THE IMPACT OF INFIELD TRAFFIC ON SUGARCANE YIELDS IN SOUTH AFRICA

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ABSTRACT

Infield traffic has been understood to cause adverse field conditions for crop growth. In this study a database consisting of traffic or compaction induced yield responses from published literature was reviewed and synthesised. Approximately 28 papers detailing 128 responses of sugarcane yield to infield traffic or compaction trials were collated. These consist of a wide variety of infield traffic treatments. The aim of compiling such a database was to establish the range and typical yield responses that occur following a traffic event and to investigate trends relating to various infield operations. Such responses are essential to estimate the economic impact of compaction and to model such impacts. The responses provide a means to determine best practices and to assess the importance of such practices to minimise the impact of yield reduction associated with infield traffic.

Results reported in literature confirm that traffic on a sugarcane row is more damaging than inter-row traffic. The soil water content at the time of infield traffic is a critical factor affecting soil compaction and sugarcane yield.

In this literature review only traffic that occurs during harvesting was considered. All other infield traffic post crop establishment is assumed to be minor in comparison to the intensity and extent of operations that occur during harvesting. Land preparation occurs infrequently and was assumed to be similar across different harvesting systems. Land preparation is, however, briefly considered under controlled traffic farming systems. Trials relating to compaction were also not included in the review, unless cane yields were measured against the compaction treatment. General soil compaction effects on soil properties were not considered as there is a substantial body of knowledge on this topic. Despite such work, few accurate, consistent and direct relationships were established between compaction treatments and yield loss when taking individual soil properties into account. Where such relationships were established, they are often site or situation specific and cannot be extrapolated to model general traffic and yield response trends.

A proposed project to determine the location, intensity, extent and potential impact on yield of infield traffic for a range of different cane loading systems applicable to southern Africa follows the review of the literature.

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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). 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. 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. More recently, 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; Braunack and Hurney, 2000; De Paula and Molin, 2013). Amongst a wide range of treatments and responses, the impact of traffic on a sugarcane row was typically found to be significantly more severe compared to inter-row traffic. These results have led to the promotion of alternative agronomic practices, harvesting systems and infield management practices.

The aim of this document is to review, collate and synthesise the knowledge from both local and international literature in order to determine the response of sugarcane to infield traffic. Modelling of this unaccounted component will allow for economic impacts and comparisons between infield traffic systems to be conducted. The objectives include:

(i) reviewing the literature for general crop yield response trends to infield traffic,
(ii) to investigate the impact of various infield traffic treatments on crop yield and
(iii) to summarise improved management practices relating to infield traffic operations.

Collating and synthesising the current body of knowledge for such yield response trends provides a sound basis from which advice and analysis on harvesting best practices and possible future changes to infield harvesting in the industry can be made.

Chapter 2 contains a background to the sugar industry and a summary of various harvesting systems typically found in South Africa. Chapter 3 contains a review of various row and vehicle spacing configurations and systems used to minimise the impact of infield vehicle traffic. Chapter 4 contains a summary of the crop response to traffic with distinctions made between soil compaction and stool damage, while Chapter 5 contains a discussion of the literature reviewed. Chapter 6 consists of a project proposal to investigate comparative infield harvesting system costs typically found in South Africa. A reference list and appendices containing data of local and international sugarcane yield responses to compaction conclude this study.

2. HARVESTING SYSTEMS USED IN SUGARCANE PRODUCTION IN SOUTH AFRICA

The South African sugar industry is comprised of approximately 24000 sugarcane growers and 14 sugar mills (Figure 2.1) producing approximately 1.9 million tons of sugar per season. Direct income of over R12 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, 2013). The total area under sugarcane production in South Africa is approximately 372 000 hectares. The average production of a large scale grower in the industry is 10 000 tons per annum and 120 tons per annum for small scale growers (Anon, 2013).

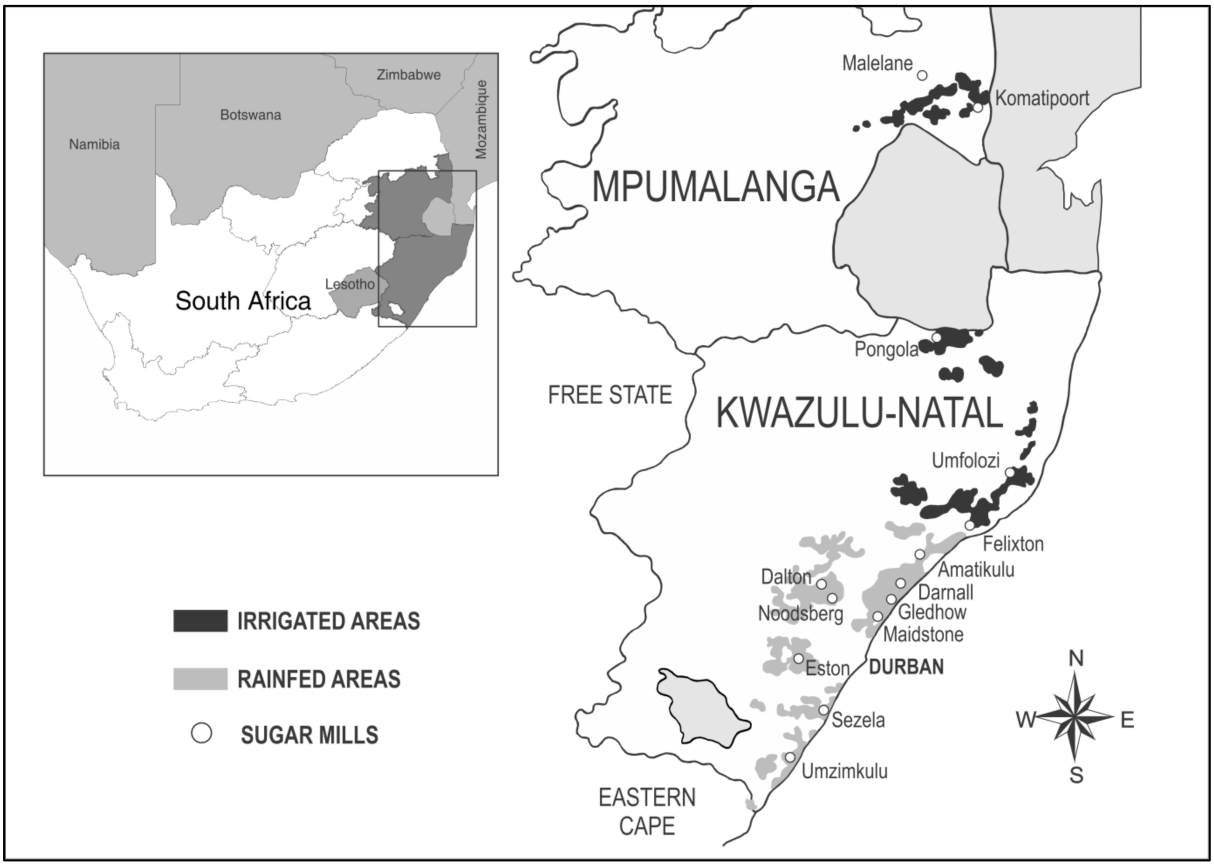

Figure 2.1 Map of the South African sugar industry showing the distribution of sugarcane growing areas (distinguishing between rain-fed and irrigated areas) and mill locations (After Anon, 2005).

Sugarcane is a perennial crop with typically between six and eight harvesting cycles 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 m to 1.5 m.

2.1 Overview of Harvesting Systems

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).

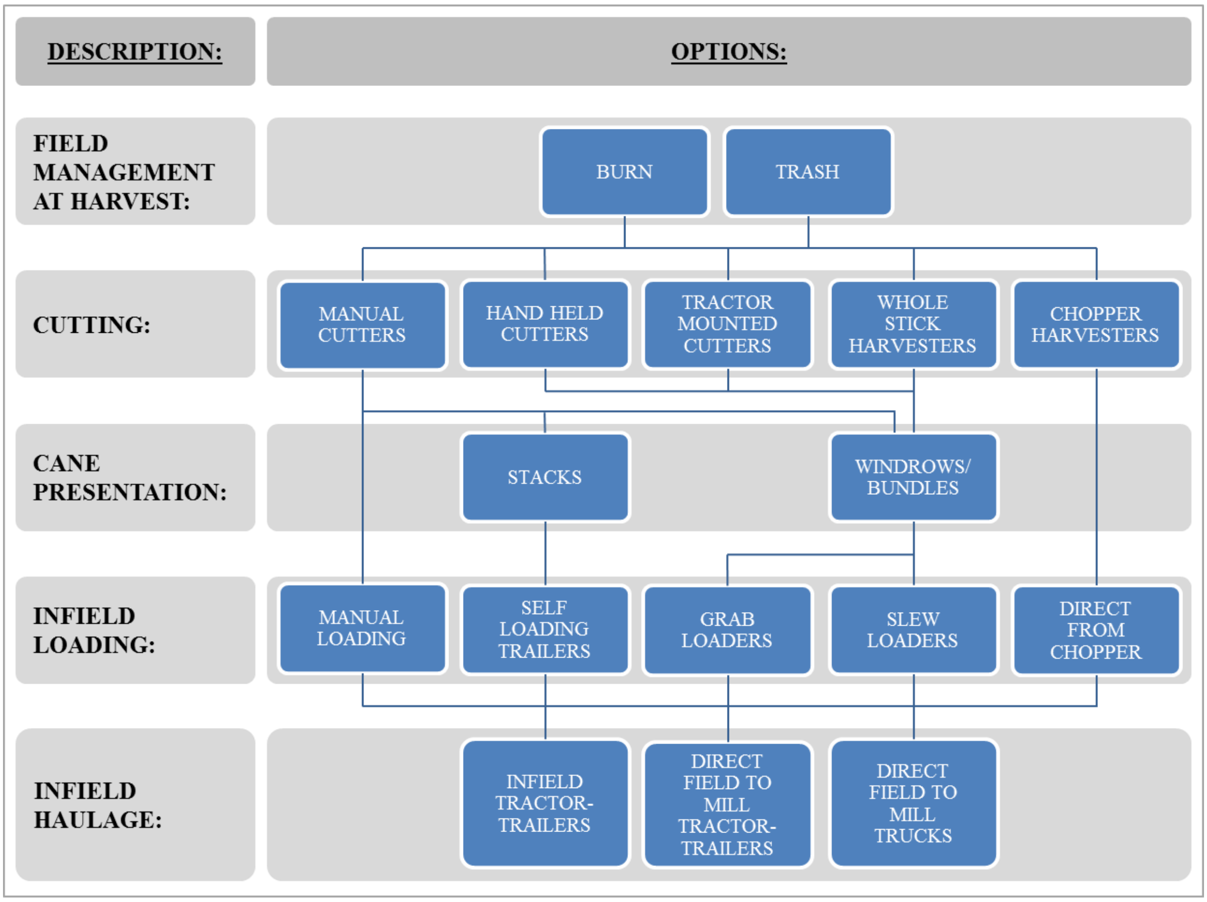

Figure 2.2 Infield harvesting and haulage options (after Braithwaite, 2013)

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	6.14	100
Harvested burnt	93.86	
Mechanical harvest	2.19	100
Manual cut and load	1.34	
Manual cut and stack	30.04	
Manual cut and windrow, Mechanically loaded	66.43	

2.2 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) conclude 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 about 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 windrowing system may have been enhanced compared to the other systems due to higher cane yields.

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 showed a decrease of about 1% 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 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) or a wide range of tractor mounted mechanical whole stick harvesters as reviewed by Meyer (1996a).

Most chopper harvesters harvest a single row, or closely spaced rows, per pass. Whole stalks entering the harvester are cut into 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).

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

The prospect of an additional revenue stream through biomass harvesting of cane is likely to increase the adoption of green cane harvesting and either change the 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). 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 20000 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. These costs are offset by the full and efficient use of these machines. Tractor mounted slew, self-propelled slew and non-slew loader variations exist. 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 push-piler in the front at a wheel spacing of 3 m.

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 advantage of the non-slew loaders are their relatively lower capital cost, rigid construction, low 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.

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 considered.

3. INFIELD VEHICLE MANAGEMENT SYSTEMS

The purpose of this chapter is to review agronomic and traffic practices that have been developed to improve and sustain crop yields. Maximising agronomic yield potential per unit area, i.e. by 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 traffic is described and various examples of implemented systems 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 (Meyer *et al.*, 2001). 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 mechanical field efficiencies. In contrast, narrow rows help to achieve early full crop canopy cover and improved light interception. The wheel tracks of all infield equipment should ideally be matched with the ideal agronomic row spacing. A trade-off may be required to best match row and wheel track spacing’s for a system that is both practical and 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.

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). Trouse (1982) motivated for a controlled traffic system primarily based on 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 strategic 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) and Garside *et al.* (2005) 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 various scenarios showing 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 meter (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).

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. The mass of harvesters are reported to have doubled and there was a migration towards higher capacity extraction equipment with large diameter and low pressure high floatation tyres. Meyer *et al*. (2005) however, reported that up to 90% of the 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 papers showing a positive response to a wider row spacing and in 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 (RS) from southern African literature.

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

Reference	**Row spacing (RS) details (m)**	**Yield response to row spacing (RS)**
Thompson and Du Toit (1965)	0.45; 0.9; 1.37	Optimum yields at 0.9 m
Boyce (1968)	0.9 to 2.15	+15%.m^{-1} decrease in RS
Singels and Smit (2002)	0.7; 1.2; 1.7; 2.2; 2.7	+13%.m^{-1} decrease in RS
Olivier and Singels (2003)	1.8 dual rows; 1.5	+23% for duals vs. 1.5 m
Singels and Smit (2009)	Wagon wheel 0.4 to 2.7	+21%.m^{-1} decrease in RS

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 0.9 m row spacing tends to yield the highest. This was more evident in the plant crop than ratoon crops. As listed in Table 3.1, this confirms the results from a number of studies and 0.9 m seems to be a reasonable 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 match up with the crop inter-rows, which will minimise traffic induced yield losses caused from travelling on the row. However, keeping wide tyres to the narrow (0.9 m) inter-row area is difficult to achieve in practice.

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. However, the system required modifications to the harvesting and extraction equipment. 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 40% to 50% at the narrower spacing's.

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 × 1.3 m spacing) to match harvester or loader systems (Figure 3.1) is described by Torres *et al.* (2010). Parabolic furrows were formed in the centre of the dual row inter-rows for furrow irrigation. Yield results were compared to conventional 1.75 m single row spacing and the results suggest that plant cane yields are compromised by the lack of crop in the wide inter-row space for the first crop, but were matched in first ratoon and improved from the second ratoon onward. 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.

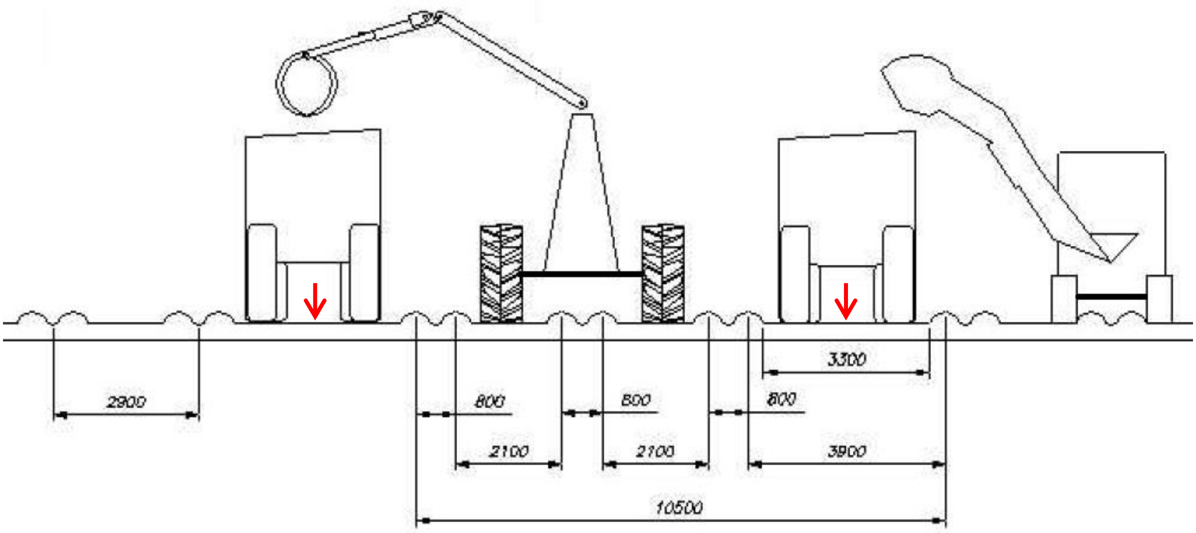

Figure 3.1 A modified dual row system developed by Torres *et al.* (2010) (units in mm)

Dual row systems with distances between close rows ranging from 0.3 to 0.8 m and overall spacing between crop zones (pairs of dual rows) ranging from 1.8 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 as shown in Figure 3.2.

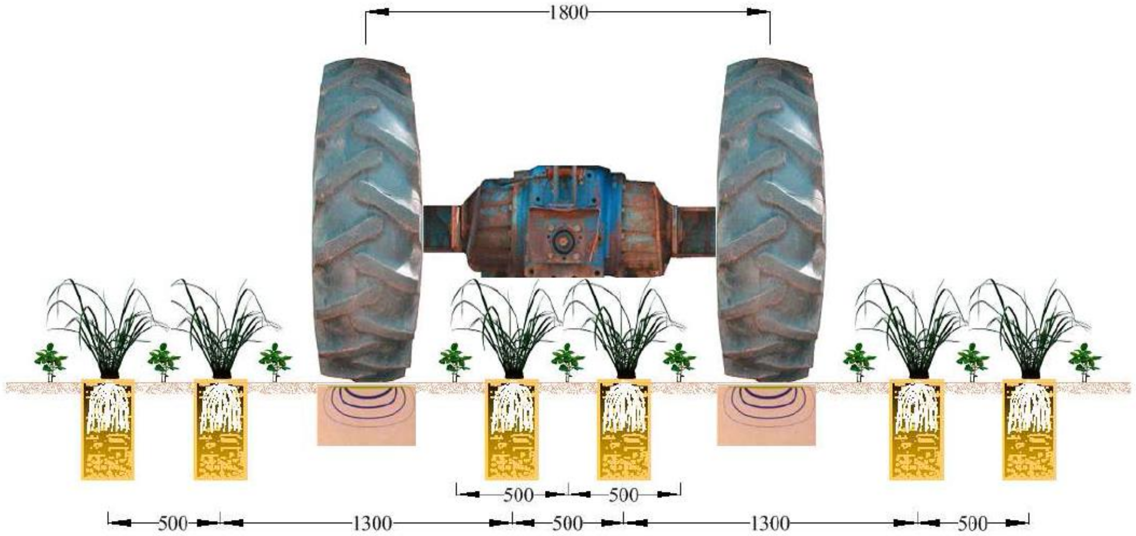

Figure 3.2 Strategic spacing of wheels and crops within a dual row system (0.5 m + 1.3 m crop spacing's and corresponding 1.8 m wheel track spacing) (units in mm) (Lecler and Tweddle, 2010)

Braunack and McGarry (2006) compared 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. The comparisons and corresponding yield benefits are shown 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
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%

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 pour rates, less turning time and less field distance travelled (Ismael *et al.*, 2007). Disadvantages are the higher amount of seedcane required during planting and 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 under 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 crops 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 CROP 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 was on sugarcane crop response unless otherwise stated. The chapter is introduced with general plant responses to soil compaction, followed by agronomic responses to variations in compaction events. A model to predict yield responses to compaction is reviewed. The chapter is concluded with a summary of results obtained from a literature survey that collates yield response trials from local and international sites.

Industries that have adopted full mechanisation have reported that the associated higher traffic intensities are likely to increase 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 (near field capacity) and where traffic is uncontrolled (Maud, 1960; Meyer *et al.*, 1996). The term “uncontrolled traffic” is used when infield vehicles are at liberty to travel anywhere in the field without restriction. On row traffic is more likely to occur when the traffic is uncontrolled or when the positions of rows are not easily visible. For example, a field practice, such as green cane harvesting, leaves high levels of residue to cover the field surface making it difficult to see where the positions of the rows and inter-rows are. Another example is the misalignment of windrows or stacks which may result in the loader operator inadvertently driving over the rows during loading operations.

On row traffic 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 Physiological Responses to Infield Traffic

For sugarcane, adverse soil properties associated with compacted soils negatively affect root growth rates (Torres and Rodrigues, 1995). Trouse (1982) describe a curtailing 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, despite differences in plant measurements, the final yields were not compromised (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. 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 yield responses 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.

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 thus 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 soil compaction (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 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).

4.3 Modelling of Yield Responses to Infield Traffic

Arvidsson and Håkansson (1991) developed a computerised empirical 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 extensive field crop trials conducted in Sweden, the model estimates total soil compaction costs 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, 25-40 cm and greater than 40 cm. 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, the shallow zone affected by axle loads above 4 tons and the 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 validated using data from multiple ratoon cane crop trials and deemed to estimate 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 in order to provide an estimating tool to allow alternative traffic scenarios to be tested. This model requires the input of un-trafficked, inter-row traffic and row traffic parameters. Traffic intensities and traffic position parameters have not been accurately characterised for systems used in the South African sugar industry.

4.4 Compaction Trial Results Database

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 in order to collate higher level trend analyses. Trial results are listed and categorised by yield responses to: no traffic, inter-row traffic, row traffic and 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 the data comprising yield responses to infield inter-row and row traffic is summarised as per Figure 4.1.

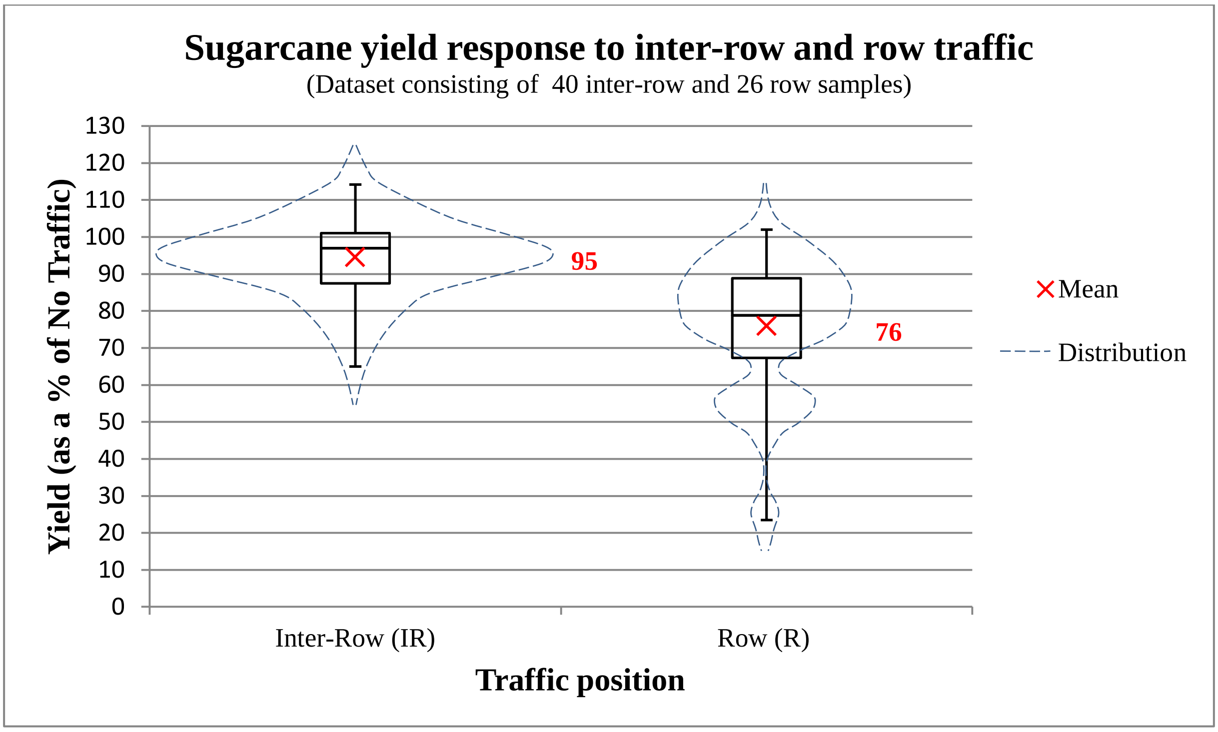

Figure 4.1 Sugarcane yield response to inter-row and row traffic.

Inter-row traffic appears less detrimental to yields compared to row traffic. The variance in yield response to row traffic indicates that there is a higher risk of causing excessive yield losses. Extreme yield losses of as much as 80% can be attributed to stool damage under unsuitable field conditions. Generally, if traffic is required to enter the field, then constraining this traffic to the inter-rows is shown to be a good practice to minimise the loss of potential yield. It should be noted that row traffic on a perenial sugarcane crop would likley result in a compounding loss of yield to subsequent ratoons.

In the chapter that follows, the peculiarities of loading systems and techniques that are used in the South African industry and the need to characterise the traffic associated with these systems are discussed. A project proposal to determine the position and attributes of infield traffic associated with different loading systems follows the discussion and conclusion on the review of the literature.

5. DISCUSSION AND CONCLUSIONS

Compaction has been understood to cause adverse field conditions for crop growth. Initially, research focused on soil compaction, but progressed to distinguish between areas of compaction relative to the crop's position. High variances in yield response to treatments have led to broad recommendations and vague estimates of crop response. In the past, much emphasis was placed on physical soil changes from different treatments, but to date no proxy has been found to determine yield loss estimates, both practically and reliably. Much of the variance is due to complex soil properties, compaction treatment and crop response interactions. Soil water content alone has a significant influencing factor and can be variable and dynamic in both the short and long term, as well as spatially within a field. The aim of this review, by compiling a database of compaction yield responses, was to assess yield response trends that dominate in these complex interactions. A preliminary analysis of yield response to infield traffic has shown significant susceptibility of the crop to row traffic over inter-row traffic treatments, providing a basis on which to compare infield vehicle operations.

Approximately two thirds of the sugarcane crop in South African crop is cut and windrowed and then mechanically loaded infield. The predominant means of loading is through the use of non-slew loaders. These loaders are a popular choice of equipment because they are productive, light, robust and relatively cost effective. However, by not being able to slew, these loaders consequently incur much wheel traffic over the crop during loading operations. An advantage of this system is the low amount of infield traffic compared to fully mechanised systems, but row traffic during loading means that controlled traffic farming recommendations, as promoted in literature as a means to sustain yields within highly mechanised systems, cannot be practiced. Variations of infield haulage for crop extraction range from small tractor-trailers to large capacity road haulage vehicles. The cut and stack system that is also widely practiced has the advantage of low amounts of field traffic by virtue that the loading and extraction operations are combined. Controlled traffic can be practiced with this system if the stacks are suitably located during preparation. The impact of loading systems, which are common to South Africa, on long-term sustainable production, is not known and little data are available to compare traffic from various infield systems. The project described in the following chapter aims to meet this shortcoming by conducting field research to survey the infield traffic associated with different infield loading systems.

6. PROJECT PROPOSAL

A project proposal to determine traffic metrics associated with typical infield loading practices is presented in this chapter. The research rationale, aims, objectives and methodology are stated, followed by a discussion of the resources required for the project. Health and safety aspects are noted and the project proposal is concluded with a plan of anticipated milestones.

6.1 Rationale

At the 2001 ISSCT Agricultural Engineering Workshop Meyer *et al.* (2001) noted a number of strategic issues requiring research. These included the determination of relationships between row spacing, mechanisation, soil compaction and cane stool damage in both an agronomic and economic sense.

Comparisons between harvesting systems has typically been limited to machinery ownership and operating costs as per standard techniques such as the Classic Machinery Costing Method as described by Meyer (2006). The estimation of an additional cost relating directly to yields or yield sustainability has not yet been developed for local conditions and systems. An investigation into the BSES model by Braunack *et al.* (2006) highlights the need for such infield traffic metrics to be determined for different systems. Metrics to be measured include: the extent and position of infield traffic; the typical intensity of the traffic and the number of passes that occur throughout the field. By determining a reasonable yield impact due to infield traffic, it follows that systems could be compared on a more holistic basis, taking into account both machinery costs and the impact of the infield traffic system.

6.2 Aim and Objectives

The aim of this study is to determine the impact that infield traffic has on the economics and sustainability of sugarcane cropping for a range of different cane loading and extraction systems applicable to southern Africa. Infield traffic data will be gathered through the GPS tracking of vehicle positions infield to determine the percent of the field that has incurred row traffic, inter-row traffic and zero traffic for each vehicle type that enters the field.

Specific objectives include:

i) Through an in-depth literature review, determine general traffic-yield response trends through the synthesis of field compaction research trial results that link sugarcane yield responses to infield traffic (row traffic, inter-row traffic and no traffic) events,

ii) Determine, through GPS tracking and vehicle monitoring, typical indices for field traffic (intensities and extents) for the following systems:

    a. the Cut and Stack system employing self-loading infield trailers,
    b. the Cut and Windrow system employing non-slew loaders and infield equipment and
    c. the Cut and Windrow system employing a slew loader and infield equipment

iii) Analyse and compare traffic metrics associated with the various infield harvesting systems,

iv) Develop an Excel based Decision Support Programme (DSP) to integrate infield mechanisation costs and modelled crop yield loss costs pertaining to infield traffic,

v) Provide recommendations to improve the management of infield traffic systems.

6.3 Proposed Methodology

The research plan consists of the following actions:

i) A comprehensive literature review and synthesis of both local and international literature relating specifically to sugarcane yield loss due to infield traffic will be conducted with the purpose of determining yield response trends to various compaction treatments under various soil conditions. These yield response trends will relate experimental trials to practical field operations.

ii) Infield experiments will be conducted to measure the extent, magnitude and position of traffic associated with various harvesting operations. Infield vehicle traffic will be surveyed using high accuracy GPS equipment. This will enable distinctions to be made between areas of inter-row, row and zero infield traffic. Axle loads will be measured or determined from typical vehicle loading data. Tyre inflation pressures will be measured infield. Soil water will not be measured, as this a variable accounted for during scenario modelling. The outputs from the field surveys are anticipated to be similar to spatial mapping of infield traffic distributions as conducted by Grisso *et al.* (2002); Kroulik *et al.*

(2009) and Duttmann *et al.* (2013) although these were for maize crops and tillage operations.

iii) An Excel DSP to compare different harvesting systems will be developed to link the infield traffic to yield impact for each harvesting system monitored. The yield impact will be determined by the position and nature of the traffic that takes place infield as determined through measurements and surveys of wheel positions infield.

6.4 Resources and Equipment Required

This project has been approved as a South African Sugarcane Research Institute (SASRI) research project. All necessary vehicle, travel and accommodation have been budgeted for in the project. SASRI has set aside a budget for the purchase or hire of equipment; GPS signal fees or field consumables as required. Vehicle position tracking using various field marking options include the use of liquid or powder dispensing equipment and consumables. Sources for GPS equipment for mapping and surveying are listed in Table 6.1.

Table 6.1 Cost and source of equipment

Instrument and Accuracy	Quantity	Means of acquisition	Approximate price [ZAR]
Trimble® Juno SB (sub 5m accuracy)	3	SASRI	In stock
Trimble® EZ-Guide 500 Light-bar and AG25 GNSS Receiver (<10cm - signal dependent)	1	UKZN	N/A
Trimble® PROXRT pathfinder with 6GB Nomad handset (DGPS) (<2.5cm with RTK)	1	UKZN	N/A
Trimble® PROXRS with TSC1 2MB collector (DGPS) (<2.5cm with RTK)	1	UKZN	N/A

The following software is available at SASRI: Pathfinder office version 5.4, Arc GIS version 10.1. Integrated surveying and CAD software would be advantageous for the downloading and mapping of GIS data.

6.5 Health and Safety Considerations

High visibility safety vests, protective boots, eye and ear protection are necessary for infield tasks. These will be provided by SASRI and are in accordance with SASA health and safety standards.

6.6 Project Plan

An overview of the projected time frames and milestones is contained in Table 6.2.

Table 6.2 Project plan

Task	**Start Date**	**End Date**
Literature review	2 May 2013	31 December 2013
Project proposal and presentation	31 December 2013	28 March 2014
Field surveys of harvesting systems	31 March 2014	29 August 2014
Modelling of systems	02 December 2013	30 September 2014
Thesis	2 May 2013	31 December 2014
Research paper	2 January 2015	31 March 2015

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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%
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
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & trailer +5t R1: 2P-IR- dry	103% NS
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & trailer +5t R2: 5P-IR- wet	97% NS
Johnston and Wood (1971)	SA- Pongola	Makatini sandy clay	Tr & tr +5t R2: 5P-IR+R- wet	96% NS- early growth slow
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R1–5 passes IR	86% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R1–7 passes R+IR	73% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R1–5 passes IR	79% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R1–7 passes R+IR	76% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R2–5 passes IR	74% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	3.7t tyre load-R2–7 passes R+IR	59% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R2–5 passes IR	65% Significant
Swinford and Boevey (1984)	SA- La Mercy	Longlands 20% clay; 8% silt	5.7t tyre load-R2–7 passes R+IR	53% Significant

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
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
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	57t truck +dual radials - IR moist	85% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	57t truck +dual radials - IR wet	92% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR dry	103% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR moist	88% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	48t truck + HF singles – IR wet	99% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tractor trailer+radials–IR dry	94% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tr/tr +radials – IR moist	93% NS
Van Antwerpen and Meyer (2001)	SA- Malelane	Hutton 63% clay;10% silt	12t tr/tr +radials – IR wet	95% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R2 - IR dry	102% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R2- IR dry	103% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R2- IR wet	98% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R2- IR wet	101% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R3- IR dry	99% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R3- IR dry	104% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +radials –R3- IR wet	97% NS
Van Antwerpen *et al.* (2008)	SA- Komatipoort	Hutton 44% clay;3.8% OM	57t truck +HF -R3- IR wet	106% NS

* 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)

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%
Braunack (1995)	Australia- Tully	?	4t tr/tr -R2- R vs IR	92%
Braunack (1995)	Australia- Ingham	?	8t tr/tr –R1- R vs IR	86%
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
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R2- R vs Z	68% Significant
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R1+wet- R vs Z	60% Significant
Braunack and Peatey (1999)	Australia- Macknade	Loam to Silty clay	9t ro/ro haulout- R2+wet- R vs Z	66% Significant
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R1 R vs IR	86% NS
Braunack and Hurney (2000)	Australia- Ingham	Grey clay	Tr/tr+2×4t ro/ro bins–R2 R vs IR	96% NS
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

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
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
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
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 4P –R vs Z	89% NS
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 9P –IR vs Z	97% NS
De Paula and Molin (2013)	Brazil- Itapira	Sandy	Tractor 3.8t- 9P –R vs Z	86% NS
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 2P -R vs Z	93% NS
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 4P –R vs Z	84% NS; Significant RvsIR
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 9P –IR vs Z	114% NS; Significant IRvsR
De Paula and Molin (2013)	Brazil- Itapira	Clay	Tractor 3.8t- 9P –R vs Z	88% NS; Significant RvsIR
Dinardo-Miranda *et al.* (2008)	Brazil- ?	Red latosol- Clay	Manual harvest +infield haulage	73%
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

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
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
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
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
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%
Srivastava (1984)	India- Lucknow	Clay loam	?	69% Significant
Srivastava (1984)	India- Lucknow	Clay loam	Soil BD increased 1.32-1.51t/m^3	79%
Srivastava (1984)	India- Lucknow	Clay loam	Soil BD increased 1.32-1.70t/m^3	62%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (8.4-9t) vs ZT – IR	110%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (8.4-9t) vs ZT – R	93%

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+4t trailer (8t-12.5t)- IR	85%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+4t trailer (8t-12.5t)- R	72%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2×7t tip- (29-44t)- IR	84%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- R	51%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- IR	84%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Tractor+2x7t tip- (29-44t)- R	42%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Dumper+4x7t trailer (43-85t)- IR	109%
Torres *et al.* (1990)	Columbia- Cauca	Mollisol- Clay loam	Dumper+4x7t trailer (43-85t)- R	24%
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%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Grab loader (8.4-9t) R	102%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Tractor+2x4t trailer (10-18t)- IR	96%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Tractor+2x4t trailer (10-18t)- R	86%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Dumper+2x7t trailer (28-55t)- IR	83%
Torres and Villegas (1995)	Columbia-Castilla	Mollisol- Clay loam	Dumper+2x7t trailer (28-55t)- R	55%
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Grab loader (13-13.8t) IR	96%

Reference:	Location:	Soil Type:	Treatment:	Yield as % of control:
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Tracked harvester (18-18.5t)- IR	99%
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Tr+ 8t Tip trailer (16.5-24.5t)- IR	97%
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Full mech: Harvester + Tr/tr-IR	95%
Torres and Pantoja (2005)	Columbia- Cauca	Mollisol- Clay loam	Semi mech: loader + Tr/tr- IR	93%
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
Usaborisut and Niyamapa (2010)	Thailand	Loam	Tractor weighing 3.5t - 15P	77% Significant
Usaborisut and Niyamapa (2010)	Thailand	Loam	Tractor weighing 3.5t - 20P	80% Significant
Yang (1977)	Taiwan- Tainan	Clay loam	Mechanical (all) vs Hand cut	85%
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%
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-wet-4P vs 2P	88%
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-dry-6P vs 2P	83%
Yang (1977)	Taiwan- Tainan	Silty loam	Harvester+6t truck-wet-6P vs 2P	77%
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-dry-4P vs 2P	96%
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-wet-4P vs 2P	92%
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-dry-6P vs 2P	92%

Reference:	**Location:**	**Soil Type:**	**Treatment:**	**Yield as % of control:**
Yang (1977)	Taiwan- Tainan	Clay loam	Harvester+6t truck-wet-6P vs 2P	81%

*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)