are required to transport harvested cane as quickly and economically as possible from the field to a trans-loading zone or directly to the mill (Meyer *et al.*, 2001). The use of trans-loading zones is essential where field conditions or management preferences preclude the use of high capacity haulage vehicles infield or where haulage distances to the mill are too far for low capacity vehicles to be operated economically. Trans-loading systems include whole stalk loose and bundle systems, loose and containerised billet systems, as well as transfer/cleaning stations to transfer cane into road or rail transport networks (Meyer *et al.*, 2001). Strategic placement of trans-loading zones is essential as short haulage tractor-trailer transportation typically incur costs of six to nine times that of truck transportation (Bezuidenhout and Meyer, 2005). Cane transport vehicles should have high speed and payload capabilities, ideally with a payload to tare weight ratio greater than 1.5 (De Beer *et al.*, 1993) and fast loading and offloading times in order to be cost effective. Infield loading of road haulage vehicles is often practiced in order to minimise double handling costs and thereby eliminating the need for trans-loading operations and infrastructure.

Little recent research and development of non-mechanised harvesting systems has been conducted. Recent research and development focus has been on how to better manage vehicles and equipment to sustain or improve crop performance. Such topics include farming systems, control traffic, minimum tillage and conservation agriculture. In the following chapter, developments and changes that have been made to infield equipment, field practices and vehicle management systems in response to improving machinery efficiencies, crop production economics and sustainable cropping practices are reviewed.

3. INFIELD VEHICLE MANAGEMENT SYSTEMS

Under commercial sugarcane farming operations, especially during harvesting and loading operations, infield traffic is required to access and remove the crop from the field. This field access will typically result in crop damage and subsequent yield loss. The purpose of this chapter is to review agronomic and traffic practices that have been developed to reduce the impact of infield traffic and thereby improve and sustain crop yields. Maximising agronomic yield potential per unit area, i.e. optimizing row spacing, needs to be managed in conjunction with high amounts of infield traffic. The concept of controlled traffic to reduce the impact of infield traffic is described and various examples of implemented systems are reviewed.

The on-farm harvesting and extraction of sugarcane is typically associated with high amounts and intensities of infield traffic due to the high biomass yield of the crop compared to other field crops (Meyer *et al.*, 2001). Research has shown that infield traffic needs to be confined to the crop inter-row in order to minimise the impact of yield loss (Torres and Villegas, 1995; Braunack and Hurney, 2000; Meyer *et al.*, 2001; De Paula and Molin, 2013). This demands the integration of: (a) a suitable crop row spacing configuration, (b) infield machinery wheel tracks to suit, and (c) practical machinery protocols to be adhered to during infield operations. Wide wheel tracks are typically preferred for improved vehicle stability and wide swaths and row spacing's can improve mechanical field capacities and efficiencies. In contrast, narrow rows help to achieve early full crop canopy cover and to improve light interception by the crop. The wheel tracks of all infield equipment should ideally be matched with the ideal agronomic row spacing (typically by straddling multiple rows). A trade-off may be required to best match row and wheel track spacing's for a system that is practical, efficient and that does not induce cane stool damage through unnecessary row traffic (Meyer *et al.*, 1999; Meyer *et al.*, 2001). Manual harvesting operations require accurate placement of windrows or stacks so that the wheels from infield loading and transport systems are able to traffic the inter-rows only.

The concept of controlled traffic is discussed in Section 3.1 and various row spacing configurations that have or are being developed and implemented internationally are described in Section 3.2.

3.1 Controlled Traffic

Controlled traffic is essentially the separation of wheel tracks from the cropping zone to create dedicated traffic and cropping zones. This requires the matching of wheel track widths and row widths with the purpose of confining infield traffic to permanent infield traffic lanes in conjunction with accurate and disciplined driving practices (Van Antwerpen *et al.*, 2000; Braunack and McGarry, 2006). This is in contrast to “uncontrolled” traffic which is used to describe systems where infield vehicles are at liberty to travel anywhere in the field without restriction. The term “random” traffic is also used to indicate uncontrolled traffic or where a mismatch of cane row spacing and equipment track widths occur.

The mismatch of traditional cane row spacing and typical infield equipment track widths are estimated in certain industries to have caused yield reductions in the order of 20 % (Norris *et al.*, 2000). Field trials conducted by Braunack and McGarry (2006) showed that crop yields tended to be lower for random traffic than controlled traffic. Trouse (1982) motivated for a controlled traffic system on the basis of reducing energy usage from periodic tillage and subsequent wheel traffic re-compaction cycles that degrade soil properties. Fuel savings alone were estimated at 10 % for tracked and 20 % for tyre fitted vehicles when travelling on compacted traffic lanes. McGarry *et al.* (1997) showed improvements in the soil physical properties after a number of ratoons, following controlled traffic practices. These consisted of a lower density, lower soil strength and greater macro and micro-pores within the crop zone combined with a hard compacted traffic zone located in the inter-row area which would be suitable for better traction and wet weather access by infield vehicles. Robotham (2003) noted that crop yield increases of 10 % and greater have been cited following the adoption of Controlled Traffic Farming (CTF). Pankhurst *et al.* (2003), Tullberg *et al.* (2003), Turner *et al.* (2004), Garside *et al.* (2005), Braunack and McGarry (2006), Tullberg (2010) and Kingwell and Fuchsbichler (2011) have all promoted controlled traffic as an effective means to sustain soil and crop health, particularly if combined with additional practices such as breaking the monoculture, reduced tillage, organic matter conservation and precision farming techniques. The combinations of these practices also assist in conserving soil water, reducing soil disturbance and associated weed germination, reducing soil erosion, improving traction, improving machinery field efficiencies, improving the timing and flexibility, as well as reducing field operations and associated input costs. All these factors are expected to contribute towards the potential for yield improvements and longer sustained cropping cycles (Braunack and McGarry, 2006). The integrated benefits of CTF were modelled by Kingwell and Fuchsbichler (2011) who report a 50 % increase in farming profit to a typical grain farming operation in south western Australia. A group of CTF adopters in southern Queensland, Australia, have reported crop production increases in the order of 37 % and machinery related cost reductions of 49 % (Tullberg, 2010). Lecler and Tweddle (2010) conducted an economic analysis on various sugarcane CTF system options for southern African conditions and indicated for different scenarios that all show significantly improved profits under CTF compared to conventional farming system practices.

In Columbia, Torres and Pantoja (2005) reported on controlled traffic being practiced on a new crop configuration developed to better match that of the equipment track widths. Yield decreases from components of a fully mechanised harvesting operation and semi-mechanised system were compared against yields from a zero traffic control where the cane was cut and extracted manually. Inter-row traffic of the harvester alone decreased yields by 1.3 %, the haulage vehicles by 3.3 % and in combination by 4.6 %. The semi-mechanised system consisting of manually cut cane placed in windrows and loaded by a slew loader into cane haulage vehicles resulted in a combined loss in yield of 7.4 %. By inference, the loaders therefore contributed approximately 4 % to the yield loss. In comparison, an adjacent field under the same management regime but without controlled traffic was reported to yield 27 % less than the zero traffic plots, and 23 % below the average of the controlled traffic plots.

3.2 Cropping System Configurations

In order to establish a suitable distance between the row and tyre edge to minimise crop yield loss, trials by Carter (1985) show only beneficial effects on a cotton crop when the wheel edge to plant distance was set at 0.75 m. A distance of 0.40 m was suggested by Van Antwerpen *et al.* (2000) for sugarcane, who subsequently found that on a high clay soil a space of 0.1 m between the cane plant and the wheels proved to be sufficient to not reduce cane yields. Maintaining this distance in commercial applications was, however, thought to be difficult to achieve since there would be little margin for operator error (Van Antwerpen *et al.*, 2008), unless vehicle guidance systems were employed.

Meyer *et al*. (2001) describe the adaptation of farming practices over time in Australia, where row spacing's were increased from 1.1 m to 1.5 m to better suit single row mechanical harvesters. In order to reduce production costs, the size of harvesters and infield equipment were also increased. During this transition period, the mass of harvesters were reported to have doubled and there was a migration towards higher capacity extraction equipment with large diameter and low pressure high floatation tyres or tracks. Meyer *et al*. (2005) however, reported that up to 90 % of the entire field area is compacted by the combination of harvesters and infield transport under the standard 1.5 m row spacing system. Soil compaction issues combined with a focus on improving and sustaining yields have further stimulated the development of alternative planting systems.

There are inconsistent results when considering optimum row spacing for cane production. Khandagave *et al.* (2005) reviewed a number of publications showing a positive response to a wider row spacing and trials conducted in India showed a significant response (64 % yield increase) to increasing the row spacing from the traditional 0.9 m to 1.5 m. Singels and Smit (2009), in contrast, referenced a number of authors showing yield increases with a reduction in row spacing. Table 3.1 gives an indication of yield responses to row spacing from southern African literature.

Table 3.1 Yield response to a change in row spacing for southern African data

Reference	**Row spacing trial details (m)**	**Optimum row spacing (m)**	**Yield response to an increase in row spacing from optimum (%/m)**
Thompson and Du Toit (1965)	0.45; 0.9; 1.37	0.45	-11 %/m
Boyce (1968)	0.9 to 2.15	0.9	-15 %/m
Singels and Smit (2002)	0.7; 1.2; 1.7; 2.2; 2.7	0.7	-13 %/m
Olivier and Singels (2003)	1.8 dual rows; 1.5	1.8 m dual rows	+23% for dual rows
Singels and Smit (2009)	Radial pattern: 0.4; 0.9; 1.3; 1.7;2.2;2.6	0.4	-22 %/m

Singels (2013) used the *My Canesim* model (Singels, 2007) to simulate crop yields for row spacing's of 0.9 m, 1.35 m and 1.8 m for three soils of different water holding capacities and two starting times for plant and ratoon crops. Simulations were conducted using 9 years of weather data from two KwaZulu-Natal south coast weather stations. The results showed that a row spacing of 0.9 m tended to yield the highest, although this was more apparent in the plant crop than ratoon crops. This supported the results from a number of studies, as per Table 3.1, where 0.9 m seems to be a reasonable and practical row spacing option corresponding to high yields under southern African conditions. It also allows commonly found tractor and equipment wheel tracks of 1.8 m to align with the crop inter-rows, which will minimise traffic induced yield losses caused from travelling on the row. However, constraining the traffic of wide tyres to the narrow (0.9 m row spacing) inter-row area during field operations is difficult to achieve in practice, with little tolerance for driver error, particularly if planting inaccuracies or crop regrowth were impinging on this area.

In Australia, the improvement in yield at narrower row spacing's led Norris *et al.* (2000) to test a "high density planting" system. This comprised of raised crop production bed consisting of four rows at 0.47 m, separated by 0.7 m traffic lanes set at a corresponding equipment track width of 2.1 m. A raised bed system 2.3 m wide with three rows set at 0.55 m apart was also tested with modified harvesters. These systems were developed following agronomic trials that indicated yield increases of between 20 % and 50 % at the narrower spacing's compared to the 1.5 m row spacing (Bull and Bull, 2000). Substantial modifications to planting, harvesting and extraction equipment were, however, reported to be required.

A modified dual row planting system with a wide inter-space (3.9 m) for crop residues (and possible intercropping) and three sets of dual rows (0.8 m + 2.1 m spacing) to match harvester or loader systems (Figure 3.1) is described by Torres *et al.* (2010), Columbia. Parabolic furrows were formed in the centre of the dual row inter-rows for furrow irrigation. Yield results compared against conventional 1.75 m single row spacing suggested that plant cane yields are compromised by the lack of crop in the wide inter-row space for the first crop, but are matched and improve in consecutive ratoons thereafter. The cropping system was further adjusted by planting a single row in the wide inter-row space to improve the yields of the plant crop. The positions of these single rows are indicated by the arrows in Figure 3.1.

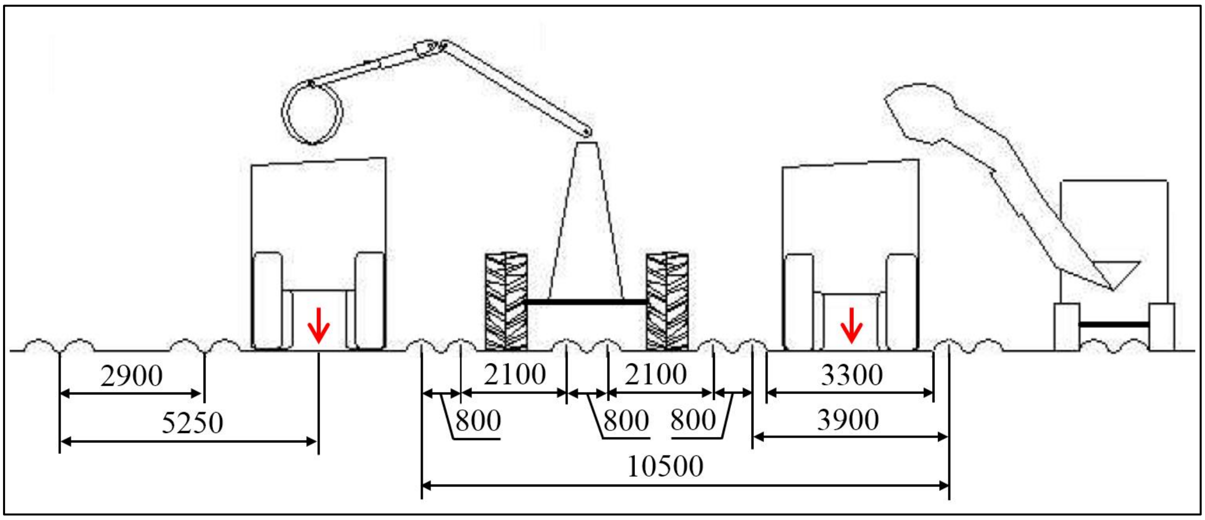

Figure 3.1 A modified dual row system after Torres *et al.* (2010) (units in mm)

Dual row systems with distances between close rows ranging from 0.3 m to 0.8 m and overall spacing between crop zones (pairs of dual rows) ranging from 1.8 m to 2.1 m have been gaining popularity (Meyer *et al.*, 2005). The choice of spacing is typically determined by the infield vehicle wheel tracks and management preferences. An example of a dual row system to cater for a wheel track spacing of 1.8 m is shown in Figure 3.2.

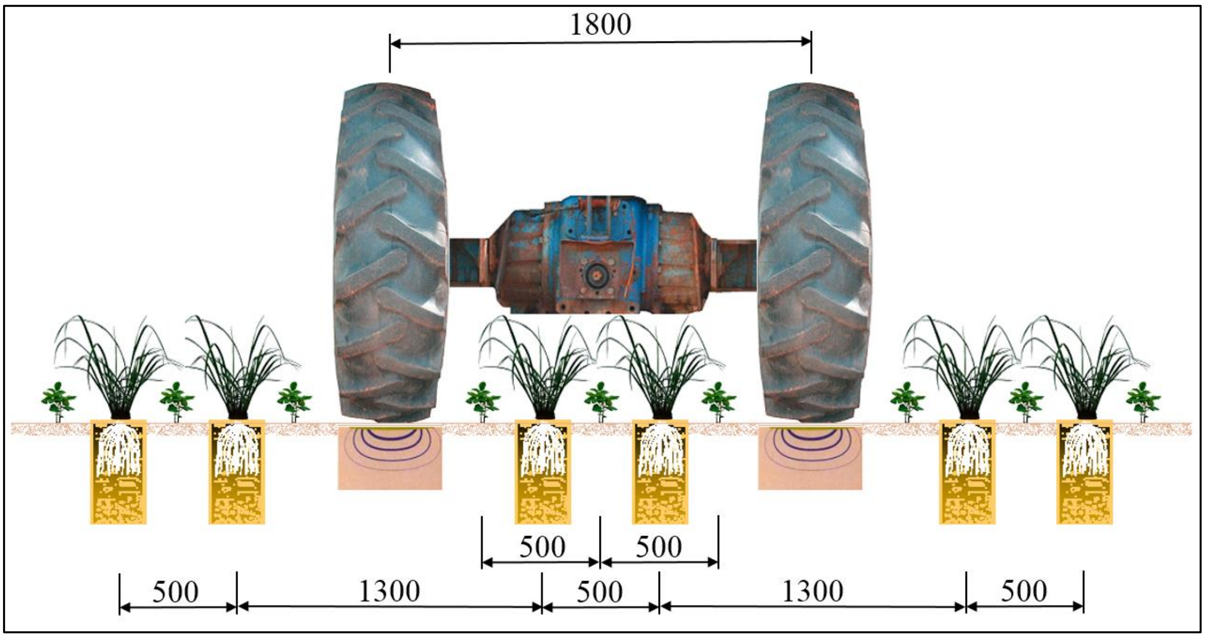

Figure 3.2 Strategic spacing of wheels, sugarcane and break crops within a dual row system (0.5 m + 1.3 m crop spacing’s) and corresponding 1.8 m wheel track spacing (Lecler and Tweddle, 2010) (units in mm)

In Zimbabwe, a system has been developed for the integration of surface furrow irrigation and mechanised planting and harvesting operations. The proposed layout consists of irrigation furrow set between dual rows of cane spaced at 0.9 m with 2.4 m between the centres of each pair of dual rows (Lecler, 2015). The 2.4 m spacing is considered suitable for a range of locally used harvesting and loading equipment.

Braunack and McGarry (2006) reported an increase in the yields from controlled traffic dual rows (0.3 m apart) at 1.8 m wheel spacing to match harvester and haul-out track widths against non-controlled traffic in a field with a crop row spacing of 1.5 m.

In South Africa, McElligott *et al.* (2014) reported an increase in cane production of 21 t/ha for a commercial farming operation through the adoption of a tramline row spacing of 0.65 x 1.15 m to match vehicle tracks, reduce infield compaction and to reduce herbicide use. A 30 % reduction in herbicide costs were also attributed to the change from the single row spacing of 1.37 m.

A range of row spacing changes and corresponding yield benefits are listed in Table 3.2.

Table 3.2 Yield response to a change from traditional single row to dual row spacing

Reference	**Traditional row spacing (m)**	**Dual row × wheel track spacing (m)**	**Yield benefit**
Anon (1998)-Zimbabwe	1.5	0.42 × 1.8	+12%
Olivier and Singels (2003)-Swaziland	1.5	0.4 × 1.6	Increase
Olivier and Singels (2003)-South Africa	1.5	0.4 × 1.8	+32%
Olivier and Singels (2003)- South Africa	1.5	0.6 × 1.8	+30%
Olivier and Singels (2003)- South Africa	1.5	0.9	+44%
Braunack and McGarry (2006)-Australia	1.5	0.3 × 1.8	Increase
Bull and Bull (2000)-Australia	1.5	0.5 x 1.8	+4% to 30%
Ismael et al. (2007)-12 trials-Mauritius	1.6	0.5 × 1.8	+3% to 28%
Klomsa-Ard *et al.* (2007)-Thailand	1.0	0.5 × 1.6	+18% to 53%
McElligott *et al.* (2014)- South Africa	1.37	0.65 × 1.15	+21 t/ha (+20%)

In addition to higher yields, other noted benefits of narrower dual rows include: Improved water use efficiency (Anon, 1998; Olivier and Singels, 2003; Klomsa-Ard *et al.*, 2007), quicker crop canopy, improved light interception and better weed management (Ismael *et al.*, 2007). Mechanical harvesting of the dual rows simultaneously lead to improved field efficiencies, improved harvesting rates, less turning time and less field distance travelled (Ismael *et al.*, 2007). Disadvantages are the higher quantity of seedcane required during planting and the tendency of the tramline spaced cane to lodge (Anon, 1998).

Reduced tillage was also compared against conventional intensive cultivation in the trials by Braunack and McGarry (2006). In both trials, the soil in the crop row remained in better physical condition when practicing controlled traffic and reduced tillage compared to conventional traffic and tillage. Yields were generally higher under controlled traffic compared to random traffic and generally higher under reduced tillage operations compared to conventional tillage production. Crop yield was not compromised by the adoption of controlled traffic and benefits were expected to accrue with time through sustained yields.

The following chapter will focus on the response of sugarcane to infield traffic. Aspects include the physiological response of sugarcane to traffic and the impact of vehicle and loading characteristics on the crop.

4. SUGARCANE RESPONSE TO INFIELD TRAFFIC

The aim of this chapter is to review compaction and infield traffic trials that have reported yield responses to various infield traffic treatments. The focus is on sugarcane unless otherwise stated. The chapter is introduced with general plant responses to soil compaction, followed by agronomic responses to variations in compaction events. A review of a model developed to predict sugarcane yield responses to compaction concludes this chapter.

Industries that have adopted full mechanisation have reported that the higher traffic intensities associated with full mechanisation have increased the risk of adverse conditions developing infield. These include soil compaction and crop damage, especially in or following wet field conditions resulting in observed yield losses and, in some cases, a reduction in ratoon cycle lengths (Braunack *et al.*, 1993; Pinto and Bellinaso, 2000).

Soil compaction, soil sealing (or capping) and physical damage to the cane stools caused by harvesting and transport equipment can have a significant impact on long term sustainability. This damage tends to be aggravated during wet field conditions (soil water content near field capacity) and where traffic is uncontrolled (Maud, 1960; Meyer *et al.*, 1996). Traffic is more likely to occur on the row when the traffic is uncontrolled or when the positions of rows are not easily visible. A field practice, such as green cane harvesting, for example, typically results in high levels of crop residue remaining on the field surface making it difficult to see where the positions of the rows and inter-rows are. Another example of where uncontrolled traffic is likely to occur, is where cane windrows or stacks are misaligned and thus requiring the loader operator to inadvertently drive over the rows during loading operations. A simple technique to guide traffic within dedicated traffic lanes is the construction of infield ridges or cropping beds and alternative traffic lanes matched to equipment wheel tracks.

Row traffic (traffic on or over the crop row) has been found to have a more severe yield impact compared to inter-row traffic (Swinford and Boevey, 1984). This provides an incentive to control the position of infield vehicle traffic. Yield decline from infield traffic is due to physical damage to stools and a breakdown in structure and surface sealing from soil compaction, particularly under critical soil moisture conditions (Meyer, 1996b).

Soil compaction and cane stool damage are distinctly different issues, but can occur simultaneously. De Beer (1989) noted that previous studies typically did not distinguish between compaction and stool damage in the reporting of yield losses. Row traffic induced yield losses of as much as 50 % and a reduction in the number of crop ratoons prior to plough-out have been reported (Van Antwerpen *et al.*, 2000)

4.1 Crop Growth and Development Responses to Infield Traffic

For sugarcane, adverse soil properties associated with compacted soils negatively affect root growth rates (Torres and Rodrigues, 1995). Trouse (1982) described the restraint of root elongation in compacted soils by as much as 12 times that of healthy roots in good soils. A likely consequence would be less moisture and nutrient absorption by the plant. Compaction may induce temporary anaerobic conditions due to slower soil water movement, especially if an impermeable subsoil layer is present. In addition, a reduction in porosity and slower infiltration rates are likely to cause surface water runoff, reduced moisture capture and water holding capacity in the soil. All these may lead to a loss of potential crop production. Georges *et al.* (1980) found that roots were negatively affected and distributed at shallower depths following mechanical harvesting under wet conditions in a high clay soil. Final yields were significantly lower by 20 % compared to manually harvested fields. Fernandes *et al.* (1983) found that root performance was adversely affected by conventional vehicle compaction to a depth of 0.4 m.

Traffic directly over the cane stool has been found to cause a number of responses. Slow initial regrowth of cane has been measured (Johnston and Wood, 1971; Georges *et al.*, 1985; Jackson *et al.*, 2000). Short term variable cane stalk population responses have been shown to decrease in some instances (Jackson *et al.*, 2000) or increase in others (Johnston and Wood, 1971; Fernandes *et al.*, 1983; Braunack *et al.*, 2006). These variable stalk population responses tend to equalize over time. A reduction in plant heights by as much as 27 % in some instances has been measured following traffic over the cane stools (Johnston and Wood, 1971; Georges *et al.*, 1980; Braunack *et al.*, 2006). Jackson *et al.* (2000) measured significantly slower canopy development and reduced light interception in wet traffic treatments, compared to a control treatment when harvesting under dry conditions. In some trials the final yields were not compromised, despite differences in plant measurements

(Georges *et al.*, 1985). In other instances, the yield losses were significantly lower (Georges *et al.*, 1980). Jackson *et al.* (2000) measured significantly smaller cane stalk diameters and lower yields in their trials. Further yield depression and lower canopy light interception were measured in subsequent ratoons, despite no further traffic treatments. The effect of a single traffic event can thus continue to negatively impact the yield of more than one successive ratoon.

Jackson *et al.* (2000) tested for genetic variation in ratoon growth and cane yield after mechanical harvesting operations under wet conditions and post-harvest waterlogged conditions across a range of 26 sugarcane clones of diverse genetic composition in Australia. Differences in varietal and genetic background (genotype × treatment interactions), although significantly different in early growth, did not translate to a significantly different response to treatments at harvest. First ratoon yields ranged from 66 % to 75 % of the control treatment, while second ratoon treatments ranged from 76 % to 81 % of the control treatments.

4.2 Vehicle Characteristics Affecting Soil Properties

Kanali *et al.* (1996) indicated that at high soil water contents, high wheel slip operations can contribute as much to soil damage through topsoil smearing as the damage caused by loading. No specific records of the impact of wheel slip on sugarcane yields have, however, been found in literature.

Load induced soil compaction is typically a function of axle load and tyre-soil contact pressure (Torres and Villegas, 1995). For a given axle load, a reduction in ground pressure will lead to an increase in tyre-soil contact area and thereby reduce the depth of compaction (Van Antwerpen *et al.*, 2000). Torres and Villegas (1995) and Torres and Rodrigues (1995), however, indicate that as the soil-tyre contact area alters, the soil surface layer’s bulk density is affected, and that depth of compaction is primarily a function of axle load magnitude, not contact area. Braunack *et al.* (1993), compared conventional and high floatation equipment and found little difference between the soil properties, despite ground pressures for the conventional equipment being almost 3.5 times higher than high floatation equipment. There was a tendency for cumulative infiltration rates to be higher for the high floatation equipment and for higher bulk densities to be found nearer the surface for the conventional equipment.

Van Antwerpen *et al.* (2008) also reported no significant reductions in compaction with the use of high flotation tyres, compared to conventional tyres (heavy axle load treatments). The tyre inflation pressure of high floatation tyres, being only 20 % less than the radial tyres, proved ineffective in reducing soil compaction damage. Water infiltration rates in this instance did not differ between tyre type treatments. Van Antwerpen and Meyer (2001) documented that for high axle loads, greater than 5 tons, tyre pressure effects were deemed insignificant and compaction impact was dominated by axle load. Subsoil compaction is primarily a function of total load and not ground pressure.

Topsoil compaction is typically a function of tyre-soil contact pressure. Pressure distribution on the soil surface by vehicles depends on the characteristics of the tire or track and of the soil surface (Torres and Rodrigues, 1995). The tyre-soil contact pressure or ground pressure is similar to the tyre inflation pressure (Van Antwerpen *et al.*, 2000). At high soil water contents and soil contact pressures, compaction, deep rutting and lateral soil displacement may occur when a vehicle sinks and the soil deforms. For the same contact area, a longer narrower tyre footprint in the direction of travel is preferred as it provides better traction and less field area being compacted (Van Antwerpen *et al.*, 2000).

For low bearing capacity soils and higher pulling capabilities, tracked machines are advantageous compared to more versatile wheeled machines. Tracked machines theoretically have a lower compaction impact. In practice, tracks in some cases have been found to distribute loads unevenly and may cause unexpected soil damage (Torres and Rodrigues, 1995). Particularly for high drawbar pull applications, the peak soil pressure distributions are highest rearward of the track centre and can be two to three times greater than expected (Torres and Rodrigues, 1995).

The first pass of a machine causes the greatest impact on a soil compared to subsequent passes under the same conditions (Maud, 1960; Fernandes *et al.*, 1983; Van Antwerpen *et al.*, 2008). Robotham (2003) indicated that between 60 % and 80 % of potential compaction occurs with the first tyre pass. Maud (1960) found that the first three passes had the greatest impact on compacting a soil with further passes having a low and diminishing effect. Tyre performance is generally improved in subsequent passes if tyres travel along the same track (Torres and Rodrigues, 1995).

It can be seen that compaction is a complex system with many interdependent factors making it difficult to obtain consistent responses. Attempts have been made to model the process and are discussed in Section 4.3.

4.3 Modelling of Yield Response to Infield Traffic for Sugarcane

Arvidsson and Håkansson (1991) developed a computational model for estimating crop yield loss caused by machinery induced soil compaction in tillage systems. The complicated interaction of soil and crop responses to traffic was deemed to inhibit the development of a mechanistic model that could practically and accurately predict such interactions. Based on empirical data from extensive field crop trials conducted in Sweden, the model estimates total costs of soil compaction on four components, namely: (a) re-compaction of a tilled topsoil, (b) structural damage in the topsoil, (c) subsoil compaction and (d) physical traffic damage to the growing crop. Re-compaction is predicted by calculating a relative yield based on the degree of soil compactness as related to soil water content and vehicle characteristics. The topsoil damage component requires the determination of traffic intensity corrected for soil water content and field equipment effects. The subsoil damage components are based on traffic intensity at two levels, namely, between 0.25 m and 0.4 m and greater than 0.4 m. The damage caused in the shallower depth is assumed to persist for 10 years while the deeper layer is deemed irreversible (permanent yield loss). The modelling of yield loss is based on axle load with a shallow zone affected by axle loads above 4 tons and a deeper zone by axle loads above 6 tons. The final component relating crop response to traffic in a growing crop is based on ley crops (seed crops followed by pasture rotation).

The model developed by Arvidsson and Håkansson (1991) was modified by Braunack *et al*. (2006) to predict crop response to machinery traffic for the Australian sugar industry. Several changes were made to adapt the model from annually cultivated cropping systems to the perennial sugarcane crop grown in rows with no annual cultivation. The topsoil compaction component relates traffic position relative to the crop and is assumed to be a function of traffic intensity corrected for soil water content and tyre inflation pressure. Subsoil compaction yield loss is based on traffic intensity at two zones (above 40 cm and below 40 cm) as per the original model. The modified model was calibrated and validated for the

Australian sugarcane industry using results from a set of ratoon cane crop trials. The results were deemed to estimate typical compaction induced yield loss with reasonable agreement for the Australian sugarcane industry. A database of machinery commonly used in the Australian industry was included in the model to allow alternative traffic scenarios to be tested. This model requires a range of inputs for a specific condition. The range of input parameters includes the following: Cropping parameters such as farm size, crop yield, cane quality and cane value; soil parameters such as clay content, topsoil and subsoil moisture conditions and vehicle parameters such as axle weights for loaded and unloaded conditions for each set of axle groups, tyre inflation pressures for each set of axle groups, number of passes, working widths and an allowance for extra driving. A further apportioning of the field by un-trafficked, inter-row traffic and row traffic percentages are required.

Traffic intensities and traffic position parameters have not been accurately characterised for systems used in the South African sugar industry. The applicability of the model for the South African sugarcane industry was uncertain as the model was calibrated to a set of Australian field trials on soils, varieties and equipment systems that could differ considerably from the South African sugarcane industry. In preference to using an empirically based model for such a complex process, it was felt necessary to examine research results to establish the trends of yield responses to infield traffic.

There are a wide range of yield responses to infield traffic. Numerous factors are stated as influencing the yield responses obtained. Such factors included: soil properties, soil moisture condition, axle loads, tyre types, tyre pressures, wheel position (row and inter-row), traffic frequency (wheel passes) and traffic intensity. In the chapter that follows, a synthesis of literature pertaining to the consequences of infield traffic on yields is detailed. The yield responses to traffic were compiled into a database of results. This synthesis constitutes a desktop study to investigate yield response trends that can be extracted from local and international literature for a range of field equipment and operations.

5. LINKING THE IMPACT OF INFIELD TRAFFIC TO SUGARCANE YIELD BASED ON LITERATURE SYNTHESIS AND META-ANALYSIS

In this chapter the compilation of a database of yield responses to infield traffic is described. Section 5.1 contains the complete set of yield results sorted by traffic position, being either row or inter-row from the database of yield responses to infield traffic. Section 5.2 contains a subset of the data excluding yield responses for traffic treatment results conducted under dry soil conditions. This data was further categorised by a subjective assessment of vehicle impact rating by taking vehicle attributes such as weight and tyre properties into consideration. The synthesis and sub-categorisation of yield responses in Section 5.2 are used as the basis for determining field based yield losses as an outcome in the results and economics chapters of this study (Chapter 7 and Chapter 9). Section 5.3 contains an analysis of the traffic yield impact database by various categories of aggregation. Aggregated analyses included testing the yield responses of row and inter-row traffic treatments with various combinations of the following factors: soil textural responses; soil moisture; vehicle axle loads; vehicle tyre pressures and gross vehicle mass. The objective of the analysis in Section 5.3 was to investigate for trends to account for the high variance in yield responses in literature. Such trends would allow for further refinement of the effect of traffic impacts on yield and associated modelling thereof. Section 5.4 concludes this chapter with an exploration into the modelling of infield traffic impacts. The impact of the number of wheel passes as a proportion of total yield loss from previous studies is explored and a regression equation developed to define this relationship. From this relationship, the impact of a single pass yield impact was estimated from the measured traffic yield responses associated with multiple passes and reverse engineered to provide the yield loss associated with a single pass impact suitable for modelling purposes. The model was then validated against the raw yield loss data and verified against independent yield loss data.

5.1 Compaction Trial Results Database: Contrasting Row and Inter-Row Traffic

A wide range of yield responses to infield traffic have been measured in the past across a varied range of sites, soils, field conditions and field treatments. In order to estimate traffic induced yield losses a database of compaction field trial results have been collated from both local and internationally published data. Yield responses in terms of tons cane per hectare were normalised into a percentage basis of the zero traffic/control treatments to allow for collation and comparison purposes. The lists of trials that have been conducted in southern Africa are contained in Appendix A and internationally are contained in Appendix B. The data makes use of mean values of yield responses from individual trials in order to establish general relationships that account for traffic induced yield losses. Trial results are listed and categorised by yield responses to: no traffic, inter-row traffic, row traffic and general infield traffic (consisting of an unspecified mix of inter-row and row traffic). Trial attributes are captured to allow for trend analysis at greater detail such as by country, soil attributes, vehicle or treatment. A preliminary high level analysis of all the data comprising yield responses to infield inter-row and row traffic is summarised as per Figure 5.1.

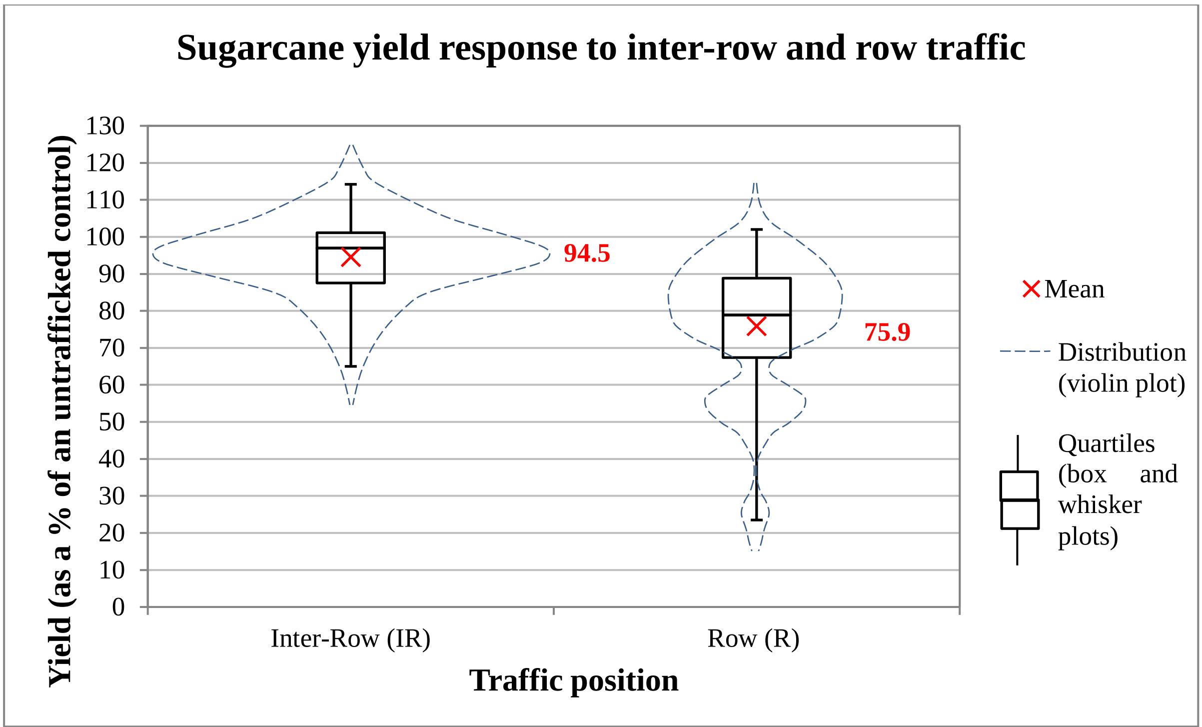

Figure 5.1 Sugarcane yield response to inter-row and row traffic based on datasets consisting of 40 inter-row and 26 row samples

Inter-row traffic appears to have far less impact on yields compared to row traffic. The large distribution and lowering of yields in response to row traffic indicates that there is a greater risk of excessive yield losses being caused through row traffic. Some trials actually indicated slight yield improvements following compaction treatments. These were typically for inter-row traffic events or drier field conditions. Such observations can be supported by literature

(Van Antwerpen *et al.*, 2000). The general indications are, however, that traffic entering a field typically result in a loss of crop yield. Extreme yield losses of as much as 80 % can be attributed to stool damage under unsuitable field conditions. These are typically for high axle load and high soil moisture conditions. Mean values from the inter-row and row groups were 94.5 % and 75.9 %, respectively. The distributions of the groups differed significantly (Mann–Whitney $U = 178$, $n_1 = 40$ $n_2 = 26$, $P < 0.001$ two-tailed).

5.2 Compaction Trial Results Database: Effects of Soil Moisture

To further scrutinise these results, trial data consisting of traffic events that had taken place under high soil moisture conditions were then plotted as per Figure 5.2.

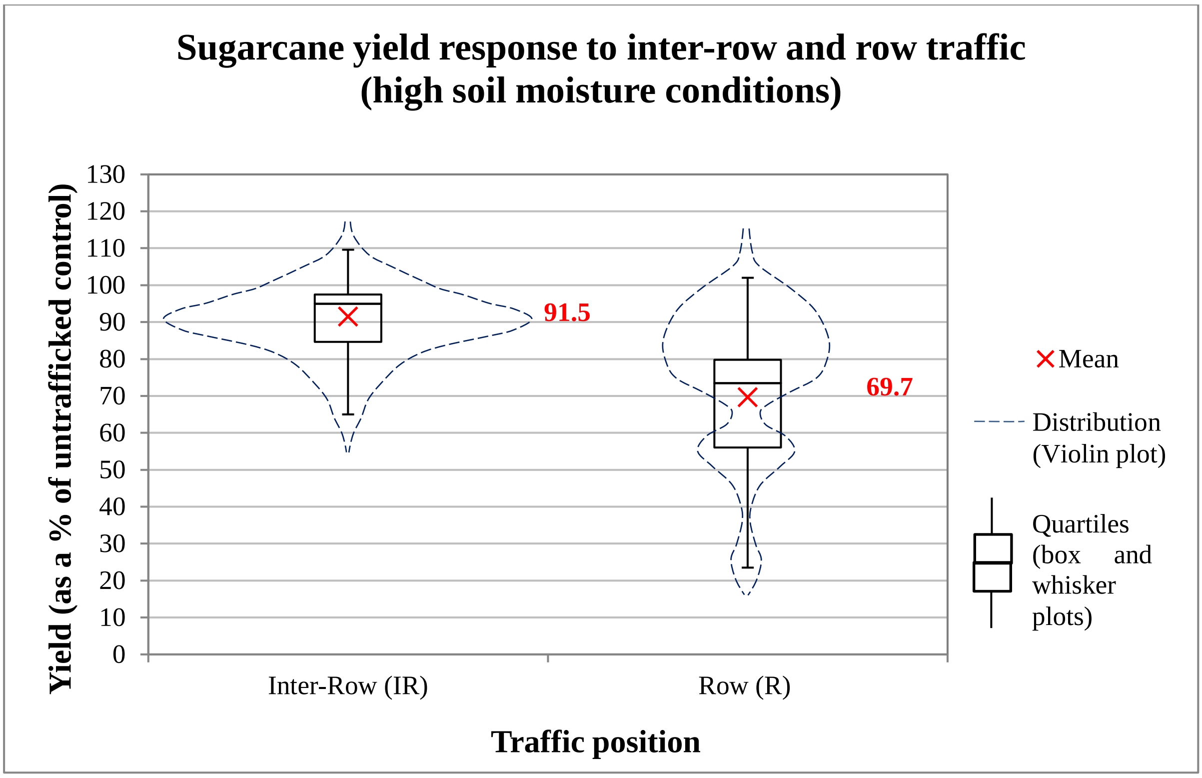

Figure 5.2 Yield response of sugarcane to inter-row and row traffic under high soil moisture conditions based on datasets consisting of 27 inter-row and 18 row samples

These results clearly indicate the risk of higher yield losses at higher soil moisture conditions with a considerable decrease in the mean values of both the inter-row and row traffic data. Mean values from the inter-row and row groups for wet conditions were 91.5 % and 69.7 %

respectively. The distributions of the groups differed significantly (Mann–Whitney $U = 75$, $n_1 = 27$ $n_2 = 18$, $P < 0.001$ two-tailed).

Further scrutiny of the data represented in Figure 5.1 for trials where traffic events that had taken place specifically under low soil moisture conditions consisted of inter-row treatments only. These 8 inter-row treatment results indicated a mean of 100.8 % relative to no traffic with a standard error of the mean of 1.2 percentage points and standard deviation of the data of 3.3 percentage points. These results substantiate the large influence that soil moisture has on the impact of yields following an infield traffic event. Traffic should thus be minimised during periods of higher soil moisture content.

In order to further interrogate the yield response dataset that was used in Figure 5.2, consisting of responses under high soil moisture conditions, the equipment was sub-categorised in terms of perceived high, medium and low impact. The classifications are based on the gross mass of equipment used in the traffic treatments. High impact equipment would consist of high gross mass equipment or high axle loads combined with high tyre pressures. Where high floatation tyres were used, the equipment was graded into a lower impact category. As a guide, the following axle loads were used to distinguish between categories: Low impact equipment- less than 3.5 t axle load; Medium impact equipment – between 3.5 t and 5.5 t axle load; high impact – greater than 5.5 t axle load. The results of categorising the inter-row and row traffic treatments are shown in Figure 5.3.

Examples of high impact treatments include infield truck rigs which typically have steering axle wheels of high pressures and high axle weights. Intermediate medium impact equipment consisted of agricultural or haulage tractors with trailers of intermediate axle loads and infield grab loaders. Low impact equipment consist of agricultural or haulage tractors with trailers of low axle loads or tracked equipment. Larger tractor trailer combinations with multiple trailers were classified as medium or high impact depending on the gross combination mass of the vehicles and corresponding mean axle load.

This classification provides a third tier of management considerations, namely the type of equipment and equipment combinations used infield (the first being a distinction in yield response between row and inter-row traffic position and the second being the moisture content of the soil at time of field operations).

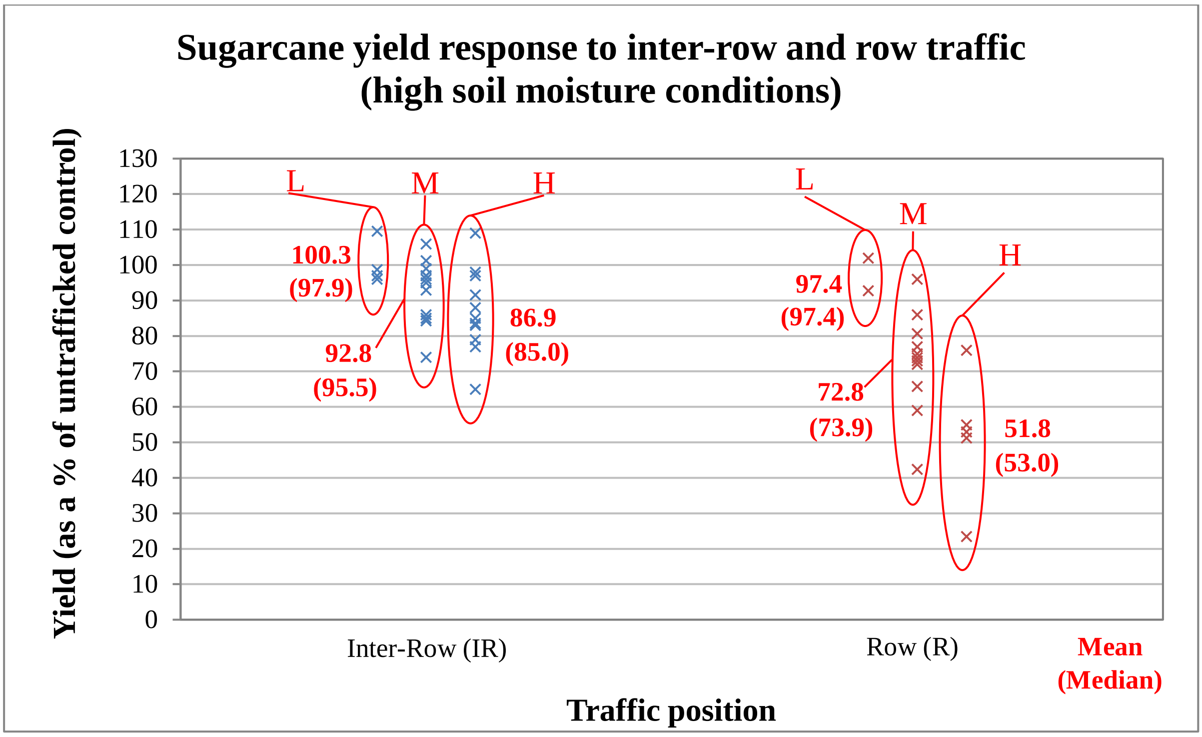

Figure 5.3 Yield response of sugarcane to inter-row and row traffic distinguishing between equipment of low (L), medium (M) and high (H) impact under high soil moisture conditions based on datasets consisting of 27 inter-row and 18 row samples

The results indicate a tendency of greater yield loss related to high impact equipment. Variances may be due to the range of equipment, soil properties and soil conditions and other factors such as multiple wheel passes. The yield loss trends indicate a linear decline for both IR and R traffic with much greater rate of decline associated with R traffic. The yield decline gradient trends are consistent and similar for mean or median yield values used. This is a useful trend as it provides a means to model yield losses for different equipment impact categories. Sub categories of LM and MH are proposed to cater for vehicles that could fall into either category of L or M (i.e. ±3.5 t) or M or H (i.e. ±5.5 t). High impact equipment typically also have a higher capacity to remove more of the cane stockpiles from the field and therefore require fewer trips infield. The management of the equipment infield should be of high managerial importance to constrain repeated extraction routes infield to the same paths in order to minimise the potential for widespread yield loss due to uncontrolled traffic throughout the field.

5.3 Investigating for Yield Response Trends of Sugarcane to Infield Traffic

To further explore yield response trends the database was filtered for results that contain sufficient information to account for wheel position, soil moisture content and soil texture. From the literature review it was noted that the impact on yield was a function of both axle mass (for soil compaction at deeper layers) and tyre pressure (for compaction effects at the soil surface). Intuitively the product of the two could potentially account for any type of wheel traffic, with a 100 % yield (no yield loss) being applicable for all zero traffic treatment controls.

The filtered data sets of yield responses to various site conditions and traffic treatments were tested using the Wald Confidence Interval method. Only the row traffic low clay treatments under high soil moisture conditions when tested against the product of axle weight and tyre pressure indicated a significant correlation at the 95 % confidence interval. All other data set comparisons did not indicate significance at the 95 % confidence interval. This is despite many individual data values being significantly different against control conditions (see Appendix A and B). The data is presented, however, to indicate the trends that were apparent from the datasets. The yield response graph accounting for all of the above metrics is shown in Figure 5.4 with all trend lines intercepting at the 100 % yield applicable to an untrafficked control. The classification of soil moisture is based on the treatment conditions of the individual trials, with dry conditions pertaining to low soil moisture conditions. Moist soil treatments being contrasted against dry through the addition of water prior to the soil compaction treatment through a rainfall or an irrigation event. Moist soil treatments apply to general treatments consisting of higher soil moisture contents and include those measured near field capacity or greater.

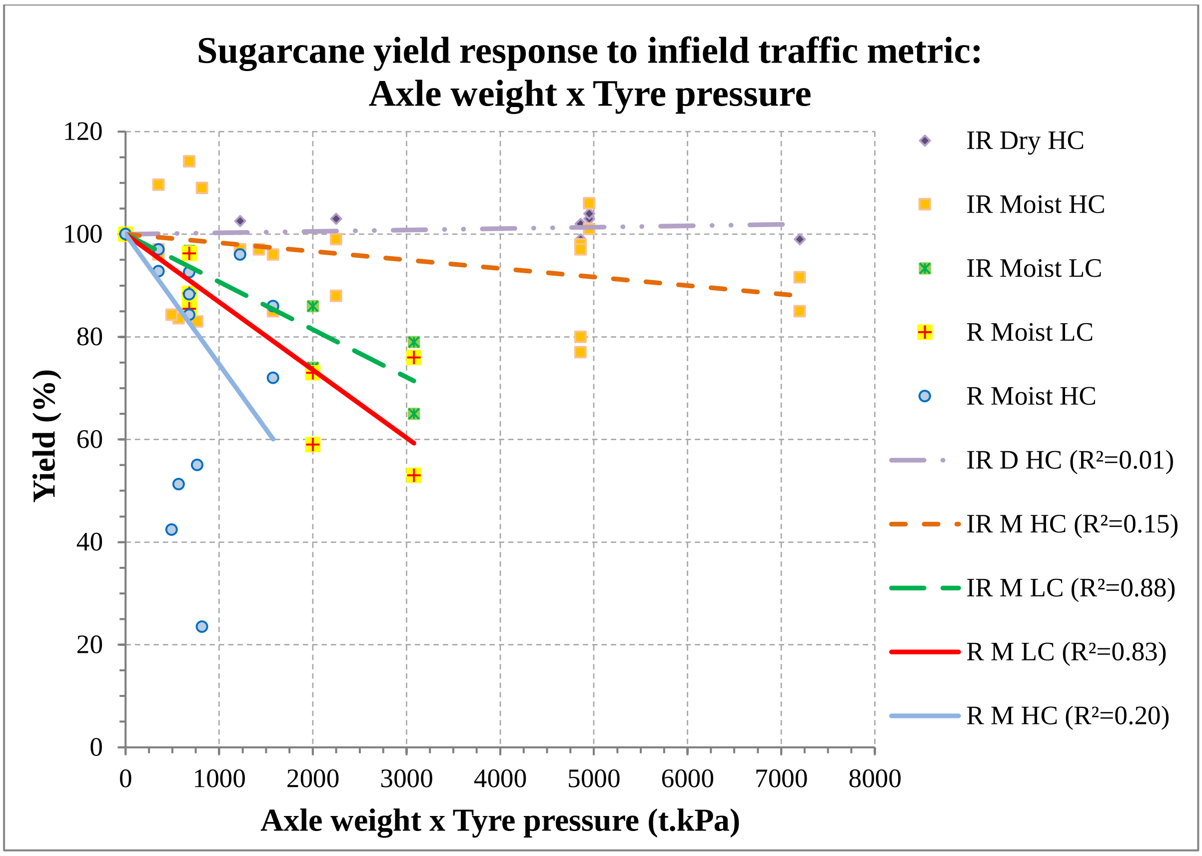

Figure 5.4 Yield response trends of sugarcane to the product of axle mass and tyre pressure aggregated to account for wheel position, soil water content and soil texture. Wheel position is designated by row (R) or inter-row (IR). Soil water content is designated as dry (D) or moist (M) and soil texture by clay percentage below 20 % (LC) or above 20 % (HC)

The data trends in Figure 5.4, although not statistically significant, adds value to the body of knowledge that exists on the subject. The trends help to translate the complex variable yield interactions and responses that occur in the data presented in literature and to provide a means to model the impact of vehicle combination that exists in practice. From the trends it can be seen that inter-row traffic under dry conditions is not impacted by traffic intensity. Row traffic data shows typically greater yield losses compared to inter-row traffic. The variation in yields when trafficked at low values of axle weights x tyre pressure and at high soil moisture content is large and unpredictable particularly for high clay soils. The yield response trends indicate that high clay soils will respond the best to control traffic practices. Lower clay soils appear susceptible to both row and inter-row traffic under high soil water conditions and are thus likely to be best managed by minimising overall compaction through the use of light equipment with low soil contact pressure and by minimising or avoiding trafficking under high soil water conditions as far as possible. This is based on the premise for lower clay soils that the yield response for traffic under dry conditions will be more favourable than for wet conditions although there were no data available at this level of aggregation to support this statement. This is however supported by broader trends examined earlier, where traffic treatments at higher moisture contents resulted in higher yield losses. Highlighting such gaps that exist in the data also provide an indication for future research needs.

5.4 Modelling Yield Response Trends of Sugarcane to Infield Traffic

The data trends shown in Figure 5.4 represent actual yield responses to various traffic treatments. These treatments in some cases included multiple wheel or traffic passes which would thereby increase the yield loss represented relative to a single pass effect. Defining a single pass effect would be valuable in order to model the yield loss impact of traffic. Treatments that specifically show the impact of multiple passes were investigated in order to refine the results shown in Figure 5.4 for individual pass effects. Specific work investigating the impact of multiple passes were studied by Johnston and Wood (1971), Yang (1977), Usaborisut and Niyamapa (2010) and De Paula and Molin (2013). These responses are summarised in Figure 5.5. A relationship between the numbers of passes as a percentage of maximum yield loss was determined from this analysis. The data is presented as the percentage yield loss relative to the average maximum yield loss from the above three studies. The regression equation was represented in order to account for a zero pass yield loss of 0 %. In practice any passes over 20 would be deemed to cause maximum potential yield loss that can be attributed to the particular wheel traffic impact event.

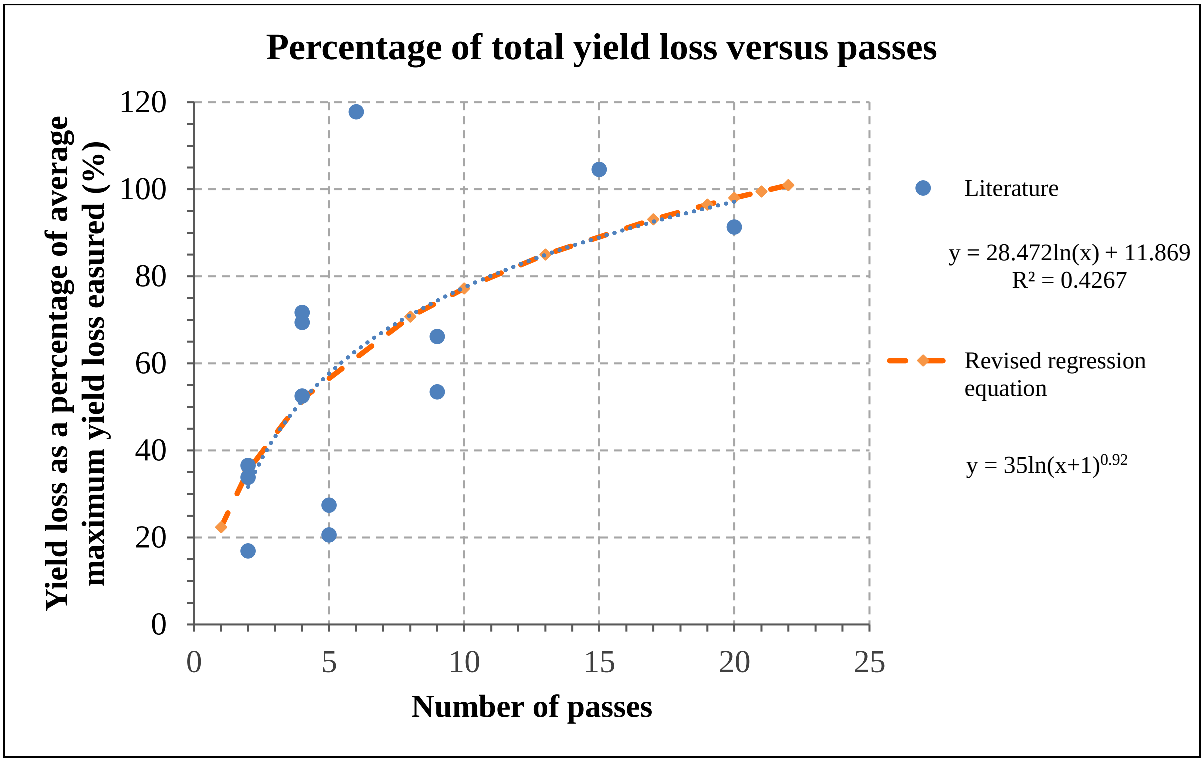

Figure 5.5 Yield responses as a result of multiple pass effects

Defining the most accurate representation of the impact of multiple wheel passes from the treatments were considered important due to the compounding effect and consequential amplification of yield responses. The regression equation shown in Figure 5.5 performed the best when tested and compared during model testing against various alternative equations that fitted the upper and lower envelopes and more aggressive per pass effects as reported in the literature study. From the database of yield responses and associated wheel passes, a model could be created from the relationships as defined in Figure 5.4 reverse engineered to account for individual wheel pass effects. The corresponding graph is presented in Figure 5.6.

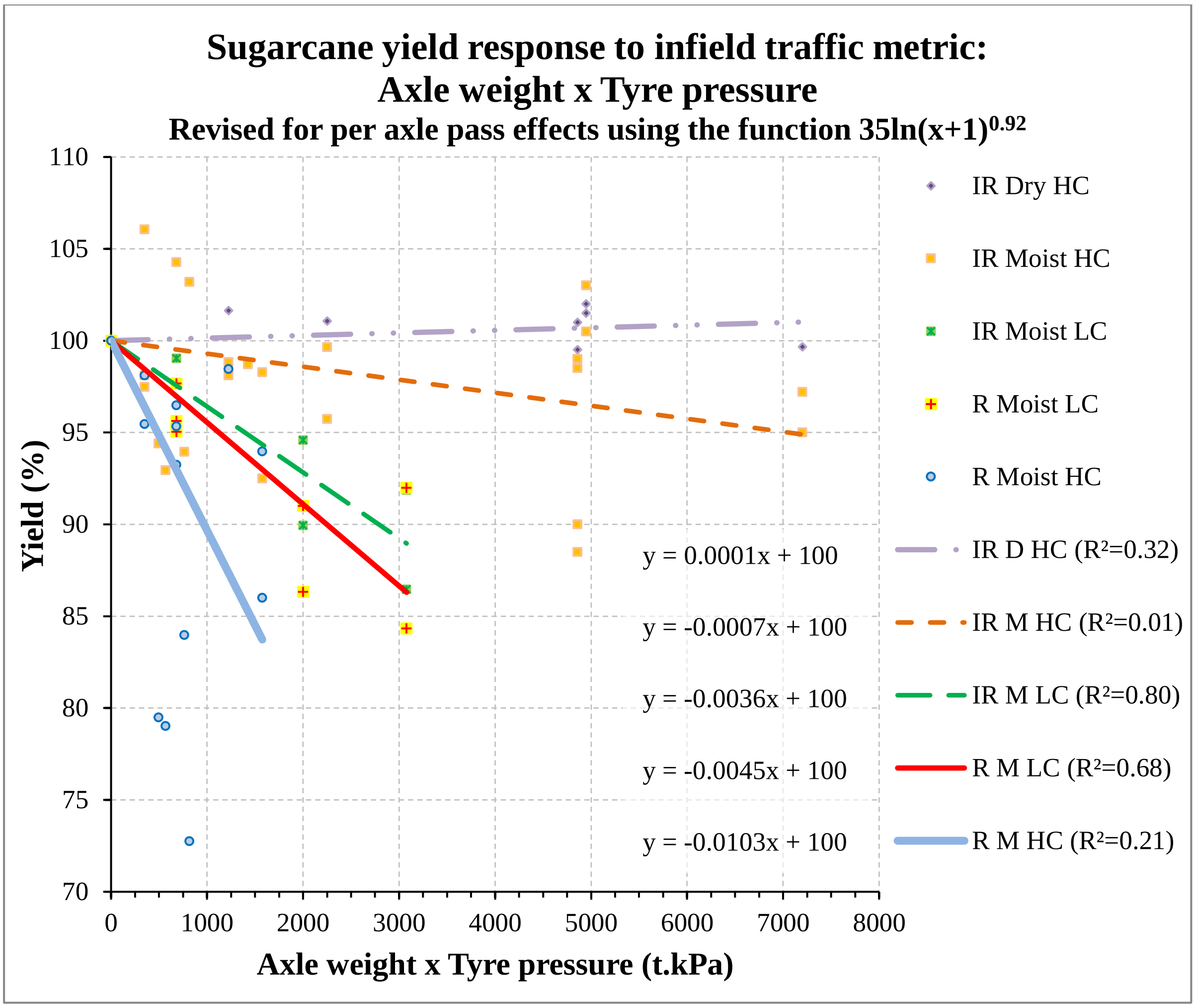

Figure 5.6 Yield response trends of sugarcane to the product of axle mass and tyre pressure aggregated to account for wheel position, soil moisture content and soil texture and adjusted for a single pass. Wheel position is designated by row (R) or inter-row (IR). Moisture content is designated as dry (D) or moist (M) and soil texture by clay percentage below 20 % (LC) or above 20 % (HC)

The trends are similar to those presented in Figure 5.4, diminished to account for per pass effects. This is an intermediate step that provides the basis for being able to model traffic induced yield losses for a range of soil conditions and vehicle traffic events. The impact of yield losses can thus be modelled if the following input parameters are available: Axle load, tyre pressure, differentiation made between high or low clay soils and the number of passes being stipulated. The model, engineered to account for individual wheel passes using the regression equation $y = 35\ln(x+1)^{0.92}$, as described in Figure 5.5 and developed from a subset of the trials, was checked against the original observed trial results consisting of multiple passes. The model was tested against South African and international trial data as shown in Figure 5.7 and Figure 5.8 respectively.

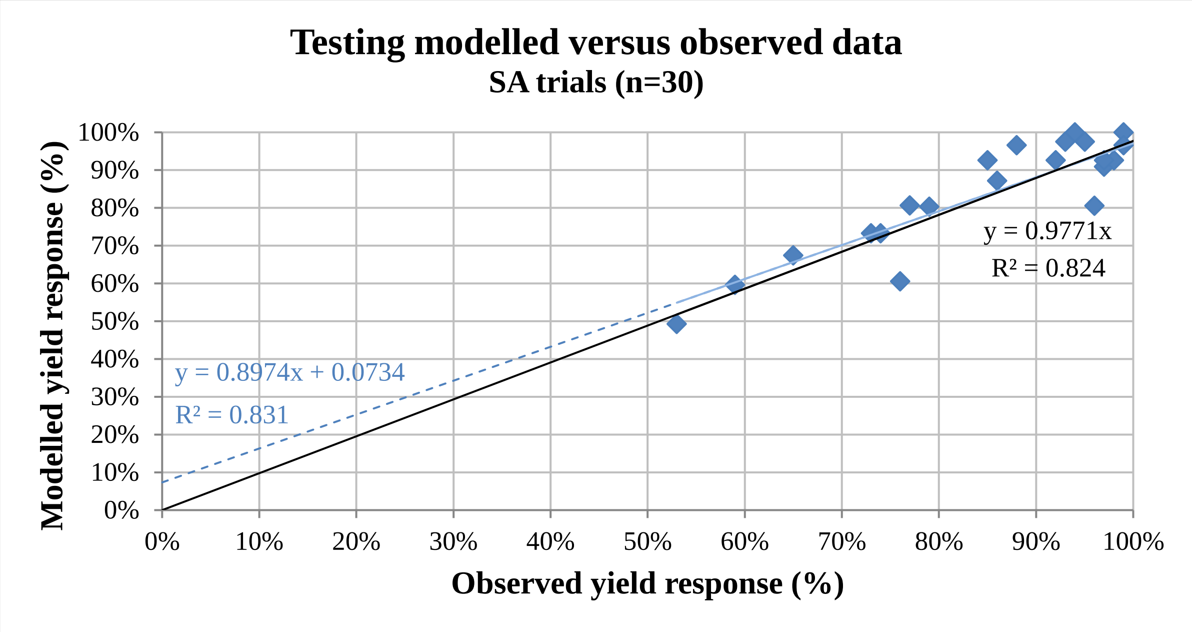

Figure 5.7 Testing modelled versus observed yield responses to traffic from South African data. Trend line differences indicate when the trend line set to intersect the origin or not

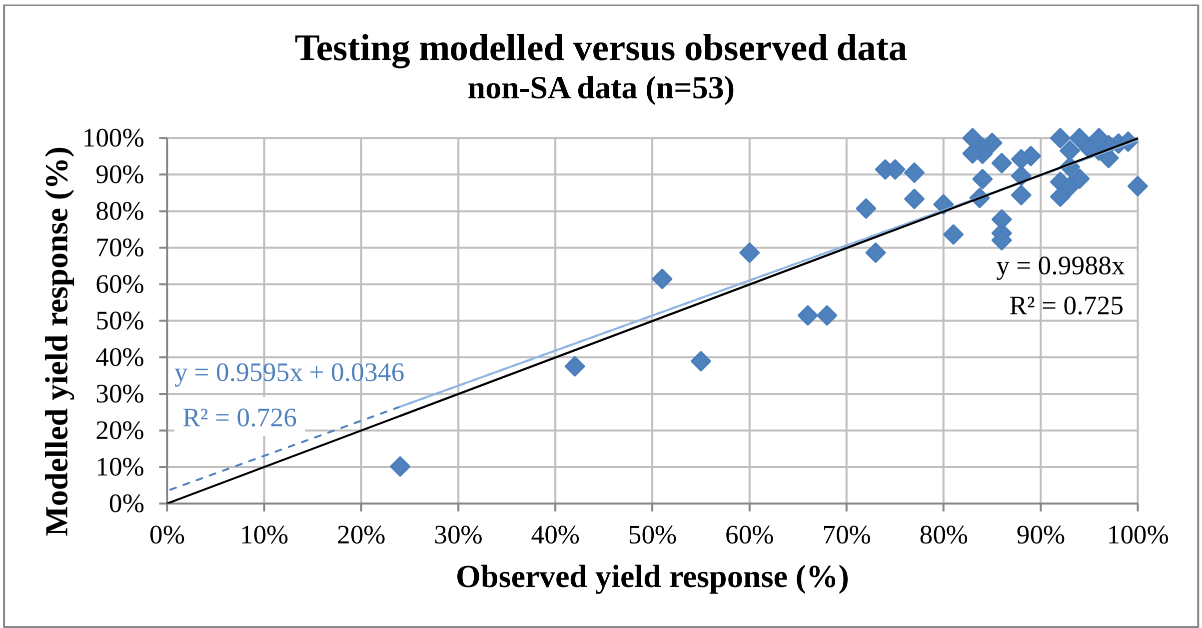

Figure 5.8 Testing modelled versus observed yield responses to traffic from International data. Trend line differences indicate when the trend line set to intersect the origin or not.

The traffic-yield response relationships were also tested against additional independent yield response data that were not used to create the model. The results from this validation of the model is shown in Figure 5.9.

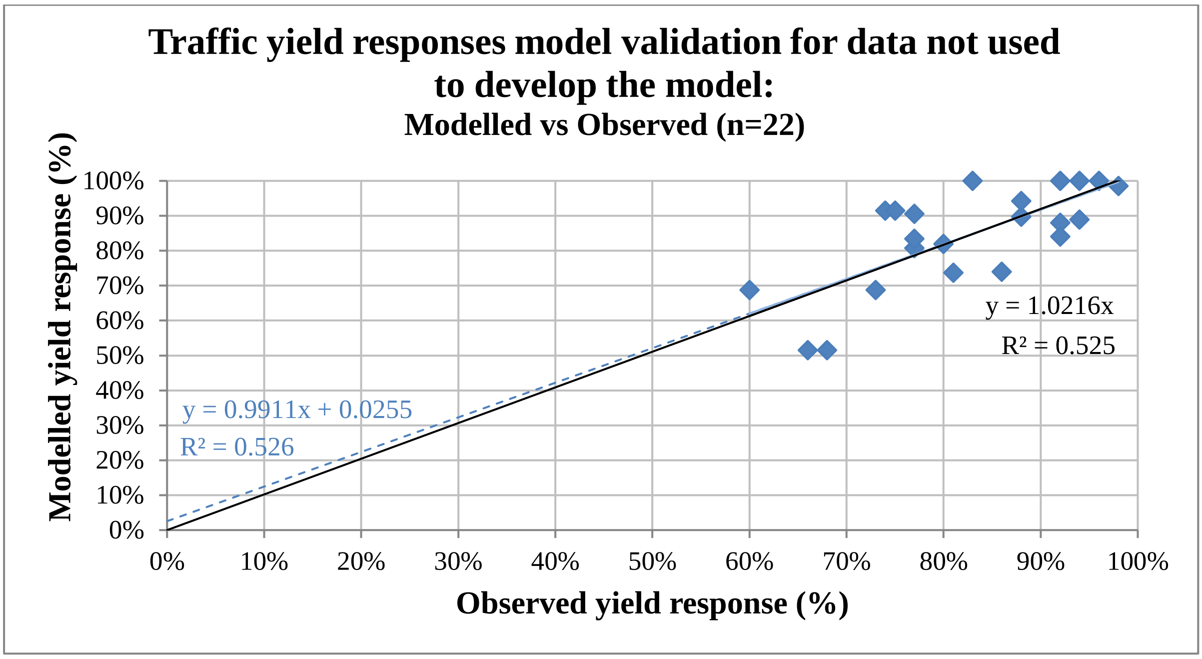

Figure 5.9 Model validation testing using independent data of yield responses to infield traffic with multiple axle passes, variable tyre inflation pressures and varying field conditions. Trend line differences indicate when the trend line set to intersect the origin or not

The independent data validation seemed to match the trend reasonably well with a correlation coefficient R^2 of 0.53, particularly considering the complex interactions between soil, crop and treatment variables and associated time lags to obtain the yield responses. The model is relatively simple and appears to capture the main factors affecting yield responses with the limited data sets available to test such interactions. Additional testing of alternative regression equations to account for per pass effects (such as more aggressive yield losses as indicated by the literature review) did not give better correlation and validation results. As an indication of the accuracy of the model, the mean is overestimated by 1.8 % with a standard error of the mean of 2.1 % and standard deviation of 9.9 %.

In summary, the synthesis of data relating yield response to infield traffic as presented in Chapter 5 contains a number of key factors that impact on sugarcane yield responses to infield traffic. Firstly, it was shown that there is a significant yield difference between the positions of wheel tracks on the crop row compared to on the inter-row. Soil moisture at time of treatment was shown to greatly impact on crop yields. The influence of soil textures seems to have an influence on the crop response to infield traffic particularly for higher clay soils where, despite weak relationships within particular categories, the contrast between R and IR traffic under wet field conditions is greatly evident and strongly supports the need for control traffic practices. These results can guide management decisions, where soil texture and soil moisture can be accounted for when planning the timing of operations for a given farming activity. Other management considerations are the type of equipment used and the constraining of traffic to inter-row areas through the adoption of CTF practices. For fields with soils that may be generally susceptible to traffic under wet field conditions (e.g. lower clay soils), irrespective of traffic position, traffic should be limited as far as possible to drier seasonal periods. The use of high impact equipment should also be limited. From the general trends and estimated yield loss relationships presented, it is hypothesised that there will be large differences in estimated yield losses between systems, with the highest losses being attributed to systems containing the largest amount of uncontrolled traffic.

The synthesis of data and yield responses to traffic as described in Chapter 5 are for an applicable point of impact. Not every point in the field, however, is subject to traffic. The impact and extent of traffic will alter depending on the compliment of infield vehicles and the position that those vehicles travel through a field. In a commercial harvesting and extraction system, only portions of the field are subjected to traffic. Determining the extent of the field trafficked by vehicle type was the next step of the process required to estimate field based yield losses for different systems. In the chapter that follows, the methodology to gather data for a range of commonly found systems for loading, and extraction of sugarcane in the South African context is described.

6. METHODOLOGY

In this chapter, the methodical approach used to conduct field studies to measure and quantify the location and distribution of traffic of vehicles infield for different systems typically found in the South African sugarcane industry is described. Surveys were limited to the cane loading and extraction processes and required that all positions of infield traffic movements of all equipment entering the field be captured. As per the literature review and the synthesis of trial results, there is significantly more crop yield loss to row traffic than to inter-row traffic events and so distinction between row and inter-row traffic needed to be determined. The purpose of this chapter is to describe the techniques used to gather, assign and attribute field survey data representative of infield traffic to either the sugarcane crop row or inter-row areas. Section 6.1 provides an overview of field, crop and traffic information and surveys required. Various techniques used to determine the position of infield traffic movements are described in Section 6.2. Details of the survey information gathered are contained in Section 6.3. Section 6.4 details the steps required to process the Global Navigation Satellite System (GNSS) data, create field maps showing the extent of field traffic and the Geographic Information System (GIS) analysis of the maps to determine the proportion of the field trafficked by the different equipment for each system analysed. A range of loading systems and loading techniques that are commonly used in the South African sugarcane industry were investigated. The systems that were surveyed are summarised in Section 6.5 and described further in Sections 6.6 to 6.11. Section 6.12 describes how equipment impact ratings were defined. Sections 6.13 and 6.14 describe the method used to estimate field scale yield losses and economics, respectively. The surveys were conducted on commercially run operations using equipment and systems that are typically available and used throughout the industry.

6.1 Field Data to Characterise Infield Traffic During Harvesting Operations

Field information was gathered prior to loading or extraction operations. At this stage of the harvesting process, a number of harvesting operations would have already have taken place. These would normally consist of the sugarcane being burnt and manually cut. During the manual cane cutting operation, the cutters combine several adjacent rows of cut cane into a continuous linear windrow (perpendicular to the cane rows) or into small bundles within a windrow or into a large stack depending on the loading and extraction equipment and systems used. The field information was gathered by manually surveying the fields using Global Navigation Satellite System (GNSS) surveying. The following surveys were conducted:

- GNSS surveying of field boundaries: to determine the field areas of each field;
- GNSS surveying of the position of cane stacks or cane windrows: to determine patterns of traffic movements relative to cane stockpile positions;
- GNSS surveying of the position of cane rows infield: to determine the position of the rows, row spacing's and inter-row areas within the field. Not every line was surveyed, but selected rows were surveyed and used to infer an entire field's position of rows and inter-row areas when processing the data in a CAD or GIS software package.

6.2 Determining the Position of Infield Vehicle Movements

Various techniques used to determine infield vehicle positions and traffic movements are described. These range from specialised surveying instruments to determine geographical location from the GNSS to simple mechanical devices and sketches to indicate vehicle movements during cane loading and extraction operations.

6.2.1 The use of GNSS to identify the position of wheel tracks infield

Infield vehicle traffic positions that occurred during the loading process were determined by the use of two survey grade GNSS receiver units (*Trimble® PROXRT pathfinder* with *Nomad* handset (DGPS) and a *Hemisphere Crescent* DGPS *XF101*). These GNSS receivers were used to survey the infield traffic movements of the loading and extraction operations. The accuracy of the *Trimble* unit is typically rated sub 30 cm accuracy with GPS post processing corrections of the GNSS data using the South African network of *TrigNet* base stations. The majority of positions surveyed using the *Trimble* unit were classified within the 5-15 cm accuracy range. The *Hemisphere* GPS unit is rated at a real time sub metre accuracy and was used to indicate the relative position of the tracks relative to the *Trimble* unit. Where the wheel tracks of vehicles were clearly visible through compaction, they were manually surveyed by following the wheel tracks produced by the vehicles as shown in Figure 6.1.

Figure 6.1 Infield traffic paths made clearly visible following soil compaction from vehicle wheel tracks

Where infield loaders were employed in the loading process, the GNSS receivers were positioned onto the loaders to survey the actual loading operation. The receiver antennae were placed over the wheel tracks to capture the movement of the loader position during the loading operations as shown in Figure 6.2.

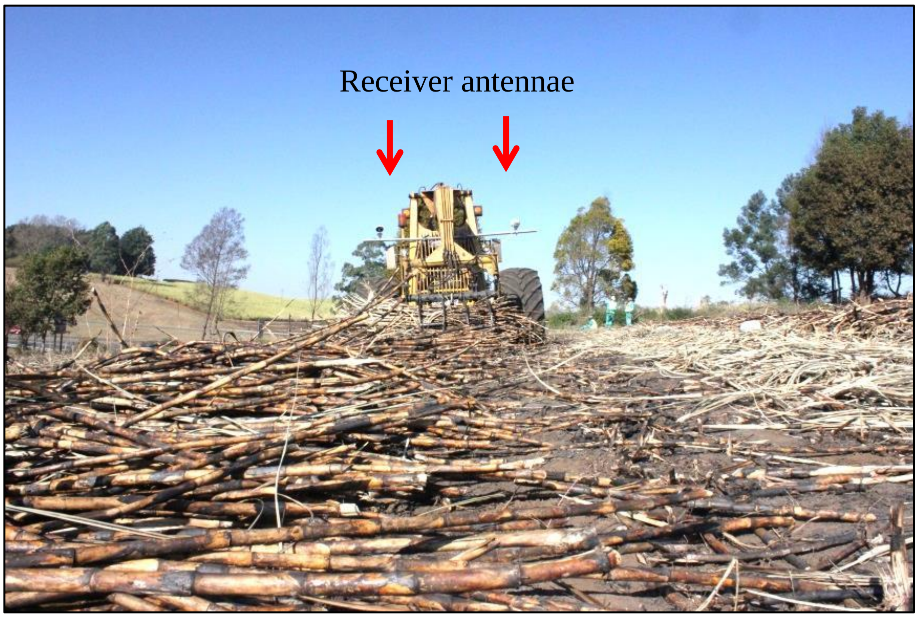

Figure 6.2 GNSS receivers positioned centrally above wheels to track wheel paths

Where multiple vehicles were entering the field simultaneously, the tracks of non-surveyed vehicles were marked using white agricultural lime, as shown in Figure 6.3 for subsequent manual surveying. Multiple tracks are visible in Figure 6.3 due to off-tracking of the trailer wheels. All of the tracks and off-tracks were subsequently marked and surveyed.

Figure 6.3 White agricultural lime used to indicate wheel path tracks for subsequent surveying of the tracks after the loading operations were complete

6.2.2 Field marking instrument

Where wheel tracks were not easily visible, a field marking instrument was designed to fit the rear wheel of the cane extraction equipment. Upon wheel rotation the instrument would dispense a line of white agricultural lime to mark the position of the wheel track. This line would then be visible for subsequent manual surveying of the traffic movements that occurred during the loading operations. The instrument was designed to be fitted to the top link position of the tractor and spring loaded to press and rotate against the tractor tyre as indicated in Figure 6.4. It was designed to be fitted to vehicles that would travel predominantly through the fields in a linear course during the cane extraction operations, such as, the tractor trailer units that are loaded by slewing or non-slewing loaders.

Figure 6.4 Field marking instrument (left) as mounted on a tractor (right) used to indicate the position of wheel tracks infield

Where the above unit was not suitable (for example multiple tractor trailer units extracting cane from the field), the agricultural lime was dispensed manually to indicate the centre of the wheel tracks. This was conducted primarily along the field entry and exit paths. The travel direction of the vehicles either entering or exiting at the field edges was also indicated. The data were further checked during data processing by, firstly, the use of field sketches made during the loading and extraction operations to indicate the movement and extraction of cane from the field and, secondly, through comparing the GNSS tracking position of the loader to the corresponding position of the adjacent infield tractor trailer units. These field and traffic positions were then manually surveyed after the loading operations had been completed and analysed with the vehicle survey data obtained.

6.2.3 Field sketches of vehicle movements

Sketches taken during the loading and extraction processes during the data collection phase proved valuable in describing the movement of vehicles during the data processing phase. The sketches included colour coding and numbering of different vehicle loads and paths. Additional details such as the position of wheels (relative to a referenced cane row) were noted. Figure 6.5 is an indication of the use of sketches to aid in the data generation and investigation phase.

Figure 6.5 Field sketches (left) to assist with GIS mapping and identifying vehicle movements infield (right)

6.3 Surveying Procedure

The field dimensions and position of cane stockpiles (stacks or linear windrows) and intermittent crop rows were surveyed and used to create an underlying field layer map as shown in Figure 6.6.

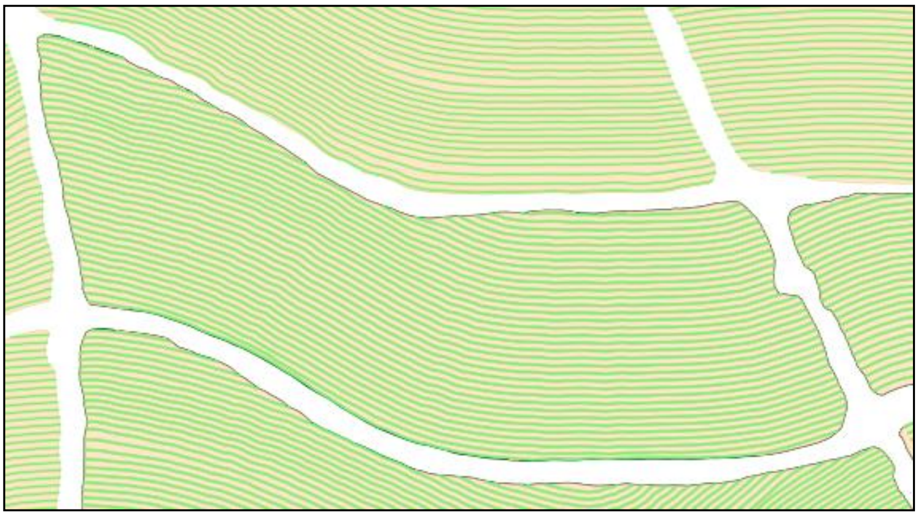

Figure 6.6 Excerpt from a field map signifying the position of field boundaries, row and inter-row areas

The positions of all infield traffic across each field were surveyed and superimposed over the field layer. The surveyed traffic layer consisted of line features to represent the positions of a specific wheel, either the left or right rear trailer wheel in the case of infield trailers. Multiple tracks from different axles developed by trailer off-tracking were also surveyed. Both of the wheel positions of the loaders were surveyed simultaneously using GNSS receivers above the centreline of each wheel track. This was required to accurately measure the wheel positions of the loaders, particularly in the case of the non-slewing loader as it pivots dynamically and swivels during the loading process. Figure 6.7 is a sample of a map that was generated from the surveyed positions that had been obtained.

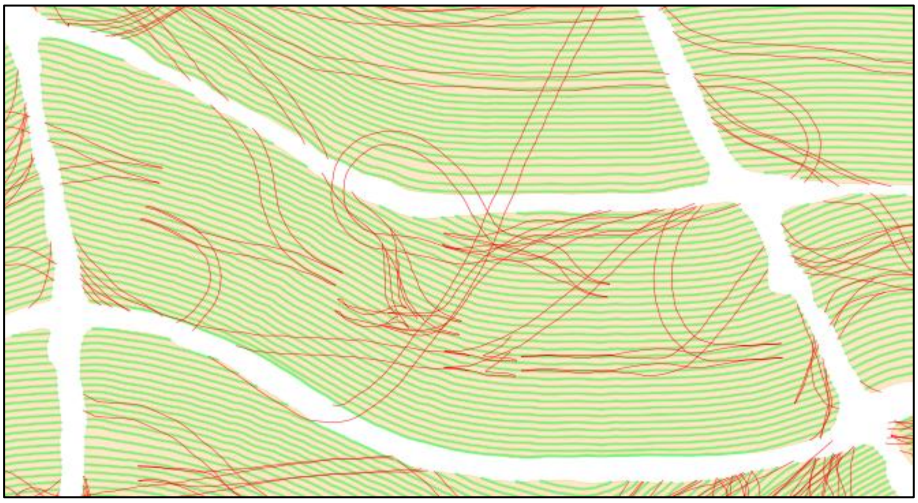

Figure 6.7 Excerpt from a map overlaid with survey data representing infield traffic movements

6.4 Field Data Processing and Analysis

The GNSS field survey from the *Trimble*® GNSS receiver were processed and corrected to enhance positional accuracy of the surveyed positions using *Pathfinder Office*® software and *TrigNet* GNSS base station data. The data output from *Pathfinder Office*® consisted of the corrected positions of the manually surveyed lines. These lines were used to indicate the position of field edges, intermittent crop rows and vehicle wheel positions. This information was exported into *ESRI*® *ArcView*® GIS software and multiple GIS shape file layers for each data type created for further processing and analysis in the *Quantum*® GIS software package. Interim processing and generation of CAD related data were conducted on the *AutoCAD*® *Civil3D*® software package. This interim CAD processing included the generation of lines to represent the centreline position of all crop rows for the entire field and all infield traffic movements. This consisted of generating and distributing line entities evenly between the intermittently surveyed crop rows to match and represent each row within the field. Surveyed lines representing the traffic of a single wheel through the field also needed to be offset for the corresponding alternative wheel. The wheelbase of the equipment was used as the distance offset to create the corresponding parallel track. Such functions are easily conducted using CAD drafting software. The set of completed CAD files consisting of line entities representing field, crop and separate vehicle traffic layers were then exported for analysis in the GIS software.

Within GIS, a polyline enclosing an area is able to be converted into a polygon area. This conversion was required where a polyline was used to represent, for example, a field edge or boundary and then be converted into a polygon area to represent the field area. This polygon area is required for field based queries and analyses to be conducted. The importing of field boundary lines and generation of field areas would typically be the first step in the GIS process.

The next step would typically consist of importing the line entities representing field and crop attributes and vehicle movements. These imported polylines from CAD, however, would need to be widened to account for the width of the rows and width of wheels for the range of equipment represented. A GIS processing technique termed "Buffering" allows for the propagation of areas surrounding drawing entities. This buffering process was used to generate an area of set distance (half of the width of a crop row or wheel width) from the polylines within an entire layer. For the purpose of this study, a width of 0.4 m for a typical sugarcane crop row was assumed to contain the majority of cane stools, although this may vary in practice depending on crop age, plant populations and row spacing configurations. Figure 6.8 gives an indication of the width of cane rows typically found infield. The lines representing crop row centrelines were thus buffered by 0.2 m to represent a crop row width of 0.4 m, for example.

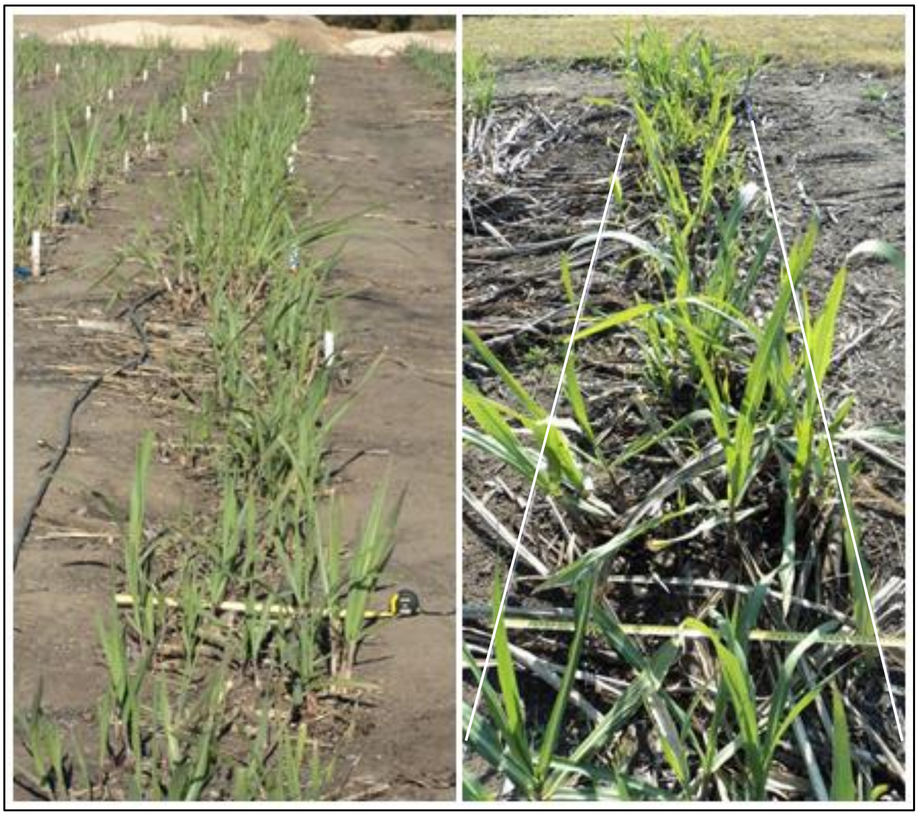

Figure 6.8 Determining the typical width of cane rows. The variance in crop row width is visible along the cane row (left) and can be as wide as 600 mm in places (right). A crop row width of 400 mm was assumed for analysis purposes

To create the crop inter-row areas, the row areas were subtracted from the polygon area representing the entire field. The entire field area was thus separated into two sub areas consisting of the rows and inter-rows, thereby allowing for row and inter-row area queries and analyses to be conducted.

The position of infield traffic movements had also been represented as line entities. In a similar way, these lines representing the position of wheel tracks and infield traffic also needed to be buffered to correspond to the width of the equipment tyres. The width of the tyre, as displayed in Figure 6.9, is required to determine the areas affected by traffic and further analyses to be conducted.

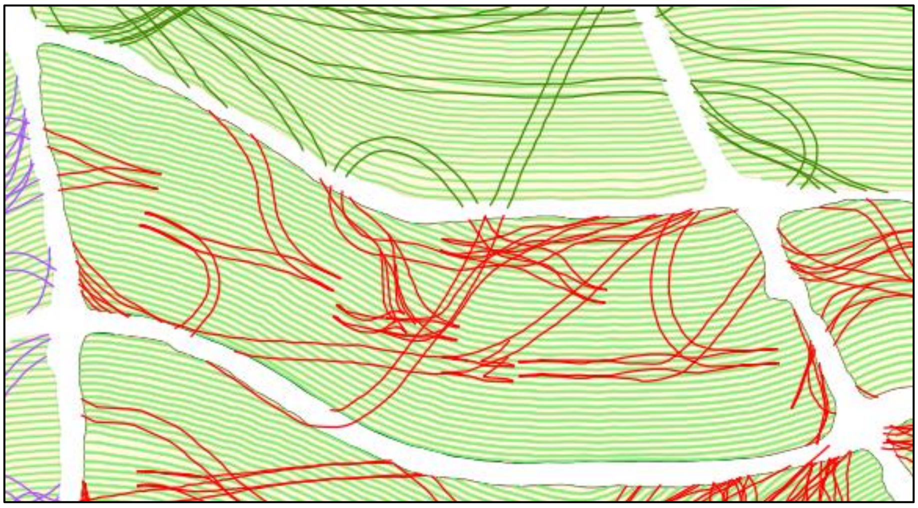

Figure 6.9 Excerpt from a map of infield traffic areas generated by the buffering of surveyed polylines to match the tyre widths of equipment used infield

The traffic layer needed to be further separated by position of either row or inter-row traffic components. In GIS there are data processing tools that allow for the intersection of vector based layers. By intersecting the traffic layer with the crop row layer, a new layer was created that consists only of traffic that occurred over the rows in the field. Similarly, the traffic layer was intersected with the crop inter-row layer. This allowed for the entire field to be categorised into areas where row traffic, inter-row traffic or no traffic had occurred. Various integration and intersections of layers were required to finally produce a map as shown in Figure 6.10 that distinguishes between areas of row traffic, inter-row traffic or where no traffic had occurred for the range of equipment used in each system.

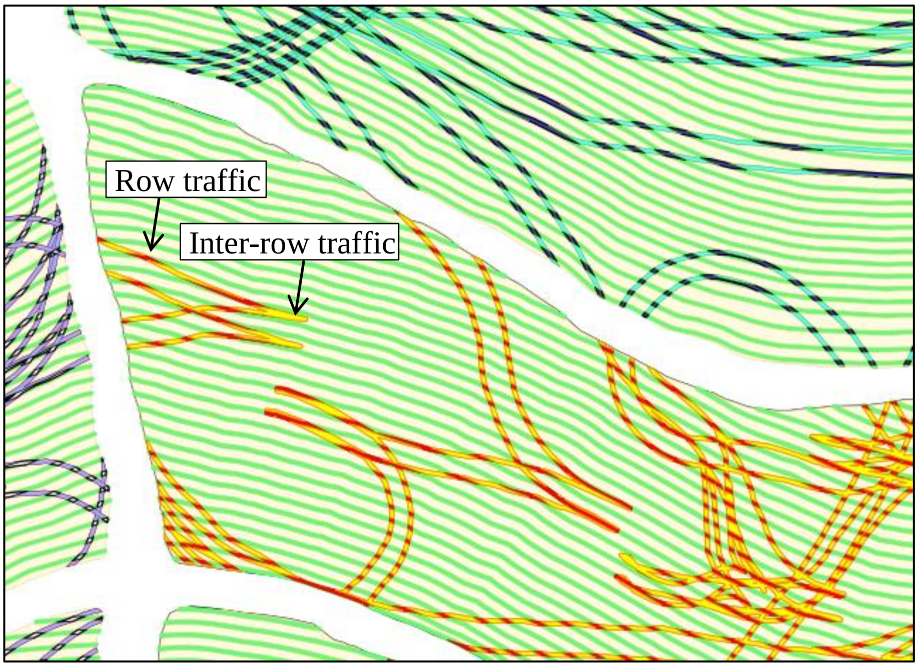

Figure 6.10 Traffic positions for a single stack self-loading trailer system further classified into row or inter-row traffic components, where the darker colours represent row traffic and the lighter colours represent inter-row traffic areas within a field

GIS software allows each layer to be analysed separately. The total area of all polygons that exist in a particular layer can be determined. In this way, each layer representing vehicle traffic within a particular system was analysed to determine the total area of row traffic, inter-row traffic and where traffic did not occur within the field. Having determined the total row and inter-row area of a field, the proportion of rows where traffic had occurred and the proportion of inter-rows that had been trafficked were determined. An estimated field based yield loss for each vehicle in the system was determined by multiplying the 'point of impact yield losses', as determined from the synthesis of literature in Chapter 5, by the proportion of row and inter-row trafficked within the field.

6.5 Summary of Systems Surveyed, Mapped and Analysed

Six field surveys labelled 'A' to 'F', covering six commercial sugarcane harvesting and extraction operations were conducted. Table 6.1 and Table 6.2 provides a summary of random and controlled traffic systems respectively that were compared.

Table 6.1 Infield random traffic harvesting and haulage systems surveyed, mapped and analysed

System:	**A_1:**	**A_2:**	**A_3:**	**B:**	**C:**
System and Equipment:	Cut and stack: Self-loading trailers (SLT's)	Cut and stack: Self-loading trailers (SLT's)	Cut and windrow: Non-slew loader and box trailers	Cut and windrow: Non-slew loader and box trailers	Cut and windrow: Non-slew loader and high capacity trailer
Traffic Management:	Random traffic	Random traffic	Random traffic	Random traffic	Random traffic
Row Spacing:	1-1.2 m	1-1.2 m	1 m	0.95 m	1 m
Wheel Track Loader:	2.0 m	2.1 m	1.9 m	2.3 m	2 m
Wheel Track Trailers:			2.1 m	2.1 m	2.1 m
Field Area:	2.5 ha	1.1 ha	1.0 ha	1.5 ha	0.25 ha
Cane Yield:	89 t/ha	89 t/ha	130 t/ha	76 t/ha	91 t/ha
Observed Field Status:	Moist	Moist	Moist	Dry	Dry
Relative Slopes (Mechanisation):	Steep midslope	Steep midslope	Footslope & valleys	Gentle midslope	Gentle midslope
Field Harvest Management:	Burnt	Burnt	Burnt	Burnt	Burnt
Cutting:	Manual	Manual	Manual	Manual	Manual
Cane Stockpile Presentation:	Stacks	Stacks	Windrow 5 rows : 1	Windrow 6 rows : 1	Windrow 6 rows : 1
Infield Loading:	Single stack SLT's	Double stack SLT's	Non-slew loader: loading 2 windrows	Non-slew loader: loading 1 windrow	Non-slew loader: loading 3 windrows
Infield Haulage: (Field to zone = FZ Field to mill = FM)	As above, FZ	As above, FZ	One low capacity box trailer, FZ	One low capacity box trailer, FZ	One high capacity tri-axle trailer, FM

Table 6.2 Infield controlled traffic harvesting and haulage systems surveyed, mapped and analysed

System:	**D:**	**E:**	**F:**
System and Equipment:	Cut and windrow: Slew loader and high capacity trailers	Chopper harvester loading into low capacity trailers	Cut and windrow: Slew loader and low capacity trailer
Traffic Management:	Control traffic	Control traffic	Control traffic
Row Spacing:	Tram 0.4 x 1.25 m	Tram 0.4 x 1.45 m	Tram 0.5 x 1.45 m
Wheel track (loader/harvester):	3.6 m	1.88 m	2.1 m
Wheel track (infield trailers):	2.15 m	1.9 m	2.2 m
Field Area:	3.1 ha	1.5 ha	1.7 ha
Cane Yield:	55 t/ha	70 t/ha	123 t/ha
Observed Field Status:	Dry	Dry	Dry
Relative Slopes (Mechanisation):	Flat	Gentle midslope	Flat
Field Harvest Management:	Burnt	Burnt	Burnt
Cutting:	Manual	Mechanical chopper harvester	Manual
Cane Stockpile Presentation:	Windrow 3 tramlines : 1 (6 rows : 1)	Windrow 1 tramline (2 rows) per pass	Windrow 4 tramlines : 1 (8 rows : 1)
Infield Loading: Swath per pass	Slewing loader: Loading 1 windrow	Chopper harvester: 1 tramline per pass	Slewing loader: Loading 1 windrow
Infield Haulage: (Field to zone = FZ Field to mill = FM)	loading 1 windrow into high capacity trailers for direct haulage to the mill FM	loading 2 rows per harvester pass into low capacity tip trailers to a zone FZ	loading 1 windrow into low capacity tip trailer to a zone FZ

Burnt cane fields were chosen for this study as it is by far the most prevalent practice in the industry. Cane rows are typically easier observed following burning than when a mulch layer is present. Burnt cane harvesting would thus minimise the likelihood of inadvertent row traffic due to inability to see the cane rows. No instructions were given to the drivers of the infield equipment to ensure that all operations were conducted as close to normal management and operating practices as possible. Furthermore, the surveying of cane rows, wheel tracks and white lime field markings following infield traffic were easily observed following a burnt cane harvesting operation.

Fields of similar row spacing's were chosen to remove any variations that row spacing may have on system comparisons when defining and relating traffic to row and inter-row areas. This excludes surveys D, E and F that practice CT on altered row spacing configurations consisting of dual rows (also termed tramlines) and wider inter-rows that have been adopted to better accommodate infield traffic.

No further field restrictions were specified when requesting assistance from the commercial farming operators when selecting fields and systems to be surveyed. Slopes were not considered restrictive when gathering infield traffic patterns and survey data, although the choice of systems and equipment access and appropriateness would become increasingly restrictive as slopes increase.

6.6 Description of Systems and Equipment Investigated in Survey A

In the first field survey conducted (Survey A), the area of the fields totalled 4.6 ha. Cane extraction operations consisted of approximately 2.5 ha of single stack self-loading trailers (Survey A_1), 1.1 ha of double stack self-loading trailers (Survey A_2) and 1.0 ha of cut and windrow loading operations (Survey A_3). All of the cane was burnt and then manually cut. The row spacing of the sugarcane was measured to be approximately 1 m. On the steeper slopes the cane stockpiles were manually gathered into stacks positioned infield for removal by self-loading trailers. On the gentler slopes, the cut cane was placed in windrows for loading by non-slew loader into box trailers. Five rows of cane were formed into a single windrow. The yields of the cane, harvested at an age of 17 months, were calculated following the gathering of stack weights at the trans-loading zone where each stack was individually weighed during the offloading process. The cut and stack area yielded approximately 98 t/ha and the cut and windrow areas had yields of about 130 t/ha.

A typical tractor drawn single stack self-loading trailer used to extract sugarcane from the fields is shown in Figure 6.11. A total of 54 loads of an average payload of 4.7 t comprising 93 stacks from approximately 2.5 ha of the field were removed using a fleet of three of these tractor trailer units to a nearby loading zone.

Figure 6.11 Field Survey “A_1”: Tractor drawn single stack self-loading trailers

An example of the tractor drawn double stack self-loading trailers is shown in Figure 6.12. A total of 10 loads of 6.5 t average payload comprising 23 stacks from approximately 1.1 ha of the field were removed to the nearby loading zone.

Figure 6.12 Field Survey "A_2": Tractor drawn double stack self-loading trailers

In the cut and windrow system, a non-slewing grab loader was employed to gather and load sugarcane from two windrows into an adjacent box trailer that progressed alongside the loader. In an initial test, a single GNSS receiver was placed on the loader to track its movement infield as it loaded approximately 0.08 ha of sugarcane. This test, however, could not be used to specifically identify individual wheel tracks and so the results obtained are rather conservative in measurement as they are simply a buffering of the wheel widths from the single surveyed line representing the centre of the loader. An example of the grab loader and box trailer used to extract sugarcane from the field from Survey A_3 is shown in Figure 6.13.

Figure 6.13 Field Survey "A_3": Low capacity tractor drawn box trailer being loaded by a non-slew loader

6.7 Description of Systems and Equipment Investigated in Survey B

The field area surveyed totalled approximately 1.5 ha. The sugarcane was burnt, cut and gathered manually into windrows. Six rows of cane were joined into a single windrow. The row spacing of the sugarcane was measured to be approximately 0.95 m. The yield was 116.3 t of sugarcane for the field which approximates to a yield of 76 t/ha. The field equipment consisted of a non-slew loader gathering sugarcane from a single windrow and loading this into adjacent low capacity tractor drawn box trailers. The loader and tractor drawn box trailers are shown in Figure 6.14 and Figure 6.15 respectively. For the purpose of this study the weight transferred by the rear jockey wheel of the loader onto the soil was assumed to be negligible and not taken into account. The reason for this assumption is that the laden grab on the front boom results in a load transfer off the rear jockey wheel and onto the front drive wheels. During loading operations, the rear jockey wheel is often observed in the air or lightly touching the ground. The effect of smearing from the rear wheel during turning manoeuvres has not been taken into account, nor has the effect of high levels of wheel slip from the drive wheels. Both of which are dependent on operator behaviour and more likely to occur at higher soil moisture field conditions.

Figure 6.14 Survey "B": Non-slewing grab loader fitted with GNSS receivers above each wheel to indicate the position of the wheel tracks of the loader about to load sugarcane into an accompanying tractor drawn low capacity box trailer

Three tractor trailer units were used to transport the sugarcane from the field to a nearby trans-loading zone. A total of 28 trips averaging a payload of 4.2 t of sugarcane per trip were removed from the field.

Figure 6.15 Survey "B": Low capacity tractor drawn box trailers

6.8 Description of Systems and Equipment Investigated in Survey C

Field survey C was a variation of the cut and windrow operation. The difference between this survey and the previous was to compare a different loading technique and the use of high capacity trailers infield. In this survey, the burnt sugarcane was loaded from a portion of the larger field area until the trailer had reached full capacity. A non-slew loader was used to load sugarcane from three windrows into a high capacity trailer that followed alongside the area being loaded. Sugarcane from six adjacent rows was joined to form a single windrow. The portion of the field loaded was measured to be 0.25 ha and the payload of the trailer was 23.1 t. This equates to a yield of about 91 t/ha. The sugarcane row spacing was measured to be approximately 1 m.

The movements of the non-slew grab loader while loading the tractor drawn high capacity tri-axle trailer, was to progressively load sugarcane from each of the adjacent windrows working away from the windrow closest to the trailer. The tractor trailer unit would only move forward when the area from all three windrows adjacent to the trailer had been cleared. The loader and high capacity tractor trailer unit is shown in Figure 6.16.

Figure 6.16 Field Survey "C": A non-slew grab loader loading sugarcane into a tractor drawn high capacity tri-axle trailer

6.9 Description of Systems and Equipment Investigated in Survey D

For the next field study (Survey "D"), a unique system incorporating controlled traffic was investigated. This system consisted of a large slewing loader and high capacity tractor drawn double-axle trailers loading from a field configured to match infield traffic wheel tracks. The field area surveyed totalled approximately 3.1 ha. The sugarcane was burnt, cut and manually placed into windrows. Six pairs of dual rows of sugarcane were joined to form a single windrow.

The field consists of a tramline planting configuration of 0.4 m dual rows and 1.25 m inter-rows. The wheel track of the loader is set at 3.6 m to straddle two sets of tramlines. The high capacity trailers are set to straddle one set of tramlines at a wheel track spacing of 2.15 m. The wide inter-row traffic zones and slightly raised crop production areas assist drivers in keeping wheel traffic away from the rows. The tramline and vehicle track positions are shown in Figure 6.17.

Figure 6.17 Field Survey "D": Slewing loader and trailer wheel track configurations to straddle dual row tramlines of sugarcane

A non-slew loader was employed to clear and stockpile cane windrows approximately 15 m infield from the field edges to improve headland turning prior to loading. The wheel track positions associated with the non-slew loader stockpiling operation were represented on CAD following repeated observations of this stockpiling operation. The equipment used during the loading operation is shown in Figure 6.18.

Figure 6.18 Field survey "D": A slewing loader loading two high capacity tractor drawn double-axle trailers

A total of six trips were required to extract the cane from the field. The average payload of the trips was measured at 28.3 t. A total of 170 t of sugarcane was removed from the field, equating to a yield of approximately 55 t/ha.

6.10 Description of Systems and Equipment Investigated in Survey E

System "E" consisted of a John Deere (2254) tracked chopper harvester, harvesting a single tramline consisting of 2 rows of sugarcane into accompanying low capacity tip trailers as shown in Figure 6.19. The tractor trailers conveyed and tipped the billeted cane onto a trans-loading zone for subsequent and independent loading into road haulage vehicles for conveyance to the mill. Three sets of similar trailers were used to transport the billets from field to zone. The tracking of multiple loading operations were used to identify repeated patterns associated with headland turning. These were used to replicate associated traffic paths in accordance with the GPS positions measured from both the harvester and single trailer GPS in order to get a representative field traffic associated with the harvesting and cane extraction system. The field area was approximately 3.8 ha although the area used in the analysis was approximately 1.5 ha. Short row lengths as the field narrowed were excluded from the analysis as the traffic patterns measured were not consistent with the longer harvester runs typically measured. On these shorter runs the harvester did not turn around at field edge but reversed and harvested in the same direction as the previous row. This decision was aggravated by the need to avoid a powerline along the field edge. The field consists of a tramline planting configuration of 0.4 m dual rows and 1.45 m inter-rows. The wheel track of the harvester tracks from each centreline is 1.88 m to straddle one set of tramlines. The trailers also straddle one set of tramlines at a wheel track spacing of 1.9 m. Although not much sugarcane is harvested in such a manner in South Africa, it was deemed an important system to investigate for the following reasons:

a) To place this research in the context of other industries where conditions led to the wide adoption of mechanized harvesting over manual harvesting practices;
b) To investigate the field impact of a mechanised chopper harvesting system for local conditions while operating on a better management principle in comparison to alternative manual harvesting systems;
c) Investigations into mechanized harvesting through large scale field trails are taking place in the northern irrigated parts of the South African industry particularly with the possibility and interest in biomass harvesting and co-generation opportunities. Estimating associated field based yield losses would be essential for quantifying such operational changes.

Figure 6.19 Field Survey “E”: Chopper harvester and accompanying low capacity tip trailers

6.11 Description of Systems and Equipment Investigated in Survey F

This system is similar to that of System “D” but uses a relatively new locally built design of a smaller slewing loader available to the South African market. Evaluating system “F” would thus provide an alternative system operating under better management controlled traffic principles as it consists of a smaller type of slewing loader loading into small capacity tip trailers as shown in Figure 6.20. This is contrasted with the large slewing loader and high capacity tractor drawn double-axle trailers of survey “D”. This system was deemed necessary to be evaluated as it is considered to be a more suitable entry-point into controlled traffic practices by merit of the lower capital costs for the system and thus easier accessibility for smaller farming operations. It may also, however, be suitable for large scale growers particularly concerned with large heavy equipment entering infield.

The field consists of a tramline planting configuration of 0.5 m dual rows and 1.45 m inter-rows. The wheel track of the loader is set at 2.1 m to straddle one set of tramlines. The low capacity double-axle tip trailers are set to straddle one set of tramlines at a wheel track spacing of 2.2 m. The wide inter-row traffic zones and slightly raised crop production areas assist drivers in keeping wheel traffic away from the rows. Three sets of tramlines are manually cut and placed into a single windrow centrally over a raised tramline to facilitate push-piling loading operations. The tramline, vehicle and windrow positions are shown in Figure 6.20.

Figure 6.20 Field survey “F”: Small slewing loader and accompanying low capacity trailer configured to straddle raised dual row tramlines of sugarcane

6.12 Defining Equipment Impact Ratings

Equipment travelling infield have been separated into 5 impact categories namely, low (L), low-medium (LM), medium (M), medium-high (MH) and high (H). These ratings are based subjectively on the size and typical weight of the equipment to correspond with the yield loss impact categories as described in the literature synthesis of Chapter 5 (Figure 5.3, Page 32) where the categories of low, medium and high were defined. The 3 categories showed large increments between the 3 categories that followed a linear decline based on the mean values for each category. The introduction of sub categories of LM and MH were introduced to lower the magnitude of the incremental steps of between categories and thus better allocate equipment to respective categories (i.e. LM = 3.5 t ± 0.5 t and MH = 5.5 t ± 0.5 t). Yield losses for the intermediate categories were linearly interpolated between the respective yield losses of the primary categories for both R and IR traffic events respectively.

In order to determine the impact of equipment with respect to the systems surveyed, load transfer calculations were conducted. A sample of the load transfer calculations are provided in Figure 6.21.

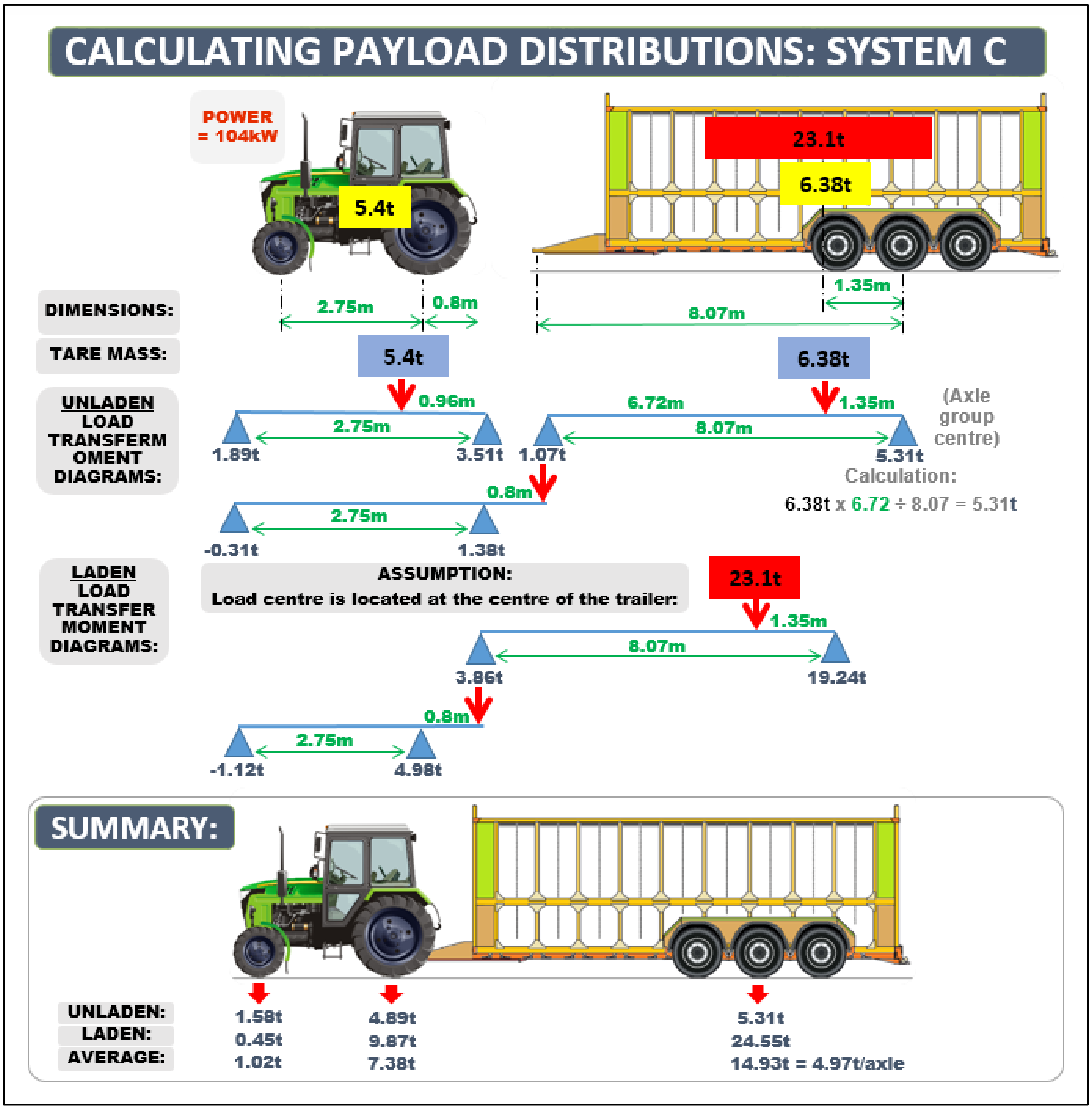

Figure 6.21 Sample load transfer diagrams and calculations relating to System C used to derive vehicle impact ratings based on axle load

The category derivations for different equipment are shown in Table 6.3. This categorisation was required for estimating individual vehicle based yield loss components into account.

Table 6.3 Defining vehicle impact categories relative to estimated axle loading parameters

System:	**Empty mass (Tons)**	**Load (Tons)**	**Part load-maximum axle mass (Tons)**	**Category (L to H)**
Single stack self-loading trailers	5.8	4.8	3.4	LM*
Double stack self-loading trailers	7.9	6.5	3.6	LM*
Non-slew loader* and	4.5	0.3	3.8	LM*
Tractor drawn box trailers	6.3	4.2–7.9	3.7	LM*
Non-slew loader* and	4.5	0.3	3.8	LM*
Tractor drawn tri-axle trailer	12.3	24.0	7.4	H*
Non-slew loader*,	4.5	0.3	3.8	LM*
Large Slew loader* and	5.9	0.4	5.5	MH*
Tractor drawn 2x 2 axle trailers	17.0	28.0	6.1	H*
Chopper harvester (tracked)* and	19.0	0.5	-	M*
Tractor & 1 axle trailers (duals)	5.6	7.0	5.3	MH
Small Slew loader* and	5.9	0.6	5.6	MH*
Tractor & 2 axle trailers*	8.8	9.0	6.3	H*

* High floatation / low inflation pressure tyres / large soil contact area

Tyre inflation pressures typically ranged between 140-240 kPa for tractors; 160-300 kPa for loaders; 280-560 kPa for infield trailers and in the region of 600 kPa for road haulage vehicles and trailer tyres.

6.13 Estimating Field Production Yield Losses

Yield losses have been defined in terms of traffic position by row or inter-row. The synthesis of yield responses from literature indicated a significant difference between row and inter-row traffic yield loss for a ‘point of impact’. The ‘point of impact’ yield losses by row were applied to the proportions of the field row areas that had incurred row traffic as derived from the field surveys. Similarly, the 'point of impact' yield losses for inter-row traffic was applied to the proportion of the field inter-row areas that had incurred inter-row traffic. Field based yield loss estimates were calculated by attributing the row yield loss and inter-row yield loss contributions for each vehicle that entered the field. These contributions were summed up for each vehicle entering the field to determine an estimated system yield loss. The surveyed traffic 'footprint' does not account for multiple passes over the same area and the additional yield loss that can be expected from multiple passes. Where traffic from different vehicle categories overlapped, then the highest impact equipment was deemed to dominate in the overlapped area and the yield impact based on the traffic of the higher impact vehicle alone.

6.14 Estimating Field Production Yield Loss Economics

Machinery costing analyses are typically reported on a cost per ton basis and these include machinery ownership and operating costs. Standard techniques such as the "Classic Machinery Costing Method" as described by Meyer (2006) are used to determine these costs and to conduct cost comparisons between systems to determine the most cost effective operation. Costings have not considered the penalty of infield traffic on yields. The value of unprocessed sugarcane is worth approximately R 475.89 /t (Anon, 2016a). The value of a loss of 1 % of sugarcane yield is therefore worth about R 4.76 /t or in other words R 4.76 /t per % loss of crop yield. The traffic induced crop yield loss can then be added to the costs of machinery to get a holistic system cost to account for both compaction and stool damage. Such comparative system costings are provided in Chapter 9.

6.15 Mechanisation performances and costings

In order to accurately attribute costs to machinery operations, performance data for the different machinery components are required to determine the utilization of the equipment and thereby account for both fixed and variable costs. The Classic Machinery Costing Method takes these factors into account when deriving a cost per ton that is based on a life cycle costing protocol. The annual SASRI mechanisation costing reports (Anon, 2016b), the SASRI machinery management, performance and utilization report (Meyer, 2000) and the ISSCT agricultural machinery costing method and standards protocol report (Meyer *et al.*,

2004) provide guideline performance standards for use in the absence of specifically measured data. Time and motion studies is an established method used to determine machinery performance standards, to measure and to predict machinery productivity and provide useful machinery management information (Murray and Meyer, 1982). It involves the direct observation and recording of activities typically against cumulative time while work operations are being conducted. Subsequent analysis can provide specific equipment performance on elements of work through to instantaneous and general productivity performances of the entire system. Other useful information can be gathered in such observation trials particularly when combined with yield data. During the field surveys, systems that had GNSS units mounted on the equipment were set to log at 1 s intervals. In essence these data points provide the cumulative timestamps that can be used for time and motion analyses. Data logging at the 1 s frequency combined with positional information provides detailed traffic movements and movement pattern records. Subsequent analysis of the GNSS point data in the GIS and CAD software has led to the generation of system linked performance data. This data has been particularly useful for determining both instantaneous loader performances and a range of overall productivities for the various systems. When combining the loader and associated trailer traffic movements, useful data such as the number of grab loads per trailer; grab loader capacity; push-piling speeds or average forward speeds of the loading systems, to name a few, can be determined. The system and equipment performance results are presented in Chapter 8.

The following chapter focuses on the results obtained from the GIS analysis of the field surveys. This includes maps showing the extent of the traffic that occurs for each system surveyed followed by the extent and proportions of row and inter-row traffic for each vehicle used in the system. Estimated yield losses for the different systems are also presented for a range of scenarios linking the literature synthesis and field analysis results.

7. FIELD SURVEYS AND MAPPING RESULTS

The extent of infield traffic surveyed for different cane extraction systems are reported in this chapter. The results are compared in terms of the proportion of row traffic, inter-row traffic and untrafficked areas within a field for each vehicle in the system. These results are integrated with the findings from the synthesis of yield responses to infield traffic based on traffic position (row or inter-row) from Chapter 5 in order to estimate field based yield losses for each system. Section 7.1 contains maps to indicate the extent of traffic for the various systems surveyed. The results of analyses conducted to quantify field traffic attributes of different harvesting and extraction systems are contained in Section 7.2. The integration of yield response results applied to the field attributes for different systems provides an estimate of traffic induced yield losses for each of the different harvesting systems. This allows for different systems to be compared in terms of their estimated impact on yield. Sections 7.3, 7.4 and 7.5 contain scenarios linking the yield losses derived in the literature synthesis conducted and described in Chapter 5 where yield losses due to row traffic were shown to be approximately 3.6 times more than inter-row yield loss. The scenario in Section 7.3 is based on the mean yield loss derived from the full database; for a partial set of the data for high soil moisture conditions in Section 7.4 and further subdivision to account for vehicle impact ratings in Section 7.5. Economics relating field based yield loss to loss of revenue are contained in Section 7.6.

7.1 Infield Traffic System Maps

Survey “A” comprised the mapping of infield traffic for a cut and stack and cut and windrow system. A map showing the distribution of cane stacks and wheel tracks for three different infield loading operations is presented in Figure 7.1.

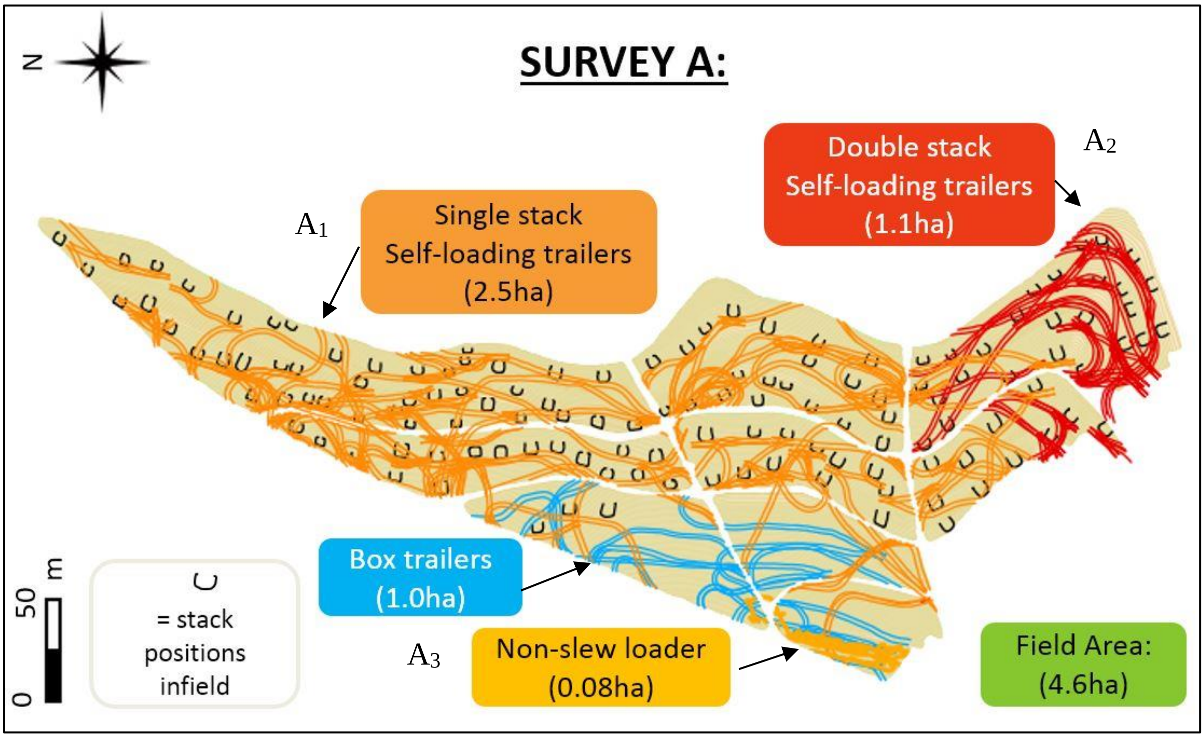

Figure 7.1 Field survey map "A" compiled to indicate vehicle movements for different types of equipment extracting sugarcane from cut and windrow operations and cut and stack harvesting systems

The cut and stack operations consisting of single stack self-loading trailers is defined as system A_1. The cut and stack operations consisting of double stack self-loading trailers is defined as system A_2. The cut and windrow operations consisting of a non-slew loader gathering cane from two windrows and loading into the adjacent infield box trailers is defined as system A_3. Considerable amounts of off-tracking of the double stack self-loading trailer wheels from the tractor path were noticed during the infield loading operations.

Survey B entailed the mapping of loading operations for a cut and windrow system, where the non-slew grab loader loaded sugarcane from a single windrow into adjacent low capacity tractor drawn box trailers as shown in Figure 7.2.

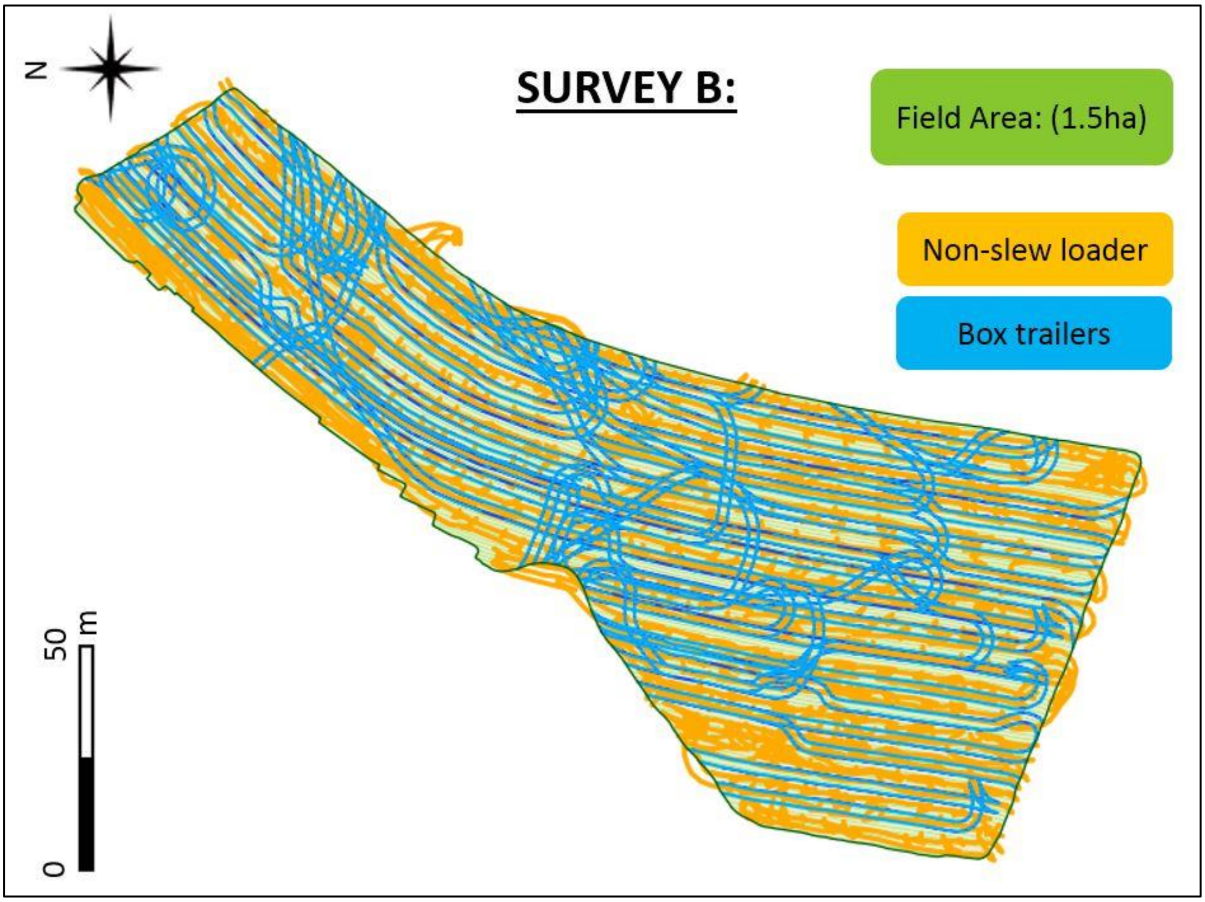

Figure 7.2 Field survey map "B" mapped to indicate the traffic of a non-slew grab loader loading sugarcane from a cut and windrow operation into adjacent low capacity tractor drawn box trailers

Large amounts of uncontrolled tractor trailer traffic are evident particularly at intermittent entry and exit positions through the field.

Survey C consisted of a variation of the cut and windrow operation, where a non-slew loader loaded sugarcane from three windrows into an adjacent high capacity trailer that followed alongside the area being loaded. The vehicle movements and area trafficked by the loader is shown in Figure 7.3. Nearly the entire field area had been trafficked by the non-slew loader by the end of the loading process.

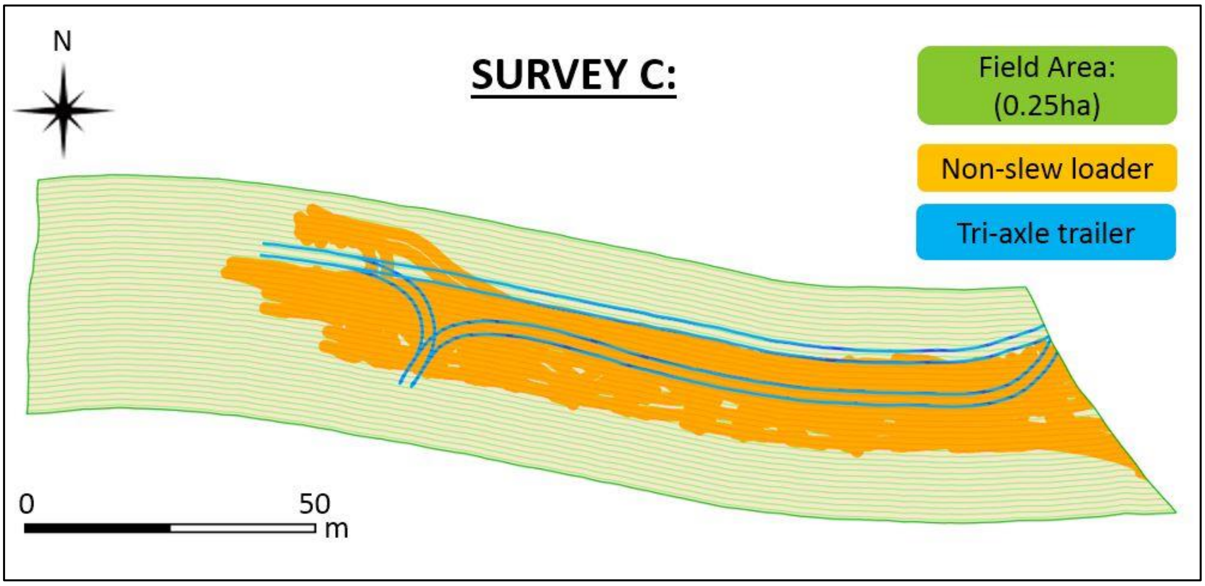

Figure 7.3 Field survey map "C" of a cut and windrow operation where three windrows of sugarcane were loaded into an accompanying high capacity tractor drawn tri-axle trailer

Survey D consisted of the mapping of a control traffic system where high capacity tractor drawn double-axle trailers are loaded by a slewing loader and where the field is configured to allow the matching of infield traffic wheel tracks to dedicated inter-row traffic zones. The field and traffic movements for the system are shown in Figure 7.4. The length of the tractor trailer combination resulted in considerable off-tracking of the high capacity trailer wheels from the tractor wheels. This combined with the poor turning ability of the wide slew loader resulted in substantial amounts of row traffic at the entry and exits of the headlands of the field.

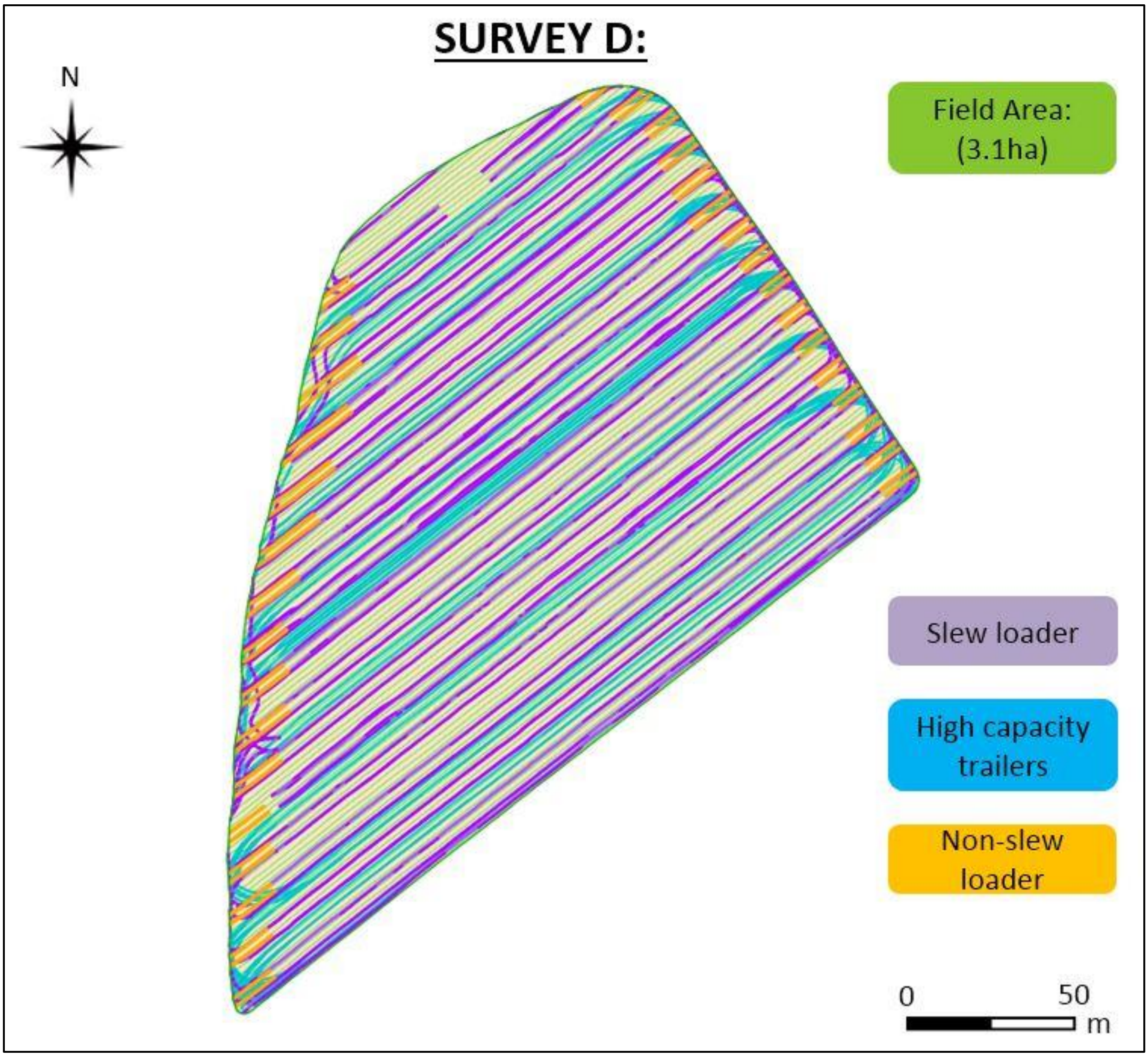

Figure 7.4 Field survey map "D" to indicate the traffic movements associated with a slewing loader loading into adjacent set of two high capacity tractor drawn tandem axle trailers

Survey E consisted of the mapping of a chopper harvesting system consisting of a tracked harvester loading into a team of three accompanying low capacity tractor drawn tip trailers. The system was operated under controlled traffic principles, by travelling on the wide inter-row dedicated traffic zones. The field and traffic movements for the system are shown in Figure 7.5. The harvester was noted to have a sharp turning circle that had resulted in minimal row traffic damage at the field edges. The tractor trailer combination although being highly manoeuvrable as opposed to longer configurations did appear to result in row traffic at the field edges when turning around to realign to the harvester. A three point turning manoeuvre at the field exit had less row traffic than a turning manoeuvre parallel to the harvester.

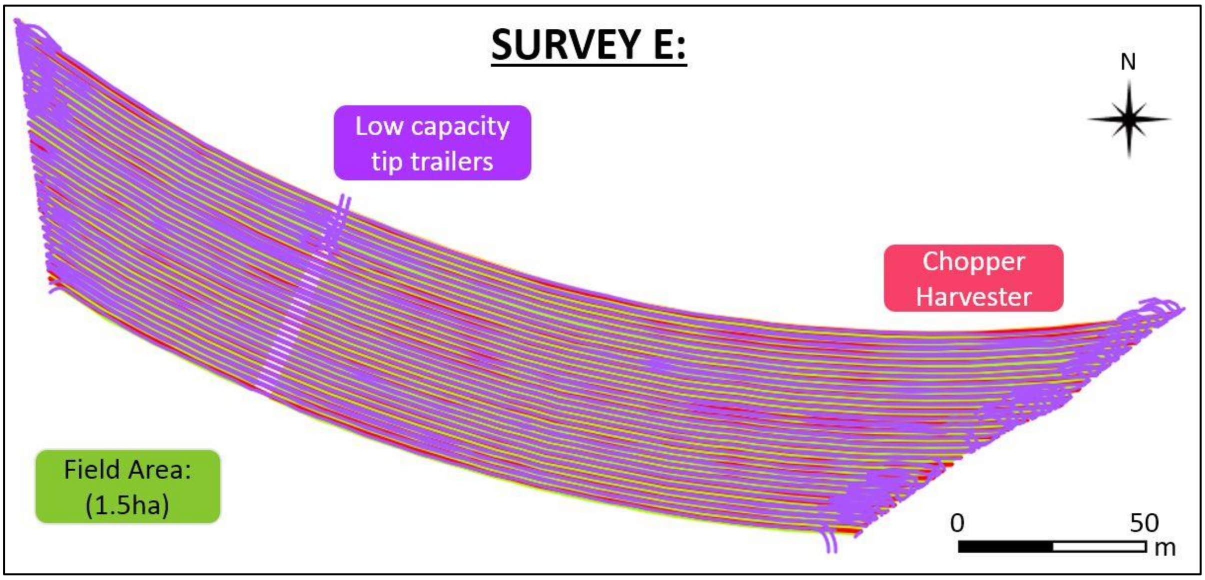

Figure 7.5 Field survey map "E" to indicate the traffic movements associated with a chopper harvester loading into adjacent set of three low capacity tractor drawn single axle trailers fitted with dual wheels

Survey F consisted of the mapping of a cut and windrow system operating on control traffic principles. The system consisted of a small slew loader and set of two low capacity tractor drawn tip trailers. The system was operated under control traffic principles, by travelling on wide inter-row dedicated traffic zones and untrafficked crop zone consisting of dual sugarcane rows. The field and traffic movements for the system are shown in Figure 7.6.

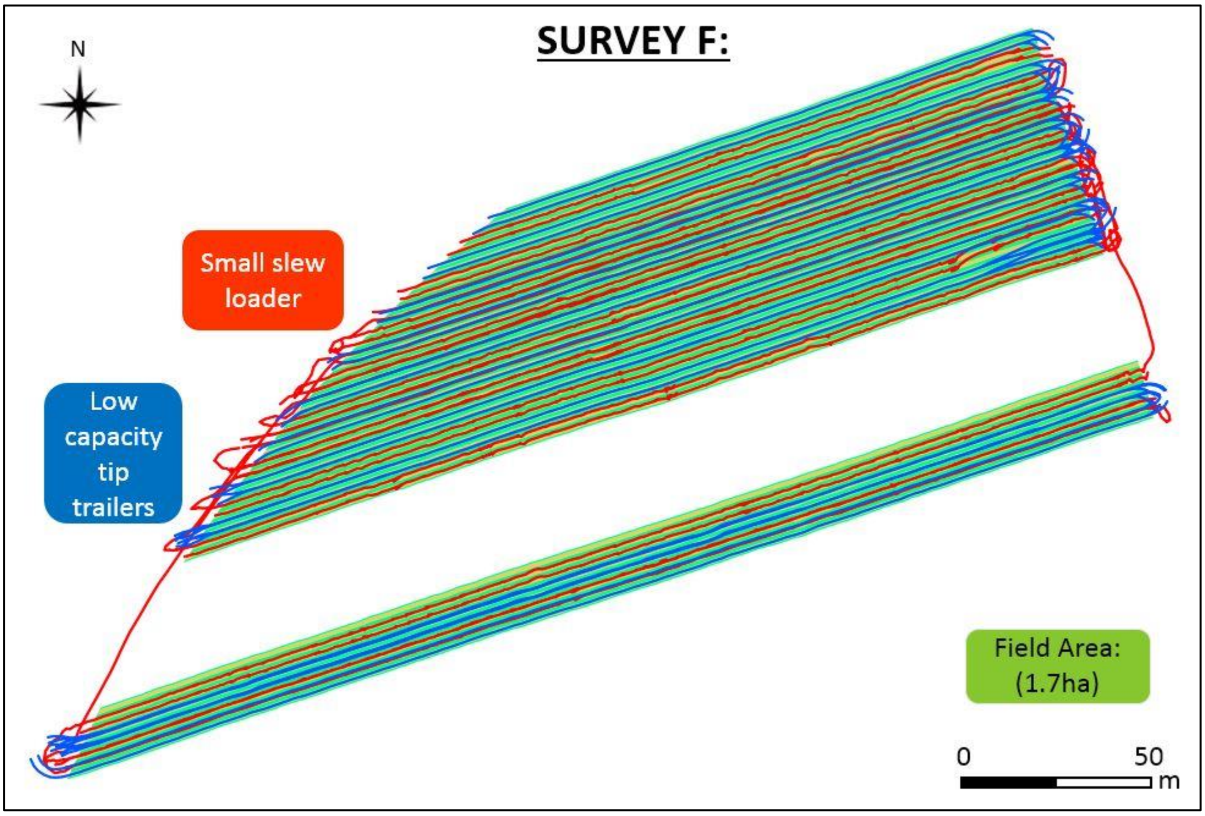

Figure 7.6 Field survey map “F” to indicate the traffic movements associated with a slew loader loading into adjacent set of two low capacity tractor drawn double axle trailers with high floatation single tyres. The untrafficked area within the field was due to a portion of the field that had not yet been fully harvested at the time of loading

7.2 Summary of the Extents of Infield Traffic for the Different Systems Surveyed

A summary of the extents of infield traffic for the range of systems that were surveyed is presented in Table 7.1. Field survey A consisting of the survey of 3 different systems were subcategorised into system A_1, A_2 and A_3, as described earlier. Where multiple vehicles enter the field for a particular system, then the combination of all traffic is included to account for the overlapping of different equipment traffic over the same paths in the field.

Table 7.1 Extent of infield traffic as a percentage of the entire field area

System:	Equipment:	Extent of traffic on a field basis (%)		
		Row traffic (%)	Inter-row traffic (%)	No traffic (%)
A_1	Single stack self-loading trailers	4.8	7.7	87.5
A_2	Double stack self-loading trailers	5.5	10.8	83.7
A_3	Non-slewing loaders	24.0	34.4	41.6
	Single box trailers	4.8	8.8	86.4
A_3	All equipment traffic: System A_3	26.2	39.0	34.8
B	Non-slewing loaders	17.3	23.7	59.0
	Single box trailers	5.5	8.9	85.6
B	All equipment traffic: System B	20.4	29.2	50.3
C	Non-slewing loaders	37.3	56.4	6.3
	Tri-axle trailer	1.6	5.1	93.3
C	All equipment traffic: System C	37.7	58.4	3.9
D	Non-slewing loaders	1.2	1.0	97.8
	Slewing loader (large)	5.7	9.0	85.2
	Two tandem axle trailers	2.5	4.7	92.8
D	All equipment traffic: System D	8.8	13.9	77.4
E	Chopper harvester (tracked)	0.4	38.9	60.7
	Single 1 axle, dual wheel trailer	4.8	37.0	58.2
E	All equipment traffic: System E	5.0	45.7	49.4
F	Slewing loader (small)	0.7	14.5	84.8
	Single tandem axle trailer	0.4	10.7	88.9
F	All equipment traffic: System F	1.1	23.6	75.3

7.3 Comparison of Estimated Yield Losses Between Systems: General Analysis

In the literature review component, the synthesis of yield responses indicated a significant difference between row and inter-row traffic yield loss. The mean yield loss at the 'point of impact' indicated that for a high level analysis, row traffic incurred a mean yield loss of 24.1 % and inter-row traffic incurred a mean yield loss of 5.5 % (Refer to Figure 5.1, page 29). These specific losses were allocated at a general high level analysis where differences in soil moisture, soil physical properties and vehicle attributes were not taken into account. Vehicle differences are based solely on the traffic 'footprint' in the field and further vehicle attributes such as vehicle mass have not been taken into account. The various systems were compared based on the amount and position of vehicle traffic infield. The results are presented in Table 7.2.

Table 7.2 Field production yield loss estimates based on the extent of infield traffic

System:	**System description:**	**Estimated field production yield loss (%)**
A_1	Single stack self-loading trailers	1.6
A_2	Double stack self-loading trailers	1.9
A_3	Non-slew loader (2 windrows)[a], box trailers	8.5
B	Non-slew loader (1 windrow)[a], box trailers	6.5
C	Non-slew loader (3 windrows)[a], tri-axle trailer	12.3
D	Large slew loader, 2x tandem-axle trailers	2.9
E	Chopper harvester, single axle tip trailers	3.7
F	Small slew loader, tandem-axle tip trailer	1.6

[a] describes the number of windrows loaded into the accompanying trailers

The yield loss estimates for this general analysis are proportional to the extent of infield traffic that occurs through the field. The lowest impact systems are the cut and stack systems (A_1 and A_2) that have much less traffic infield compared to other systems. The control traffic systems with dedicated traffic lanes (D, E and F) and reduced row traffic showed lower crop impact than all the other cut and windrow systems with non-slew loaders (A_3, B and C) irrespective of associated extraction vehicles and systems.

7.4 Comparison of Estimated Yield Losses Between Systems for High Soil Moisture Conditions

An analysis on the effect of traffic on yields, based on the synthesis of yield responses for traffic operated infield at higher soil moisture content was conducted. Vehicle differences are based solely on traffic 'footprint' in the field. Traffic induced yield loss at the 'point of impact' for high soil moisture conditions indicated that row traffic incurred a mean yield loss of 30.3 % and inter-row traffic incurred a mean yield loss of 8.5 % (Refer to Figure 5.2, page 30). Using these yield loss values, a comparison of various systems in terms of an estimated field production yield loss on a percentage basis under higher moisture conditions are presented in Table 7.3.

Table 7.3 Field production yield loss estimates based on the extent of infield traffic and under high soil moisture conditions

System:	**System description:**	**Estimated field production yield loss (%)**
A_1	Single stack self-loading trailers	2.1
A_2	Double stack self-loading trailers	2.6
A_3	Non-slew loader- 2 windrows, box trailers	11.3
B	Non-slew loader- 1 windrow, box trailers	8.7
C	Non-slew loader- 3 windrows, tri-axle trailer	16.4
D	Slew loader, 2x tandem-axle trailers	3.8
E	Chopper harvester, single axle tip trailers	5.4
F	Small slew loader, tandem-axle tip trailer	2.3

The yield loss estimates for high soil moisture conditions are similar in trend to those of the general analysis, but exacerbated through higher yield losses due to poor field conditions for traffic operations. This provides an indication of the risk of mechanised operations and the systems that are particularly vulnerable to significant yield losses. The systems with the highest proportions of infield traffic and in particular, row traffic are most vulnerable, namely the cut and windrow systems with non-slew loaders (A_3, B and C). The systems that have the lowest modelled yield loss are those with the lowest extent of infield traffic or those with traffic primarily constrained to the inter-rows and dedicated traffic lanes. This analysis is based solely on the extent of traffic footprint of systems where vehicle attributes and vehicle differences have not been taken into account.

7.5 Comparison of Estimated Yield Losses Between Systems for High Soil Moisture Conditions Based on Vehicle Impact Ratings

In order to further distinguish between differences between infield vehicles, vehicle impact ratings were taken into account. Where traffic areas from different vehicle categories overlapped, then the highest impact equipment was deemed to dominate in this overlapped area and the yield impact based on the traffic of the higher impact vehicle alone. The synthesis of literature indicated that yield losses for row traffic were typically about 3.6 times more than inter-row yield loss. The exception for this was for low impact equipment where the data were variable and the mean value obtained indicated a yield increase following inter-row traffic despite the majority of yield responses indicating a yield decrease. A response of 3.6 times less than the row traffic mean value (2.6 % loss) would intuitively be more appropriate and congruent with the larger dataset trends. This would indicate an approximate yield loss of 0.7 % for an inter-row traffic event for low vehicle category. This value would be more conservative than using the median value of 2.1 % yield loss for the inter row response dataset for low impact equipment. The synthesis of literature for high soil moisture conditions distinguishing between the characteristics of the equipment entering the field provided the following yield loss trend as shown in Table 7.4 (Refer to Figure 5.3, page 32).

Table 7.4 Point of impact yield losses attributed to row and inter-row traffic for high soil moisture conditions and low (L), medium (M) and high (H) equipment impact ratings

	Row traffic	**Inter-row traffic**	**No traffic**
Mean yield loss (%): L	2.6	-0.3[a,b,c]	0
Mean yield loss (%): M	27.2	7.2	0
Mean yield loss (%): H	48.2	13.1	0

[a] Mean value from the dataset: -0.3 %
[b] If a value of 3.6 times less than the row mean value were used: 0.7 %
[c] The median value from the dataset: 2.1 %

Comparing the various systems in terms of an estimated yield loss under higher moisture conditions are presented in Table 7.5. It must be noted that these results are expected to be much lower under dry field conditions. The results show the implication of using the mean inter-row low impact equipment yield loss value of -0.3 % (a) versus a value based on a 0.7 % yield loss (b). The results indicated little difference in the estimated field production yield loss between the two values.

Table 7.5 Field production yield loss estimates based on the extent of infield traffic and under high soil moisture conditions taking vehicle impact ratings into account

System:	**System description: (subjective impact rating - refer to: Table 6.3, page 66)**	**Estimated field production yield loss (%)** [a,b]	
		% [a]	% [b]
A_1	Single stack self-loading trailers (L/M)	1.0	1.0
A_2	Double stack self-loading trailers (L/M)	1.2	1.2
A_3	Non-slew loader- 2 windrows (L/M), box trailers (L/M)	5.8	6.0
B	Non-slew loader- 1 windrow (L/M), box trailers (L/M)	4.5	4.7
C	Non-slew loader- 3 windrows (L/M), tri-axle trailer (H)	8.9	9.2
D	Slew loader (M/H), 2x tandem-axle trailers (H)	5.1	5.1
E	Chopper harvester (M), single axle tip trailers (M/H)	8.5	8.5
F	Small slew loader (M/H), tandem-axle tip trailer (H)	3.3	3.3

[a] Inter-row traffic, low impact equipment category yield loss of -0.3 %
[b] Inter-row traffic, low impact equipment category yield loss of 0.7 %

The yield loss estimates for the various systems under high soil moisture conditions and taking perceived vehicle impacts into account, indicate that the systems with the lowest extent of infield traffic appear to have the lowest yield losses. The cut and windrow system with slew loader, despite having the heaviest infield equipment seemed to be able to mitigate yield losses through the practicing of control traffic principles by endeavouring to constrain much of the infield traffic to dedicated inter-row traffic lanes.

7.6 Comparison of Estimated Economic Losses Between Systems

Table 7.6 indicates the estimated costs associated with a loss of cane yield. These costs do not include the compounding losses that row traffic has on successive ratoons or losses that are expected with uncontrolled traffic practices or the accrued effect of trafficking over previously un-trafficked areas in subsequent ratoon crops or seasons. The minimum and maximum yield loss values are a summary from the previous analyses to indicate the range of cost estimates that may be likely under the various scenarios presented.

Table 7.6 Estimated costs of decreased field production yield losses (2015/2016 costs)

System:	System description:	Estimated minimum yield loss (%)	Estimated maximum yield loss (%)	Estimated minimum loss (R/t)	Estimated maximum loss (R/t)
A_1	Single stack self-loading trailers	1.0	2.1	4.75	9.99
A_2	Double stack self-loading trailers	1.2	2.6	5.71	12.37
A_3	Non-slew loader- 2 windrows, box trailers	5.8	11.3	27.60	53.77
B	Non-slew loader- 1 windrow, box trailers	4.5	8.7	21.41	41.40
C	Non-slew loader- 3 windrows, tri-axle trailer	8.9	16.4	42.35	78.05
D	Slew loader, 2x tandem-axle trailers	2.9	5.1	13.81	24.27
E	Chopper harvester, single axle tip trailers	3.7	8.5	17.61	40.45
F	Small slew loader, tandem-axle tip trailer	1.6	3.3	7.61	15.70

In the following chapter a synopsis of the performance data gathered during the field studies for each of the systems are presented. This provides a basis upon which to conduct economic analyses for the various systems investigated.

8. SYSTEMS PERFORMANCE ANALYSES

Geospatial analysis of the GNSS data, GIS maps and CAD features has provided the results as contained in Table 8.1. Field and cane stockpile presentation data are provided to contextualise the results.

Table 8.1 System performance measurements determined from field survey data

System:	A_1	A_2	A_3	B	C	D	E	F
Test area (ha)	2.5	1.1	0.1	1.5	0.25	3.1	1.5	1.7
Yield (t/ha)	89		115	76	91	55	70	123
Row length (m)	180	135	90	160	140	200	250	225
Stockpile presentation	2.8 t in field stacks		5 m swath	5.6 m swath	6 m swath	10 m swath	1.85 m swath	7.8 m swath
Stockpile swath mass (kg/m)	N/A - 116 stacks		59	42	54	54	13	95
Loads or trips measured	54	10	1	28	1	6	36 rows	27
Payload (t)	4.7	6.5	7.9	4.2	23.1	28.3	7	9
Loaders (no.)	3	2	1	1	1	1	1	1
Trailers (no.)			1	3	1	2	3	2
Lead dist. (km)	1.7	1.7	1.5	0.85	F-M	F-M	0.5	1.25
Productivity per load (t/h)	43	41	47	44	39	64	46 pour	120
Overall loader performance (t/h/vehicle)	11.7	12.6	- *	31	- *	39	32	76
Average loading speed (km/h)	N/A	N/A	0.8	0.9	0.7	1.0	3.5 harvest	1.3
Overall system performance (t/h)	30.8	25.3	- *	31	- *	22**	32	52
Support equipment performance (t/h)	N/A	N/A	- ***	- ***	- ***	- ***	20	31

* only 1 load measured ** mill delays *** not measured

The data presented forms the basis for the assumptions used to conduct the mechanisation cost analyses. The performances of the various equipment compared against those stated in the literature study of Chapter 2 are as follows: the overall performance rates for the self-loading trailers (A_1 and A_2) and the large slewing loader (D) appear to be well matched; the small slewing loader (F) and the non-slewing loaders (A3, B and C) performed better and the chopper harvester (E) performed at a lower pour rate. Chopper harvester pour rates were noted to be highly dependent on influencing factors such as cane presentation, field conditions and associated ancillary support system performance.

In the following chapter, results from an economic analysis are presented. The first analysis that is presented is for the direct cost of machinery operations. These are conducted on a life cycle costing protocol. Issues pertaining to cash flows or tax implications that are considered as unique and specific to a particular business operation are thus not taken into consideration. Subsequent analyses attribute differing yield loss cost scenarios to match earlier annual yield loss estimates as described in Chapter 6. The impact that such losses would have when compounded through to subsequent ratoon cutting cycles on a whole cycle basis are included. An analysis is also presented where yield losses under adverse soil conditions pertaining to wet periods are discounted by the proportion of time across the milling season where adverse soil moisture conditions may occur. This is based on modelled soil moisture content linked to long term seasonal climatic conditions.

9. ECONOMIC ANALYSIS: CASE SUDY

Machinery costing analyses are typically reported on a cost per ton basis and these include machinery ownership and operating costs. Standard techniques such as the "Classic Machinery Costing Method" as described by Meyer (2006) are used to determine these costs and to conduct cost comparisons between systems to determine the most cost effective operation. Costings in the past have not considered the penalty of infield traffic on yields as this is an undefined and highly variable factor which are affected by variability in soils, soil moisture and vehicle interactions.

In this chapter, a series of economic analyses are presented. The first analysis provides an overview of typical mechanisation base costs for each of the systems, not taking yield losses into account. This indicates the economic driver for typical decision making when yield impacts of mechanisation are not considered. Over and above this base cost, the costs relating to a loss of productive income due to yield loss estimates for each of the systems from Chapter 7, pertaining to treatments under high soil moisture contents, are presented. These yield loss estimates were discounted to account for the fraction of operations where low risk of yield loss would be applicable, namely for treatments occurring on compaction resistant soils during drier periods of the season. Details pertaining to how this discounting was conducted are described in more details in the analyses that follow. The discounted yield loss estimates represent only a single traffic system treatment event. The impact of repeated harvest operations over an entire cropping cycle would result in a compounding yield loss effect being carried through into successive ratoon cycles. To account for this, a whole cropping cycle simulation was conducted to compare the revenue differences between a hypothetical system against another of higher rate of yield loss in order to determine a "compounding effect" factor. The compounding factor was used to determine a final yield loss estimate for each system. This was converted to a cost per ton based on the current cane price and summed to the base mechanisation cost to determine the real system cost. Regional or farm specific analyses can be conducted in a similar manner.

9.1 Machinery system costs

In order to conduct an economic comparison between systems a number of assumptions must be made as the costs are dependent on both overhead (fixed) costs and variable costs. In order to not penalise a system due to poor utilization, a large scale operation was chosen, namely 100 000 t of cane harvested per annum. The purposes of this study are focused on the impact of infield operations on cane yields and sustainability. The choice of system, however, does impact on equipment requirements. For instance, the use of heavy infield equipment infield is offset by cost savings of not requiring further trans-shipment operations into higher capacity road haulage vehicles as per Systems “C” and “D”. Thus the economic impacts of trans-shipment and road haulage operations need to be taken into account when comparing systems holistically. Similarly, the use of the chopper harvester System “E” does not require manual cutting and thus, for comparative purposes, the cost component of manual cutting was included for all systems. The manual cutters also have a drop in productivity when forming stacks infield for Systems “A_1”and “A_2” and so this was also accounted for. In order to standardise the costings a field to zone distance of 1 km was chosen. All associated mechanisation system costing assumptions are provided in Appendix C. These are based on the measured performance of the systems and in accordance with data contained in the annual SASRI mechanisation costing reports (Anon, 2016b).

A System “G” has been included for costing purposes, which is essentially a duplicate of System “C” with a non-slewing loader but loading into a high impact road haulage truck direct infield as opposed to the haulage tractor with spiller trailers for System “C”. The field impact is assumed to be similar to System “C” in the absence of such a system being surveyed. In practice the impact would remain the same but the distribution of field traffic would likely be greater than System “C” due to greater wheel track off-tracking. For the purposes of the analyses, the impact and distribution of traffic was deemed the same as System “C”. The reason for including the operation is that the use of road haulage systems are popular in many areas of the industry. The use of a road haulage truck is generally more suited to longer road haulage operations compared to the high capacity haulage tractor systems (System “C”) which are governed to travel at a maximum speed of 40 km/h.

Table 9.1 is used to depict the mechanisation cost comparisons for a range of haulage distances based on well utilised system of 100 000 t. Cell colours range from green to red indicating the lowest to highest cost respectively.

Table 9.1 Estimated costs (R/t) for harvesting to mill delivery for the various systems for a well utilized scenario (100 000 t)

	SYSTEMS:								
Lead distance:	**A_1**	**A_2**	**A_3**	**B**	**C**	**D**	**E**	**F**	**G**
5 km	61.68	59.74	51.69	54.36	58.27	64.58	86.06	43.08	34.79
15 km	67.41	69.74	57.42	60.09	64.12	73.93	91.79	48.81	45.04
25 km	73.49	75.82	63.50	66.17	74.87	86.05	97.87	54.89	51.11

Figure 9.1 provides a graphical representations of the mechanisation costs based on a 15 km haulage distance as system operation size varies.

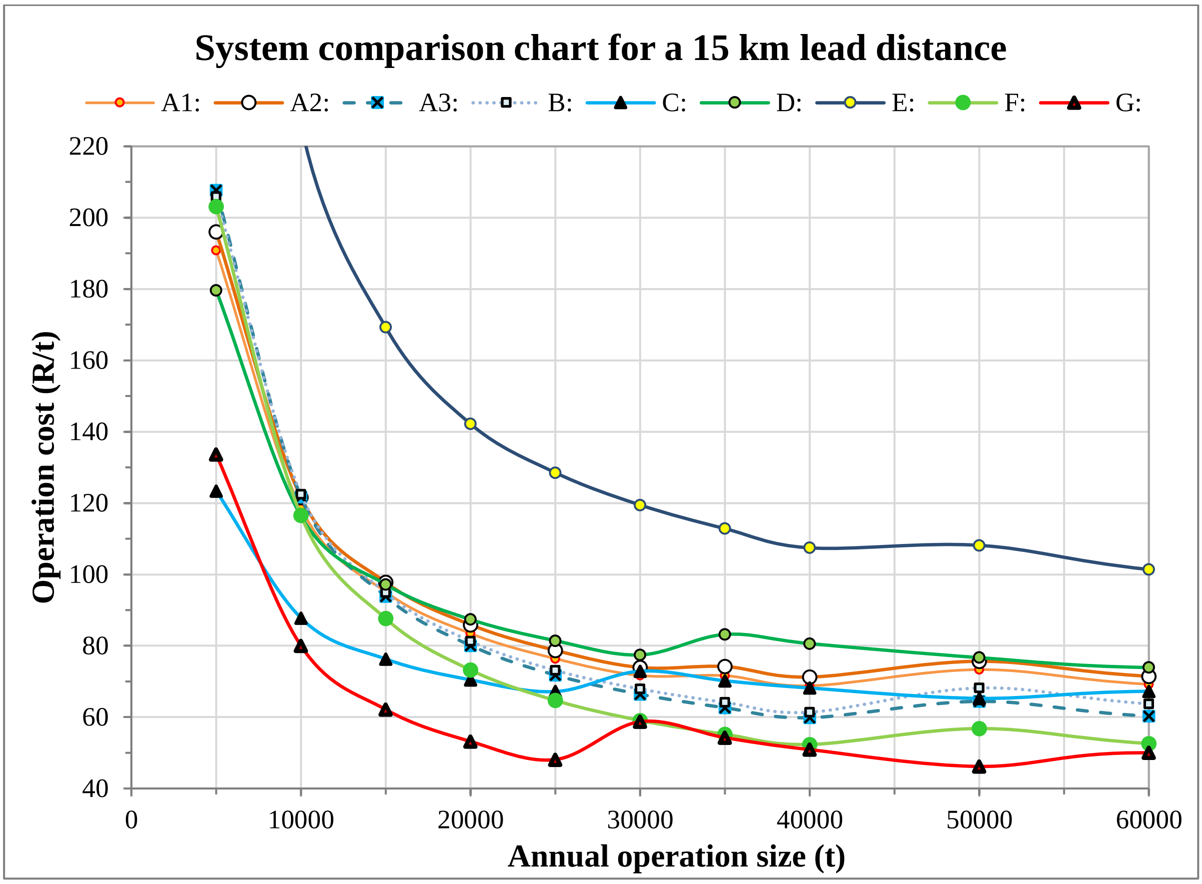

Figure 9.1 The full system mechanisation costs associated with the supply chain from burning to mill facility delivery based on a 15 km transport lead distance excluding the effect of yield losses

Typical costing analyses derive the direct costs relating to individual equipment and operational components summed to derive particular system costs for a particular operation size as can be extracted from Figure 9.1. For smaller sized operations that do not employ harvesting contractors, it appears that the best systems are those with a direct haulage route to the mill (Systems C and G). For operations between 30 000 t and 40 000 t the small slewing loader with trans-loading operation (System F) becomes cost competitive comparable to the direct haulage route using infield truck haulage rigs (System G). Concerns relating to yield loss through compaction and stool damage are often raised by farmers but the means to estimate such costs are not readily available, leaving much speculation when comparing systems as to which is the most optimal solution for their particular scenario. In the next section, the costs attributed to yield losses in order to further determine a cost penalty relating to compaction and stool damage are investigated.

9.2 The value of a loss in cane production for a single harvesting event

The value of unprocessed sugarcane is worth approximately R 475,89 /t (Anon, 2016a). The value of a loss of 1 % of sugarcane yield is therefore worth about R 4.76 /t. The traffic induced crop yield loss can then be added to the costs of machinery to get a holistic system cost (for both compaction and stool damage). The costs of the Estimated Field Yield Loss (EFYL) carried through from Table 7.5[b] (Page 80) are presented in Table 9.2 colour coded from low (green) to high (red).

Table 9.2 Costs of estimated single harvesting event field based yield losses for high risk periods (R/t)

SYSTEMS:	**A_1**	**A_2**	**A_3**	**B**	**C**	**D**	**E**	**F**	**G**
EFYL: (%)	1.0	1.2	6.0	4.7	9.2	5.1	8.5	3.3	9.2
Cost: (R/t)	4.76	5.71	28.56	22.37	43.79	24.28	40.46	15.71	43.79

This cost is only applicable to a single period harvesting event related to the system employed. The impact of this yield loss being repeated year on year through the crop cycle is investigated in the next section.

9.3 The compounding influence of annual yield losses on a whole crop cycle

The yield losses presented thus far are reported for a single harvesting event. In a commercial farming operation there are a range of fields with varying degrees of historical trafficking. Typically poorer yielding fields are replanted when a yield based economic threshold has been reached (Hoekstra, 1976). Industry data for crop cycle lengths are highly variable. Henry and Ellis (1996) showed that in Swaziland, fields could be replaced as early as after 5 ratoons or last as long as 18 ratoons before being replanted. Industry norms suggest that 10 % of the farming area is typically targeted for replant. In order to examine this further, a simple modelling of yield loss compounded over multiple ratoons over a 10 period crop cycle is presented. The cumulative impact of yield loss through a crop cycle is shown to be in the order of a magnitude of about 4 times greater than that of a single season. This compounding factor (CF) does vary based on the percentage yield loss per season. In order to best illustrate this effect the range of scenarios are presented with varying rates of yield loss decline from a base of 100 units (Table 9.3).

Table 9.3 The compounding effect of a consistent seasonal decline through a ten season cycle from a normalised base of 100 %

	Percentage seasonal yield loss decline (a):						
Season:	**0 %**	**0.5 %**	**1 %**	**2 %**	**3 %**	**5 %**	**10 %**
1 (No traffic)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
2 (1st ratoon crop)	100.00	99.50	99.00	98.00	97.00	95.00	90.00
3	100.00	99.00	98.01	96.04	94.09	90.25	81.00
4	100.00	98.51	97.03	94.12	91.27	85.74	72.90
5	100.00	98.01	96.06	92.24	88.53	81.45	65.61
6	100.00	97.52	95.10	90.39	85.87	77.38	59.05
7	100.00	97.04	94.15	88.58	83.30	73.51	53.14
8	100.00	96.55	93.21	86.81	80.80	69.83	47.83
9	100.00	96.07	92.27	85.08	78.37	66.34	43.05
10	100.00	95.59	91.35	83.37	76.02	63.02	38.74
Average:	**100.00**	**97.78**	**95.62**	**91.46**	**87.53**	**80.25**	**65.13**
% loss (b):	**0.00**	**2.22**	**4.38**	**8.54**	**12.47**	**19.75**	**34.87**
CF: (c) = (b) ÷ (a)	**-**	**4.44**	**4.38**	**4.27**	**4.16**	**3.95**	**3.49**

A graphical illustration of the above for two scenarios, namely one with a 5 % period on period yield reduction and the second with a 10 % yield reduction is presented in Figure 9.2.

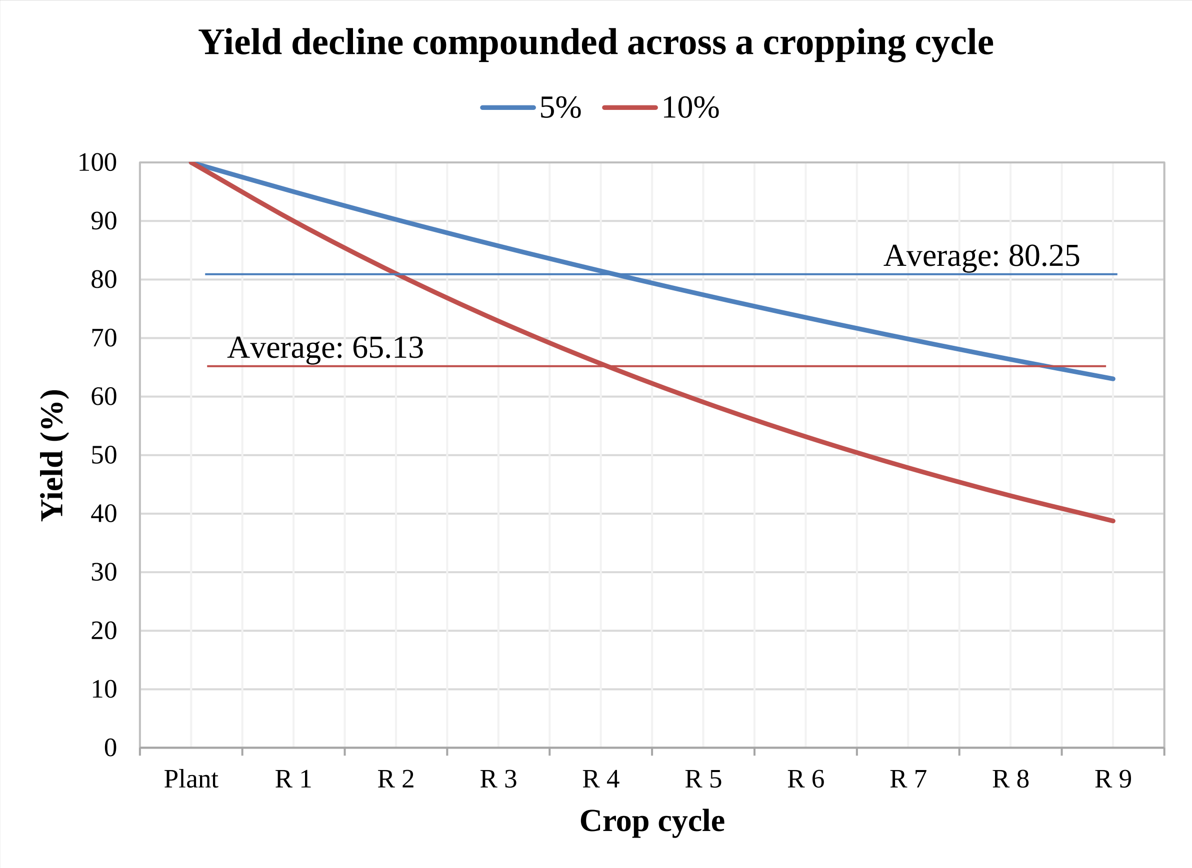

Figure 9.2 The compounding effect of yield loss over multiple ratoons

Figure 9.2 shows a difference in average values of 18.84 % for a 5 % relative decline. The use of the CF is to account for the % decline year on year yield loss that compounds over the entire crop cycle. These results of the Estimated Cropping Cycle Yield Loss (ECCYL) and appropriate compounding factors (CF) are presented in Table 9.4 for the harvesting systems investigated.

Table 9.4 Estimated cropping cycle yield loss percentage for high risk periods of high soil moisture conditions

SYSTEMS:	A_1	A_2	A_3	B	C	D	E	F	G
EFYL%	1.0	1.2	6.0	4.7	9.2	5.1	8.5	3.3	9.2
CF:	4.38	4.36	3.85	3.98	3.56	3.94	3.62	4.13	3.56
ECCYL%	4.38	5.23	23.10	18.71	32.71	20.09	30.77	13.62	32.71

Note that this would represent the percentage loss reflected in the average yield of the system relative to the plant crop yield loss if the entire crop were repeatedly harvested and extracted from the field under constantly wet field conditions for the entire cropping cycle. The cropping cycle is assumed to be in system equilibrium with 10 % of the crop being proportionally harvested through each ratoon life stage of production. The position of the traffic in subsequent ratoons and associated yield losses are assumed to perform at the same yield loss rate as per the single crop cycle loss. This is suitable for controlled traffic scenarios where the losses will remain consistent. In the case of uncontrolled traffic, a further stool damage memory effect, as described in Section 4.1, page 22, has been reported which is particularly applicable to areas which received traffic in the previous season but not in the current season. Such subsequent repeated field surveys were not conducted and thus are not taken into account. It is expected that the systems practicing controlled traffic would thus perform better than uncontrolled traffic although the extent of this additional yield loss component was not estimated. The ECCYL% described does not take seasonal soil moisture variations into account, but these are investigated in the next section.

9.4 Yield loss cost taking seasonal factors into account

The yield loss values presented in Section 9.3 would only be applicable for the proportion of fields trafficked during harvesting periods of high soil moisture where fields are the most vulnerable to traffic induced yield losses.

Bezuidenhout *et al.* (2006) developed a reference traffic season for the South African industry to account for when the risk of soil compaction would result in a high risk status for in-field sugarcane mechanisation operations. This was based on over 50 years of daily soil moisture content simulations to account where soil deformation would be likely to occur to a depth sufficient to cause severe compaction and cane stool damage based on a reference sandy clay loam soil and reference radial tyre with an inflation pressure of 200 kPa and a load of 2 000 kg. This work was used by Mthembu (2011) to provide regional GIS maps for the industry showing the proportion of time where the field would be within high risk periods where the soil moisture exceeded a critical value of 80 % of field capacity. The crop in South Africa is harvested predominantly in the drier winter months where the risk of field damage is lowest, but may start and end in periods of high risk. A regional overview of the high risk periods are contained in Appendix D and summarised to an industry level based on area weighted deliveries for the regions for the 2013/14 milling season (Table 9.5). The 2013/14 data was chosen as more representative in order to remove data distortions due to the subsequent drought periods since 2014.

Table 9.5 Number of days of risk of adverse soil moisture conditions occurring during the year and during a typical milling season of 220 days

	INDUSTRY: Annual cycle	**INDUSTRY: Milling season of 220 days**
January	13.7	0.0
February	12.0	0.0
March	12.3	0.0
April	8.2	4.1
May	3.9	3.9
June	3.1	3.1
July	3.2	3.2
Aug	2.9	2.9
September	4.4	4.4
October	9.1	9.1
November	11.4	8.0
December	13.0	0.0
TOTAL:	**97.1**	**38.6**

This data indicates that during the milling season harvesting operations are likely to be at risk for 38.6 days out of a typical season length of 220 days. Over the course of the milling season 17.5 % of the crop is thus prone to harvesting under high risk field conditions and associated yield loss due to adverse soil moisture conditions. This provides a dilution factor applicable to the EFYL based on yield loss applicable to wet periods. Data on trafficking clay soils under dry conditions, indicate negligible yield losses for IR traffic (Figure 5.4, page 34) irrespective of the axle mass or tyre inflation pressures used. For the balance of the season and due to the absence of sufficient trial data, the dry period yield losses were conservatively assumed to be negligible. In practice, however, the presence of row traffic would be anticipated to cause some degree of yield loss less than the magnitude of row traffic under wet field conditions, although this research has yet to be conducted. The value of the modelling approach does allow for incremental yield loss scenarios and sensitivities to be tested. Based on the abovementioned conservative approach, the ECCYL accounting for general South African sugar industry weather variability and associated high risk soil moisture conditions are presented in Table 9.6. Cell colours range from green to red indicating the lowest to highest cost respectively.

Table 9.6 Estimated yield losses and cost taking seasonal risks and crop cycle compounding effects into account

SYSTEMS:	**A_1**	**A_2**	**A_3**	**B**	**C**	**D**	**E**	**F**	**G**
EFYL% pa^w	1.0	1.2	6.0	4.7	9.2	5.1	8.5	3.3	9.2
EFYL% pa^s	0.18	0.21	1.05	0.83	1.62	0.90	1.49	0.58	1.62
ECCYL% ^{s}	0.77	0.92	4.06	3.28	5.74	3.53	5.40	2.39	5.74
ECCYL Cost: (R/t)	3.66	4.37	19.31	15.63	27.34	16.79	25.70	11.38	27.34

^{w} Wet field conditions ^{s} Seasonal field conditions

9.5 Overall system costs

The summation of direct machinery system costs and the hidden costs associated with the loss of cane production provides the means to estimate the real costs associates with a mechanisation practice or a particular system. This is particularly useful when comparing systems relative to another, where the methodology is consistent and the assumptions are relatively unbiased and practically achievable.

Table 9.7 contains a list of the overall system costs that account for both the direct machinery costs and the costs associated with a yield loss. The list compares the system costs for a range of haulage distances based on well utilised system of 100 000 t. In practical application these economic analyses can be tailored for a particular farming enterprise with specific equipment utilizations and haulage distances to determine the most cost effective or sustainable practices available at that particular time. Cell colours range from green to red indicating the lowest to highest cost respectively.

Table 9.7 Estimated sugar industry based cost comparisons between systems (R/t) including the cost of yield loss compounded through successive ratoon crops based on a 100 000 t scenario

	SYSTEMS:								
Lead distance:	**A_1**	**A_2**	**A_3**	**B**	**C**	**D**	**E**	**F**	**G**
5 km	65.34	64.11	71.00	69.99	85.61	81.37	111.76	54.46	62.13
15 km	71.07	74.11	76.73	75.72	91.46	90.72	117.49	60.19	72.38
25 km	77.15	80.19	82.81	81.80	102.21	102.84	123.57	66.27	78.45

Figure 9.3 illustrates the mechanisation cost comparisons for different enterprise sizes based on an intermediate cane delivery distance of 15 km.

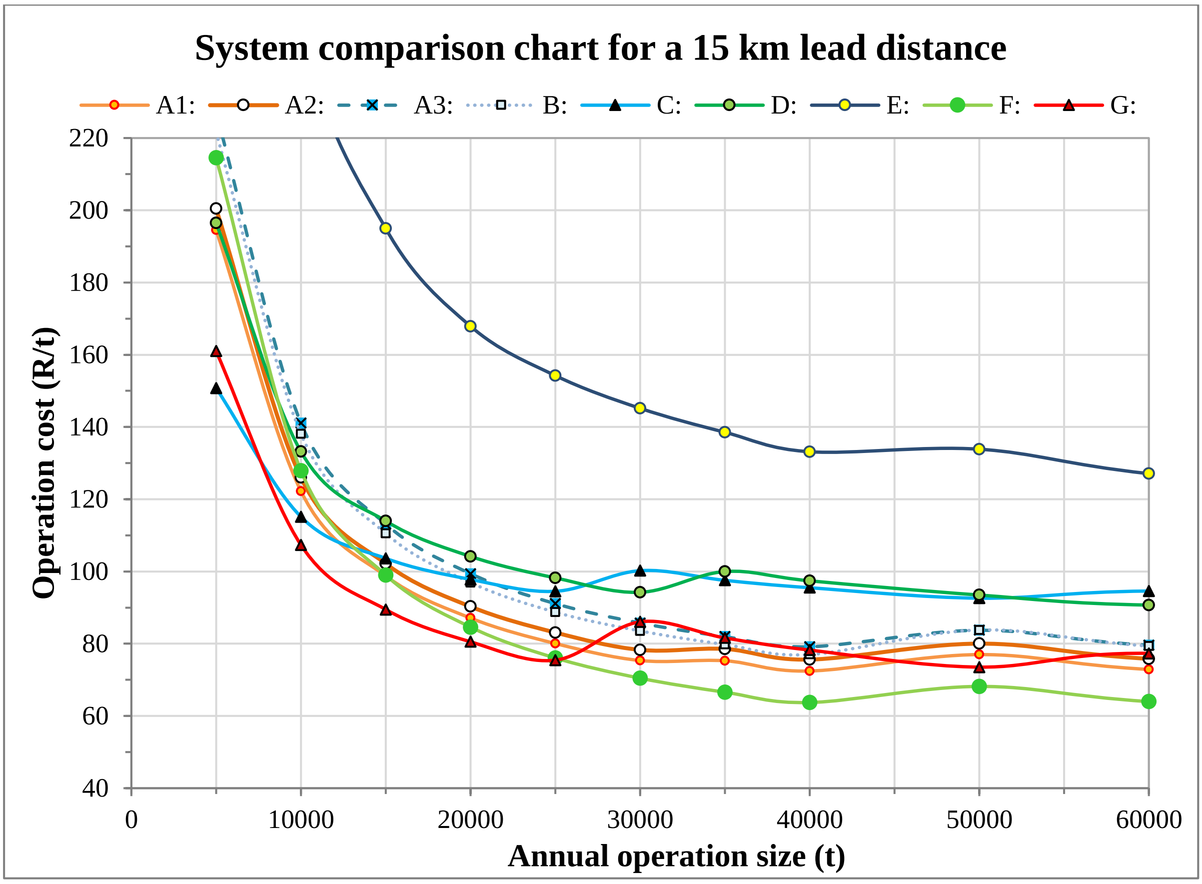

Figure 9.3 The full mechanisation costs associated with the supply chain from burning to mill facility delivery based on a 15 km transport lead distance including the effect of yield losses compounded through the cropping cycle

In the chapter that follows, the results of the field trials and economics studies are discussed and conclusions drawn from the studies conducted. A recommendation containing future research and furthering or enhancement of the current work conclude this dissertation.

10. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Compaction has been understood to cause adverse field conditions for crop growth. Research trials on this topic have changed over time to include distinguishing between traffic over the inter-row (resulting in soil compaction) and traffic over the row (resulting in stool damage) of the sugarcane crop. High variances in yield response to treatments have led to broad recommendations and vague estimates of crop response. Much of the variance is due to complex soil properties, compaction treatment and crop response interactions. Soil water content alone has a significant influence and can be variable and dynamic in both the short and long term, as well as spatially within a field. The impact of systems on long term sustainability and yield is often questioned, but little data are available to validate or alleviate these concerns.

High amounts of infield traffic typically occur during the harvesting, loading and extraction of agricultural commodities under commercial operations. This is of particular interest where high biomass yields are removed from the fields as is the case for sugarcane. Mechanisation systems used to remove the crop are likely to cause crop yield losses as a result of infield traffic. Traffic induced crop losses are expected to compound into successive ratoons in conjunction with subsequent traffic induced losses. This study was conducted to develop yield loss estimates based on a range of typical harvesting operations in South Africa. This work is important to provide an understanding of potential yield loss risks that are associated with infield traffic and to provide a means to quantify and compare a variety of typical mechanisation systems that are found in the South African sugarcane industry.

Quantification of traffic induced yield loss at a particular point of impact within a field was derived from a synthesis of local and international literature, where differentiation was made between row and inter-row traffic position. Typical systems used infield for sugarcane harvesting and extraction operations within the South African industry were reviewed. Field studies were conducted to measure and quantify the location and distribution of infield traffic to determine a field scale productivity loss for different systems. This allows for systems to be compared against each other.

An economics analysis was conducted to complete the study to show the mechanisation cost component and the additional yield loss cost comparisons for each of the systems. This work provides a holistic framework and new approach to costing of infield sugarcane mechanisation systems into the future. Researchers have been attempting to present this without success. This has now been achieved. This work shows that that current machinery costing techniques are not adequate and that the impact of infield traffic systems needs to be considered.

10.1 Discussion and Conclusions

The purpose of this study was to address the impact of loading systems, which are common to South Africa, on long-term sustainable production. Both the desktop literature study findings and subsequent field work results are discussed.

The synthesis of crop yield responses to compaction treatments has provided a means to improve yield response estimates to infield traffic and yield response trends that dominate these complex interactions. These include the quantification of typical yield responses to row and inter-row traffic for all treatments. The analysis of yield responses to infield traffic indicated significant susceptibility of the crop to row traffic compared to inter-row traffic treatments. The impact of traffic at high soil moisture on yields was expected. Further aggregation of the data was useful in providing yield response trends. Aggregation by soil texture (based on clay content) and vehicle characteristics were developed. Although not statistically significant, these trends indicate a number of interesting responses. Generally, as traffic intensity is increased, yields correspondingly decrease. Yields seem to be the least affected by inter-row traffic under dry conditions for high clay soils even over a range of traffic intensities. Row traffic under moist conditions seems to be the least resilient with large yield losses even at low traffic intensities. The variation in yields at low axle weights and tyre pressures is large and unpredictable. The yield response trends suggest that high clay soils will respond the best to control traffic practices under wet field conditions. Lower clay soils are generally highly susceptible to infield traffic and should be best managed by minimising overall compaction through the use of light equipment and by minimising infield traffic as far as practically and economically viable. An example of achieving this could be by placing cane stockpiles adjacent to the field edge to minimise infield traffic operations.

The cut and stack system (A_1 and A_2) is a well-established system that is widely practiced and especially suitable for the steeper slopes of the industry. It has the advantage of low amounts of infield traffic by virtue that the loading and extraction operations are combined. The tractor trailer combinations are relatively light weight, durable and low maintenance. Disadvantages of the system are the higher labour requirement to form stacks infield and the low capacity of trailers that would therefore require higher traffic volumes infield. Results from the field studies indicate that the system of self-loading trailers had the least amounts of traffic in the field. The operations did not practice controlled traffic principles and with some effort in training staff and drivers, further gains in reducing the field impact could be made. This would require that stacks were aligned during preparation, that tractor trailer and row spacing's are matched and where traffic are constrained to travel along predetermined infield extraction routes through the cane field, both in the current and successive ratoon cycles. The cut and stack system does require numerous operational considerations but does provides an effective low impact, low yield loss system that is generally cost effective and suitable for a wide range of slopes and scale of operations.

The majority of the sugarcane crop in South Africa is cut and windrowed and then mechanically loaded infield. A general advantage of typical systems used in South Africa is the low amount of infield traffic compared to fully mechanised systems that need to harvest each row in a field. The predominant means of loading is through the use of non-slew loaders (A_3, B, C and G). These loaders are a popular choice of equipment because they are productive, robust and relatively cost effective. By not being able to slew, these loaders do however incur much wheel traffic over the sugarcane rows during loading operations. Controlled traffic farming recommendations as promoted in literature, as a means to sustain yields within highly mechanised systems, cannot therefore be practiced. Increasing the capacity of windrows by increasing the number of rows to make an individual windrow may be used as a means to reduce infield traffic, but the cost and benefit of this practice was not examined in this study. Very little data on the impact of non-slewing loaders on yield are available. From the literature collated, it appears that the yield impact of the cut and windrow system using non-slewing loaders may be low and comparable to other systems under suitable field conditions, but are likely to be severe under unsuitable field conditions due to the high amounts of uncontrolled traffic in the field. Furthermore, the effects of wheel slip and associated smearing at the soil surface under adverse field conditions, and the impact of the rear jockey wheel have not been taken into account in these analyses. The extent and impact of multiple passes, as would be particularly applicable to non-slew loaders by virtue of their infield manoeuvrings, were also not derived or taken into account in the yield loss estimates reported in this study. The results indicated that by virtue of the high level of traffic of the non-slewing loader the risk of high yield losses when operated under unfavourable conditions may be severe. Assuming that the loaders are less damaging than heavier equipment, systems making use of the non-slew loaders still appear to be worse than many of the other systems. This would be further exacerbated through smearing damage caused by wheel slip, the impact of the jockey wheel and where multiple wheel passes occur over the same position in the field. The inability of the loader to be able to practice controlled traffic principles during loading or through to subsequent ratoons increases the risk for further damage particularly when field conditions are not suitable for infield traffic. The estimated field productivity yield losses still appear to be less than those reported in other industries also employing semi-mechanical operations, such as Columbia, although those industries are reported to have severe field conditions for longer periods of the cane harvesting season. The hypothesis that high yield differences are attributed to systems of high levels of uncontrolled traffic did seem evident from the results obtained, however, of primary importance was to examine systems in their entirety, namely the combination of extent, position and impact of the equipment. The yield loss estimates, when comparing different windrow gathering practices for the non-slew loader although not conclusive, did seem to suggest that the use of smaller infield trailers and fetching from fewer windrows appeared better from a yield loss perspective, but not necessarily from a system costing perspective. From a yield loss aspect, it would be recommended that infield trailers follow consistent traffic paths for multiple windrow passes. It appeared that practices should be determined and matched to the choice of extraction vehicle. Gathering individual windrows adjacent to low capacity trailers appeared advantageous in reduced impact compared to the practice of gathering multiple windrows into high capacity trailers. It would not be recommended, for example, that individual windrows be loaded into adjacent high capacity trailers. There is a trade-off between loader and extraction vehicle traffic, where the heavier the extraction equipment, the more ‘tolerable’ it is for loader traffic to fetch cane from a further distance away from the extraction vehicle. This would be less applicable if heavy infield extraction equipment were constrained to dedicated infield traffic paths and controlled traffic principles applied. In all cases, there was evidence that field compaction and cane stool damage could have been reduced by simply restraining extraction vehicles (particularly repeat passes) to dedicated extraction routes through the field. These routes should ideally also be used repeatedly for future harvesting cycles. Cut and windrow systems involving direct haulage operations (C and G) generally appear cost competitive for smaller scale operations but less suited for larger scale operations after taking anticipated yield losses into account.

Cut and windrow operations using high cost slewing type loaders (D and F) are typically found in larger operations. Their higher productivity requires large throughput to ensure high utilization to make them suitably cost effective. The larger slew loader and heavy infield trailers (D) despite being operated under controlled traffic showed high yield losses compared to other perceived lower impact systems not practicing controlled traffic. Had this system not practiced controlled traffic then the yield losses would have been anticipated to be much greater. This particular controlled traffic system showed room for improvement through better matching of traffic wheel tracks to dedicated inter-row traffic lanes. The lower impact slew loading system (F) also operating under controlled traffic principles performed much better. This system had a smaller slew loader and small infield tractor trailers extracting the cane to a trans-loading zone. The wheel tracks were well matched to the inter-row spacing of the field. This system, particularly for larger operation sizes, was shown to be both cost effective and relatively low impact through the practice of controlled traffic principles. This should provide reassurance to larger farmers or estates investigating the adoption of control traffic systems, that low yield losses are possible for larger commercial operations. This is possible through the choice of low impact equipment combined with appropriate field configurations and strict adherence to controlled traffic principles. The general yield loss estimates on a field basis under moist field conditions ranged from 1.6% to 3.3 % for the smaller slew loading system to 2.9 % to 5.1 % for the larger slew loading system. These seem to be conservatively lower compared to CT studies conducted in Columbia, by Torres and Pantoja (2005), where the yield losses were measured on a field basis for traffic consisting of slew loader and infield tractor-trailers under wet field conditions for a clay loam soil at 7.4 %.

From the analyses conducted, mechanical harvesting using chopper harvesters (E) seem to have both severe impact and poor economic viability despite the practicing of controlled traffic principles. The larger contributor to the high yield loss estimate was attributed to the low capacity infield trailers that had severe impact through poor weight transfer characteristics. This highlights the need to consider vehicle design characteristics. The combination of high operational costs, particularly attributed to underutilization of the mechanical harvester, and high yield loss estimates caused the mechanical harvesting system to perform poorly compared to any of the other systems. These factors may partially account for the higher estimated yield loss range of between 3.7 % and 8.5 % when compared to CT studies conducted in Columbia, by Torres and Pantoja (2005), where the tracked harvester and infield haulage system resulted in a 4.6 % yield loss. Yang (1977), however, measured an 8 % relative yield loss when comparing a 2 pass mechanical harvesting operation on high clay soils against a comparable adjacent hand cut field operation consisting of no infield traffic. Robotham (2003) also detailed a 12 % yield loss due to infield cane harvester traffic. Trouse Jr and Humbert (1961) showed an average field yield loss of 32 % over 2 mechanised harvests compared to hand cut fields. Given the range of results, the yield loss estimates seem to be reasonable compared against actual field losses measured in practice.

Variations of accompanying infield haulage for crop extraction range from small tractor-trailers to large capacity road haulage vehicles. The choice and selection of haulage vehicle depends greatly on costs, productivity and utilization of equipment. The risks of higher yield losses appear greater as the capacity and gross mass of the equipment increases. This is however offset by the reduced number of trips required infield. Lower impact, lower capacity vehicles require more trips infield. Dedicated extraction routes constraining infield traffic to the inter-rows should be considered especially when fields are likely to be trafficked under high soil moisture conditions. The design of particular equipment has a large influence on the axle loading when weight transfer is considered. In the case of the self-loading and tip trailers, the axles are typically located at the rear of the trailers resulting in the load being transferred onto the rear axle of the tractor unit. In the case of loaders, high axle loads are placed the front axle, exacerbated during push-piling and loading operations. In many cases the load was not evenly distributed across the axles of the equipment. This may be an area where considerable improvements can be made to lower the axle loads and resulting impact ratings of the equipment.

A primary outcome was to confirm that infield traffic should be constrained to the inter-rows to minimise the loss of potential yield. It should also be noted that row traffic on a perennial sugarcane crop would likely result in a compounding loss of yield into subsequent ratoons. These results strongly support the recommendation of control traffic practices. From a timing perspective, infield traffic should be managed to periods of lowest soil moisture content where practically possible.

The positioning of cane stockpiles (stacks or windrows) is important to ensure that loading and extraction vehicles are able to abide to control traffic principles where possible. These should ideally be placed in the same position year on year and aligned and positioned to minimise as much infield traffic as possible and to minimise unnecessary row traffic.

The combination of equipment and the management of the equipment infield should be carefully considered. Dedicated extraction paths (controlled traffic routes) are recommended particularly for high clay soils trafficked frequently under moist soil conditions. Lower clay soils appear to be susceptible to both soil compaction and stool damage under high soil moisture conditions and thus infield traffic should be minimised during these times where possible. Adoption of controlled traffic practices may require changes to be made to either the wheel track spacing of equipment (to allow for all axle groups of all equipment to match the same wheel track paths corresponding to the crop inter-rows) and/or to change the crop row spacing to widen the inter-row areas where traffic is anticipated. Dedicated routes should be used for repeated or multiple passes of extraction vehicles. These routes should remain in the same position from season to season to thereby minimise and constrain compaction and stool damage to a minimum within a field.

The use of high accuracy Global Navigation Satellite System (GNSS) steering would help to ensure that controlled traffic practices are adhered to especially if field conditions or field practices make the inter-rows difficult to see by drivers during infield operations, or where the inter-row wheel traffic area is narrow and difficult to keep to. The construction of slightly raised crop production areas or cropping beds and alternative widened inter-row traffic lanes matched to equipment wheel tracks can also be used to assist drivers to keep wheel traffic away from the crop rows where GNSS systems are not used.

The hypothesis that large differences in estimated yield losses would be found between the various systems typically used in South Africa was validated. The hypothesis that the highest losses would be attributed to systems containing the largest amount of uncontrolled traffic was generally correct if one excludes the mechanical harvester (E) that had higher impact equipment and high amounts of infield traffic despite practicing CT. The findings highlight the need to consider systems in their entirety, namely the combination of extent, position and impact of the equipment. From the field studies, the cut and stack system with single stack self-loading trailers (A_1 and A_2) had the lowest impact on yields despite not practicing controlled traffic. This was due to the low amounts of infield traffic and that the equipment is relatively low in mass. Good harvesting practices as mentioned above and the adoption of control traffic principles may further enhance the cut and stack system in general. Improvements within the cut and windrow systems (A_3, B, C, D, F and G) to reduce yield losses can be achieved through widening the swath between windrows. The benefits would however need to be offset against the costs of doing so. Improvements relating to management of the cut and windrow systems with slewing loaders (D and F) is possible through the use of lower impact slewing loaders operating strictly under controlled traffic principles. Improvements in the cut and windrow systems employing non-slew loaders (A_3, B and C) would be primarily governed by the choice of extraction equipment. The results indicated that the cut and windrow systems using non-slew loaders were the most variable and generally the highest impact systems. The non-slew loader collecting from multiple windrows into high capacity trailers (C) have greater impact compared to loading light low capacity trailers from a single windrow (B). The impact of multiple passes over the same area, the impact of smearing or jockey wheel traffic by the non-slew loader was not taken into account. The principle of confining multiple extraction paths to similar routes for the extraction trailers would have reduced the yield impact from the low capacity trailer study (B). Despite such improvements, it is not possible for the non-slew loader to practice control traffic principles. The compounding impact of traffic induced stool damage into successive ratoon yields is further reason to promote controlled traffic principles. This is particularly applicable for high impact vehicles entering the field.

10.2 Recommendations

A simple spreadsheet decision support programme was developed to model existing knowledge and to cater for specific vehicle characteristics, soils and soil moisture condition scenarios. There were a number of gaps that were evident from the literature study, yield response database and associated modelling. Such research would enhance understanding in this field of work. Gaps and recommendations for future research include trials to determine the yield response of row and inter-row traffic treatments on low clay soils under dry conditions and row traffic treatments for high clay soils under dry conditions. It is expected that these yield responses will be minimal however, as traffic induced yield loss under drier conditions tend to be far less than under moist or wet soil moisture conditions. Such trials would improve the modelling of yield responses to infield traffic and better quantify expected losses. Minimal data are available to determine the sugarcane yield response to soil surface smearing caused by infield equipment. Such events are more prevalent in particular equipment systems and aggravated by poor driver behaviour. The existing perceptions are based on field observances and anecdotal evidence with no research data conducted to substantiate. Ideally, future traffic induced, soil compaction and yield loss studies should include detailed traits such as:

- Crop information: Crop yield, field layout, crop row and inter-row spacing's, specific management conditions (e.g. irrigated/dryland, burnt/green), ratoon, varieties;
- Soil information: Soil constituents, clay content, soil moisture content, clay type; organic matter content, bulk density (pre and post treatment), water infiltration rates (pre and post treatment), soil depth, effective rooting depth;
- Mechanisation and transport: Machinery and equipment or compaction treatment scenarios, position of tyres/wheel tracks relative to the crop, axle masses (empty and laden or treatment condition), tyre inflation pressures, number of wheel passes, track width, tyre type, tyre size, tyre width;
- General observances: Comparative crop regrowth and vigour, growing season conditions.

Taking a critical look at the field work component of the study, it is possible to improve the surveying component for future trials, particularly as access to multiple high accuracy GNSS receivers (sub 30 cm accuracy) become more readily available and as their costs reduce. Possible studies include the fitting of GNSS receivers above all wheels of all vehicles entering a field to map the entire loading and transport operations. Complimenting GNSS logging with other infield measurements such as equipment load cells data to provide maps indicating the spatial variability of loading across the field and thus estimate the yield impact variability and yield losses at a spatial level.

The field survey component of the study gave an overview of six typical operations to cover a range of equipment and practices that exist in practice. These surveys were conducted for particular harvesting methods on the row spacing's for that particular operation. Scope exists for further analysis of the data gathered from the study, such as:

- Estimating the severity of yield loss caused at portions of the field such as the headlands of fields where widespread compaction and stool damage is likely due to off tracking of long tractor-trailer configurations with multiple trailers. This would provide a useful economic value against which to justify whether remedial actions or resources would be warranted.
- To repeat the analyses on a 'better managed' scenario for each of the systems where row traffic is minimised and traffic confined to the inter-rows for systems where this is possible. This allows the value that is available for the adoption of a particular technology such as GNSS steering or for field layout and configuration changes, for example, to be determined.
- Further GIS analysis of the field surveys to examine the magnitude and extent of multiple passes by different equipment, distinguishing between areas of the field containing 2, 3 or more passes per equipment type.
- To investigate system hybridization using alternative combinations of loaders and extraction vehicles. This would require the examination of the field maps and typical extraction patterns to guide the estimation of row and inter-row traffic extents and position in order to determine an estimated yield loss for the defined system.

A useful economics study would be to determine the cost of employing manual labourers to increasing windrow widths (during or subsequent to harvesting), thereby constraining the infield traffic to more confined swaths through the field.

In general, the surveys performed in this study do not cater for within system variations but do provided detailed equipment traffic movement patterns for a particular operation. System variations that occur in practice include: alternative row spacing configurations, sugarcane yields, sugarcane densities, cane stockpile positions and alignment, loading techniques, driver behaviour patterns or combinations of the aforementioned items. Further enhancement to the current work may be to investigate and develop modelling tools and/or simulations to account for such system alternatives. Such modelling would build upon the data from the existing surveys and traffic patterns for particular equipment. The modelling output would need to provide estimates of row, inter-row and no traffic areas as a percentage of field area for yield loss comparisons for alternative practices. The use of the time and motion and performance studies may be used to model anticipated equipment operating times and equipment performance could be used to adapt economic machinery costing comparisons for each system. Thus, a holistic costing approach including both machinery costings and crop yield loss estimates could be integrated for overall machinery cost comparisons for a range of scenarios. Further modelling and simulation studies may be ideally suited to support this current study.

The work conducted in this study has resulted in the development of yield loss estimation models and an accompanying costing framework that considers base economic costs of systems and additional yield loss impact cost components. Such work allows for numerous additional costing and break-even analyses to be conducted. The yield loss models consist of a detailed yield estimation model that considers case specific inputs pertaining to vehicle parameters, soil type, number of passes and soil moisture status and a generalised model developed for higher level analyses and system comparisons that takes vehicle impact ratings and generalised yield responses into account. The framework to quantify seasonal periods of high risk where field conditions are more susceptible to yield loss has been reported and can be customised for areas within the industry. The compounding effect of infield traffic impacts through into successive ratoons has been investigated to allow for various analyses to be conducted.

This dissertation has fully achieved the stated objectives of the study by:

a) Reviewing the typical complement of equipment and systems used infield for sugarcane harvesting and extraction operations within the South African industry.
b) Reviewing techniques, practices and systems that are being developed and promoted locally and internationally to minimise the impact of infield traffic.
c) Derived infield traffic induced sugarcane yield loss estimation models based on collated and synthesised local and international literature.

d) Determined through field investigations, the extent and severity of infield traffic across a range of sugarcane harvesting and extraction systems typically found in the South African sugarcane industry.
e) Provided a set of results and the framework to conduct overall cost comparisons between typical systems used in the South African sugarcane industry taking the cost of mechanisation and the cost of associated yield loss estimates into account.

The application of this work is not only essential in the identification of overall and system costs for comparing existing systems but also for future strategic analyses. Determining the impact of adopting green cane harvesting systems or determining cost benefit analyses for effective infield biomass recovery systems for electricity cogeneration are two examples of where this work would provide significant value to the sugar industry.

11. REFERENCES

Anon. 1985. *SASIAA field report 1573*. South African Sugar Industry Agronomists Association, South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Anon. 1998. *SASIAA field report 4200/18*. South African Sugar Industry Agronomists Association, South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Anon. 2005. *South African Sugarcane Research Institute Progress Report 2004/2005*. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Anon. 2016a. *South African Sugar Industry Directory 2016/2017*. External Affairs Division, South African Sugar Association, Mount Edgecombe, South Africa.

Anon. 2016b. *South African Sugarcane Research Institute Mechanisation Report No. 1 & No. 2*. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Arvidsson, J and Håkansson, I. 1991. A model for estimating crop yield losses caused by soil compaction. *Soil and Tillage Research* 20 (2): 319-332.

Bezuidenhout, C and Meyer, E. 2005. A decision support tool for upgrading farm roads, locating loading zones and establishing cane extraction profiles. *Proceedings of the South African Sugar Technologists' Association*, 79: 394-401. SASTA, Durban, South Africa.

Bezuidenhout, C, Schulze, R, Marx, B, Maharaj, M, Hull, P and Lyne, P. 2006. An approach towards the derivation of a reference traffic season for sugarcane in South Africa to manage soil compaction. *Proceedings of the South African Sugar Technologists' Association*, 80: 108-111. SASTA, Durban, South Africa.

Boyce, J. 1968. Plant crop results of a row spacing experiment at Pongola. *Proceedings of the South African Sugar Technologists' Association*, 42: 136-142. SASTA, Durban, South Africa.

Braithwaite, P. 2013. Harvesting and haulage. In: eds. Meyer, J, Rein, P, Turner, P and Mathias, K, *Good management practices for the cane sugar industry*. Ch. 11, 355-374. Verlag Dr. Albert Bartens KG, Berlin, Germany.

Braunack, M. 1995. In-field traffic position affects yield. *BSES Bulletin* 51: 3-4. BSES, Brisbane, Australia.

Braunack, M. 1997. The effect of soil physical properties on growth and yield on sugarcane. *Sugarcane* 2: 4-12.

Braunack, M, Arvidsson, J and Håkansson, I. 2006. Effect of harvest traffic position on soil conditions and sugarcane (*Saccharum officinarum*) response to environmental conditions in Queensland, Australia. *Soil and Tillage Research* 89 (1): 103-121.

Braunack, M and Hurney, A. 2000. The position of harvesting traffic does affect yield. *Proceedings of the Australian Society of Sugar Cane Technologists*, 22: 126-132. PK Editorial Services, Bundaberg, Queensland, Australia.

Braunack, M and McGarry, D. 2006. Traffic control and tillage strategies for harvesting and planting of sugarcane (*Saccharum officinarum*) in Australia. *Soil and Tillage Research* 89 (1): 86-102.

Braunack, M and Peatey, T. 1999. Changes in soil physical properties after one pass of a sugarcane haulout unit. *Animal Production Science* 39 (6): 733-742.

Braunack, M, Wood, A, Dick, R and Gilmour, J. 1993. The extent of soil compaction in sugarcane soils and a technique to minimize it. *Sugar cane* 5: 12-18.

Bull, T and Bull, J. 2000. High density planting as an economic production strategy:(a) overview and potential benefits. *Proceedings of the Australian Society of Sugar Cane Technologists*, 9-15. PK Editorial Services, Bundaberg, Queensland, Australia.

Carter, L. 1985. Wheel traffic is costly. *Transactions of the ASAE-American Society of Agricultural Engineers* 28 (2): 430-434.

Cleasby, T. 1964. Symposium on soil compaction. *Proceedings of the South African Sugar Technologists' Association*, 38: 144-153. SASTA, Durban, South Africa.

De Beer, A. 1989. The findings of the sectional committee on mechanical harvesting and handling of sugarcane. *Proceedings of the XX Congress of the International Society of Sugar Cane Technologists*, 2: XLII - L. ISSCT, Sao Paulo, Brazil.

De Beer, A, Hudson, J, Meyer, E and Torres, J. 1993. Cost effective mechanization. *Sugar Cane* 4: 11-16.

De Paula, V and Molin, J. 2013. Assessing damage caused by accidental vehicle traffic on sugarcane ratoon. *Applied Engineering in Agriculture* 29 (2): 161-169.

Dinardo-Miranda, LL, de Vasconcellos, ACM and de Andrade Landell, MG. 2008. *Cana-de-açúcar*. Instituto Agronômico, Ribeirão Preto, São Paulo, Brazil.

Fernandes, J, Ripoli, T and Millan, M. 1983. A compactação do solo ea brotação das soqueiras. *Álcool & Açúcar* 3 (12): 12-17.

Garside, A, Bell, M, Robotham, B, Magarey, R and Stirling, G. 2005. Managing yield decline in sugarcane cropping systems. *International Sugar Journal* 107 (1273): 16-26.

Georges, J, Lopez, M and Madrazo, C. 1980. Effects of harvest traffic and soil water content on soil compaction and regrowth of sugar cane. *Proceedings of the XII Congress of the International Society of Sugar Cane Technologists*, 1: 1078-1089. ISSCT, Manilla, Philippines.

Georges, J, Mohammed, M and Harvey, W. 1985. Effects on soil water content and compactive effort on soil compaction and sugar cane regrowth. *Proceedings of the West Indies Sugar Technologists Conference*, 23: 635-640. Trinidad and Tobago, West Indies.

Hassuani, S, da Silva, J and Neves, J. 2005. Sugarcane trash recovery alternatives for power generation. *Proceedings of the XXV Congress of the International Society of Sugar Cane Technologists,* 2: 394-402. Guatemalan Association of Sugarcane Technologists, ATAGUA and the Guatemalan Sugarcane Research and Training Center, CENGICANA, Guatemala City, Guatemala.

Henry, P and Ellis, R. 1996. Soil as a factor in sugarcane ratoon yield decline on an irrigated estate in Swaziland. *Proceedings of the XXII Congress of the International Society of Sugar Cane Technologists*, 2: 84-91. ISSCT, Carthagena, Colombia.

Hoekstra, R. 1976. Analysis of when to plough out a sugarcane field. *Proceedings of the South African Sugar Technologists' Association*, 50: 103-113. SASTA, Durban, South Africa.

Ismael, F, Seeruttun, S, Barbe, C and Gaungoo, A. 2007. Improving cane productivity with dual row planting in Mauritius. *Proceedings of the XXVI Congress of the International Society of Sugar Cane Technologists*, 220-228. ISSCT, Durban, South Africa.

Jackson, P, Braunack, M, Foreman, J and Peatey, T. 2000. Genetic variation in sugarcane for ratooning after harvester damage in wet soil. *Euphytica* 111 (1): 1-8.

Johnston, M and Wood, R. 1971. Soil compaction studies at Pongola. *Proceedings of the South African Sugar Technologists' Association*, 45: 261-265. SASTA, Durban, South Africa.

Kanali, C, Kaumbutho, P, Maende, C and Kamau, J. 1996. Establishment of safe axle loads for sugarcane soils under varying moisture content. *Journal of Terramechanics* 33 (2): 81-90.

Khandagave, R, Hapase, D and Somaiya, S. 2005. Maximisation of sugarcane yields and reduction of production costs- a participatory rural appraisal. *Proceedings of the XXV Congress of the International Society of Sugar Cane Technologists*, 2: 154-159. Guatemalan Association of Sugarcane Technologists, ATAGUA and the Guatemalan Sugarcane Research and Training Center, CENGICANA, Guatemala City, Guatemala.

Kingwell, R and Fuchsbichler, A. 2011. The whole-farm benefits of controlled traffic farming: An Australian appraisal. *Agricultural Systems* 104 (7): 513-521.

Klomsa-Ard, T, Prasantree, C, Jomsri, S, Tenglolai, A, Prammanee, P and Weerathaworn, P. 2007. Dual row planting-a system to increase Thai farmers' cane yield and economic returns. *Proceedings of the XXVI Congress of the International Society of Sugar Cane Technologists,* 298-301. ISSCT, Durban, South Africa.

Langton, M, Harding, T and Lyne, P. 2008. Preliminary results of the Canethumper® operating on the lower south coast of South Africa. *Proceedings of the South African Sugar Technologists' Association*, 81: 402-407. SASTA, Durban, South Africa.

Langton, M, Smithers, J, Bezuidenhout, C and Lyne, P. 2006. Evaluation of the Illovo mechanical cane cutter. *Proceedings of the South African Sugar Technologists' Association*, 80: 100-103. SASTA, Durban, South Africa.

Lecler, N. 2015. A synergetic system to produce sugarcane using surface irrigation. *Proceedings of the South African Sugar Technologists' Association*, 88: 387-391. SASTA, Durban, South Africa.

Lecler, N and Tweddle, P. 2010. Double profits with a controlled traffic zero-till irrigation farming system? *Proceedings of the South African Sugar Technologists' Association*, 83: 46-62. SASTA, Durban, South Africa.

Marx, B, Bezuidenhout, C, Lyne, P and Van Antwerpen, R. 2006. Soil compaction decision support. *Proceedings of the South African Sugar Technologists' Association*, 80: 104-107. SASTA, Durban, South Africa.

Maud, R. 1960. The compaction of sugar-belt soils at various moisture levels. *Proceedings of the South African Sugar Technologists' Association*, 34: 154-156. SASTA, Durban, South Africa.

McElligott, D, Van Antwerpen, R and Ducasse, G. 2014. An extension specialist's yield and gross revenue database, used to guide recommendations and improve grower profitability. *Proceedings of the South African Sugar Technologists' Association*, 87: 372-393. SASTA, Pietermaritzburg, South Africa.

McGarry, D, Braunack, M, Cunningham, G, Halpin, N, Sailaway, M and Waters, D. 1997. Comparison of soil physical properties of row and inter-row: a basis for control traffic in cane. *Proceedings of the Australian Society of Sugar Cane Technologists*, 19: 263-269. Watson Ferguson and Company, Cairns, Queensland, Australia.

Mendoza, T, Samson, R and Elepano, A. 2002. Renewable biomass fuel as 'green power' alternative for sugarcane milling in the Philippines. *Philippine Journal of Crop Science* 27 (3): 23-39.

Meyer, E. 1996a. A review of mechanised cane harvesting systems in Southern Africa. *Proceedings of the South African Sugar Technologists' Association*, 70: 77-84. SASTA, Durban, South Africa.

Meyer, E. 1999. Some measurements of mechanical sugarcane harvester performance. *Proceedings of the South African Sugar Technologists' Association*, 73: 16-19. SASTA, Durban, South Africa.

Meyer, E. 2000. *Machinery management, performance and utilization*. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Meyer, E. 2005. *Machinery systems for sugarcane production in South Africa*. MScEng Seminar, School of Bioresources Engineering and Environmental Hydrology, University of kwaZulu-Natal, Pietermaritzburg, South Africa.

Meyer, E. 2006. *Agricultural machinery costing methods and standards*. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Meyer, E and Fenwick, L. 2003. Manual sugarcane cutter performances in the southern African region. *Proceedings of the South African Sugar Technologists' Association*, 77: 150-157. SASTA, Durban, South Africa.

Meyer, E, Jacquin, E, Norris, C, Richard, C and Scandaliaris, J. 2004. *Agricultural machinery costing method and standard protocol*. International Society of Sugar Cane Technologists.

Meyer, E, Norris, C, Jacquin, E, Richard, C and Scandaliaris, J. 2001. Infield loading, transloading, transport and mill receiving facilities. *Proceedings of the XXIV Congress of the International Society of Sugar Cane Technologists*, 2: 224-229. Australian Society of Sugar Cane Technologists, Brisbane, Australia.

Meyer, E, Norris, C, Jacquin, E, Richard, C and Scandaliaris, J. 2005. Burnt versus green cane harvesting: Agricultural engineering challenges. *International Sugar Journal* 107 (1281): 506-513.

Meyer, E, Singh, V and Kumar, V. 1999. Issues to consider when implementing a mechanical harvesting system. *Proceedings of the XXIII Congress of the International Society of Sugar Cane Technologists*, 2: 147-154. Sugar Technologists' Association of India, New Delhi, India.

Meyer, J. 1996b. Soil management research for sustainable ratoon cane production in the South African sugar industry. *Proceedings of the XXII Congress of the International Society of Sugar Cane Technologists*, 2:14-21. ISSCT, Carthagena, Colombia.

Meyer, J, Hobson, P and Schultmann, F. 2012. The potential for centralised second generation hydrocarbons and ethanol production in the Australian sugar industry. *Proceedings of the Australian Society of Sugar Cane Technologists*, 34: 12p. Cairns, Australia.

Meyer, J, Van Antwerpen, R and Meyer, E. 1996. A review of soil degradation and management research under intensive sugarcane cropping. *Proceedings of the South African Sugar Technologists' Association*, 70: 22-28. SASTA, Durban, South Africa.

Mthembu, I. 2011. *Mapping land suitability for mechanized harvesting in cane growing areas, South Africa*. SASRI internal project report: 07RE06. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Murray, J. 2009. A regional analysis of labour trends in the South African sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 82: 58-66. SASTA, Durban, South Africa.

Murray, J and van Walbeek, C. 2007. Impact of the sectoral determination for farm workers on the South African sugar industry: Case study of the KwaZulu-Natal north and south coasts. *Agrekon* 46 (1): 94-112.

Murray, T and Meyer, E. 1982. Time study as a method for measuring machinery performance. *Proceedings of the South African Sugar Technologists' Association*, 56: 153-156. SASTA, Durban, South Africa.

Norris, C, Robotham, B and Bull, T. 2000. High density planting as an economic production strategy:(c) a farming system and equipment requirements. *Proceedings of the Australian Society of Sugar Cane Technologists*, 113-118. PK Editorial Services, Bundaberg, Queensland, Australia.

Olivier, F and Singels, A. 2003. Water use efficiency of irrigated sugarcane as affected by row spacing and variety. *Proceedings of the South African Sugar Technologists' Association*, 77: 347-351. SASTA, Durban, South Africa.

Pankhurst, C, Magarey, R, Stirling, G, Blair, B, Bell, M and Garside, A. 2003. Management practices to improve soil health and reduce the effects of detrimental soil biota associated with yield decline of sugarcane in Queensland, Australia. *Soil and Tillage Research* 72 (2): 125-137.

Pearce, B. 2009a. Personal communication, South African Cane Growers Association, Eston, South Africa, 23 September 2009.

Pearce, B. 2009b. SuSFarMS^{TM} The Cost Benefit Question. *The Cane Grower* 16:2, 1-4. SACGA, Mount Edgecombe, South Africa.

Pinto, A and Bellinaso, I. 2000. Chopped sugarcane harvesting: Equipment traffic studies and effects on yields. *Proceedings of the International Society of Sugar Cane Technologists Agricultural Engineering Workshop*, 75-81. ISSCT, Malelane, South Africa.

Rees, B, Smithers, J, Lyne, P and Van Antwerpen, R. 2014. Sugarcane trash recovery systems for cogeneration. *Proceedings of the South African Sugar Technologists' Association*, 87: 478-481. SASTA, Durban, South Africa.

Robotham, B. 2003. Why the Australian sugar industry must adopt controlled traffic and minimum tillage. *BSES Bulletin* 82: 14-16. BSES, Brisbane, Australia.

Singels, A. 2007. A new approach to implementing computer-based decision support for sugarcane farmers and extension staff: the case of *My Canesim*. *Proceedings of the XXVI Congress of the International Society of Sugar Cane Technologists*, 211-219. ISSCT, Durban, South Africa.

Singels, A. 2013. Personal communication, South African Sugarcane Research Institute, Mount Edgecombe, South Africa, 20 September 2013.

Singels, A and Smit, M. 2002. The effect of row spacing on an irrigated plant crop of sugarcane variety NCo376. *Proceedings of the South African Sugar Technologists' Association*, 76: 94-105. SASTA, Durban, South Africa.

Singels, A and Smit, M. 2009. Sugarcane response to row spacing-induced competition for light. *Field Crops Research* 113 (2): 149-155.

Smithers, J. 2014. Review of sugarcane trash recovery systems for energy cogeneration in South Africa. *Renewable and Sustainable Energy Reviews* 32 (1): 915-925.

Srivastava, A. 1984. Soil compaction: a problem in sugarcane culture. *Indian Sugar* 34: 503-504.

Swinford, J and Boevey, T. 1984. The effects of soil compaction due to infield transport on ratoon cane yields and soil physical characteristics. *Proceedings of the South African Sugar Technologists' Association*, 58: 198-203. SASTA, Durban, South Africa.

Thompson, G and Du Toit, J. 1965. The effects of row spacing on sugarcane crops in Natal. *Proceedings of the XII Congress of the International Society of Sugar Cane Technologists*, 103-111. ISSCT, San Juan, Puerto Rico.

Torres, J and Pantoja, J. 2005. Soil compaction due to mechanical harvesting in wet soil. *Sugar Cane International* 23 (4): 16.

Torres, J and Rodrigues, L. 1995. Soil compaction management for sugarcane. *Proceedings of the XXII Congress of the International Society of Sugar Cane Technologists*, 7-15. ISSCT, Carthagena, Colombia.

Torres, J and Villegas, F. 1995. Differentiation of soil compaction and cane stool damage. *Proceedings of the XXI Congress of the International Society of Sugar Cane Technologists*, 2: 294-305. ISSCT, Bangkok, Thailand.

Torres, J, Villegas, F and Duran, A. 2010. Modified dual row planting system for green cane management in the tropics. *Proceedings of the XXVII Congress of the International Society of Sugar Cane Technologists*, 1-7. ISSCT, Veracruz, Mexico.

Torres, J, Yang, S and Villegas, F. 1990. Soil compaction and cane stool damage by semimechanized harvesting systems in the wet season. *Sugar Cane* 5: 12-16.

Trouse Jr, A. 1982. Effect of tillage and traffic on cane production in Hawaiian soils. *Proceedings of the Hawaiian Sugar Technologists Association*, 41: 77-79. Hawaii, USA.

Trouse Jr, A and Humbert, R. 1961. Some effects of soil compaction on the development of sugar cane roots. *Soil Science* 91 (3): 208-217.

Tullberg, J. 2010. Tillage, traffic and sustainability—a challenge for ISTRO. *Soil and Tillage Research* 111 (1): 26-32.

Tullberg, J, Yule, D and McGarry, D. 2003. "On track" to sustainable cropping systems in Australia. *Proceedings of the International Soil Tillage Research Organisation Conference*, 16: 14p. University of Queensland, Brisbane, Australia.

Turner, J, Mason, F and Willcox, T. 2004. The revolution of resource management in the Australian sugarcane industry. *Proceedings of the International Soil Conservation Organisation Conference*, 13: Paper 1021, 4p. ISCO, Brisbane, Australia.

Usaborisut, P and Niyamapa, T. 2010. Effects of machine-induced soil compaction on growth and yield of sugarcane. *American Journal of Agricultural and Biological Science* 5 (3): 269-273.

Van Antwerpen, R. 2007. *SASRI Information Sheet 14.4. Soil Compaction Management.* South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Van Antwerpen, R, Boote, D, Campbell, P, Jumman, A, Mhlaba, S, Searle, A, Wilkinson, D and Adendorff, M. 2013. *South African Sugarcane Research Institute Internal Travel Report: 11TD12 - Sugarcane Production Systems Aimed to Eliminate Stool Damage - Controlled Traffic Best Management Practice Tour to the Northern Irrigated Areas*. South African Sugarcane Research Institute, Mount Edgecombe, South Africa.

Van Antwerpen, R, Lyne, P, Meyer, E and Brouwers, M. 2008. Effect of surface applied pressure by vehicles fitted with pneumatic tyres on properties of a virgin soil. *Proceedings of the South African Sugar Technologists' Association*, 81: 408-417. SASTA, Durban, South Africa.

Van Antwerpen, R and Meyer, E. 2001. The effect of residue management and vehicle characteristics on soil compaction. *Proceedings of the South African Sugar Technologists' Association*, 75: 137-142. SASTA, Durban, South Africa.

Van Antwerpen, R, Meyer, J and Meyer, E. 2000. Soil compaction in the South African sugar industry-a review. *Proceedings of the South African Sugar Technologists' Association*, 74: 101-108. SASTA, Durban, South Africa.

Yang, S. 1977. Soil physical properties and the growth of ratoon cane as influenced by mechanical harvesting. *Proceedings of the XVI Congress of the International Society of Sugar Cane Technologists*, 835-847. ISSCT, Sao Paulo, Brazil.

12. APPENDIX A: SOUTHERN AFRICAN DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED IN SOUTHERN AFRICA: *

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
Anon (1985)	SA- Komatipoort	Shortlands 52%clay;13%silt	Trucks + Poclan loader-3R- IR	77% Significant
Cleasby (1964)	SA- Mt Edgecombe	28% clay; 15% silt	Tractor & trailer + 2½ tons cane	77% [TV]
Cleasby (1964)	SA- ? -Mr Chance	?	Multiple tractor passes	64%
Johnston and Wood (1971)	SA- Mt Edgecombe	?	? Compaction trial	78%
Johnston and Wood (1971)	SA- Tongaat	Windermere clay loam	?	91% NS- high variability
Johnston and Wood (1971)	SA- Chaka's Kraal	Waldene sandy clay loam	?	86% NS- site variability
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & trailer +5t R1: 2P-IR- wet	101% NS [T]
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & trailer +5t R1: 2P-IR- dry	103% NS [CT]
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & trailer +5t R2: 5P-IR- wet	97% NS [CT]
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & tr +5t R2: 5P-IR+R- wet	96% NS-early growth slow[CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R1–5 passes IR	86% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R1–7 passes R+IR	73% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R1–5 passes IR	79% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R1–7 passes R+IR	76% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R2–5 passes IR	74% Significant [CT]

* Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX A: SOUTHERN AFRICAN DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED IN SOUTHERN AFRICA: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R2–7 passes R+IR	59% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R2–5 passes IR	65% Significant [CT]
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R2–7 passes R+IR	53% Significant [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt; 2.9-3.4% OM	57t truck +dual radials - IR dry	99% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	57t truck +dual radials - IR moist	85% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	57t truck +dual radials - IR wet	92% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR dry	103% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR moist	88% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR wet	99% NS [CT]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tractor trailer+radials–IR dry	94% NS [T]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tr/tr +radials – IR moist	93% NS [T]
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tr/tr +radials – IR wet	95% NS [T]
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R2 - IR dry	102% NS [CT]
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R2- IR dry	103% NS [CT]

* Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX A: SOUTHERN AFRICAN DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED IN SOUTHERN AFRICA: *

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R2- IR wet	98% NS ^{CT}
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R2- IR wet	101% NS ^{CT}
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R3- IR dry	99% NS ^{CT}
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R3- IR dry	104% NS ^{CT}
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R3- IR wet	97% NS ^{CT}
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R3- IR wet	106% NS ^{CT}

* Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Create model (^{C}); Test model (^{T}); Validate model (^{M})

13. APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Bellinaso and Donzelli unpublished	Brazil	Clay	Tractor and 2×Trailers?	96%
Bellinaso and Donzelli unpublished	Brazil	Clay	Truck?	89%
Bellinaso and Donzelli unpublished	Brazil	Sand	Tractor and 2×Trailers?	98%
Bellinaso and Donzelli unpublished	Brazil	Sand	Truck?	95%
Braunack (1995)	Australia- Tully	?	4t tr/tr –R1- R vs IR	98% [TV]
Braunack (1995)	Australia- Tully	?	4t tr/tr -R2- R vs IR	92% [TV]
Braunack (1995)	Australia- Ingham	?	8t tr/tr –R1- R vs IR	86% [TV]
Braunack (1997) – Hurney 1975	Australia-?	?	Tr/tr+4t cane bin	96% NS
Braunack (1997) – Hurney 1975	Australia-?	?	Tr/tr+10t cane bin	105% NS
Braunack (1997) – Hurney 1975	Australia-?	?	Tr/tr+10t cane bin	109% NS
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R1- R vs Z	73% Significant [TV]
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R2- R vs Z	68% Significant [TV]
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R1+wet- R vs Z	60% Significant [TV]
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R2+wet- R vs Z	66% Significant [TV]
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R1 R vs IR	86% NS [T]

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R2 R vs IR	96% NS [T]
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R3 R vs IR	84% NS
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R4 R vs IR	100% NS
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R5 R vs IR	82% NS
Braunack and Hurney (2000)	Australia- Tully	Brown silty clay	Tr/tr+4t tip+HF tyres–R1 R vs IR	100% NS [T]
Braunack and Hurney (2000)	Australia- Tully	Brown silty clay	Tr/tr+4t tip+HF tyres–R2 R vs IR	91% NS
Braunack and Hurney (2000)	Australia- Tully	Brown silty clay	Tr/tr+4t tip+HF tyres–R3 R vs IR	91% Significant (Var: Q138)
Braunack and Hurney (2000)	Australia- Tully	Brown silty clay	Tr/tr+4t tip+HF tyres–R4 R vs IR	107% Significant (All)
Cleasby (1964)	Hawaii	?	Manual vs 2 Mechanical harvests	68% Significant
Cleasby (1964)	Hawaii	?	Manual vs 3 Mechanical harvests	42% Significant
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 2P –R vs Z	96% NS [CT]
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 4P –R vs Z	89% NS [CT]
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 9P –IR vs Z	97% NS [CT]
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 9P –R vs Z	86% NS [CT]
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 2P -R vs Z	93% NS [CT]

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 4P –R vs Z	84% NS; Significant RvsIR [CT]
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 9P –IR vs Z	114% NS; Significant IRvsR [CT]
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 9P –R vs Z	88% NS; Significant RvsIR [CT]
Dinardo-Miranda *et al.* (2008)	Brazil- ?	Red latosol- Clay	Manual harvest +infield haulage	73% [TV]
Dinardo-Miranda *et al.* (2008)	Brazil- ?	Red latosol- Clay	Harvester only	79%
Dinardo-Miranda *et al.* (2008)	Brazil- ?	Red latosol- Clay	Harvester +infield haulage	70%
Dinardo-Miranda *et al.* (2008)	Brazil- ?	Red latosol- Clay	Harvester +infield truck	64%
Georges *et al.* (1985)	W. Indies- Trinidad	Clay	Harvester (10t) + Tr/tr 10-15t	100% NS – Shrink swell Cl
Georges *et al.* (1985)	W. Indies- Trinidad	Silty clay loam	Harvester (10t) + Tr/tr 10-15t	100% NS – Shrink swell Cl
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	Tr/tr+ro/ro bin+1.5t – R1	74% Significant [TV]
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	Tr/tr+ro/ro bin+4t – R2	81% Significant
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	Tr/tr+ro/ro bin+1.5t – R1 + irrn.	75% Significant [TV]
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	Tr/tr+ro/ro bin+4t – R2 + irrn.	77% Significant
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	Tr/tr+ro/ro bin+1.5t – R1	66% Significant
Jackson *et al.* (2000)	Australia- Macknade	Alluvial soil	No treatment (R1 memory) – R2	76% Significant

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Maud (1960)	Hawaii	? reconditioned road	? reconditioned road	73% of uncompacted -
Maud (1960)	Hawaii	? reconditioned road	? reconditioned road	76% of uncompacted -
Norris *et al.* (2000)	Australia	Industry wide	?	80%
Pinto and Bellinaso (2000)	Brazil- Sao Paulo	Red latosol- Clay	Tr/tr+container bins- R1- IR	98%
Pinto and Bellinaso (2000)	Brazil- Sao Paulo	Red latosol- Clay	Tr/tr+container bins- R1- R	94%
Pinto and Bellinaso (2000)	Brazil- Sao Paulo	Red latosol- Clay	Truck- R1- IR	93%
Pinto and Bellinaso (2000)	Brazil- Sao Paulo	Red latosol- Clay	Truck- R1- R	89%
Robotham (2003)	Australia	?	Harvester traffic	88% [TV]
Srivastava (1984)	India- Lucknow	Clay loam	?	69% Significant
Srivastava (1984)	India- Lucknow	Clay loam	Soil BD increased 1.32-1.51t/m³	79%
Srivastava (1984)	India- Lucknow	Clay loam	Soil BD increased 1.32-1.70t/m³	62%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (8.4-9t) vs ZT – IR	110% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (8.4-9t) vs ZT – R	93% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+4t trailer (8t-12.5t)- IR	85% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+4t trailer (8t-12.5t)- R	72% [CT]

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2×7t tip- (29-44t)- IR	84% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- R	51% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- IR	84% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- R	42% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Dumper+4x7t trailer (43-85t)- IR	109% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Dumper+4x7t trailer (43-85t)- R	24% [CT]
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (8.4-9t)	104%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+4t trailer (8t-12.5t)	79%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)	67%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)	94%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Dumper+20t trailer (20-40t)	82%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Grab loader (8.4-9t) IR	96% [CT]
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Grab loader (8.4-9t) R	102% [C]
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Tractor+2x4t trailer (10-18t)- IR	96% [CT]
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Tractor+2x4t trailer (10-18t)- R	86% [CT]

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model ([C]); Test model ([T]); Validate model ([M])

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Dumper+2x7t trailer (28-55t)- IR	83% CT
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Dumper+2x7t trailer (28-55t)- R	55% CT
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (13-13.8t) IR	96% CT
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Tracked harvester (18-18.5t)- IR	99% T
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Tr+ 8t Tip trailer (16.5-24.5t)- IR	97% CT
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Full mech: Harvester + Tr/tr-IR	95% T
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Semi mech: loader + Tr/tr- IR	93% T
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Uncontrolled traffic system	88%
Trouse (1982)	Hawaii	?	Compacted soil?	50%
Trouse Jr and Humbert (1961)	Hawaii	Hydrol humic latosol	Mechanical vs Hand harvested	84%
Trouse Jr and Humbert (1961)	Hawaii	Hydrol humic latosol	Mechanical vs Hand harvested	81%
Usaborisut and Niyamapa (2010)	Thailand	Loam	Tractor weighing 3.5t – 5P	94% NS TV
Usaborisut and Niyamapa (2010)	Thailand	Loam	Tractor weighing 3.5t - 15P	77% Significant TV
Usaborisut and Niyamapa (2010)	Thailand	Loam	Tractor weighing 3.5t - 20P	80% Significant TV
Yang (1977)	Taiwan- Tainan	Clay loam	Mechanical (all) vs Hand cut	85%

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model (C); Test model (T); Validate model (M)

APPENDIX B: INTERNATIONAL DATA

SUMMARY OF SOIL COMPACTION TRIALS CONDUCTED INTERNATIONALLY: *

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Yang (1977)	Taiwan- Tainan	Clay loam	Mechanical (2 pass) vs Hand cut	92%
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-dry-4P vs 2P	94% ^{TV}
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-wet-4P vs 2P	88% ^{TV}
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-dry-6P vs 2P	83% ^{TV}
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-wet-6P vs 2P	77% ^{TV}
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-dry-4P vs 2P	96% ^{TV}
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-wet-4P vs 2P	92% ^{TV}
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-dry-6P vs 2P	92% ^{TV}
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-wet-6P vs 2P	81% ^{TV}

*Abbreviations: Not significant (NS); Inter-Row (IR); Row (R); Zero Traffic (Z) First ratoon (R1); Tractor trailer with twelve ton payload (12t tr/tr); High floatation (HF); Roll on – Roll off (ro/ro); Passes (P); Clay (Cl); Variety (Var); Create model (^{C}); Test model (^{T}); Validate model (^{M})

14. APPENDIX C: MECHANISATION SYSTEM COSTING ASSUMPTIONS

Item:	**A_1:**	**A_2:**	**A_3:**	**B:**	**C:**	**D:**	**E:**	**F:**	**G:**
Row Spacing (m)	1.0-1.2 m	1.0-1.2 m	1.0 m	0.95 m	1.0 m	0.4x1.25 m	0.5x1.45 m	0.4x1.45 m	1.0 m
Loader Wheel Track (m)	2.0 m	2.1 m	1.9 m	2.3 m	2.0 m	3.6 m	1.88 m	2.1 m	2.0 m
Trailer Wheel Track (m)			2.1 m	2.1 m	2.1 m	2.1 m	1.9 m	2.2 m	2.1 m
Field preparation:	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt
Harvesting method:	Manual: cut, stack	Manual: cut, stack	Manual: cut, windrow	Manual: cut, windrow	Manual: cut, windrow	Manual: cut, windrow	Mechanical: CH	Manual: cut, windrow	Manual: cut, windrow
Harvesting rate (t/period)	4.2 t/md	4.2 t/md	8 t/md	8 t/md	8 t/md	8 t/md	46 t/h pour	8 t/md	8 t/md
Harvester cost (R/unit)	R128/md	R128/md	R128/md	R128/md	R128/md	R128/md	R6 500 000	R128/md	R128/md
Infield loading equipment:	1 stack SLT	2 stack SLT	Non-slew L	Non-slew L	Non-slew L	Slew-large	As above CH	Slew-small	Non-slew L
Infield loading rate (t/h)	11.7 t/h	12.7 t/h	33 t/h	31 t/h	27 t/h	39 t/h	32 t/h	76 t/h	27 t/h
Infield loader cost (R/unit)	R480 000	R675 000	R730 000	R730 000	R730 000	R2 500 000	R6 500 000	R1 250 000	R730 000
Infield haulage equipment:	As above 1 stack SLT	As above 2 stack SLT	Box trailers	Box trailers	1 x Triaxle spiller trailer	2 x Tandem axle spillers	Tip trailers	Tip trailers	Rigid truck + trailer
Infield haulage payloads (t)	4.7 t	6.5 t	7.9 t	4.2 t	23.1 t	28.3 t	7 t	9 t	32 t
Infield haulage vehicle costs	R480 000	R675 000	R620 000	R455 000	R1 690 000	R2 190 000	R610 000	R670 000	R2 030 000
Trans-loading equipment:	Crane	Crane	Crane	Crane	N/A	N/A	Non-slew L	Non-slew L	N/A
Trans-loading rate (t/h)	60 t/h	60 t/h	60 t/h	60 t/h	-	-	40 t/h	40 t/h	-
Trans-loading cost (R/unit)	R845 000	R845 000	R845 000	R845 000	-	-	R760 000	R760 000	-
Road haulage equipment:	Truck tractor Interlink	Truck tractor Interlink	Truck tractor Interlink	Truck tractor Interlink	N/A	N/A	Truck tractor Interlink	Truck tractor Interlink	N/A
Road haulage payloads (t)	32 t	32 t	32 t	32 t	-	-	32 t	32 t	-
Road haulage cost (R/unit)	R2 065 000	R2 065 000	R2 065 000	R2 065 000	-	-	R2 065 000	R2 065 000	-

Key: CH = Chopper harvester; SLT's = Self-loading trailers;

15. APPENDIX D: RISK OF ADVERSE SOIL MOISTURE CONDITIONS BY REGION

Days suitable for mechanisation (Soil moisture content < 80% of Field capacity) after Mthembu (2011)

Season length assumed to start from middle of April and 220 days in length.

REGION:	**ML,K**	**PG**	**Umf**	**Fx**	**Am**	**Dn**	**Gl**	**Ms**	**Nb, Uc**	**Es**	**Sz,Uk**	**Industry**
January	18.0	19.9	20.3	20.3	20.8	15.4	14.3	15.2	14.3	15.4	17.1	**17.3**
February	18.0	18.5	18.5	17.6	18.1	15.4	13.0	12.5	17.0	13.0	14.5	**16.0**
March	21.0	21.8	20.3	19.9	20.8	18.5	17.2	17.0	16.3	16.4	17.1	**18.7**
April	24.2	26.2	21.5	22.5	22.1	22.1	20.3	21.7	20.8	20.3	19.4	**21.8**
May	29.0	28.0	25.5	24.8	25.4	28.0	27.0	26.0	29.0	27.5	26.8	**27.1**
June	28.0	28.0	25.5	24.8	25.4	27.5	27.5	26.0	27.0	27.5	27.8	**26.9**
July	29.0	28.5	25.5	27.0	28.0	28.0	28.0	26.0	28.0	28.0	28.3	**27.8**
Aug	29.0	28.5	28.0	28.0	28.0	28.0	28.0	26.0	28.0	28.0	28.3	**28.1**
September	28.0	28.0	28.0	24.8	25.1	23.6	25.1	25.4	25.7	25.1	23.4	**25.6**
October	26.2	21.5	22.1	21.8	22.6	20.6	20.6	20.0	21.4	22.1	20.0	**21.9**
November	20.8	17.6	18.5	20.3	18.5	18.5	17.2	18.5	16.5	19.0	17.8	**18.6**
December	19.9	18.5	18.5	20.3	20.8	17.0	16.1	18.1	14.9	16.3	16.6	**18.0**

Key: Ml = Malelane; K = Komati; Umf = Umfolozi; Fx = Felixton; Am = Amatikulu; Dn = Darnall; Gl = Gledhow; Ms = Maidstone; Nb = Noodsberg; Uc = Union Co; Es = Eston; Sz = Sezela; Uk = Umzimkulu

16. APPENDIX E: QUICK REFERENCE GUIDE TO MECHANISATION SYSTEMS

Survey:	**A_1:**	**A_2:**	**A_3:**	**B:**	**C:**	**D:**	**E:**	**F:**	**G:**
System and Equipment:	Cut and stack: Self- loading trailers (SLT's)	Cut and stack: Self- loading trailers (SLT's)	Cut and windrow: Non-slew loader and box trailers	Cut and windrow: Non-slew loader and box trailers	Cut and windrow: Non-slew loader and high capacity trailer	Cut and windrow: Slew loader and high capacity trailer	Chopper harvester loading into low capacity trailers	Cut and windrow: Slew loader and low capacity trailer	Cut and windrow: Non-slew loader and rigid truck
Traffic Management:	Random traffic	Random traffic	Random traffic	Random traffic	Random traffic	Control traffic	Control traffic	Control traffic	Random traffic
Row Spacing:	1-1.2 m	1-1.2 m	1 m	0.95 m	1 m	Tram 0.4x1.25 m	Tram 0.4x1.45 m	Tram 0.5x1.45 m	1 m
Wheel Track Loader:	2.0 m	2.1 m	1.9 m	2.3 m	2 m	3.6 m	1.88 m	2.1 m	2 m
Wheel Track Trailers:			2.1 m	2.1 m	2.1 m	2.15 m	1.9 m	2.2 m	2.1 m
Field Area:	2.5 ha	1.1 ha	1.0 ha	1.5 ha	0.25 ha	3.1 ha	1.5 ha	1.7 ha	0.25 ha
Cane Yield:	89 t/ha	89 t/ha	130 t/ha	76 t/ha	91 t/ha	55 t/ha	70 t/ha	123 t/ha	91 t/ha
Harvest Preparation:	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt
Cutting:	Manual	Manual	Manual	Manual	Manual	Manual	Mechanical	Manual	Manual
Cane Stockpile Presentation:	Stacks	Stacks	Windrow 5 rows : 1	Windrow 6 rows : 1	Windrow 6 rows : 1	Windrow 3 tram (6 rows) : 1	1 tramline (2 rows) per pass	Windrow 4 tram (8 rows) : 1	Windrow 6 rows : 1
Infield Loading:	Single stack SLT's	Double stack SLT's	Non-slew loader: load 2 windrows	Non-slew loader: load 1 windrow	Non-slew loader: load 3 windrows	Slewing loader: load 1 windrow	Chopper harvester 1 tramline per pass	Slewing loader: load 1 windrow	Non-slew loader: load 3 windrows
Infield Haulage: (Field to zone = FZ Field to mill = FM)	4.7 t as above, FZ	6.5 t as above, FZ	7.9 t low capacity box trailers, FZ	4.2 t low capacity box trailer, FZ	23.1 t high capacity 3-axle trailer, FM	28.3 t high capacity 2 x 2-axle trailers, FM	7 t single axle tip trailer, FZ	9 t double axle tip trailer FZ	32 t rigid truck, FM
Trans-loading:	Crane	Crane	Crane	Crane	N/A (see above)	N/A (see above)	Non-slew loader	Non-slew loader	N/A (see above)
Road Haulage:	32 t interlink truck	32 t interlink truck	32 t interlink truck	32 t interlink truck	N/A	N/A	32 t interlink truck	32 t interlink truck	N/A
Loaders:									
Infield haulage vehicles:									
Trans-loading operations:					N/A	N/A			N/A
Road haulage vehicles:					N/A	N/A			N/A
Survey:	**A_1:**	**A_2:**	**A_3:**	**B:**	**C:**	**D:**	**E:**	**F:**	**G:**