Effect of steam weeding equipment on the growth and yield of broccoli

Confidential report to Steamwand International Pty Ltd

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Executive summary

While herbicides allow farmers to remove or suppress weeds with very good results compared to those of purely mechanical weed control. More recently, society have become aware that these chemicals can cause long-term damage to our agricultural ecosystems and many people are now looking at more sustainable ways of farming that reduce potentially negative environmental and human health problems. This has created a need for a more diversified approach to weed management, including greater use of biological control, strategic crop rotations, cultivar selection, improved tillage implements and a wide range of novel weed control methods such as bioherbicides and various thermal weeding methods. The increasing interest in low-input agricultural systems, especially certified organic production, has provided further demand for non-chemical weed control methods.

Thermal weeding methods such as solarisation, flame weeding, steam weeding and direct burning have been receiving considerable research and commercial development over the past decade. A range of flame and steam weeders have been developed with the latter offering better heat transfer, less fire hazard risk and more versatile fuel requirements. Steam weeding can provide an effective alternative to shallow tillage for killing weeds after preparing the planting beds, preventing further soil disturbance and the consequent new flush of weed seedlings. Pre-emergence treatment with steam weeders can also be carried out to provide a further growth advantage to the crop.

Although it has been reported that the initial costs for steam weeding are commonly higher than most tillage implements (e.g. 2 – 4 times higher), thermal weeding can be cheaper (e.g. 50 – 80% less) than hand-weeding due to the high cost of labour. Thermal weeding costs have been reported to be reasonable for an area of 6-20 hectares and treating smaller areas depends on the selection of higher value crops.

This report investigated the effect of several commonly used organic (non-chemical) weeding control methods and a common herbicide. Treatments evaluated were steam weeding using either hand-held or tractor-mounted applicators, a pine-oil based 'bioherbicide', shallow tillage and hand-chipping and the herbicide glyphosate. The project aims were:

1. Determine the efficacy and cost-effectiveness of the various treatments for controlling broadleaf and grass weeds in a vegetable cropping system.
2. Determine the efficacy and cost-effectiveness of the steam weeding treatment at four speeds: 1, 1.5, 2, and 2.5 km/hr.

The field trials were conducted on a fruit and vegetable farm at Myocum on the north coast of NSW. The farm has been organically certified for five years and is used to produce a range of salad vegetables for the fresh food market as well as some citrus and other sub-tropical fruit production.

The trial plots were based on ~1.5 m row widths and were 5 m long. Atomic F1 hybrid broccoli seedlings were planted on 8/7/08 in three rows along the beds at ~20 cm spacings. Standard organic practices were uniformly used on all plots, including irrigation and fertilisation. The timing of the treatment applications was based on the natural emergence of weeds after bed preparation and planting of the crop. The following six treatments were applied on 12/8/08: control (unweeded); herbicide (glyphosate); bioherbicide (pine oil); steam weeding (hand application); steam weeding (tractor application); and tillage (mechanical tillage + hand chipping).

The effectiveness and economics of steam weeding was determined at four tractor speeds: 1, 1.5, 2, and 2.5 km/hr. This trial was carried out on similar prepared beds as for Trial 1, but without broccoli as the aim was to evaluate the effect of tractor speed on weed control.

Weed density was counted fortnightly for broadleaf and grass weeds and the crop yield was measured at harvest (10/9/08). Yield was converted to a hectare basis (kg/ha) and multiplied by the current wholesale price to determine the gross income for each treatment. The costs of each weeding treatment were recorded and a cost/benefit analysis performed to determine the economic performance of the treatments.

The results indicate that the steam weeding equipment provided equivalent weed control to common organic weeding methods including tillage/chipping and to novel methods such as pine oil bioherbicide. Compared with glyphosate, the level of weed control was similar. Hand-applied steam weeding was usually more effective and less variable due to better targeting and slower application speed. The steam application speed of 2 km/hr was the most suitable for the crop used in the trail and the weed species encountered. The number of broadleaf weeds remaining after steam treatment was reduced by applying at lower speeds and variability also decreased as speed decreased.

The steam weeding equipment was less effective for grass weeds compared with broadleaf weeds as a result of the different growth forms of the two weed types. Broadleaf weeds were reduced by about 50 – 60% compared with the unweeded control treatment, whereas grass weeds were generally equivalent between the steam treatment sand the unweeded control. The main growing points (meristems) of grasses are concealed within the new leaves, whereas the meristems in broadleaf species are usually exposed and are more susceptible to control measures. This is a known issue for many weed control methods that are non-systemic, including contact bioherbicides and thermal weeding methods such as flaming and steaming. The strategies for over-coming this limitation include careful timing of application to ensure the weeds are as young as possible, and slower application speeds to increase the ability of the steam to heat and kill the concealed meristems.

Crop yields were similar for all treatments except the control, indicating that the weeding methods were largely effective and/or that broccoli was able to tolerate the existing weed competition. The gross income was generally equivalent for the active treatments (i.e. not the control), except the herbicide (glyphosate) treatment which was significantly lower due to the lower wholesale price used for non-organic produce.

The costs for the weed control treatments, including labour, machinery costs and material inputs, are listed in Table 1. Treatments that required hand labour (e.g. chipping, steam application by hand) incur considerably higher costs overall (e.g. 2 – 6 times more). The cheapest treatments were glyphosate, followed by steam application by tractor.

Table 1. Total cost ($/ha) of weed control treatments used in the study.

Treatment	Cost ($/ha)
Control	0
Glyphosate	644
Pine oil	3,864
Steamwand – hand	904
Steamwand – tractor	738
Tillage + chipping	1,156

Adjusted income (i.e. gross income – weeding costs) was highest for both Steamwand treatments and for tillage/chipping. Glyphosate had the lowest adjusted income due to the lower prices received, while pine oil was also low due to the high cost of materials used. The adjusted income for slower tractor application of steam (1 km/hr) was midway between the income for hand application and the 2 km/hr tractor application. This compares favourably in economic terms despite the longer time required (14 hr/ha compared with 8 hr/ha) and may achieve better weed control when applied when weeds are young.

This study has shown that steam-weeding can be both effective and economically viable compared with standard weed control methods currently in use in organic vegetable farming systems. In addition, steam-weeding are cost effective compared with herbicide due to the extra income gained through organic premiums for certified produce. Tractor applications of steam show promise for rapid control of weeds under condition that are unsuitable for tillage and where further stimulation of weed growth is not wanted.

For future trials the following variables could be investigated: different crop types (e.g. canopy shape, growth rates, season length), different soil types (e.g. sandy versus clay), and different climatic conditions (e.g. very dry or very wet conditions). These variables could be tested under simulated conditions, for example in a glasshouse using large soil containers that enable finer control of soil type, soil moisture, and weed density, species and age.

1. Introduction

1.1. Background

For centuries, growing crops as a part of agriculture has changed natural vegetation, including plants that we now class as weed species. Crop production practices such as tillage, the use of monoculture, introduction of new crop varieties and the extensive use of herbicides have also affected agricultural ecosystems and the plants that inhabit these environments.

After World War 2, herbicides allowed farmers to remove or suppress weeds with very good results compared to those of purely mechanical weed control. Indeed using a combination of herbicides in conjunction with some mechanical weed control can keep a field almost completely weed free throughout a crops growing season therefore increasing the crops yield. One of the main advantages of herbicides is that they can be used to successfully control intra-row weeds, as well as inter row weeds (Henderson and Bishop 2000). For many years, the majority of farmers have been controlling their weeds mainly with herbicides, not only because herbicides were effective but also economical with the farmer having to spend much less money on labour.

More recently, farmers, agricultural researchers and ecologists have become aware that these chemicals can cause long-term damage to our agricultural ecosystems (Batchelor 2000). With the loss of species diversity, contamination of water, etc. many farmers are now looking into farming in a more sustainable way that better looks after our agricultural ecosystems. One particular area that this is being done is in the control of weeds.

Due to the widespread popularity of herbicides, more money and research has gone into the development of more herbicides and herbicide sprayers rather than other methods of weed control. However, with growing concerns about damage to our environment, food safety and quality, increasing herbicide resistance and the recent spike in herbicide costs (Kudsk and Streibig 2003, ABC Rural 2008), the need for a more diversified approach to weed management is gaining increasing attention, with greater use of biological control and strategic crop rotations and cultivar selection concepts such as integrated weed management (IWM) are gaining more interest from weed researchers in Australia (Sindel 2000) and over seas (Liebman *et al.* 2001).

Organic agriculture has also led to a shift towards a more holistic approach to weed control, making use of good rotations, smother crops, primary tillage and false seedbed techniques (Henderson and Bishop 2000). However, many of these methods are only partially successful and weeds are often seen as the most serious threat to organic crop production (Beveridge and Naylor 1999, Penfold 2001, Kristiansen *et al.* 2003, Walz 2004). Even though tillage implements such as finger weeders and vertical-axis brush weeders can give high levels of weed control, it is not always possible to use them at optimal times, due to weather conditions and the sensitivity of the crop (Bond and Grundy 2001).

1.2. New developments in alternative weed management

In the search for new weeding methods, some researchers and commercial organisations have been developing a range of non-chemical or low-toxicity sprays, or bioherbicides. These include essential oil preparations based on pine and citrus oils for example (James *et al.* 2002, Tworkoski 2002, Batish *et al.* 2004, Certified Organics Australia Pty Ltd 2008); acetic acid (vinegar) (Radhakrishnan *et al.* 2002, Curran 2004); and corn gluten (McDade and Christians

2000, Christians 2002). A common limitation with this bioherbicide approach is that the preparations are not systemic and that older weeds, or those with vigorous root systems are poorly controlled. Also, the large volumes required often make costs prohibitive for larger farming operations and mean that the products are best suited to high-value crops grown on small acreages such as herbs and vegetables (Duke *et al.* 2000).

A wide range of organic mulch materials such as hay, *in situ* crop residues and paper rolls have also been investigated in organic and non-chemical weed control research (Schonbeck and Evanylo 1998, Olsen and Gounder 2001, Ngouajio *et al.* 2003) and suggested for use in organic production guides (Bennett 1993, Whitten 1999). In addition to suppressing weeds, mulches usually have other benefits such as conserving soil moisture, reducing fluctuations in soil temperature, adding organic matter and nutrients to the soil and preventing soil from splashing onto crop leaves. Several problems have been reported with the use of mulches for weed control including cost, handling difficulties, introducing weed seeds, poor control of weeds and interfering with harvesting (Kristiansen *et al.* 2007). The lack of efficient equipment for laying organic mulches is a serious constraint to wider commercial usage (Olsen and Gounder 2001, Schäfer *et al.* 2001). Further problems with mulches are their potential negative effects on crop yield as they can interfere with crop growth by nutrient immobilisation (especially nitrogen), release of plant toxins and increased pests levels.

Other alternatives to the use of herbicides include the various thermal weeding methods such solarisation, flame weeding, steam weeding and direct burning (Ascard 1998, Melander *et al.* 2002, Bond *et al.* 2007). Current thermal weed control methods use a variety of energy sources to generate the heat needed to kill weed seeds and weed seedlings. Thermal weeding creates intense heat that ruptures plant cells, but does not burn the plant material. It is not systemic and the long-term effect depends on whether the injured plants recover and on the extent of subsequent weed emergence (Bond *et al.* 2007).

Steam weeding provides an alternative to shallow tillage for killing weeds after preparing the planting beds. This prevents further soil disturbance and the consequent new flush of weed seedlings. Crops can then be sown or planted into the beds with fewer weed seeds and weed seedlings to compete with the crop. Pre-emergence treatment (before the sown crop emerges) can also be carried out to provide a further growth advantage to the crop (Bond *et al.* 2007).

A range of flame and steam weeders have been developed with the latter offering better heat transfer, less fire hazard risk and more versatile fuel requirements (Merfield 2008). Steam-weeding machines can be used during all weather conditions, assuming the land is not so saturated that a tractor can’t be driven on it. Steaming tends to be more effective in sandier soils than a loamy or clay soils due better heat transfer, and increasing the soil moisture content increased the susceptibility of weed seeds (Hewitt *et al.* 1998).

Thermal methods are selective in their control of weeds and weed seeds, tending to be more effective on soft-seeded species; for dicotyledonous weeds (e.g. fat hen, amaranths) rather than monocotyledonous species (e.g. grasses); and when plants are young and soft, with exposed growth points (Finger *et al.* 1998, Melander *et al.* 2002, Hatcher and Melander 2003, Wszelaki *et al.* 2007). The viability of steam weed control can be hindered by heat dissipating before it reaches the target, and poor targeting thus damaging the growing crop or not getting satisfactory weed control.

Although it has been reported that the initial costs for steam weeding are commonly higher than most tillage implements (e.g. 2 – 4 times higher), thermal weeding can be cheaper (e.g. 50 – 80% less) than hand-weeding due to the high cost of labour. Thermal weeding costs have been reported to be reasonable for an area of 6-20 hectares and treating smaller areas depends on the selection of higher value crops (Nemming 1994, Litterick *et al.* 1999).

1.3. Project aims

This report looks at the effect of several commonly used organic (non-chemical) weeding control methods and a common herbicide. Treatments evaluated were steam weeding using either hand-held or tractor-mounted applicators, a pine-oil based 'bioherbicide', shallow tillage and hand-chipping and the herbicide glyphosate.

1. Determine the efficacy and cost-effectiveness of the various treatments for controlling broadleaf and grass weeds in a vegetable cropping system.
2. Determine the efficacy and cost-effectiveness of the steam weeding treatment at four speeds: 1, 1.5, 2, and 2.5 km/hr.

2. Materials and methods

2.1. Field site and test crop

The field trials were conducted on a commercial 52 hectare fruit and vegetable farm at Myocum, NSW (latitude 28° 37’ S, longitude 153° 30’, elevation 24 m). The farm has been organically certified for five years and is used to produce a range of salad vegetables for the fresh food market as well as some citrus and other sub-tropical fruit production. The soil in the test paddock was a heavy clay loam Vertosol (Isbell 1996) with a pH of 5.6 and adequate macronutrients including sulphur and phosphorus (see Appendix 6.1). The farm uses dam water for irrigation via trickle tape (Figure 1).

Figure 1. Measuring plots at the field trial site showing rows of broccoli seedlings, drip irrigation lines and wooden pegs indicating the trial plots (18 July 2008).

Broccoli was used as the test crop. It is in the cabbage family, Brassicaceae (formerly Cruciferae). It is classified as the Italica cultivar group of the species *Brassica oleracea*. Broccoli possesses abundant fleshy flower heads, usually green in colour, arranged in a tree-like fashion on branches sprouting from a thick, edible stalk. The large mass of flower heads is surrounded by leaves (Hartmann *et al.* 1988).

Broccoli is a cool-weather crop that does poorly in hot summer weather. It grows best when exposed to an average daily temperature between 18-23°C. Factors such as a good stone free even seedbed, good use of nitrogen, early planting, good irrigation, spacing, and timeliness of operations especially the timing of weed control and sowing date in broccoli are very important factors to consider (Salvestrin 1998). Uncontrolled weeds in broccoli can significantly reduce yields. Broccoli was selected for these trials as it was suited to the available growing season; has a moderately long growing season (increasing it’s susceptibility to weeds over time) and is vulnerable to weed competition (especially for light) because it is a relatively low standing crop.

An existing cropping area on the farm was used for the trials. The plots were based on ~1.5 m row widths and were 5 m long, with 24 beds in total. Atomic F1 hybrid broccoli seedlings were planted on 8/7/08 in three rows along the beds at ~20 cm spacings. Standard organic practices were uniformly used on all plots, including irrigation and fertilisation. A crop inspection carried out on 1/8/08 and Dipel® (*Bacillus thurengensis*) was applied on the following day to crop to control cabbage white moth. Broccoli heads started to form at around 2/9/08.

2.2. Experimental treatments

2.2.1. Comparison of weed control methods

Each treatment was replicated four times, except the bioherbicide, which was replicated twice. Steamwand supplied the steam weeding equipment. The timing of the treatment applications was based on the natural emergence of weeds after bed preparation and planting of the crop. The following treatments were used:

1. control (unweeded)
2. herbicide (glyphosate)
3. bioherbicide (pine oil), certified organic
4. steam weeding (hand application), certified organic
5. steam weeding (tractor application), certified organic
6. tillage (mechanical tillage + hand chipping), certified organic

Control (unweeded)

An unweeded control treatment was used to compare the effect of the other treatments with the effect of doing nothing. In some cases, e.g. quick short terms crops such as lettuce and radish, it can be more cost-effective in the short term to not apply a weed control treatment (Bond *et al.* 2000, Kristiansen *et al.* 2008b). However that strategy may have serious implications for weed seed production and potentially severe weed problems in subsequent crops.

Herbicide (glyphosate)

Glyphosate is a very commonly used herbicide in horticulture (Henderson and Bishop 2000) and other farming systems. This treatment provides a useful comparison with the various organically certified methods (i.e. bioherbicide, tillage) and steam weeding. Exemption from the requirements of organic certification was granted from the certifying agency for the specific area being used in the trials plus a 15 m buffer surrounding that area. That area will be not used for organic production for a period of 36 months. Roundup Extra® (active ingredient: glyphosate) was mixed with water (10ml of bioherbicide per litre of water) and applied at a diluted rate of 1,400 Litres/ha on 12/8/08 using a standard hand-operated spray-pack supplied by the University of New England.

Bioherbicide (pine oil)

A commercially available pine oil based product, Interceptor®, was used as a comparative method as this product is widely marketed to the organic farming sector (Certified Organics Australia Pty Ltd 2008). The bioherbicide was mixed with water (200ml of bioherbicide per litre of water) and applied at a diluted rate of 1,400 Litres/ha on 12/8/08 using a standard hand-operated spray-pack supplied by Organic Knowledge.

Steam weeding

The machine is used either (A) with a wand attachment for very selective and awkward to reach weeds or for smaller-scale usage (Figure 2) or (B) with tractor-mounted hoods for inter-row weeding of larger areas (Figure 3). Both applications methods were tested in these trials.

Figure 2. Hand-held applicator for steam weeding (Photo: Steamwand).

Figure 3. Tractor-mounted applicator for steam weeding.

The steam was applied by hand much the same way as a vacuum is used for cleaning. The wand was held and brushed around the broccoli plants and down the inter-rows. The tractor-mounted steam weeding was applied at 2 km/hr, with the four hoods set on either side of the rows of broccoli seedlings. The body of the machine consists of a water heater and a tank for the fuel with a row of hoods attached to it. It is possible to adjust the height, the angle, and tractor speed.

Tillage

The tillage implement used for primary weed control in the crop was Farmall AV Tractor with a mid-mounted duck-foot plough with four tines spaced 25cm apart. The plough operated at a depth of 15cm in the soil. Hand-weeding (or chipping) involved walking along the crop row and removing the weeds with a hand held hoe or chipper after the mechanical tillage operation to remove any remain weeds in the crop row. Hand chipping is labour intensive and therefore costly, and there can be problems with the availability and the management of this labour.

2.2.2. Evaluation of tractor speed on steam weeding

The effectiveness and economics of steam weeding was determined at four speeds: 1, 1.5, 2, and 2.5 km/hr. This trial was carried out on similar prepared beds as for Trial 1, but without broccoli planted and focussed on the before and after effects on weed density and species present. No crop was used in this trial as the aim was to evaluate the effect of tractor speed on weed control.

2.3. Weed measurements

Weed population counts were assessed during the growing season using 50cm x 50cm quadrat counts to monitor changes in weed density and flora in both trials. In order to determine whether steam application selectively controls some weeds and not others, the weed density counts were separated into broadleaf and grass weeds. Quadrats were placed in the same position within the plot at each sampling time and weed density was recorded fortnightly.

2.4. Crop measurements

Broccoli yield was measured at harvest (10/9/08). The crop was harvested by cutting the plants at 15cm, removing excess leaves and recording the fresh weight. Crop yield (kg/plot) was converted to a hectare basis (kg/ha) and multiplied by the current wholesale price for organic broccoli ($3.20/kg) for all treatments except glyphosate which was priced at $1.75 (Passmore 2008).

2.5. Economic analysis

An economic comparison of the weed management systems was carried out by recording the fixed and variable costs of each weeding treatment and the yields produced. The costs associated with each treatment are detailed in Table 4 in *Section 3.1.3* below. A cost/benefit analysis performed to determine the economic performance of the treatments used by subtracting the costs from the gross income to give an adjusted income for each treatment. It was assumed that all other costs were equal for the treatments, such as fertilising, irrigation and harvesting labour.

2.6. Experimental design and statistical analysis

These trials were conducted as completely randomised design with four replicates for each treatment (three replicates for the tractor speed evaluation). The data was statistically evaluated with analysis of variance (ANOVA) using the R statistical program (R Development Core Team 2003) to identify the significant differences between treatments. Treatment averages were compared using standard errors, where overlaps indicate a lack of significant differences (Webster 2007). A line of best fit (linear regression) was calculated for measurements taken over time and 95% confidence limits determined to indicate the variability.

3. Results and discussion

3.1. Comparison of weed control methods

3.1.1. Weed growth

The density of both the grass weeds (Figure 4) and broadleaf weeds (Figure 5) the over time were significantly different between the weed control treatments ($P \leq 0.02$). In general, there was very good control of broadleaf weeds, with all treatments reducing weed levels compared with the unweeded control. Glyphosate has the lowest density of broadleaf weeds, though this only occurred towards the end of the cropping period, just prior to harvest. The steam weeding treatments were similar to pine oil and tillage/chipping.

There were some problems controlling grass weeds with the steam treatments, especially the tractor application, which had variable effectiveness. Confirming previous research on thermal weeding, steam weeding compared favourably with herbicides, but was more variable and sensitive to environmental and application conditions than is generally expected of herbicides (Wszelaki *et al.* 2007).

There was a late reduction in grass weeds in the glyphosate treatment, with tillage/chipping providing a similar level of control. It is assumed that the different weed responses are due to the growth habit of grasses and other monocotyledonous plants (e.g. sedges, palms, onions) in which the main growing point (meristem) is protected deep within many layers of leaves. While the open leaves will be killed, the meristem may be undamaged, allowing the plant to continue growing. On the other hand, dicotyledonous species have exposed meristems making them considerably more susceptible to permanent damage from heat (Bond *et al.* 2007, Wszelaki *et al.* 2007).

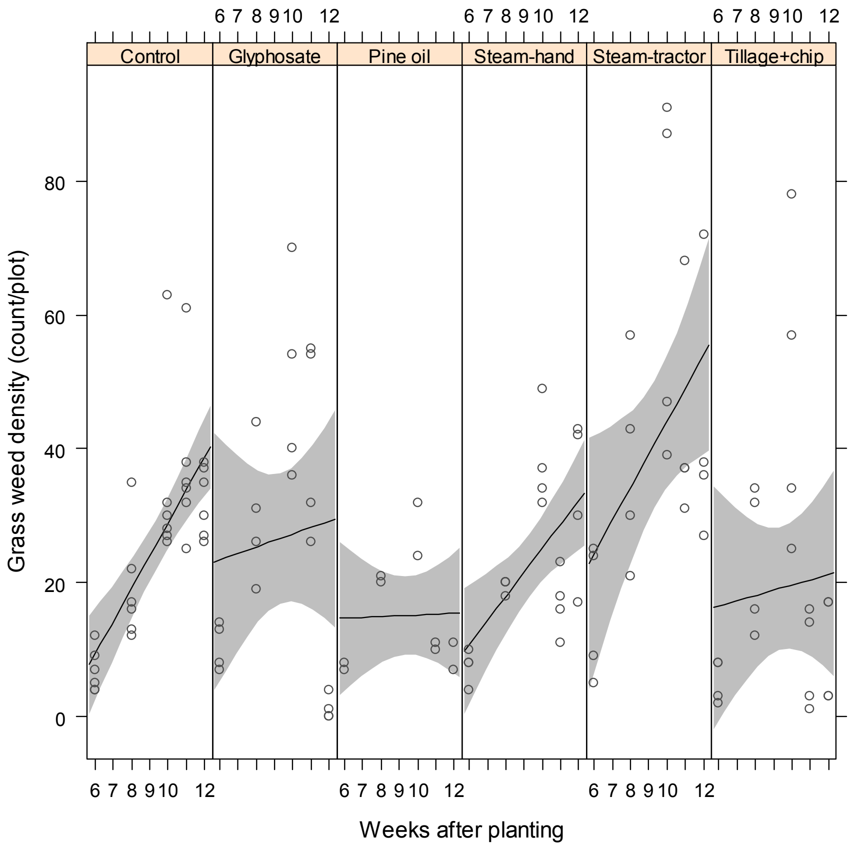

Figure 4. Effect of weed control treatments on grass weed density over time. The circles indicate the data points for each plot, the black line shows the line of best fit (linear regression) and the grey shaded area is the variability of the data (95% confidence limit).

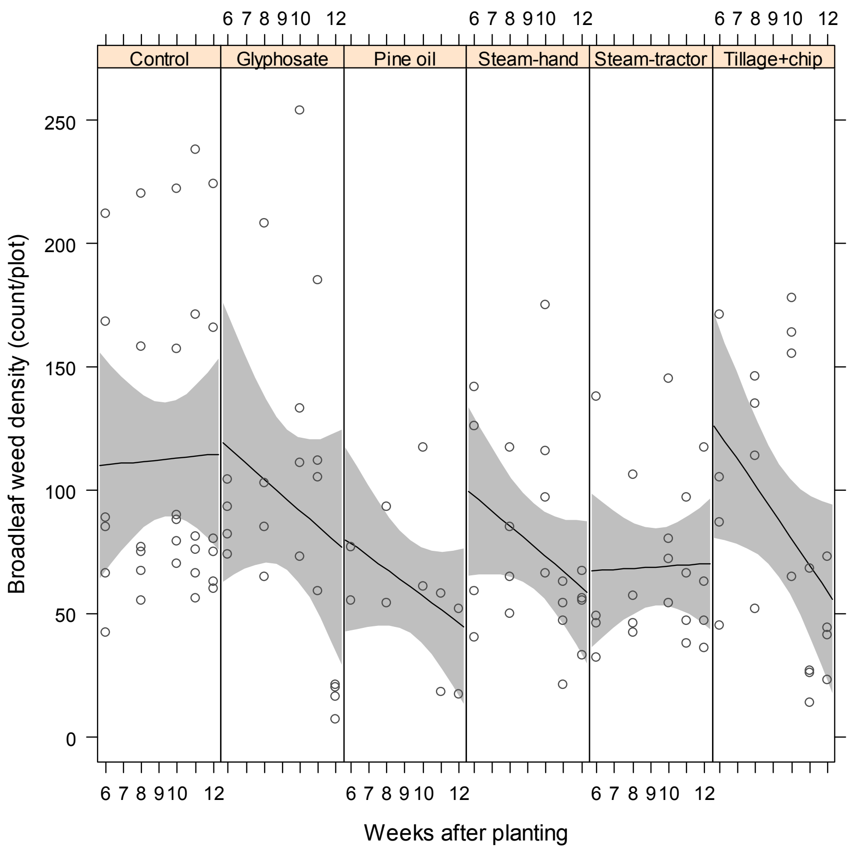

Figure 5. Effect of weed control treatments on broadleaf weed density over time. The circles indicate the data points for each plot, the black line shows the line of best fit (linear regression) and the grey shaded area is the variability of the data (95% confidence limit).

3.1.2. Crop yield

The overall effect of the weed control treatments on crop yield (Table 2) was not significantly different (*P* = 0.81), except that the control was lower than the other treatments (*P* = 0.05). Tillage/chipping, the standard practice in organic vegetable production, was quite variable, indicating that poor tillage can lead to large yield reductions. Stream weeding was less variable when applied by hand, rather than by tractor, due to the better targeting of weeds by the operator. However, this accuracy comes at the cost of greater labour expense for the hand application method (Table 4).

The similar yields for the various treatments suggests that, (a) the active treatments (i.e. not the control) were largely effective in reducing weeds, and (b) the broccoli crop was moderately tolerant of competition from the remaining weed populations. Slower growing crops may be subject to a larger yield loss from weeds, while quicker crops would be largely unaffected in terms of yield.

While broccoli is reported to yield up to 5 tonnes/ha in organic production (Lampkin *et al.* 2006), the yields achieved in these trials were lower, with an average of 2.7 tonnes/ha for the active treatments (i.e. not the control). This lower overall yield was due to the single harvest (rather than several repeat harvests) and wet weather causing less than optimum soil conditions for broccoli growth.

Table 2. Effect of weed control treatments on the yield of broccoli (tonne/hectare). Average and standard errors shown.

Treatment	Adjusted income (tonne/hectare)
Control	1.90 (± 0.24)
Glyphosate	2.57 (± 0.24)
Pine oil	2.76 (± 0.07)
Steam – hand	2.57 (± 0.36)
Steam – tractor	2.76 (± 0.59)
Tillage + chipping	3.03 (± 0.53)

3.1.3. Economic comparison

The gross income (

Table 3) was calculated from the harvested crop yield, based on a wholesale price of $3.20/kg for organic broccoli and $1.75/kg for conventional broccoli. There was a significant difference ($P = 0.04$) in gross income between treatments with all treatments giving similar returns of about $8,000/ha except glyphosate which was worth about half ($4,500/ha) due to the different wholesale price for organic versus conventional broccoli. Without the premium for certified organic produce, the gross incomes would be similar for all treatments, including the unweeded control. While it has been suggested that premiums for organic goods may decline with greater adoption of organic farming methods (e.g. Elliot and Mumford 2002), continued growth in demand in Australia (Kristiansen *et al.* 2008a) and globally (Dimitri and Greene 2002, Willer *et al.* 2008) provides evidence that consumers are willing to pay extra for the perceived differences in quality.

Table 3. Effect of weed control treatments on gross crop income ($/hectare). Average and standard errors shown.

Treatment	Gross income ($/hectare)
Control	6,079 (± 770)
Glyphosate	4,498 (± 425)
Pine oil	8,840 (± 222)
Steam – hand	8,229 (± 1,147)
Steam – tractor	8,822 (± 1,883)
Tillage + chipping	9,705 (± 1,706)

The total cost of implementing each treatment was calculated based on tractor use (including labour for the driver), materials and labour, and was expressed on a $/ha basis (Table 4). Treatments that required direct labour input (i.e. Steamwand hand application, and chipping) were more expensive than tractor-applied treatments such as herbicide spraying and steam application.

The glyphosate treatment was the cheapest (apart from the unweeded control) and the tractor applied Steamwand treatment was the next cheapest, being 14% more than herbicide. The difference in cost between these two treatments was due to the application speed leading to higher tractor and driver costs ($168/ha). However, the cost of materials for the steam treatment was lower ($76/ha).

The bioherbicide treatment was the most expensive (five times dearer than Steamwand tractor application) due the high concentrations recommended for the product. Previous work on pine oil indicated that for dense pasture mown to 50 mm, optimum application volumes ranged from 1,600 to 3,200 litres/ha (James *et al.* 2002). However, the slightly smaller volume (1,400 litres/ha) used in our trials was sufficient for the lower weed vegetation levels encountered in the broccoli crop. It is possible that lower rates could be used if the timing was optimised.

Table 4. Costs of weed control treatments.

	Total cost	**Tractor + labour**			**Materials**				**Labour**		
Treatment	**$/ha**	**hr/ha**	**$/hr**	**$/ha**		**unit/ha**	**$/unit**	**$/ha**	**hr/ha**	**$/hr**	**$/ha**
Control	0										
Glyphosate	644	6	84	504	Herbicide (litres)	14	10	140			
Pine oil	3,864	6	84	504	Bioherbicide (litres)	280	12	3360			
Steamwand - hand	904				Steamwand gear (hour)	15	8.28	124	40.2	19.4	780
Steamwand - tractor	738	8	84	672	Steamwand gear (hour)	8	8.28	66			
Tillage + chipping	1,156	4	84	336	Tillage gear (hour)	4	10	40	40.2	19.4	780

The adjusted income (gross income less the cost of the weeding method) is shown in Table 5. Adjusted income was significantly higher for the two Steamwand treatments and tillage, with herbicide being 48% lower and bioherbicide 62% lower ($P = 0.05$). The adjusted income for the control treatment was lower than the Steamwand treatments, but not significantly different.

The lower income from glyphosate, despite its lower cost compared with the other treatments, was due to the lower wholesale price used to calculate income for the non-organic treatments. If prices for organic and conventional broccoli were similar the adjusted income for glyphosate would be equivalent to that of the Steamwand and tillage treatments. Although the yield of pine oil was similar to the other applied treatments, its high cost reduced the adjusted yield significantly.

Table 5. Crop income after weeding costs ($/hectare). Average and standard errors shown.

Treatment	Adjusted income ($/hectare)
Control	6,079 (± 770)
Glyphosate	3,854 (± 425)
Pine oil	4,977 (± 222)
Steam – hand	7,325 (± 1,147)
Steam – tractor	8,083 (± 1,883)
Tillage + chipping	8,549 (± 1,706)

3.2. Evaluation of tractor speed and effectiveness of steam weeding

3.2.1. Weed growth

The effect of increasing tractor speed was different for grass weeds (Figure 6) and broadleaf weeds (Figure 7). The number of broadleaf weeds present was proportional to the tractor speed, with slower speeds providing better weed control. At the highest speed, the effect on weed control was very variable, partly due to the variability of the weed levels in each plot.

On the other hand, grass weeds were controlled better by the 2 km/hr treatment than the slower or faster speeds. The cause of the result for grass weeds is unclear as it is assumed that slower speeds would provide a longer period of heating, thus penetrating the sheathed leaves of grasses (Wszelaki *et al.* 2007). It is worth noting that the number of grass weeds (20-30 weeds/plot) was significantly lower than broadleaf weeds (70-120 weeds/plot) indicating that the results for grass weeds are based on a very small absolute weed density.

While not directly comparable to steam weeding due to differences in heat transfer, other researchers using flame weeding equipment found that a speed of between 1 and 1.5 km/hr produced a similar lettuce yield to that of herbicide application (Balsari *et al.* 1994). However, other trials, also using flame weeders, showed that some dicotyledonous species were controlled at higher speeds (e.g. 5 km/hr) while monocotyledonous species resisted treatment and regenerated at the slowest speed of 0.6 km/h (Finger *et al.* 1998).

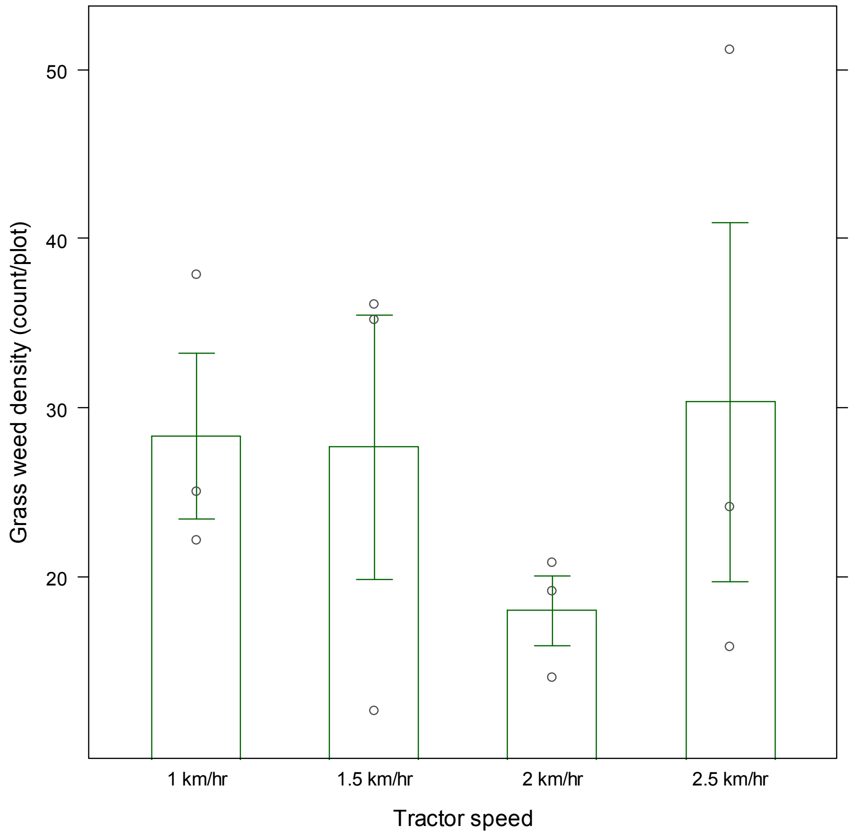

Figure 6. Effect of speed of steam-weeding on grass weed density after two weeks. The circles indicate the data points for each plot, the columns show the treatment average and the error bars represent the standard error of the average.

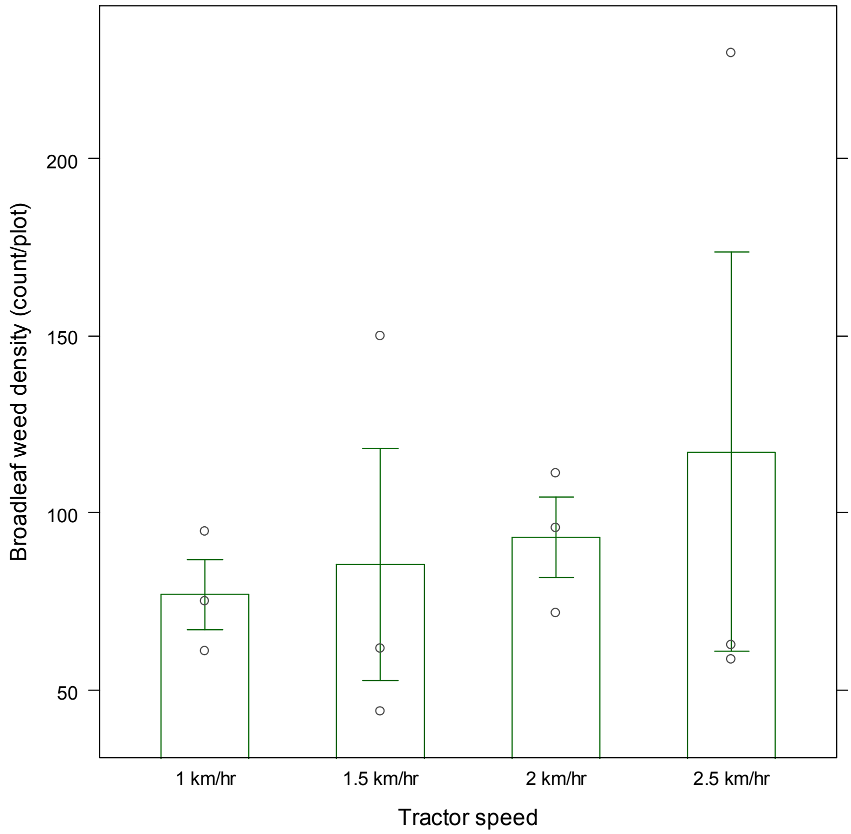

Figure 7. Effect of speed of steam-weeding on broadleaf weed density after two weeks. The circles indicate the data points for each plot, the columns show the treatment average and the error bars represent the standard error of the average.

3.2.2. Economic comparison

Given the lack of clear differences between the effect of speeds on weed control, the economic performance would be lower in the slow speeds due to increased time for labour and equipment running costs. For the 1km/hr treatment, the cost would be $1,292, assuming tractor and driver costs of $1,176 and running costs of $116/hr based on an application time of 14 hr/ha (double time in the field but not start-up and finishing times). This indicates an increased cost of 75% compared to the 2 km/hr treatment.

If the gross income remains the same as for 2 km/hr (i.e. $8,821/ha), then the adjusted income for the 1 km/hr treatment would be $7,529/ha. Therefore the adjusted income would be slightly higher than the adjusted income for the hand-applied steam treatment and slightly lower than the 2 km/hr steam weeding (
Table 5).

4. Conclusions

4.1. Summary of findings

The steam weeding equipment provided equivalent weed control to common organic weeding methods including tillage/chipping and to novel methods such as pine oil bioherbicide. Compared with glyphosate, a commonly used herbicide in horticulture and agriculture, the level of weed control was similar. Hand-applied steam weeding was usually more effective and less variable due to better targeting and slower application speed.

The steam application speed of 2 km/hr was the most suitable for the crop used in the trail and the weed species encountered. The number of broadleaf weeds remaining after steam treatment was reduced by applying at lower speeds and variability also decreased as speed decreased.

The steam weeding equipment was less effective for grass weeds compared with broadleaf weeds as a result of the different growth forms of the two weed types. The main growing points (meristems) of grasses are concealed within the new leaves, whereas the meristems in broadleaf species are usually exposed and are more susceptible to control measures. This is a known issue for many weed control methods that are non-systemic, including contact bioherbicides and thermal weeding methods such as flaming and steaming. The strategies for over-coming this limitation include careful timing of application to ensure the weeds are as young as possible, and slower application speeds to increase the ability of the steam to heat and kill the concealed meristems.

Crop yields were similar for all treatments except the control, indicating that the weeding methods were largely effective and/or that broccoli was able to tolerate the existing weed competition. The gross income was generally equivalent for the active treatments (i.e. not the control), except the herbicide (glyphosate) treatment which was significantly lower due to the lower wholesale price used for non-organic produce.

Treatments that required hand labour (e.g. chipping, steam application by hand) incur considerably higher costs overall. The cheapest treatments were glyphosate, followed by steam application by tractor. Adjusted income (i.e. gross income – weeding costs) was highest for both Steamwand treatments and for tillage/chipping. Glyphosate had the lowest adjusted income due to the lower prices received, while pine oil was also low due to the high cost of materials used. The adjusted income for slower tractor application of steam (1 km/hr) is likely to be midway between the income for hand application and the 2 km/hr tractor application. This compares favourably in economic terms despite the longer time required (14 hr/ha compared with 8 hr/ha) and may achieve better weed control when applied when weeds are young.

For large-scale commercial uptake of the steam weeding equipment, future machines need to combine a high working quality with low additional costs in order to be able to compete with current mechanical weeding implements. The additional costs for the steam machine have to be the same or less than other options and in particular herbicide, which is still widely used by conventional growers. However, the advantages of steam weeding also include the ability to control weeds when climatic and soil conditions are unsuitable for other methods (e.g. tillage, herbicides) and the ability to control weeds without causing further soil disturbance compared with tillage.

It should also be reiterated that sound organic weed management relies the use of a mixture of strategies to provide season-long success across years, rather than simply relying on one technique (Bond and Grundy 2001). Each method is only one part of a long-term weed management strategy that includes strategic rotations, cultural techniques (e.g. planting configuration), mechanical methods and other approaches appropriate to each farm.

4.2. Suggestions for future research

To get a clearer estimation of the effectiveness of the various treatments, further trials could be conducted that include the following variables:
* different crop types (e.g. canopy shape, growth rates, season length),
* different soil types (e.g. sandy versus clay), and
* different climatic conditions (e.g. very dry or very wet conditions).

Some of these variables could be tested under simulated conditions, for example in a glasshouse using large soil containers that enable finer control of soil type, soil moisture, and weed density, species and age.

It may also be worth exploring hood size and shape for the steam applicator in order to maximise heat transfer, and the use of wider toolbars to cover greater area (e.g. three beds at a time) and improve overall efficiency. Using mechanical tines (e.g. goose-foot or spring tines) attached in front of the Steamwand toolbar may give better weed control by causing shallow soil disturbance immediately before the steam application. It is also suggested that a temperature gauge in the tractor cab (or on the machine) would allow the operator to know the best time to use the equipment.

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6. Appendices

6.1. Soil test

The soil test results are given in Table 6.

Table 6. Soil test results for the trial site.

Nutrient (units)	Value
Texture	Clay
Colour	Dark Grey
pH (1:5 water)	5.6
Conductivity (1:5 water) (µS/cm)	120
Total Carbon (%)	2.9
Organic Matter (%)	5.0
Total Nitrogen (%)	0.24
Carbon/Nitrogen ratio	12
Nitrate (ppm)	16
Ammonium (ppm)	5.1
Phosphorus (Colwell) (ppm)	64
Sulphate Sulphur (ppm)	22
Potassium (cmol+/Kg)	0.45
Calcium (cmol+/Kg)	16
Magnesium (cmol+/Kg)	7.7
Sodium (cmol+/Kg)	0.52
Aluminium (cmol+/Kg)	0.22
Cation Exchange Capacity (cmol+/Kg)	24
Calcium/Magnesium ratio	2.0
Zinc (ppm)	3.0
Manganese (ppm)	169
Iron (ppm)	116
Copper (ppm)	1.3
Boron (ppm)	0.50
Silicon (ppm)	54