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AGRONOMY & SOILS

Advances in Cotton Harvesting Technology: a Review and Implications for the John Deere Round Baler Cotton Picker

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ABSTRACT

To address the progressive increase in farmed land and the decline in labor, cotton production in more developed agricultural systems has seen a movement towards larger, heavier machinery with increased capacity. Recent innovation of on-board module building technology for cotton harvesters follows this trend, which has caused concern for the potential impact of the machine on the farming system. This review acknowledges past and present developments within the cotton harvesting system from both the machine- and soil-management perspectives to inform land managers, machinery manufacturers, technical advisors, and the scientific community of the incidence of soil compaction associated with technology uptake in cotton-based systems. Emphasis is made on the need to ensure that the effects of traffic-induced soil compaction are minimized. For this, the feasibility of confining compaction to the least possible area of permanent traffic lanes is examined along with engineering design constraints of commercially available cotton pickers. Fundamental information is elicited, which provided insights as to why this movement has occurred and how associated problems might be addressed. Within the Australia context, these cotton harvesters have undergone rapid adoption. This review uses this case-study to elucidate direct and latent impacts of the machine to help identify risks and develop management strategies as further technology is developed and adopted. Knowledge gaps that merit a research priority within soil compaction work for cotton-based systems are presented and a synthesis of how to proceed conceptualized.

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The efficiency of farming activities is largely dictated by economies of scale, which means that significant cost advantages are obtained by increasing the size and speed of operations (Rickard, 2006). Increasing the size of farming enterprises requires increased level of management, which can strain productivity when coupled with expensive or limited availability of labor, particularly, in developed countries. This creates a need for higher capacity machines to increase timeliness and work rates, and reduce labor requirements (Tullberg, 2014). The trend observed in the past few decades toward the use and development of larger and more powerful agricultural machinery will likely continue (Kutzbach, 2000). One of the drawbacks of increased machinery size is the associated increase in axle loads, which has offset advances made by the industry in developing improved running gear, such as in tire and track designs, to reduce contact pressures (Misiewicz et al., 2015; Tijink et al., 1995). The progressive increase in axle loads have resulted in increased subsoil stresses (Keller and Arvidsson, 2004). In grain cropping, Chamen (2014), based on models of Koolen et al. (1992) and Keller et al. (2007), estimated an average 14-fold increase in subsoil stresses (from about 0.02 to 0.28 MPa at 400 mm deep) between 1930 (horse-plowing) and 2010 (30 Mg combine harvesters), respectively. In cotton (*Gossypium hirsutum* L.) cropping, similar trends have been observed owing to recent developments in harvesting technology. Despite the latest cotton pickers being fitted with dual tires on the front axle, subsoil stresses are comparable to those reported by Chamen (2014) for commercially available combine harvesters. Consequently, the drive towards adoption of more efficient machines to reduce costs and increase work rates has brought about concern due to the potentially negative effects of increased soil compaction and the associated need for tillage repair.

The aim of the work reported in this article is to review past and recent developments in cotton harvesting technology from the machine- and soil-management perspectives to inform land managers, machinery manufacturers, technical advisors, and the scientific community of the incidence of soil compaction associated with technology uptake in cotton-based systems. Therefore, the objectives of this review were to: (1) critically discuss about the mechanisms leading to increased adoption of novel harvesting technology with particular reference to the round baler cotton picker, and (2) examine the practicalities of confining all traffic-induced soil compaction to the least possible area of permanent traffic lanes, namely controlled traffic farming (CTF), within Australian cotton-based systems. The above information is complemented by perspective on the John Deere 7760 cotton picking system provided by Australian cotton growers. Knowledge gaps are identified that merit research priority within soil compaction work in cotton-based systems.

Advances in Cotton Picking Techniques and Technology Uptake. Since the inception of machine-based cotton pickers having on-board module building, the time required to pick a bale of cotton (weight range: 2-2.5 Mg) has decreased from approximately 50 to 70 man-hours (hand-picking) down to eight minutes (Narayanan, 2005; Wattonville, 2008; Willcutt et al., 2009). Adoption of spindle-type pickers in the United States (U.S.) occurred progressively from the west to the east of the cotton belt, which responded to the absence of an effective and well-established manual labor harvesting system that was originally in place in the southeast. In the western cotton belt, where yields were relatively higher, the potential to grow cotton was limited by availability of labor (Musoke and Olmstead, 1982). Hence, the industry was smaller and less developed compared with the east. However, the introduction of cotton-picking machines in 1948 enabled this limitation to be overcome and resulted in rapid adoption of cotton pickers (approximately 10% and 75% by 1951 and 1959, respectively), which drove the industry forward (Heinicke and Grove, 2008; Musoke and Olmstead, 1982). Conversely, the picker did not offer the same range of benefits in the south where labor was needed for three seasonal peaks, namely, planting, weeding, and harvest, and therefore adoption was relatively slower (approximately 10% by 1960) (Heinicke and Grove, 2008; Musoke and Olmstead, 1982). These peaks required that ordinary farm workers were given a share of the profit in a share-farming setup to entice them to stay all year round (Holley, 2000). Because mechanical or chemical weed control techniques had not been developed, machine-picking would have negatively impacted the system almost to failure. In the west, the risk of crop failure due to incidence of weeds was lower because they could be controlled, with some degree of efficacy, by means of timely irrigations in the drier environment. The cotton stripper, as opposed to the cotton picker, was initially adopted in Texas because lower yields in that part of the cotton belt did not warrant the relatively higher cost of pickers. The stripper provided higher harvest rates compared with the picker, but increased contamination of lint with cotton trash to a greater extent than the picker. Cultivars that were amenable to mechanical harvest progressively replaced those that were hand-picked. These cultivars had improved performance in narrower rows, stronger fiber-to-boll attachment, shorter requirements for growing season, shorter limbs, and closer boll set (Narayanan, 2003, 2005). To a limited extent, some of these crop characteristics facilitated mechanical picking and therefore sped-up adoption of pickers. However, this process also led to increased pressure on gins due to faster delivery rate from the field (Hughs et al., 2008; Musoke and Olmstead, 1982). Subsequently, the development of field-based module building systems in the late 1970s reduced gin downtime and removed this pressure, but reduced safety in the work environment (Fragar and Temperley, 2011).

Innovation and automation in cotton picking technology are often regarded as key drivers for a successful and competitive industry. However, mechanization of cotton harvesting brought about contrasting effects; for example, increased picking rates, ability to manage greater land areas, and lower labor requirements, but also resulted in gin downtime and safety issues (Fragar and Temperley, 2011; Holley, 2000; Key, 1985). In mechanized agriculture, higher capacity machines have contributed to reduce risk associated with climate uncertainty (timeliness), improve harvest rates and overall system efficiency but, often, at the expense of increased weight of farm equipment. Cotton production systems are no exception; cotton pickers feature more design constraints than other systems because of the picking action of the spindle. Maximizing picking efficiency, that is the percent of cotton picked from the crop, requires plants to pass through the spindle mechanism (Willcutt et al., 2010). Consequently, the direction of travel must be the same for that of planting. Because the majority of Australian cotton growers (approximately 80%) utilize furrow irrigation (Roth et al., 2013; Silburn et al., 2013), picking must be conducted in the same direction as the furrows in any location in the field. Other crops such as winter cereals do not have this limitation because the plants can be cut at any position relative to the front of the machine by harvesting first. Hence, the direction of harvest can change from the planting direction, allowing for increases of turning space. Conversely, furrow-irrigated cotton fields in Australia are characterized by “dead space” at the head ditch reserved for turning machinery, which cannot be increased by harvesting first. Therefore, the turning circle has to be small to minimize turning time, which is enabled by maintaining a short wheel-base and a relatively narrow, rear track-gauge width (Deutsch et al., 2001). The latest cotton pickers manufactured by John Deere (e.g., JD7760 and CP690), commonly referred to as round balers (RB), utilize on-board module building (OBMB), as opposed to the conventional boll basket picker (BP), which requires external module building and additional in-field equipment support to operate (Deere and Company, 2014; Willcutt, 2011). The weight of the RB is approximately 36 Mg fully loaded, with a rear axle load reaching 16.5 Mg; this represents a weight increase of about 50% compared with the BP (Deere and Company 2012). This has several engineering design implications for the RB, including: (1) increased dimensions of rear tires, (2) repositioning of engine, and (3) raised chassis. The increase in the overall weight of the machine has resulted in increased risk of soil damage due to compaction, which is recognized in several studies to be one of the main causes of soil degradation in cotton-based systems in Australia (e.g., Bennett et al., 2014; Braunack and Johnston, 2014). Estimates for Australia indicate that the cost of soil compaction, determined as equivalent agricultural production loss, is approximately AUD 850 million per year (Walsh, 2002). The incidence of soil compaction has brought about increased questioning on the maximum acceptable axle load for agricultural machinery with large physical footprints (Mosaddeghi et al., 2007). Despite this, the Australian cotton industry has seen a rapid adoption of RB, with approximately 80% of the cotton area harvested in the 2012-2013 season picked by RB pickers (Bennett, 2013). Further, 36% of RB owners have more than one RB picker (Bennett, 2013). The RB picker has been labeled as a revolution in cotton picking (Wattonville, 2008); however, improved understanding of its potential impacts on the cotton production system is required.

Overview of Efficiency Gains. Harvest rates of cotton pickers have increased with the increase in harvest frontage width from approximately 0.35 ha h^{-1} for a two-row cotton picker to 3.5 ha h^{-1} for the six-row RB picker (Key, 1985; Willcutt et al., 2009). This is shown in Fig. 1(d) based on several studies (Chen and Baillie, 2009; Kocher et al., 1989; Kulkarni et al., 2008; Parvin and Martin, 2005; Wanjura et al., 2013; Wilcutt, 2011). Field efficiency has remained close to constant for the BP system using baskets for uncompressed boll capture, whereas OBMB is greater by approximately 75%. Effective capacity is derived from field efficiency and forward speed, and appears to be the parameter upon which mechanization had the greatest effect.

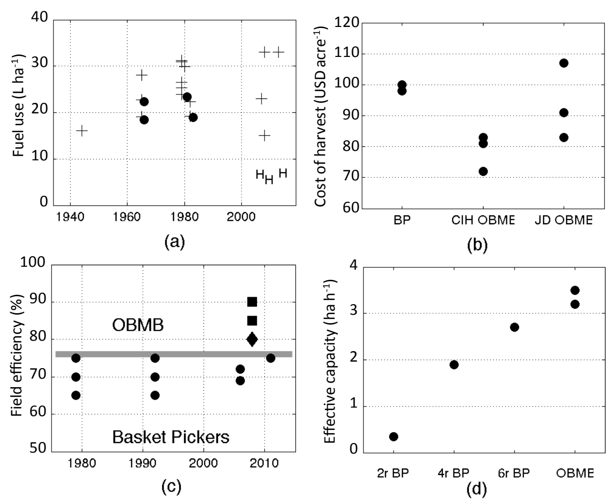

Figure 1. (a) Fuel use during first (+) and second picking (●), and the handling system (H); (b) Cost of harvest for basket pickers (BP), CASE IH OBMB, and the JD OBMB; (c) Field efficiency over time for basket pickers (●), CASE IH OBMB (♦), and the JD OBMB (■); (d) Effective capacity for two- (2r), four- (4r) and six-row (6r) basket pickers, and the OBMB.

The increase in cotton picking rate indicated in Fig. 1 has not translated into increased fuel, which has remained close to constant despite the operating capacity gains. Three main constraints on field machinery operations exist that affect the theoretical capacity (TC): (1) operational, (2) power- and machine-related, and (3) weather-related (Gao and Hunt, 1985). Therefore, the actual or effective capacity (EC) is somewhat less than TC. The EC depends on field efficiency (FE), which considers the total effect of the following factors contributing to time waste (Edwards and Boehlje, 1980; Gao and Hunt, 1985): (1) non-operating turns, (2) less than full-width operation, and (3) stopped time (e.g., refueling, machine adjustments). The FE is therefore the ratio of time effectively used to total time spent processing an area, that is, the ratio effective to theoretical field capacity (Gao and Hunt, 1985). These relationships are shown in the following equation:

$$EC = TC \times FE$$

where: EC is effective capacity, TC is theoretical capacity, and FE is field efficiency.

EC appears to be the main factor underlying machine innovation and technology uptake. The need for increased EC has influenced cotton production systems in several ways. In the 1940s, on the high-yielding West Coast of the U.S., the cotton spindle picker rapidly replaced hand-picking (Heinicke and Grove, 2008). As a result of technology uptake, farm incomes, farm size, and productivity increased, which are perceived benefits of increased EC. Conversely, pickers' adoption in the southeastern U.S. was slower, as discussed earlier. Share-farming was a system where farm owners would share profits with former slaves and the poor, promoting reliable and permanent labor supply. The region was tailored for hand-picking through natural climate, small land holdings, and the lack of effective mechanical and chemical means for weed control. Consequently, the picker was not readily adopted due to fear that cotton growers would lose labor for field operations (Heinicke and Grove, 2008; Musoke and Olmstead, 1982). During the 1960s and 1970s, developments in herbicide technology reduced the need for on-farm labor (Duke and Powles, 2008; Holley, 2000). At the same time, economic growth and rising wages motivated migration from rural to urban areas (Holley, 2000). Higher wages and prospects in cities pulled 60 to 80% of rural workers to urban areas, whereas only 20 to 40% of workers from cities left to fill the void of workforce requirement in rural areas. The net result was a 40% workforce deficit (Holley, 2000; Peterson and Kislev, 1986). Although the impact of mechanization in the West was largely positive, in the South, the debate continued as to whether the cotton picker was or was not the main cause of mass exodus (Grove, 2002).

Between 1955 and 1965, adoption of cotton pickers in the U.S. increased from 12 to 100%, which made it difficult for ginners to process the influx of machine-picked cotton (Anthony and Mayfield, 1995). Gins became the bottleneck in the harvest chain system, which led to farmers dumping cotton at the ends of rows to enable picking to continue (Anthony and Mayfield, 1995). In the late 1960s, the caddy and the ricker became the first devices to form a free-standing stack of cotton (Anthony and Mayfield, 1995). However, these free-standing stacks were inefficient in comparison to the conventional system developed later by Cotton Incorporated known as the module building (MB) system (Jones and Wilkes, 1973). Complete adoption of the MB system did not happen until four-row cotton pickers increased field efficiency in the 1980s. Although the MB system was successful in removing the gin as the main impedance from an occupational health and safety perspective, it significantly increased the risk of injury (Willcutt et al., 2009). In Australia, from the 1997-1998 to the 2005-2006 seasons, the MB system was responsible for 723 workers compensation claims and claimed four lives (Fragar and Temperley, 2011).

Mechanical picking introduced trash to the gin; attempts to remove it would often downgrade the cotton even further, due to tangles and broken fiber (Hughs et al., 2008; Williford et al., 1986). Plant breeding programs implemented to improve plant architecture along with development of improved agrochemicals enabled more efficient mechanical harvest and enhanced quality of cotton (Narayanan, 2003, 2012; Street, 1955). Manipulation of plant structure and physiology to favor mechanical picking made hand-picking harder, which accelerated adoption (Musoke and Olmstead, 1982). Although hand-picking is the slowest method, it is the cleanest in terms of trash content, and in developing countries, the cheapest in terms of capital outlay (Narayanan, 2005). Hand-picking is still the dominant method worldwide with approximately 70 to 80% of total cotton produced globally being collected manually (Fig. 2). Stripping is the fastest method but relatively less clean, whereas mechanical picking is the compromise between speed and cleanliness (Wanjura et al., 2013). Figure 2 also shows that the U.S. is the largest market for cotton pickers with approximately 30% of cotton production originating in Texas, which has 85% adoption of strippers.

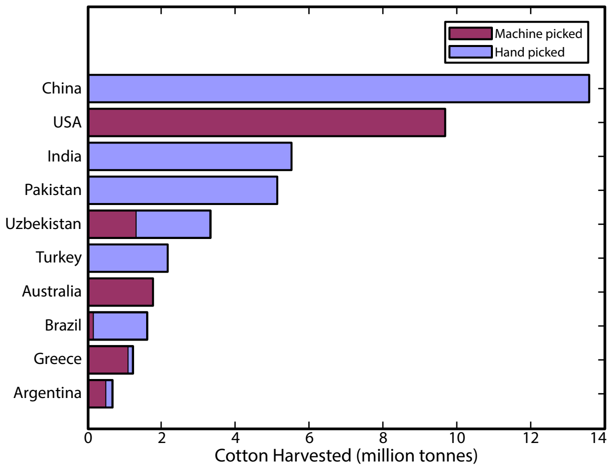

Figure 2. Top ten producers of cotton in the world, based on data from Chaudhry (1997) and Narayanan (2005), showing the ratio of machine-picking to hand-picking. FAOSTATS (2013) shows higher production in India compared with the U.S.

Overview of Cotton-Picking Systems in Australia. The growing conditions and yields for cotton in Australia are similar to those in the western U.S. (USDA, 2015). Both regions have seen similar rates of adoption of novel picking technology (Bennett, 2013; Musoke and Olmstead, 1982). Differences between the RB and BP system fronts are minimal; however, the former machine does not require stopping to unload into boll buggies, which is the main gain in terms of improved efficiency (Willcutt et al., 2009). On average, one boll buggy and one MB are required for every six rows of cotton harvest, meaning that the OBMB demands approximately the equivalent of 2.5 tractors per 1000 ha (Parvin and Martin, 2005).

Relatively high yields per hectare in Australia, as compared to the U.S. result in an approximate requirement for 1.5 boll buggies or 2.5 module builders per 1000 ha of cotton picked at six rows. Consequently, labor requirement was reduced by eight people every 1000 ha. Another effect identified with the use of OBMB, particularly the RB, is that cotton presents larger moisture variation to ginners in a ginning run, due to a mixture of cotton bales picked at different times during the day (Houlahan, 2012). There is less mixing of cotton in the RB system compared to the BP, which stores cotton in a basket and is subsequently transferred either into a boll buggy or a MB, which receives multiple compressions (Willcutt et al., 2010). In the RB, cotton is compressed only once following picking, which reduces the opportunities for airing (Willcutt et al., 2010). This increases variation at the gin, as round modules reflect field variation, although are internally homogeneous and arrive at the gin often not in sequence, whereas conventional modules builders homogenize field variability into larger modules and are sequenced easily, meaning less variability at the gin (Willcutt et al., 2010). Several studies (e.g., Houlahan, 2012; Vanderstok, 2012) highlighted additional costs associated with the RB system such as the wrap and increased cost of transport due to weight and size of harvesting equipment.

To increase EC, machine efficiency and process automation are the main requirements. Direct benefits on productivity also carry latent effects on the system, such as those relating to decreased workforce availability, health and safety-related issues, and potential impacts on social capital at the regional scale. The Australian cotton industry is characterized by its resilience and responsiveness to technological changes; for example, by strengthening production and processing systems. This process has been acknowledged as ad-hoc and reactive, rather than structured and mitigative. Early identification of likely technological effects on cotton production and processing systems would enable systems optimization prior to significant technology uptake across the industry.

Implications of Increased EC. Initial concepts to compress cotton on-board began in the early 1920s with an all-in-one picking and ginning machine, and continued in the 1950s and 1960s (Nickla, 1968; Silverthorne, 1919; Wagnon, 1956). However, the physical properties of cotton have presented machinery designers with challenges, which led to the development of augers to compact cotton on harvesters (Deutsch, 1989). Subsequently, this concept led to the design of the first OBMB in the 1980s consisting of an auger 1.5 m in diameter and two module chambers (Fachini and Orsborn, 1985). The first OBMB was developed by John Deere and CASE IH in the early 2000s (Covington et al., 2003). John Deere combined the cotton picker with design and principles applied to hay balers, whereas CASE IH used proven concepts of the MB (Gola et al., 2000; Viaud, 1990). Due to the automation of the module-forming process, both John Deere and CASE IH developments improved overall occupational health and safety aspects of cotton harvest (Fragar and Temperley, 2011). However, the focus on improving EC also resulted in increased overall machinery weight compared with conventional BP. The increase from two- to four-row pickers revealed a number of design constraints such as the relationship between spindle size and forward speed of the machine (Fig. 3). When forward speed is increased, the speed of the row of spindles needs to be increased to maintain a zero velocity relative to the cotton plant. The rotational speed of the surface of the spindle also needs to be increased so that the barb can continue to attach to the cotton fiber and be removed from the plant (Baker et al., 2015). This problem can be overcome by increasing the revolutions per minute of the spindle or by increasing its diameter (Baker et al., 2015). The latter solution results in increased weight of the spindle and cost of material; hence, increased rotational speed is the preferred option. The drawback is that higher revolutions per minute might decrease lint quality through higher counts of short fiber and tiny knots (neps), suggested to double occurrence for every 1000 rpm increase (Armijo et al., 2006; Baker et al., 2010).

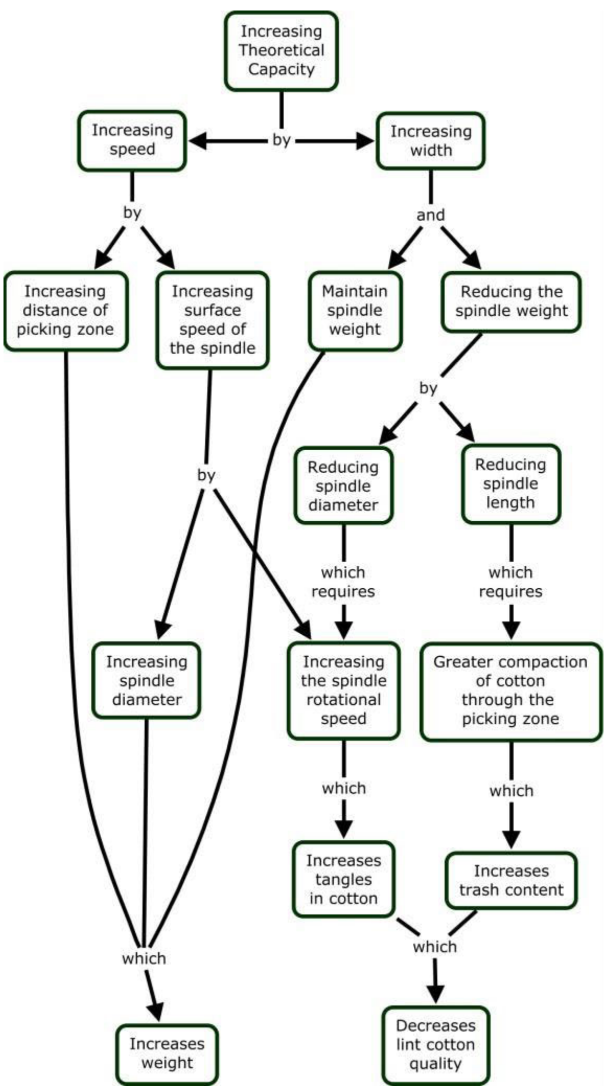

Figure 3. Constraints and possible engineering solutions to optimize forward speed, speed of spindles relative to the ground, speed of the surface of the spindle, which enables the attachment of cotton, and rotational speed, which can potentially tangle cotton.

Theoretical capacity can also be improved by increasing operating width. This option requires increasing the length and diameter of spindles, which increases overall machinery weight (Key, 1985), as shown for CASE IH cotton pickers when the two-row machine was widened to four. The drawback of this is two-fold: (1) with shorter spindles, cotton needs to be compressed to a greater extent to ensure sufficient contact with barbs, which therefore adds trash to cotton seeds, and (2) reducing spindles' diameter requires an increase in their rotational speed, which has the complications discussed earlier. Therefore, the design of a faster machine requires optimization of engineering components affecting the quality of cotton picked and the overall weight of the machine. The OBMB significantly increased field efficiency in RB pickers (Fig. 4) primarily due to unloading time, an additional 12 Mg were added to the machine, including 9 Mg on the rear axle (Wattonville, 2008). The dynamic axle loading of the RB picker (Fig. 5) can be estimated using the field-ready starting weight of 32 Mg (Deere and Company, 2012), and by applying force and moment equilibrium analyses using the relative position of bales from the scaled-drawing shown in Fig. 4. Axle loading was estimated by bale position, specifically, leverage and load spread over the axles. Therefore, the center of gravity of the first bale was laterally determined as 3.9 m from the front wheel (dimension E) and the center of the rear bale to be 7.5 m (dimension F).

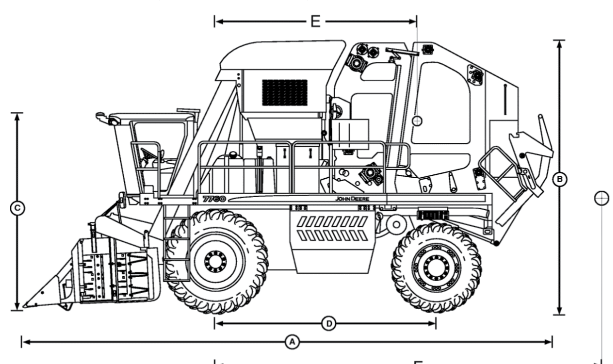

Figure 4. Side drawing of the JD7760 cotton picker (after Deere and Company, 2012). Dimensions are: (A): 10.1 m, (B): 5.25 m, (C): 3.81 m, (D): 4.32 m, (E): 3.89 m, (F): 7.48 m.

In Fig. 5, the starting weight includes the weight contribution of fluids, five rolls of wrap, dual wheels, and six-row PRO-16™ picking units. During the formation of the initial RB, the front axle load remains relatively constant at approximately 21.5 Mg. Subsequently, it decreases to slightly less than 20 Mg as the bale moves to the rear platform. The load on the rear axle is more dynamic compared with the front axle having an initial weight of approximately 10.6 Mg when the machine is empty and increasing to 12.8 Mg after the first RB is formed. Subsequently, the rear axle load changes from 14.5 Mg to 16.5 Mg when the second RB is formed, which equates to approximately 45% of the total load of the machine. The absolute maximum (dynamic) weight of the machine fully loaded with cotton and assuming the weight of a round module to be 2.27 Mg (Deere and Company, 2012) is estimated to be 36.5 Mg. This analysis does not compute the weight of the cotton in the accumulator.

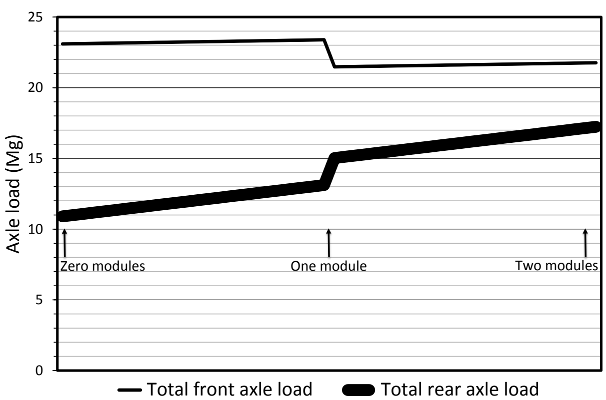

Figure 5. Dynamic axle loads for front and rear axles of a round baler cotton picker. The x-axis represents the time that takes to form a round bale. The space between these points is the transition phase as a bale is produced.

An increase in machine length could alleviate the significant increase in dynamic load on the rear axle but such a configuration could have a negative effect on turning efficiency. Tight turnings allow for reductions in turning times (Renoll, 1979). It also enables the machine to fit between the head ditch and the start of the row in situations where cotton is furrow-irrigated. Therefore, a short wheel base with high angle pivoting rear tires is critical (Wong, 2001). John Deere expressed difficulties in accommodating for larger wheels and maintaining a tight turning circle (Fox et al., 2009). This would necessitate repositioning and realignment of the engine, and raising the rear wheel cavity accordingly to create the required space (Fox et al., 2009). Tire dimensions for the JD7760 are 520/85R42 R1 (inflation pressure: 0.25 MPa) and 520/85R34 R1 (inflation pressure: 0.32 MPa) for the standard dual front and standard steering tires, respectively (Deere and Company, 2014). Increasing the wheelbase and track width requires sharper steering of the wheel to maintain the same turning circle (Wong, 2001). Constraints from the cotton production system and machine design characteristics have resulted in restrictions in all three dimensions: height (storage and transport), width (cost and weight of additional picking units), and length (turning circle radius). Space for the addition of the OBMB is limited, resulting in much of the excess weight positioned on the rear axle. The following sections review the implications of increased axle load, with particular regards to its effects on soil compaction.

SUSTAINABILITY CONSIDERATIONS IN COTTON HARVESTING

Soil Compaction. Compaction is regarded as one of the main causes of soil degradation worldwide and has negative effects on the wider environment (Hamza and Anderson, 2005). The development of agricultural machines with increased EC brought about increased risk of soil damage due to compaction (Chamen, 2014; Kutzbach, 2000). Attempts to mitigate such a risk require concerted effort from machinery manufacturers, growers, and advisors as well as farming system considerations (Etana and Håkansson, 1994; Raper, 2005). Compaction occurs when the load applied to the soil exceeds its precompression strength, which results in increased bulk density (Chancellor and Schmidt, 1962). Consequently, total pore space is reduced and pore geometry is distorted (Alaoui et al., 2011; Lipiec et al., 2012). This process reduces soil aeration, water infiltration, and hydraulic conductivity, and increases the risk of waterlogging (Berisso et al., 2012; Chyba et al., 2014; Vomocil and Flocker, 1961). Compaction is also recognized as a constituent of soil physical degradation that accelerates erosion processes (Reed, 1983; Tullberg et al., 2001) and loss of soil organic carbon (Kadlec et al., 2012; Lal, 2004). There exists a positive, linear relationship between nitrous oxide (N_2O) emissions and the combined effects of soil bulk density and clay content, but bulk density has a relatively higher influence on regulating fluxes than clay content (Ball, 2013). The effect of soil compaction on N_2O emissions is due to impaired surface and internal drainage, which in turn increases the risk of waterlogging (Antille et al., 2015). Under conditions of high (>60%) water-filled pore space, NO_3^--N undergoes denitrification, which releases N_2O (Bremner and Shaw, 1958).

When soils are relatively dry, precompression strength is high, but reduces rapidly as soil moisture approaches field capacity (Hamza et al., 2011; Van den Akker and Soane, 2005). The rate at which this reduction occurs is largely dependent on clay content (Håkansson et al., 1987). Confinement of all load-bearing wheels to permanent traffic lanes (or CTF), offers an effective means for compaction management (Tullberg et al., 2007). The establishment of permanent traffic lanes offers the advantage of improved trafficability (reduced rolling resistance and wheel-slip) and timeliness to conduct field operations, which in turn reduces timeliness costs (Bochtis et al., 2010; De Toro and Hansson, 2004; Tullberg, 2014). However, CTF systems require that all machinery has the same, or modular, working and track gauge widths, which is seen as the main constraint for increased adoption within cotton-based systems in Australia (Braunack and Johnston, 2014; Tullberg, 2010). Without CTF, varying equipment operating and track gauge widths often result in random traffic patterns, which can cover up to 85% of the cultivated area each time a crop is produced (Kroulík et al., 2009; Tullberg, 2010). The following sections discuss soil compaction from the machine traffic perspective and consider the RB cotton picker through examination of similarly heavy machines used in other agricultural industries.

Importance of Axle Load. The relative importance of axle load and tire characteristics (size, inflation pressure, aspect ratio) has been extensively debated in soil compaction research (e.g., Bédard et al., 1997; Lamandé and Schjønning, 2011; Soane et al., 1981a, b; Tijink et al., 1995; Way et al., 1997, 2009). The continuous increase in axle loads has brought about increased questioning on the maximum acceptable mechanical compressibility of arable soils (Mosaddeghi et al., 2007). As a result, the relative advantages of tires and rubber tracks to cope with high axle loads, in terms of their tractive performance and impacts on soil, have received considerable attention (e.g., Alakukku et al., 2003; Ansorge and Godwin, 2007, 2008; Erbach, 1994; Kirby et al., 1997; Pagliai et al., 2003). In addition, weight limits to axle and wheel loads have been suggested. For example, Danfors (1994) suggested a threshold value for machine axle load of 6 Mg (single axle) or 8 Mg (tandem axle) to minimize the risk of irreversible soil compaction. Generally, an increase in tire size is accompanied by a decrease in tire inflation pressure to support a given axle load. This also provides improved tractive performance and reduces soil displacement because the average soil contact pressure under the tire is approximately equal to inflation pressure plus pressure caused by carcass stiffness (Misiewicz et al., 2015; Plackett, 1984). However, the type and size of the undercarriage system fitted to the vehicle are restricted by engineering- and design-related aspects of the machine. Hence, the importance of limiting axle loads in situations where the undercarriage system is not readily modifiable. Under CTF, this consideration is less critical because traffic occurs on consolidated wheel-lanes. However, the incompatibility between tire configuration and track width of pickers, particularly the RB and crop row spacing makes it difficult to apply a true CTF system for cotton (Antille et al., 2015; Bennett et al., 2014; Braunack and Johnston, 2014).

Traffic-induced compaction can be explained by principles relating to soil mechanics and includes elastic and plastic deformation, and failure phases (Défossez and Richard, 2002; Nawaz et al., 2013; Upadhyaya et al., 2009). The elastic phase represents reversible compression that changes to irreversible as the plastic deformation phase is reached. This means that the effects of compaction can change from reversible to irreversible as compression stress exceeds precompression stress. Thus, conventional farm machinery with axle loads often exceeding 10 Mg presents a concern for irreversible soil compaction when considering the axle load threshold suggested by Danfors (1994). In such situations, alleviation of compaction by means of tillage is required to restore its physical conditions and functions (Batey 2009; Spoor, 2006). However, tillage repair is energy demanding, particularly when compaction is present relatively deep (e.g., $\geq$ 300 mm) in the profile (Godwin, 2012; Tullberg, 2000). Readers are referred to several reviews regarding requirements, equipment, and techniques available to alleviate soil compaction (e.g., Batey, 2009; Godwin, 2007; Godwin et al., 1984; Raper and MacKirby, 2006; Spoor, 2006). Some clay soils with shrink-swell properties, for example, are self-restructuring and can recover from the effect of field traffic to a greater extent than typically sandy and silty soils, which do not restructure naturally following cycles of wetting-drying (Pollard and Webster, 1978).

Several studies have been conducted worldwide with axle loads in the range of 10 to 25 Mg, which corresponds to that of the RB cotton picker (e.g., Arvidsson, 2001; Ansorge and Godwin, 2008; Etana and Håkansson, 1994; Flowers and Lal, 1998; Gameda et al., 1994; Håkansson, 1985; Lal and Ahmadi, 2000; Schäfer-Landefeld et al., 2004). Research has shown that compaction decreases with an increase in soil depth up to a about 800 mm (Berisso et al., 2012; Gysi et al., 2000; Håkansson et al., 1987; Wood et al., 1993). Studies on medium-textured soils (e.g., Ansorge and Godwin, 2007; Antille et al., 2013) showed that soil displacement (effective change in soil bulk density) induced by a single pass of a combine harvester tire loaded to 10.5 Mg decreases approximately linearly from the surface to a depth of 700 mm. Differences in axle load aside, compaction is a function of soil mechanical strength, which is governed by properties such as clay, organic matter, moisture content, soil structure, and the tilled state of the soil prior to traffic (Guérif, 1984; Hamza et al., 2011; Hettiaratchi, 1987; Imhoff et al., 2004; Larson et al., 1980; O'Sullivan et al., 1999). Changes in these characteristics between soils account for variation in compaction depth not explained by axle load. Therefore, soil stresses resulting from axle loading will determine the potential risk of soil compaction, whereas the actual risk is a combination of soil strength and soil stress.

Keller and Arvidsson (2004) observed that axle load is less important than the individual wheel load in an experiment comparing dual- and tandem-wheel configurations. Their study indicated that soil compaction is mainly a function of the stress on the soil surface and contact area, which can be derived from wheel load, wheel arrangement, tire inflation pressure, contact stress distribution, and soil conditions. Although they further stated that soil compaction is not a direct function of axle load or total machine load, such loads influence contact pressure. Thus, wheel load can be used to describe the potential for soil compaction when parameters such as tire size and inflation pressure are accounted for (Berisso et al., 2013; Keller and Arvidsson, 2004). Several studies (e.g., Ansorge and Godwin, 2007; Antille et al., 2013; Schjønning et al., 2012) have shown that although soil stress is a function of surface loading, tire dimensions and inflation pressure have a relatively larger impact at shallower depths, whereas wheel load is the controlling factor at greater depths. Raper and MacKirby (2006) indicated that a heavier machine will induce deeper compaction than a lighter one when soil stresses at the surface are the same. For a given axle load, larger (overall) tire diameter will reduce contact pressure because it requires a lower inflation pressure. However, some studies (e.g., Raper, 2005) showed that pressure caused by tire carcass stiffness increased with an increase in overall tire diameter. Wide tires and dual or multiple tire configurations enable reductions in tire inflation pressure and contact pressure for a given axle load. However, in the field, the main drawback of these arrangements is the associated increase in the area that receives traffic.

A further consideration is the use of rubber tracks, which have demonstrated advantages compared with wheels in terms of reduced soil compaction, as shown by Ansorge and Godwin (2007, 2008) for combine harvesters loaded to 24 Mg on medium-textured soil (bulk density 1.40 g cm^{-3} at approximately 50% field capacity). This is partially due to greater shear force exerted for longer beneath the rubber track, which creates a dense layer near the surface (depth range: 0-150 mm) (Ansorge and Godwin, 2008). Densification of near-the-surface soil prevents further compaction caused by the rear tire following a leading rubber track, whereas additional compaction can occur when the rear tire follows a leading tire (Ansorge and Godwin, 2008). The practical implication of that observation lies in the fact that removal of compaction caused by a rubber track will require a significantly shallower tillage operation and consequently less draft (Godwin, 2007). The relative advantages of tires and rubber tracks are discussed in several reviews (e.g., Arvidsson et al., 2011; Hamza and Anderson, 2005; Raper, 2005). Specifically for the RB cotton picker, rubber tracks can prevent tight turnings and consequently its use might not offer the tractive advantages and versatility observed for combine harvesters. However, further research is needed to determine if gains in EC could be realized within the current design of the picker and without the need to increase significantly the overall weight of the machine.

Compaction Lessons from Sugar Beet and Grain Harvesting. The weight of sugar beet (*Beta vulgaris* L.) harvesters is reported to be in excess of 40 Mg when the machine is fully loaded, with maximum axle loads reaching about 27 Mg (Schäfer-Landefeld et al., 2004). More recent developments of sugar beet harvesters, such as the Holmer T4-40 beet harvester, have a total weight of 32 Mg empty and up to 60 Mg when fully loaded (Chamen, 2014; Demmel et al., 2008). Such high axle loads cause concern over long-term effects of soil compaction (Arvidsson, 2001). In this respect, work by Berisso et al. (2012) suggested that the effects of compaction caused by sugar beet harvesters can persist for up to 15 years. Similar observations were reported in other studies (e.g., Demmel et al., 2008).

In grain cropping situations, the introduction of zero- and minimum-tillage systems advanced, to some extent, soil recuperative processes (including maintenance of soil fertility and organic matter), and contributed to reduce runoff and erosion, increasing water (rainfall) use efficiency (Derpsch et al., 2010; Kirkegaard et al., 2014). However, increased adoption of those systems led to increased interest in long-term effects of soil compaction (Díaz-Zorita et al., 2002). Developments in grain harvesting technology also have resulted in increased machinery size, which has enabled increasing the frontage harvested (increased EC). Such machines weigh up to 30 Mg fully loaded carrying approximately 70% and 30% on the front and rear axles, respectively (Ansorge and Godwin, 2007). Table 1 compiles information available in the literature showing crop yield reduction caused by traffic-induced soil compaction. These data confirm that crop yield is significantly affected by soil compaction and that yield penalties are expected to be greater in situations where heavier axle loads are used, as well as soils with higher clay content. For cotton, Hadas et al. (1985) observed that residual compaction caused yield reduction through reduced plant population (poor establishment) and increased stand variability, particularly when soil bulk density (sandy loam) was higher than approximately 1.25 g cm^{-3}. McGarry (1990) observed a 73% cotton lint yield reduction in a compacted Vertisol (depth range: 200-400 mm), which impeded root growth and water permeability at the first irrigation causing waterlogging and lodging.

Potential Effects of the RB Cotton Picker. The John Deere RB has a six-row cotton frontage, which is compatible with a 12-m planting system common to cotton (Fig. 6). Because the machine is fitted with dual tires on the front axle, the area traversed is larger compared to conventional four-row pickers. In skip-row systems, the impact of conventional pickers is lower if the tool bar is accommodated to operate on a six-row frontage with four picking units. The wheels can be aligned with the wheels of the RB between rows 2 and 3, and rows 4 and 5, respectively (Fig. 6). However, in Australia, this modification has also been undertaken on the RB to allow an eight-row frontage with six picking units, which is not compatible with 12-m planting systems. Estimates for Australia indicated that less than 20% of farmers across all industries use CTF in the true sense of permanent wheel tracks and matching machine centers (Tullberg et al., 2007). Many intend to implement CTF, but find it cumbersome due to the costs of conversion, incompatibility of existing equipment on farm (e.g., track width, implement width, or both), and warranty issues. Modification to an eight-row frontage (six-row pick) is seen by cotton growers as effective in terms of increased EC, but potentially detrimental from the soil compaction perspective. Whether using CTF, picking in skip-row, or solid cotton systems, the dual

Table 1. Yield loss and calculated gross income penalty observed in arable crops affected by compaction during harvest of the previous crops

Crop	Yield loss (Mg ha^{-1})	Yield reduction (%)	Value (AUD ha^{-1})	Source
Sorghum (grain)	0.9	50^z	221	Jensen et al. (2000)
Wheat	0.75	30^z	236	Jensen et al. (2000)
Wheat	0.7	21	221	Radford et al. (2001)
Wheat	0.9	15	284	Neale (2011)
Maize	0.41	30^z	72	Jensen et al. (2000)
Maize	2.18	43	382	Radford et al. (2001)
Soybean	0.79	30	379	Botta et al. (2007)
Canola	2.1	66^z	1050	Chan et al. (2006)
Cotton (seed)	0.11	7	30	Ishaq et al. (2003)
Cotton (seed)	0.95	22	257	Kulkarni et al. (2010)

Sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum* L.), maize (*Zea Mays* L.), soybean (*Glycine max* L.), canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.).

^{z} Reduction of yield in traffic-affected rows only as compared to non-traffic affected rows.

Value is yield loss (Mg ha^{-1}) × price of crop (AUD Mg^{-1}) based on the average grain price for the period 2009-2013 (Flores-Piran, 2014).

wheels of the RB increase the total area subjected to traffic compared to conventional pickers. The use of BP requires boll buggies, which enable machine downtime to be minimized by unloading a full basket into the boll buggy. Therefore, the picker can work continuously without the need to leave the field. Figure 6 only portrays the traffic path of the picker; it does not show the traffic patterns caused by field support equipment during harvest. Although boll buggies are of less concern from the soil compaction perspective, additional traffic is created between rows 2 and 3, and rows 4 and 5, respectively (Fig. 6).

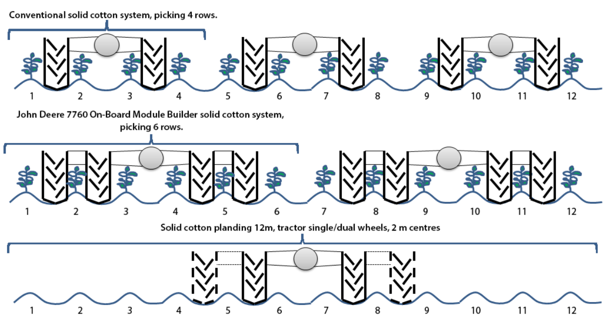

Figure 6. Schematic depiction of a solid cotton system planted in 12 m frontages at 2-m machine centers and harvested using a four-row conventional picker in comparison to the JD7760. Hashed lines show the effect of using a dual-wheeled tractor for planting. The spacing of the dual wheels in the JD7760 is not aligned with furrow centers and encroaches on cotton hills of rows 2, 5, 8, and 11, respectively.

The positioning of machine transient load affects individual wheel loads in a nonuniform fashion. For this reason, Keller and Arvidsson (2004) suggested that wheel load is relatively more important than axle load when soil stresses are estimated, and that each wheel of the machine should be considered independently. In this respect, Schjønning et al. (2012) proposed the 50:50 rule, which refers to the avoidance of traffic in soils with moisture contents near field capacity if soil stresses at 50 cm deep exceed 50 kPa. Other approaches based on critical soil moisture levels for field traffic have been used satisfactorily (e.g., Earl, 1997; Ohu et al., 1989; Vero et al., 2014). For the RB, the dual wheels configuration results in an average wheel load of approximately 5.4 Mg on the front axle, which decreases to approximately 5 Mg as a round module is transferred to the rear haulage basket. The average load on each rear wheel increases from approximately 5.3 to 8.25 Mg, during the same process (Fig. 5). The average wheel load of the RB approaches for all wheels, and in the rear axle, it largely exceeds the threshold load suggested by Danfors (1994). Vertical soil stress simulations using the SoilFlex model (Keller et al., 2007) were performed for the front and rear tires of the JD7760 and JD9996 cotton pickers (Fig. 7). Given the assumptions made in the analyses, results for the dual tires of the JD7760 showed that vertical stresses (100-200 kPa) can occur at 300 mm depth compared with 75-100 kPa under the JD9996 at the same depth in the profile (Fig. 7a,c). Vertical stress caused by a single tire (front axle) under the JD9996 are of similar magnitude compared to each of the dual tires under the JD7760 at 300 mm depth, despite that total contact area is approximately half (Fig. 7a, e). For the rear tires, soil stresses at 300 mm depth are approximately double under the JD7760 compared with the JD9996. Simulated vertical soil stresses for both machines are in close agreement with those reported by Braunack and Johnston (2014), and generally exceed the threshold value suggested by Schjønning et al. (2012).

Further work by Braunack and Johnston (2014) showed that average soil strength (cone index) increased to a similar extent following traffic with conventional BP and RB pickers (depth range: 0-600 mm). However, traffic with the RB caused increased strength (3000 kPa) at a slightly shallower depth (300 mm) compared with the conventional picker (400 mm). Soil strength greater than 2000 kPa causes significant root growth retardation in cotton (Coates 2000). A study by Kulkarni et al. (2010) showed that soil compaction increased progressively in the direction of travel due to the change in cyclic loading that is characteristic in harvesting equipment. The RB places the round module (weight: 2.3 Mg) on the ground as it travels, which commonly occurs in-field given the length of Australian cotton fields. A tractor then needs to remove the module from the field, which increases traffic intensity, albeit on the same tracks. This problem is sometimes overcome by attaching a trailer behind the picker, which is capable of carrying up to four bales, therefore enabling reduction in traffic intensity. The trailer also reduces the period of time in which the load of the rear axle is elevated to 8.25 Mg by distributing the load over tandem axles on the trailer. However, effects of the pass of the trailer over the same pass of the picker require investigation to determine whether additional compaction is created. Although preliminary studies conducted by the authors (Antille et al., 2014) suggested that RB pickers have the potential to increase soil compaction but further work on the extent and management of this damage is needed. It appears that confining traffic to permanent lanes would potentially address this issue. However, several limitations have been identified in similar studies (e.g., Braunack and Johnston, 2014). The area affected by traffic when dual tires are used appears to be one of the main concerns associated with RB cotton pickers. Innovative Australian growers have adapted their machines to suit true CTF system using single tire configurations both on the front and rear axles (e.g., 3-m wheel-spacing on 1-m row-plant spacing). However, such modifications void the machine warranty, which therefore discourages growers from adapting their equipment to make them compatible with CTF systems (Tullberg et al., 2007). Comparative studies are being conducted on the effects of dual-wheeled and single-wheeled RB pickers, which will identify potential benefits for either system, including tillage requirements for compaction repair, and possibly justify costs of conversion to CTF (Bennett et al., 2013).

Managing Soil Compaction and Controlled Traffic Considerations. Approaches to compaction alleviation and management are discussed in several studies, including aspects of machine-soil interactions (e.g., Alakukku et al., 2003; Chamen et al., 2003; Batey, 2009; Spoor et al., 2003; Spoor, 2006; Spoor and Godwin, 1981). An important practical consideration is the correct diagnostic of such compaction in the field (Batey and McKenzie, 2006), including position within the soil profile (surface or deep compaction), thickness of compacted layer and severity (Batey, 2009). For shallow compaction (≤ 300 mm deep) relatively light tillage operations shortly after occurrence are often effective (Birkas, 2008). In some soils, such as those with hardsetting behavior, the response to tillage is variable and additional management strategies might be required (see Daniells, 2012; Fabiola et al., 2003). Subsoil compaction requires deep loosening and its requirements, equipment and techniques are discussed in several reviews (e.g., Chamen et al., 2003; Godwin et al., 1984; Spoor, 2006; Spoor and Godwin, 1978). Field traffic and soil management after deep loosening is performed will have a significant effect on the longevity and effectiveness of the operation, which is due to the susceptibility of recompaction of that soil at greater depths (Batey, 2009; Soane et al., 1986; Soane et al., 1987). Field inspection conducted during deep loosening operations will ensure that the required disturbance is being achieved (Spoor, 2006). Subsoiling needs to be performed below the compacted layer and with the appropriate moisture conditions to ensure sufficient soil fissuring is created (Spoor, 2006). For optimal tine arrangements on the subsoiler's frame, tine geometry and progressive loosening techniques, which are required for effective remediation of deeper compaction (e.g., ≥ 450 mm deep), the reader is referred to work dealing specifically with these aspects (e.g., Godwin, 2007; Godwin and Spoor, 1977; Godwin et al., 1984; Spoor and Godwin, 1978; Spoor et al., 2003).

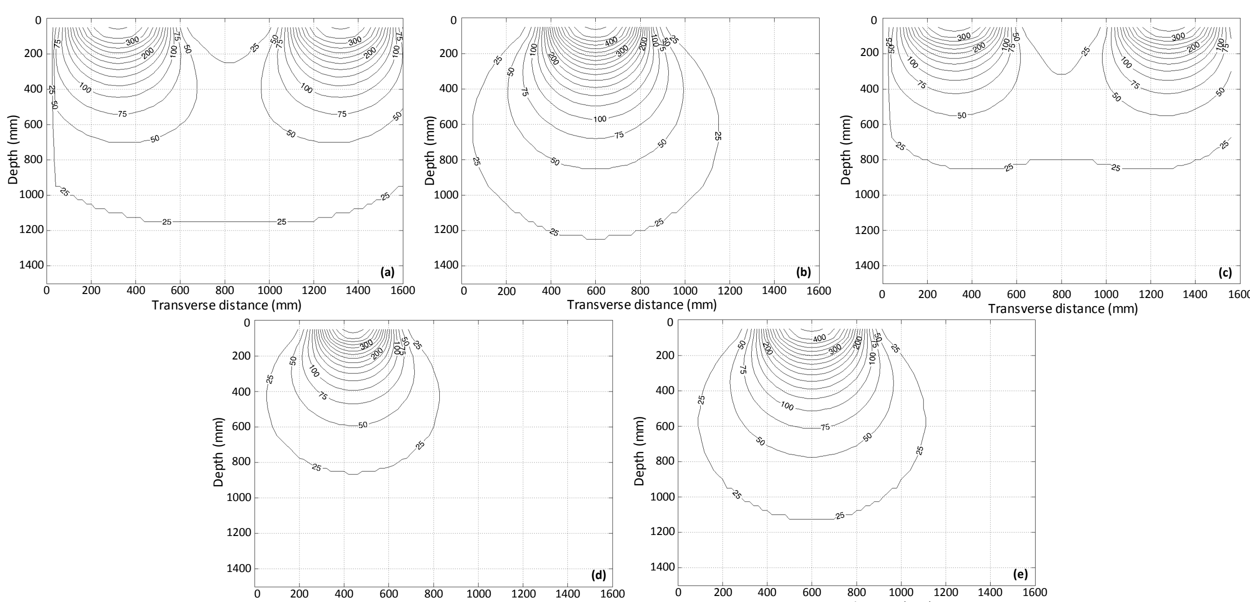

Figure 7. Simulated vertical stress beneath tires using the SoilFlex model (Keller et al. 2007): (a) Dual front tires of JD7760 (520/85R42-R1, average wheel load: 5.43 Mg, inflation pressure: 0.25 MPa); (b) Rear tire of JD7760 (520/85R34-R1, average wheel load: 8.25 Mg, inflation pressure: 0.32 MPa); (c) Dual front tires of JD9996 (20.8-42 14PR-R1, average wheel load: 3.49 Mg, inflation pressure: 0.25 MPa); (d) Rear tire of JD9996 (14.9-24 12PR-R2, average wheel load: 4.08 Mg, inflation pressure: 0.29 MPa); and (e) Single front tire of JD9996 (20.8-42 14PR-R1 or R2, average wheel load: 6.97 Mg, inflation pressure: 0.29 MPa).

In Australia, the SOILpak for Cotton Growers (Daniells et al., 1996) provides guidelines for managing soil compaction in cotton-based systems, and it identifies CTF as a primary recommendation. Despite this and effort spent on education and extension, the rate of adoption of CTF in Australia has been relatively slow, mainly due to incompatibility of imported equipment from North America or Europe, associated costs of conversion and warranties, as discussed earlier (Chamen, 2014; Tullberg et al., 2007). A further consideration is the modified machinery value of re-sell. Adoption of CTF would likely increase if such barriers could be removed, particularly, in regard to customization of farm equipment by manufacturers. For grain cropping situations, Neale (2011) compared the cost of modifying machinery to 3-m wheel-track in a grain system (usually between AUD 5000 and AUD 30,000) and related this to the potential gains to be made by limiting compaction in the field (based on a nominal AUD 200 per ha gain). Based on this, the expense was justifiable and likely to be recovered within a season, or within the first few seasons for an average farm, which was defined by Neale (2011) to be between 1000 and 3000 ha. Similar observations were also made by Kingwell and Fuchsbichler (2011) for grain cropping in Australia, and by Chamen et al. (2015) for the United Kingdom. Improved communication through extension effort and exemplification of this economic rationale would facilitate increased adoption of CTF, which requires involvement of machinery manufacturers to ensure their product is CTF compatible. In situations where CTF cannot be justified, likely soil damage due to compaction can be predicted prior to trafficking. Tools such as SoilFlex (Keller et al., 2007) and Terramino® (Stettler et al., 2014) can be applied to this end using readily available input parameters relating to soil and machine characteristics. Subsequently, further assessment of potential soil damage can be conducted based on the principles outlined in Schjønning et al. (2012).

AUSTRALIAN GROWER PERSPECTIVE OF THE RB COTTON PICKER

An attempt was made to provide an initial perspective on the RB from Australian cotton growers. This exercise was based on the rapid adoption of this machine in Australia and the previous discussions concerning the potential impacts that technological innovations might have upon farming systems. The information presented herein is intended to address the paucity of direct information pertaining to the RB cotton picker and associated impacts on the system. Emphasis is placed on collection of "rich" data (Kelly et al., 2009) through a series of four face-to-face discussion forums held throughout the Australian cotton industry including New South Wales (Hillston, Warren, and Narrabri), and Queensland (Dalby and Goondiwindi). These forums focused on four key discussion points: (1) technology uptake, (2) incorporation of technology to the farming system, (3) perceived and evident impacts of technology, and (4) technical support and communication. The forums were attended by growers, industry representatives, and extensionists who provided valuable industry perspective. A summary of the grower perspectives is shown in Table 2.

To augment these rich data, growers provided information on their on-farm integration of, and attitudes towards, the JD7760 via the annual Cotton Research and Development Corporation (CRDC) growers survey in 2013 (Roth Rural, 2013). The JD7760-specific questions were incorporated into the survey to provide information to this project. The survey was mailed to an effective grower population of 837 with a response of 362 (43% response rate) completed surveys and 134 (16% effective response) completing the cotton harvest section to some extent. The total response represented 23% and 27% of the Australian irrigated and dryland cotton crops, respectively, with regional representation within this ranging from 12 to 30%. The full dataset and survey implement are available from CRDC (http://www.crdc.com.au/) upon request. A summary of the JD7760 and cotton harvest findings collected for this review are provided in Tables 3 and 4, respectively.

Grower estimation of adoption by 2013 is in excess of 80% across all cotton-producing areas, except for Dalby (Queensland, Australia), where growers were uncertain of adoption rate. This agrees with the proportion of the 2013 cotton crops picked by JD7760 machines (approximately 82%), but survey response indicates that 70% of growers own a JD7760 (Fig. 8). Additionally, the proportion of crop picked by a JD7760 machine based on survey response is supported by ginning data that take into account the proportion of the seasonal cotton pick arriving at the gin in round module form (Table 5).

Table 2. Summary of emerging themes for discussion forums held in the Australian cotton industry ordered in terms of key discussion points. Total participants for the five forums were twelve. RB is round baler cotton picker. For frequency of response use N = 12. For number of forums representing view use N = 5

Emerging theme	Frequency of response (%)	No. of forums representing view
Technology adoption		
Adoption of RB influenced by contractors	33	4
Harvest cost reduction is not an adoption driver	92	5
Increased safety	100	5
Management stress is reduced by the RB	42	4
The CASE IH Module Express did not meet the needs compared with the RB	100	5
Incorporation of technology to the farming system		
Cost of wrap per ha is reducing bottom-line	67	3
Skilled operators are required	33	2
Need to be more careful with module moisture	25	3
Parts can be hard to source	58	2
The 2012 RB model accumulator is too small	75	3
Easy control of moisture allowing higher moisture pick (Vomax moisture sensor is a key support tool)	42	3
Machine electronics can cause downtime and frustration	75	4
Perceived and evident impacts of the technology		
Increased effective capacity	67	5
Reduced need for seasonal workforce	50	3
Increased tillage requirement post-harvest	25	3
Soil compaction is an issue	50	5
Decreased workplace health and safety risk	100	5
Increased contamination of modules	33	2
Technical support and communication for the technology		
Technical support provided by dealers is adequate	42	5
John Deere link system	33	3

Table 3. Considerations made by growers prior to purchasing the John Deere 7760 on board module builder and cotton picker

Pre-purchase considerations	Level of consideration				Total responses (n =)
	None	Minor	Mild	Major	
Fuel consumption	29	49	22	0	41
Lubricants consumption	41	41	12	5	41
Machine weight	5	33	38	24	42
Ability to transport	18	20	28	35	40
Potential for soil compaction	5	40	29	26	42
Parts availability	15	27	22	37	41
Ability to service nearby	15	20	20	46	41
Cost of wrap	10	13	25	53	40
Transport of modules	15	23	18	44	39
Controlled traffic compatibility	28	35	23	15	40

Table 4. Perceived impacts of the John Deere 7760 on board module builder and cotton picker since incorporation into cotton growers farming systems

"The JD7760 has…"	Grower response (%)					Total responses (n =)
	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree	
Increased soil compaction	2	18	32	31	17	88
Caused a decline in yield	30	49	17	2	1	86
Reduced my labor requirement	3	7	8	29	54	91
Provided financial savings compared to my previous conventional systems	13	26	31	16	14	85
Had issues with high module moisture	22	42	25	11	0	88
Increased total fuel use	10	36	40	8	6	80
Led to my soil being noticeably harder to cultivate/till/form beds	5	48	34	6	7	85
Increased my picking window	6	24	47	23	0	86
Increased the frequency with which I incur fiber quality downgrades	19	48	26	8	0	80
Better access to information about crop performance within fields	2	14	26	41	16	87

Table 5. Round cotton modules ginned in New South Wales and southern Queensland (Australia) following the release of the RB cotton picker in 2008 (after Vanderstok, 2012)

Location of gin	Round bales ginned at season finish (%)				
Year	2008	2009	2010	2011	2012
MacIntyre	0	0	0	41	62
Mungindi	0	0	26	29	73
Ashley	24	40	39	48	75
Wathagar	0	0	0	20	45
Moomin	0	0	0	28	69
Yarraman	0	0	0	0	26
Merah	0	0	0	0	34
Boaggabri	0	0	0	24	38
Trangie	0	0	0	0	65
Hillston	0	0	0	57	74

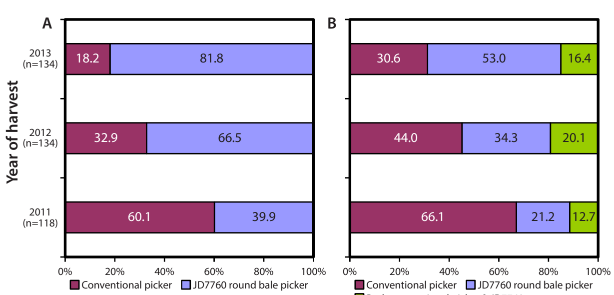

Figure 8. Percentage of cotton growers by year of harvest who: (A) harvested their cotton crop using a JD7760 or conventional picker; and (B) own a JD7760 or conventional picker; n is number of respondents.

Initial insights into adoption drivers suggest that the RB has been adopted due to perceived improvements in system's efficiency, rather than immediate productivity gains, which is often regarded as primary driver of adoption (Kelly et al., 2009). The RB represents a substantial investment (market price at the time this work was undertaken was approximately AUD 750,000), which might be considered as a barrier to technology adoption (Bennett and Cattle, 2014). However, Australian cotton growers do not appear to see this level of capital investment as a barrier for adoption of the RB (Tables 3 and 4). This is explained by the fact that John Deere has elucidated the benefits of the machine to the agricultural system in a way that reduced the perceived risk of investment to growers. The forums identified major adoption drivers as: (1) increased safety on farm, (2) improved effective capacity, and (3) reduced labor requirements coupled with decreased management-related stresses, which is supported by survey data. The vast majority of survey respondents (70%) considered the JD7760 picking system to be on par, or potentially more expensive, than the basket picking system. Furthermore, the survey forum also revealed that 92% of growers agree that increased productivity, which is cost reduction in harvesting operations (crop return considered to be equal irrespective of harvest system utilized), did not drive adoption. This finding supports the finding that growers consider, primarily, the overall benefits to the agricultural system in the decision-making process for technology uptake. In addition, issues with availability of parts and access to qualified mechanical expertise were of concern to 58% of growers in Warren and Hillston (New South Wales, Australia). In Warren, growers indicated that this was due to qualified personnel being relocated away from the region, whereas those in Hillston are more geographically displaced from the center of the cotton industry and might find access to services limited. These aspects also featured heavily in pre-purchase considerations.

The cost of plastic wrap is seen as a latent impact because growers can source it from only one manufacturer, which was echoed in survey responses. The general consent from forums is that this issue will be addressed and that an alternate source of wrap will be developed, ideally within Australia. Prior to purchase, machine and modules transport were major considerations for 33% and 44% of growers, respectively. Approximately 25% of forum participants found the machine difficult to transport, but the large majority (99%) expressed no problems in transporting round modules. This reflects the fact that transport infrastructure does not continue to constitute an impediment post-purchase, possibly due to capacity of fleet and road infrastructure, and a concerted effort by the cotton industry to address interstate regulations concerning transport of modules and pickers (Houlahan, 2012). Approximately, a third of participants agreed that the use of RBs has increased contamination compared with the traditional module, which agrees with observations made in earlier studies (e.g., Krajewski and Gordon, 2010).

Soil compaction was not a major consideration prior to purchase of a JD7760 for approximately three quarters of growers responding to the survey, however, 48% agreed it had increased soil compaction (Table 4). Also, 50% of participants indicated that soil compaction was a problem associated with the RB cotton picker. In Warren, cotton has only been reinstated in the rotation since 2012, due to drought, which means that the use of the RB in that region is only recent. These participants indicated that soil conditions during harvest were rather dry, and therefore, significant damage due to compaction was not observed in 2012. If participants from Warren were removed from the survey, about 80% of responses linked increased soil compaction at harvest with the RB cotton picker. Overall weight of machine was a relatively greater consideration than soil compaction prior to purchase (Table 3), which is presumably related to road traffic and freight considerations.

SYNTHESIS

Towards an Informed Decision-Making Framework. Although the decision to adopt the JD7760 cotton picking system is not in question, the rate of technology uptake has brought about concern over sustainability aspects of intensively managed agricultural soils. These sustainability aspects include potential long-term effects on crop productivity and energy use in tillage repair. Increasing harvest rates in cotton cropping via the range of innovations discussed in this review has shown both positive and negative effects on the overall dynamics and efficiency of the system. To enable such effects to be determined prior to technology adoption and identify possible mitigation options, an impact assessment framework has been developed (Fig. 9). This framework identifies potential impacts considered to be major, based on the information compiled in this work, to assist in informed decision-making.

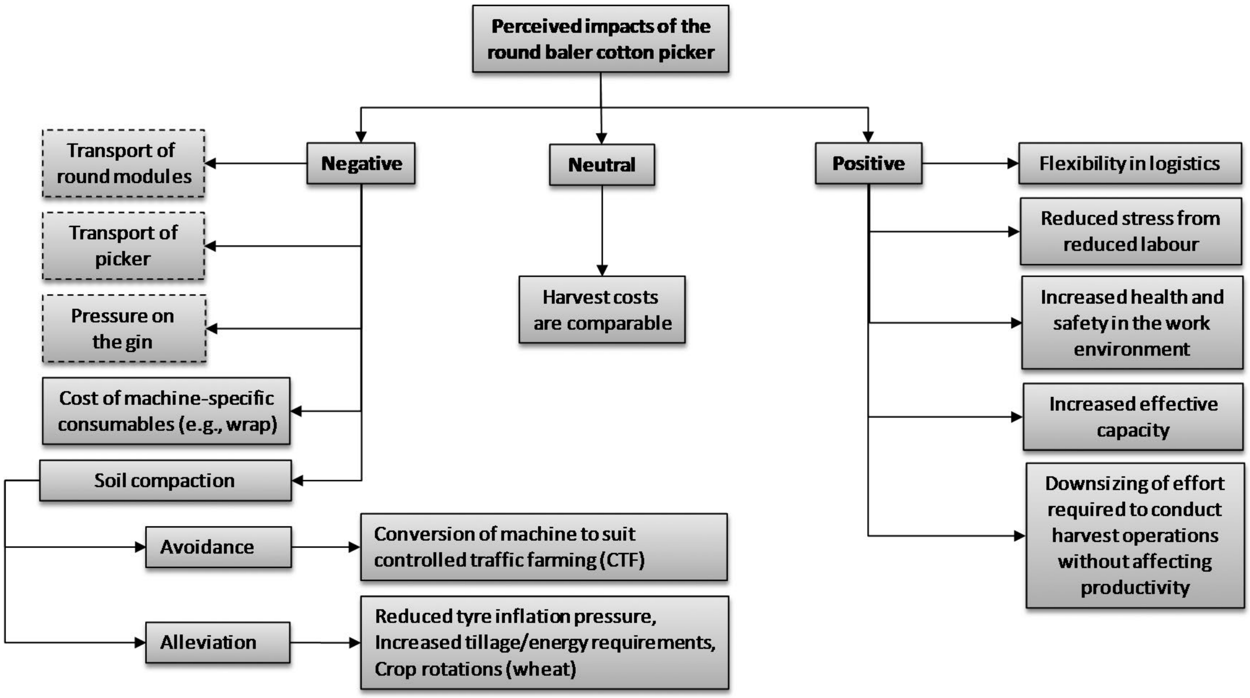

Figure 9. Summary of impacts identified following the introduction of the round baler picker into the Australian cotton system. Information drawn from the Australian perspective and the literature reviewed in this work. Dashed lines indicate that those issues are already dealt with by the industry.

Moving Towards Preempting Risk of Future Innovations. To preempt concerning impacts of future innovations, a structured framework and analysis method should be used. One option is adaptation of a process called Hazard Analysis and Critical Control Point (HACCP) theory. HACCP is a well-established methodology used in the food industry to ensure high quality products with minimum health risks to consumers (FAO, 1998). In agriculture, HACCP approaches have been made to extend the food safety chain back onto farm (e.g., Toregeani-Mendes et al., 2011) and it has also been regarded as a potential tool to improve management and increase productivity (Campden-BRI, 2009). The implementation of best management practices requires the establishment of a logical approach, such as HACCP, to allow for identification and correct application of relevant technologies (Banhazi and Black, 2009). This concept was further progressed by Garmendia and Jensen (2015) using critical control point theory to identify precision agriculture (PA) technologies relevant to sugarcane (*Saccharum officinarum* L.) farming systems, as well as possible constraints for adoption of those technologies by farmers.

Such a process should identify vulnerabilities within the farming system prior to incorporation of a technology, or change in practice, allowing these vulnerabilities to be addressed in optimizing the incorporation and impacts of subsequent technological innovations. However, such a process is useful to eliminate the reactive approach to system hazard analysis; it currently does not quantify the likelihood of hazard occurrence and the potential impact. Accordingly, using soil compaction as an example, Troldborg et al. (2013) employed probabilistic models, such as Bayesian Belief Networks (BBN) (Cooper, 1990), to determine the susceptibility of Scottish soils to compaction at a national level. BBN enable analysis of relatively complex systems, and accommodate uncertainty and variability in modelled predictions due to the probabilistic approach (Henriksen et al., 2007; Uusitalo, 2007). Of importance to farming systems, BBN address instances where empirical data are not available by utilizing a mixture of both qualitative and quantitative data to strengthen results, and produce both diagnostic and predictive outcomes (Henriksen and Barlebo, 2008). This allows a nonreductionist approach to understanding complex systems and it allows reasonable population of variables with limited data, which is often the case on-farm. Troldborg et al. (2013) demonstrated that reasonable predictions could be made to determine susceptibility of soil to compaction through incorporation of existing empirical data, discrete data, derived data (e.g., pedotransfer functions), and expert knowledge. Where models normally seek to simplify the system through assumptions, the BBN approach captures the complexity of the system and explicitly accounts for uncertainties (Troldborg et al., 2013). A critical aspect of this approach is developing the network through determination of variables and their interactions (Marcot et al., 2006). One way to simplify this is the application of HACCP to identify hazards and critical control points so as to form the basis of the network. This also provides a means to quantify the susceptibility of each hazard to change using the probabilistic predictive capability of the BBN. Agricultural systems require a means by which to make informed decisions at a whole-farm or system level for the adoption of innovative technology and its likely impact. The effects of the JD7760 picker on the cotton system provided in this work could be further refined through structured analysis using the HACCP approach. Quantification of likelihood of impacts would be required at a later stage, using available information at hand but allowing for some degree of uncertainty. We hypothesize that a nonreductionist approach utilizing available data (e.g., open source, on-farm and expert opinion), such as BBN incorporated with HACCP, could prove an effective means by which likelihood of impacts can be estimated.

CONCLUSIONS

This work examined the effects of increasing harvest rates on the cotton system from the perspective of the machine, the machine and soil interaction, and socioeconomics. The main conclusions derived from this review are:

1. Technology uptake is largely driven by the need to improve EC with less labor and in a safe manner. However, technological advances and progressive increase in EC require that potential impacts associated with technology uptake are identified as early as possible in the adoption process. Australian cotton growers have embraced the RB on the basis of clearly elucidated benefits to the harvesting system. John Deere's success in elucidating these benefits, highlights that large capital outlay can be overcome by clear communication. On the basis of understanding what the RB offered the farming system, growers have actively worked with the industry to rapidly overcome associated issues within the cotton production system,
2. The bulk of impacts caused by the RB cotton picker are perceived as positive. Despite this, the majority of growers picking cotton in regular seasons suggest that the use of the RB has implications on soil compaction, which needs to be considered in managing agricultural systems into the future. Limited published information and ongoing research at the University of Southern Queensland (Toowoomba, Australia) confirm observations made by growers in relation to increased soil compaction. Further work including associated effects on energy use in tillage repair treatments, long-term effects on crop yield, and soil sustainability merits a research priority. Soil compaction research in grain cropping has shown that production loss, and soil, water, and energy conservation, are significant and points towards increased adoption of CTF. However, there are perceived financial restraints to adopting CTF such as initial capital outlay and risk of loss of product warranty,
3. Further innovation to these machines might be needed, for example, variable wheel-track options to accommodate to CTF systems. Concerted communication from dominating machinery markets and the cotton industry needs to clearly justify and demonstrate the benefits of CTF to the whole farming system to facilitate its adoption. Where CTF is not adopted by growers, simplified means of accounting for the effects of soil compaction would be valuable to: (1) assist decision-making and (2) minimize impacts where these are unavoidable.
4. Even though the implications of the RB upon the cotton system in terms of transport and ginning have been rapidly identified and adjusted for, a desirable option would be for growers to identify these effects prior to adoption to have mitigation plans in place and minimize potential negative impacts on the system. To enable this, decision support systems are required to assist in quantifying benefits as well as potential impacts and costs associated with those impacts. Such a framework could be applied to demonstrate the benefits of CTF and the feasibility for its adoption in cotton-based systems,
5. The RB has provided a useful case study in identifying impacts associated with rapid adoption of novel technology where outcomes of such a process were unknown. There are potential solutions in the use of hazard analysis, identifying critical control points, and providing estimates of hazard likelihood. Future research should focus on optimizing whole-system (holistic approach) and providing useful tools for practitioners to take mitigation-based action, rather than reaction.

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DISCLAIMER

Mention of trade names or commercial products in this article is solely for the purpose of providing accurate information and does not imply recommendation, endorsement or otherwise by the authors or their institutions.

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