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An integrated mechanical and chemical method for managing prostrate cover crops on permanent beds

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Abstract

Cover crops in minimum or no-tilled systems are usually killed by applying one or more herbicides, thus significantly increasing costs. Applying herbicides at lower rates with mechanical interventions that do not disturb or bury cover crop residues can, however, reduce costs. Our objective was to develop a management system with the above-mentioned features for prostrate cover crops on permanent beds in an irrigated Vertisol. The implement developed consisted of a toolbar to which were attached spring-loaded pairs of parallel coulter discs, one set of nozzles between the individual coulter discs that directed a contact herbicide to the bed surfaces to kill the cover crop and a second set of nozzles located to direct the cheaper glyphosate to the furrow to kill weeds. The management system killed a prostrate cover crop with less trafficking, reduced the use of more toxic herbicides, carbon footprint, labor and risk to operators. Maximum depth of compaction was more but average increase was less than that with the boom sprayer control.

Key words: stubble, Vertisol, crop rotation, herbicide, toolbar, emissions

Introduction

Cover crops are frequently sown in rotation with high-value crops in many annual cropping systems. Several comprehensive reviews have been conducted on the subject during the past 15 years[1–4]. The cited advantages include better soil physical, chemical and biological quality (e.g., improved soil structure and water-holding capacity, higher soil organic carbon, increased numbers of beneficial micro-organisms and macrofauna, reduced numbers of disease-carrying micro-organisms and pests such as nematodes), improved nutrient recycling, weed control, soil hydrology (e.g., increased soil water storage and infiltration, reduced evaporation and runoff) and reduction in wind and water erosion[1–3,5–8]. In addition, leguminous cover crops can fix atmospheric nitrogen thus reducing costs of inputs[1,3,4] whereas cereals and grasses can take up excess residual nitrates, thereby reducing leaching and contamination of groundwater[3,4,7,9]. Disadvantages of cover crops include additional financial and environmental costs related to their sowing, management and control before sowing the main crop in the cropping system, potential weediness in subsequent crops and possible allelopathic, disease-enhancement and hosting of insect and other pests with respect to the main crop in the cropping system[1,4]. In cooler regions, cover crop mulch may reduce soil temperatures, thus affecting initial growth of the main crop[3]. Similarly, under conditions of reduced rainfall, the cover crop may have a negative effect on available soil water stocks[2].

In conventionally tilled systems the cover crop is usually mowed and incorporated before or during land preparation, and is commonly referred to as 'green manuring', whereas in minimum or no-tilled systems the cover crop is usually killed by applying one or more herbicides[4,10–12]. The latter contributes significantly to the costs of cover cropping in no-till systems[4]. In addition, the herbicides can be costly in terms of environmental quality. Consequently, several researchers have experimented with combining herbicides (at lower rates) with selected mechanical interventions that do not disturb or bury cover crop residues such as flail mowing, rolling, roller/crimper combinations, undercutting, etc.[10,13–19]. The literature suggests that most authors studied the use of mechanical methods, either alone or in combination with herbicides, with the objectives of rapid control of the cover, weed management and early planting.

Figure 1. Killed vetch residues retained as *in situ* mulch in a bed-furrow system.

Some[14,15,18,19] also considered reducing herbicides due to environmental pollution or because cover cropping could be included in organic farming systems in which tillage could be excluded and the residues retained as surface mulch. The need to reduce amounts of herbicides such as *N*,*N*′-dimethyl-4,4′-bipyridinium dichloride (Paraquat) and 2,4-dichlorophenoxyacetic acid (2,4-D) due to their cost and toxicity (i.e., occupational health and safety reasons) was not a consideration in any of the studies reported in the literature. Among the above-cited research, most were conducted in flat-planted systems with only a very few addressing bed planting of cover crops[14,15].

Mechanical methods alone were variable with respect to cover crop control, with efficacy ranging from 10 to 100% and post-control emergence of weeds high in most instances. Teasdale and Rosecrance[10] and Kornecki et al.[18] reported that broadleaved covers such as hairy vetch [*Vicia villosa* Roth. (L.)] were not well controlled by mechanical methods alone, whereas Creamer et al.[15] and Creamer and Dabney[14] stated otherwise. Factors such as the height that the implement was set at, plot size, soil type and climatic variability may have contributed to this variation. Cereal cover crops such as rye (*Secale cereale* L.) could, however, be adequately controlled by mechanical means, particularly when control treatments were implemented post-anthesis[10,16–19]. Best control of a broadleaved prostrate cover crop and subsequent weed growth was when a contact herbicide (e.g., 2,4-D, Paraquat) was combined with mechanical methods, with treatments being implemented during early to mid-flowering[10,13], although Creamer et al.[15] and Creamer and Dabney[14] suggest that any time between early flowering and fruiting gave good control, even when mechanical means were the sole method of control. Herbicide such as glyphosate [*N*-(phosphonomethyl) glycine], a cheaper and safer option, could be used for covers such as rye[10,16–19]. No significant differences were reported when residual herbicides were combined with the contact herbicides.

The objective of this study was to develop an economically and environmentally acceptable management system which, relative to herbicide application with a boom-sprayer, minimized trafficking and reduced the use of the more toxic herbicides for killing a prostrate cover crop in furrow-irrigated permanent beds in a Vertisol. The cropping system tested was one in which vetch (*V. villosa* L. Roth, *Vicia benghalensis* L.), a prostrate leguminous cover crop, was followed by row-cropped cotton (*Gossypium hirsutum* L.). Our ultimate objective was to retain the vetch residues killed by the herbicides as *in situ* mulch into which the following cotton could be sown (Fig. 1). This report summarizes the development of an implement to manage vetch cover crops in a rotation experiment conducted from 2002 to 2010 in northern New South Wales (NSW), Australia.

The vetch cover crops have several issues and constraints that need to be addressed when their termination is under consideration:

- Vetch is a prostrate crop that forms adventitious roots through its lateral stems (also referred to as stolons or runners) and produces dry matter in the range of ~5–7 t ha^{-1} (Fig. 2). The bulk can be reduced by mowing with a slasher mower (Fig. 3). Depending on

Figure 2. Mowed (right) and unmowed (left) vetch crop.

Figure 3. Mowing vetch with a slasher-mower.

Figure 4. Applying Spray.Seed® in a single pass with an intermediate stage ('Later stage') of the mulching implement. (a) Complete implement under field conditions. (b) Close-up of strip cut by coulter discs. (c) Close-up of coulter-discs and nozzle.

climatic conditions, this kills about 20–50% of the vetch. The remainder can be killed either by incorporation or by application of a contact herbicide such as Spray.Seed® [11.5% (w/v) Paraquat and 9.8% (w/v) 6,7-dihydro-dipyrido(1,2-a:2′,1′-c)pyrazinediium dibromide (1,1′-ethylene-2,2′-bipyridyldiylium dibromide). The formulation is more commonly stated as: Paraquat 135 $g\,l^{-1}$ + Diquat 115 $g\,l^{-1}$). Mature vetch is tolerant of glyphosate.

- Spray.Seed® is highly toxic[20] and costlier than Roundup®. A 20 litre drum of Spray.Seed® is of the order of $A 215 (1 $A = 1 $US (January 2011)) and Roundup® (Glyphosate 450®, glyphosate 450 $g\,l^{-1}$) $A 80 (October 2010 prices).
- Survival of the prostrate vetch cover is enhanced through adventitious roots formed by the lateral stems. Personal observations by the authors suggest that adventitious root formation by the laterals is stimulated by mowing. Cutting the lateral stems can, however, minimize proliferation of adventitious roots.

The implement described in this report addresses the above constraints and issues in a single pass subsequent to mowing.

Figure 5. Applying Spray.Seed® to bed surfaces and Glyphosate 450® to furrows in a single pass with the final version of the mulching implement ('Final design').

Materials and Methods

Implement design

The design objectives of the implement were to kill and retain vetch residues as an *in situ* mulch while reducing the use of the more expensive and toxic herbicide Spray.Seed®. As noted previously, post-mowing survival of vetch could be reduced by mechanical methods that cut off the lateral stems, thus minimizing adventitious root proliferation. The initial design (Fig. 4a) consisted of a toolbar to which paired sets of parallel coulter discs were rigidly attached. The pairs of discs were located such that they ran on either side of the vetch plant line to a depth of ~2–4 cm, thus cutting off any lateral stems (Fig. 4b). It was assumed that the discs would follow the bed contours, thus ensuring a uniform cutting depth. A set of nozzles that directed herbicide (Spray.Seed®) to the vetch plant line on bed surfaces was located between individual disc pairs (Fig. 4c). The nozzles were attached to a tank that contained the herbicide. The discs also minimized herbicide drift. While this design was successful in reducing Spray.Seed® application amounts and killing the vetch, it also resulted in winter weeds such as wild Phalaris (*Phalaris paradoxa* L.), milk thistle (*Sonchus oleraceus* L.), dead nettle (*Lamium amplexicaule* L.) and wild turnip (*Brassica tournefortii* L., *Raphanus raphanistrum* L., *Rapistrum rugosum* L.) proliferating in the furrows, thus necessitating an additional application of a herbicide such as Glyphosate 450® with a boom sprayer.

The implement was subsequently modified to include a second tank and a second set of nozzles that directed an appropriate herbicide such as Glyphosate 450® to the furrows to control winter weeds. In addition, the rigidly attached coulters discs were replaced with spring-loaded coulter discs as the cutting depth of the former was variable. Thus, the final design consisted of a toolbar to which were attached four sets of spring-loaded pairs of parallel coulter discs, one set of nozzles that applied

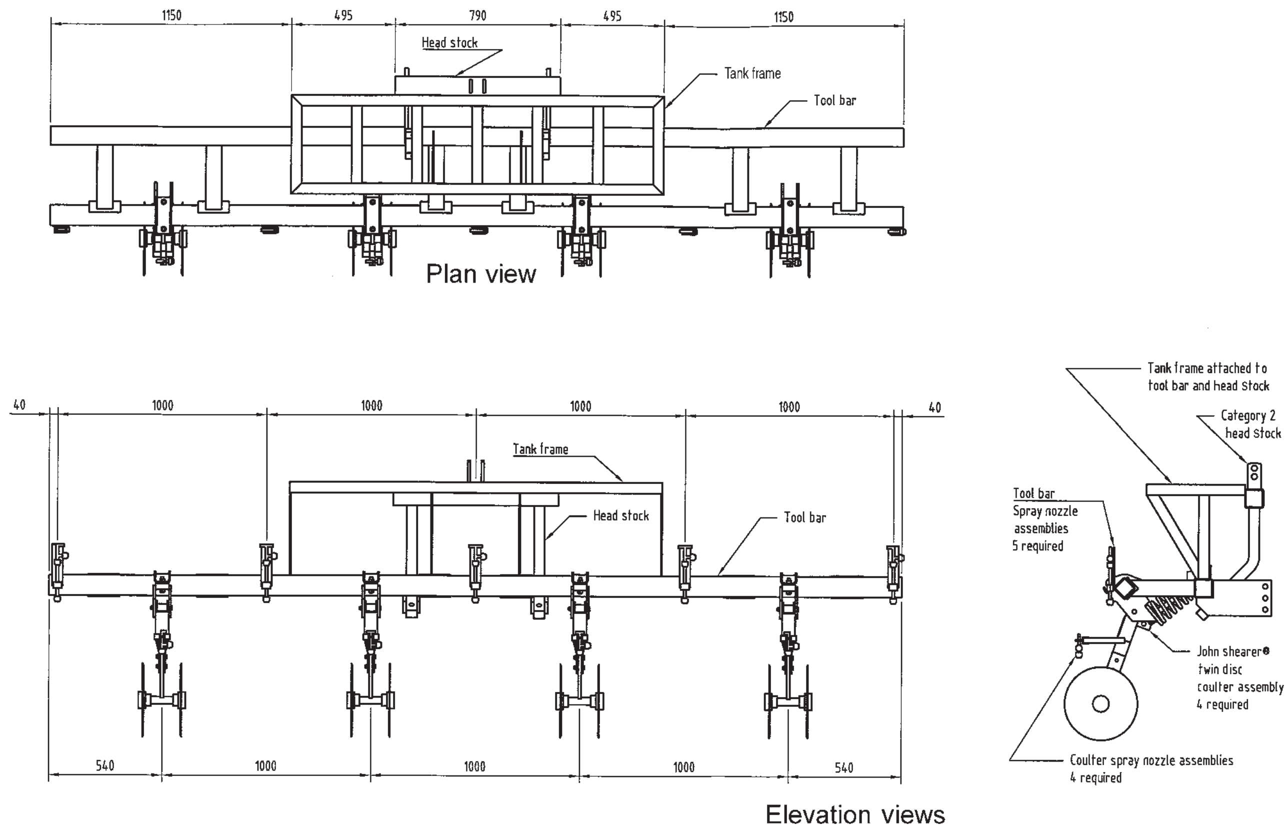

Figure 6. Line drawing of the final version of the mulching implement that was able to apply Spray.Seed® and Glyphosate 450® in a single pass. All component parts were purchased 'Off-the-shelf'. An image of the implement is shown in Figure 5.

herbicide (Spray.Seed®) to the bed surfaces located between individual discs and a second set of nozzles located to direct Glyphosate 450® to the furrow (Figs. 5 and 6). The two groups of nozzles were attached to separate tanks that contained the two different herbicides. Limiting Spray.Seed® application to a narrow band between two coulter discs ensures that herbicide drift is greatly reduced, thus minimizing non-target crop damage, and reducing exposure of farm workers to Spray.Seed®. Commercially available, 'off-the-shelf' components (nozzles, coulter discs, tanks, etc.) were used at all times.

Experimental

The mulching implement was developed during a cropping system experiment that commenced in 2002. The experiment was located at the Australian Cotton Research Institute, near Narrabri (149°47′E, 30°13′S) in NSW, Australia. Narrabri has a semi-arid climate and experiences four distinct seasons with a mild winter and a hot summer. The hottest month is January (mean daily maximum of 35°C and minimum of 19°C) and July the coldest (mean daily maximum of 18°C and minimum of 3°C). Mean annual rainfall is 593 mm. The soil at the experimental site is an alkaline, self-mulching, gray clay, classified as a fine, thermic, smectitic, Typic Haplustert[21] with a mean particle size distribution in the 0–1 m depth of 64 g/100 g clay, 11 g/100 g silt and 25 g/100 g sand.

The experimental treatments consisted of four irrigated cotton-based rotation systems sown on permanent beds: cotton monoculture, cotton–vetch, cotton–wheat (*Triticum aestivum* L.) where wheat stubble was incorporated into the beds after harvest with a disc-hiller, and cotton–wheat–vetch where wheat stubble was retained as an *in situ* mulch into which the following vetch crop was sown. Vetch in cotton–vetch and cotton–wheat–vetch rotations was killed before sowing cotton as described in the previous section and the residues retained as *in situ* mulch into which the following cotton was sown. Hairy vetch (*V. villosa* L. Roth) was sown from 2002 to 2004 and Popany vetch (*V. benghalensis* L.), which has an identical growth habit but is less hard seeded than hairy vetch, thereafter at sowing rates of 20 kg ha^{-1}. In NSW cotton is sown in October and picked in late April or early May after defoliation. Wheat and vetch in the cotton–vetch rotation were sown in May after cotton stubble was incorporated into the beds with a disc-hiller. Vetch in the cotton–wheat–vetch rotation was sown into wheat stubble after commencement of autumn rains, usually between late February and early April. Vetch was not fertilized and, depending on winter rainfall, received 1–2 irrigations of 100 mm each per season. Vetch was mowed with a 4-row slasher at 50% flowering. Vetch dry matter production at time of mowing was estimated by

Table 1. Estimated emissions and labor requirements (including setting-up time). JD, John Deere; weight of the JD 8100 was 8.8 t, JD 6200 3.8 t, 8-row boom sprayer with 550 l of herbicide 1.0 t and 4-row coulter/band sprayers in Stages 2 and 3, 0.6 and 0.7 t, respectively. Emissions estimated for herbicide and fuel production include those associated with transport.

Options	Operation	Tractor	Implement	Diesel used ($l\,ha^{-1}$)	In-field emissions	Herbicide production emissions	Fuel production emissions	Total	Labor (man h ha^{-1})
					CO_2-e ($kg\,ha^{-1}$)				
Stage 1 (no implement)	Mowing	JD 8100	4-row slasher	10.7	31.0		4.5	35.5	3.5
	Applying Spray.Seed® ($3\,l\,ha^{-1}$) × 2	JD 6200	8-row boom sprayer	4.4	12.8	20.0	1.9	34.7	5.0
	Applying Glyphosate 450® ($3\,l\,ha^{-1}$)	JD 6200	8-row boom sprayer	2.2	6.4	28.8	0.9	36.1	2.5
Total				17.3	50.1	48.8	7.4	106.3	11.0
Stage 2 (later stage)	Mowing	JD 8100	4-row slasher	10.7	31.0		4.5	35.5	3.5
	Applying Spray.Seed® ($3\,l\,ha^{-1}$)	JD 6200	4-row coulter/band sprayer	6.2	17.8	10.0	2.6	30.4	3.5
	Applying Glyphosate 450® ($3\,l\,ha^{-1}$)	JD 6200	8-row boom sprayer	2.2	6.4	28.8	0.9	36.1	2.5
Total				19.1	55.1	38.8	8.1	102.0	9.5
Stage 3 (final design)	Mowing	JD 8100	4-row slasher	10.7	31.0		4.5	35.5	3.5
	Applying Spray.Seed® ($3\,l/\,ha^{-1}$)+ Glyphosate 450® ($3\,l\,ha^{-1}$)	JD 6200	4-row coulter/band sprayer	6.2	17.8	38.8	2.6	59.2	3.5
Total				16.9	48.8	38.8	7.2	94.7	7.0

harvesting $3 \times 1\,m^2$ sub-plots in each plot and means compared with Student's *t*-test. After mowing, the previously described implement was employed to kill vetch re-growth.

The experiment was laid out as a randomized complete block with three replications and designed such that both cotton and rotation crop phases in the last two rotation treatments were sown every year. Individual plots were 165 m long and 20 rows wide. The rows (beds) were spaced at 1 m intervals with vehicular traffic being restricted to every second furrow. Details of soil and crop management practiced in this experiment have been reported by Hulugalle et al.[22].

Detailed records were maintained of labor requirements associated with both setting up and in-field operation of the implement in its early and final versions. Detailed records were also kept of fuel use, herbicide application rates and costs. Fuel use and greenhouse gas emissions [as carbon dioxide equivalents (CO_2-e)] associated with vetch control, herbicide and fuel production and transport were estimated from available sources[23–26]. The above information was used to assess labor requirements, and greenhouse gas emissions associated with herbicide and fuel production for three developmental stages of the vetch management system (Table 1). Briefly, these were:

- Stage 1: Mowing followed by applying Spray.Seed® with two passes of an 8-row boom sprayer ('No implement'). Occasionally, an additional application of Glyphosate 450® with a single pass of a boom sprayer was required.
- Stage 2: Mowing followed by applying Spray.Seed® in a single pass with an intermediate stage of the implement (Fig. 4a) and Glyphosate 450® with a single pass of an 8-row boom sprayer ('Later stage').
- Stage 3: Mowing followed by applying Spray.Seed® and Glyphosate 450® with the final version of the implement in a single pass (Fig. 5) ('Final design').

During October 1, 2010, the effects of trafficking associated with the three developmental phases of the implement (no implement, later stage, final design, see Table 1 for details) on penetrometer resistance, which is related to soil compaction[27], was evaluated in wheel-tracked furrows of plots sown with the cotton–vetch rotation. Due to obsolescence, the JD 6200 tractor (3.8 t) used to pull the implement and the boom sprayer was replaced in 2010 with a JD 6130 (6.0 t) for the 8-row boom sprayer operations (Stages 1 and 2) and a JD 5303 (3.8 t) for the 4-row implement used in Stages 2 and 3. Penetrometer resistance to a depth of 0.45 m was measured before and after trafficking at 15 mm depth increments in six sites (three insertions per site) selected at random in each plot in wheel-tracked furrows with a Rimik® CP10 recording cone penetrometer fitted with a standard 30° circular stainless-steel cone of 12.83 mm diameter and a 9.83 mm-diameter shaft. Gravimetric water content was measured at 0.10 m depth intervals in soil sampled at the same time from the same locations with a tractor-mounted soil corer. Penetrometer

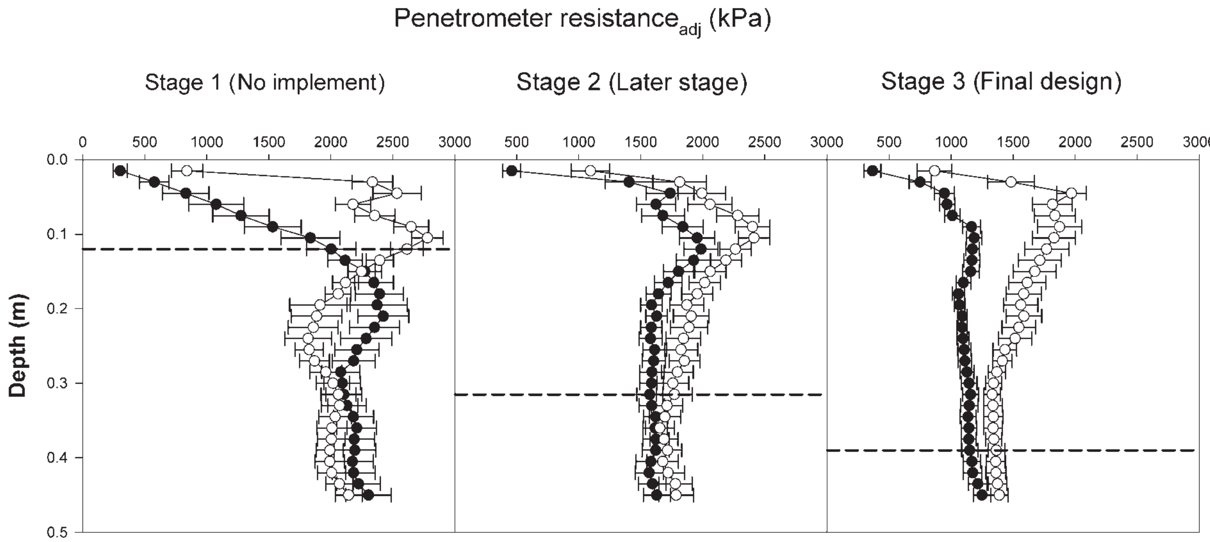

Figure 7. Penetrometer resistance (standardized to a gravimetric soil water content of 0.275 g g^{-1}) to a depth of 0.45 m with the three developmental stages (Table 1) of vetch management, October 5, 2010. ●, Before trafficking; ○, after trafficking. Stage 1: Mowing followed by applying Spray.Seed® with two passes of an 8-row boom sprayer ('No implement'); Stage 2: Mowing followed by applying Spray.Seed® in a single pass with an intermediate stage of the implement and Glyphosate 450® with a single pass of an 8-row boom sprayer ('Later stage'); Stage 3: Mowing followed by applying Spray.Seed® and Glyphosate 450® with the final version of the implement in a single pass ('Final design'). Horizontal bars are standard errors of the means. The dotted line represents the maximum depth at which significant changes were detected.

readings were adjusted to a standard water content of 0.275 g g^{-1} (~field capacity)[28] and pre- and post-trafficking values were compared by means of a Student's *t*-test. Standard errors of individual means were computed.

Results and Discussion

Vetch dry matter production

Dry matter (mean ± standard deviation) produced by vetch at the time of harvest was 3.4 ± 1.2 t ha^{-1} in the cotton–vetch rotation and 5.0 ± 1.7 t ha^{-1} in the cotton–wheat–vetch. The higher ($t = 7.28$, df = 53, $P < 0.001$) yield in the latter rotation was probably due to a longer growing season (5–6 months) relative to the vetch in the cotton–vetch rotation (~4 months).

Greenhouse gas emissions, and herbicide and labor costs

In-field fuel use and greenhouse gas emissions, and emissions associated with fuel production and transport were in the order of Stage 2>Stage 1>Stage 3 (Table 1). This was because, relative to Stage 1, 10% more fuel was used by Stage 2 and 3% less by Stage 3. Emissions associated with herbicide production and transport were, however, in the order of Stage 1>Stage 2 = Stage 3. In comparison with Stage 1, herbicide production and transport resulted in Stages 2 and 3 emitting 21% less CO_2-e. This was because Stages 2 and 3 used less herbicides. Overall, emissions associated with in-field activities, and herbicide and fuel production and transport were least in Stage 3: 11% less than Stage 1 and 7% less than Stage 2.

A significant proportion of emissions (32–37%) in all three stages were accounted for by the mowing. It is likely that major improvements in terms of fuel and emission reduction may be achieved by seeking alternatives to the slasher. Kornecki et al.[16,17] have suggested using various forms and combinations of roller crimpers. Flail mowers, undercutters, cutter bars and band mowers are other possible alternatives[14,15,29,30]. An alternative to mowing may be to graze the vetch with livestock, although this may result in N fixed by the vetch moving off-field when the stock are relocated. The subsequent crop may, therefore, not benefit from the N fixation by the vetch.

Costs of herbicides (using September 2010 prices of $A 10.75 litre^{-1} of Spray.Seed® and $A 4 litre^{-1} of Glyphosate 450®) were of the order of $A 75.50 ha^{-1} for Stage 1, and $A 44.25 ha^{-1} for Stages 2 and 3. In all three stages, a complete kill of vetch and weeds was obtained. In Stage 3 ('Final design'), Spray.Seed® was applied at an overall average rate of 3 l ha^{-1} to a 0.2 m wide band at 1 m intervals (i.e., 20% of the land area). Glyphosate 450® was similarly applied to 80% of the area.

Labor requirements were of the order of Stage 1> Stage 2> Stage 3 (Table 1). Stage 3 required 36% less labor than Stage 1, and 26% less labor than Stage 2. This is a significant cost saving. For example, assuming that the hourly cost to an employer for a farm worker is $A 31.55 h^{-1} [salary of $A 45,000/annum and on-costs (sum of payroll tax, workers compensation, leave loading,

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extended leave and superannuation) of 35%], then estimated labor costs ha^{-1} would be of the order of $A 347 for Stage 1, $A 300 for Stage 2 and $A 221 for Stage 3. Other benefits would include reduced herbicide exposure and fatigue to workers due to reduced working hours and Spray.Seed® application rates.

Penetrometer resistance

Depth and pattern of compaction in furrows, as indicated by changes in penetrometer resistance, differed among the three stages (Fig. 7). Maximum statistically significant depth of compaction was shallow in Stage 1 and was of the order 0.120 m with an average (geometrical mean) increase of 101% in the 0–0.120 m depth, whereas maximum depths of compaction in Stages 2 and 3 were 0.315 and 0.390 m, respectively, and average increases to maximum depths of compaction were 20 and 39%, respectively. In other words, Stage 1 (total weight of 6.9 t, axel load of 1.0 t) had a shallow but intense pattern of compaction, whereas Stages 2 and 3 had less intense but deep compaction patterns. In comparison with Stage 2, more intense and deeper compaction occurred with Stage 3. Although there was a weight differential between Stage 3 (total weight of 4.5 t, axel load of 0.7 t) and Stage 2 (total weight of 4.4 t, axel load of 0.6 t), the small difference of 0.1 t alone does not adequately explain the near doubling of compaction between the two stages. We surmise that relative to Stage 2 (Fig. 4a), the inclusion of an additional tank and altered weight distribution in Stage 3 (Fig. 5) may have resulted in a significant increase in vibrations, and when combined with the relatively moist, clayey soil, a deeper and more intense compaction (and possibly, smearing) may have occurred in the latter[31]. The varying patterns of compaction between Stage 1, and Stages 2 and 3 may be due to a combination of factors such as greater weight of the tractor/boom sprayer/herbicide tank combination (6.9 t), more vehicle passes and wider tyres in the JD 6130 used in Stage 1 (Table 1) relative to the JD 5303 used in Stages 2 and 3[31]. Widths of the front and back tyres of the JD 6130 were 410 and 320 mm, respectively, and of the JD 5303 were 370 and 240 mm, respectively. Air pressure in the tyres is unlikely to have been a contributory factor as those in the JD 6130 were higher (207 and 117 kPa in the front and back tyres, respectively) than those in the JD 5303 (124 and 103 kPa in the front and back tyres, respectively). Soane et al.[31] note that shallow compaction patterns are characteristic of wider tyres and low air pressure.

Conclusions

An integrated mechanical and chemical management system that was able to kill aggressive and bulky prostrate cover crops such as vetch with fewer machine passes, also reduced use of more toxic herbicides such as Spray.Seed®, decreased labor, lowered risk to operators and had a lower carbon footprint. In comparison with spraying with an 8-row boom sprayer, the depth of compaction was more when this 4-row implement was used, although the former resulted in more intense and shallower compaction.

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