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Effect of Steam Application on Cropland Weeds[1]

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Abstract: Plot-scale field studies were conducted to evaluate the efficacy of steam for the control of cropland weeds in comparison with common herbicides. Weed densities, biomass, or emergence after treatment were measured. Steam (3,200 kg/ha, energy dosage equivalent to 890 kJ/m^2, speed of 0.8 m/s) and glyphosate (560 g ai/ha) gave similar control ($>$ 90%) of seedling common lambsquarters and seedling redroot pigweed. Applied at heading, steam was comparable to glyphosate in reducing green foxtail biomass at heading 2 wk after application. Steam applied at a rate of 3,200 kg/ha significantly reduced weed biomass (mixed stand, treated at seedling stage) 9 wk after application compared with the control, whereas steam applied at a rate of 1,600 kg/ha (1.6 m/s) did not. Biomass of downy brome treated with steam was reduced more at anthesis than at the seedling growth stage. Emergence of common lambsquarters, redroot pigweed, and black nightshade was not affected by steam application. Amount of steam applied, weed species, and growth stage are key factors in determining control effectiveness.

Nomenclature: Glyphosate; black nightshade, *Solanum nigrum* L. #[3] SOLNI; downy brome, *Bromus tectorum* L. # BROTE; common lambsquarters, *Chenopodium album* L. # CHEAL; green foxtail, *Setaria viridis* L. # SETVI; redroot pigweed, *Amaranthus retroflexus* L. # AMARE.

Additional index words: *Kochia scoparia* L. Schrad., KOCSC, paraquat, pelargonic acid, SALIB, *Salsola iberica* Sennen & Pau.

INTRODUCTION

Several phenomena over the past 10 to 15 yr have prompted a search for alternative methods of weed control. A trend presently exists where governmental regulation of agricultural chemicals is gradually becoming more stringent. New regulations such as the Food Quality Protection Act of 1996, which places increased restrictions on allowable pesticide residues in food, are likely to continue. Also, an increase in public awareness of chemical use in food production and processing will continue to call for further reductions in these practices, based on health and environmental concerns. Reports of weed resistance to commonly used herbicides have also been increasing (Gill 1995; Moss and Rubin 1993; Shaner 1995). Often, the only alternative is to use other herbicides with different modes of action, usually at a higher cost. There is a demonstrated need for an economically competitive, environmentally benign method of weed control.

Steam has been used in the greenhouse and nursery industry for soil pasteurization. Field applications have been performed in orchards (Moyls and Hocking 1994), in forests (Norberg et al. 1997), and for insect control (Pelletier et al. 1998). Research is lacking on the effects of steam on weeds under field conditions. Alternative weed control methods that would decrease or eliminate pesticide use could impact producers' cropping system options by allowing the inclusion of higher value commodities, switching to organic production, or permitting more flexible crop rotational sequences.

The objective of this study was to evaluate the weed control effectiveness of steam application under field conditions compared with herbicides.

MATERIALS AND METHODS

Machine Description. Steam was applied using a custom-built prototype steam generator–applicator machine (Figure 1A). Steam was generated using a propane burner with the option of diverting exhaust heat from the

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

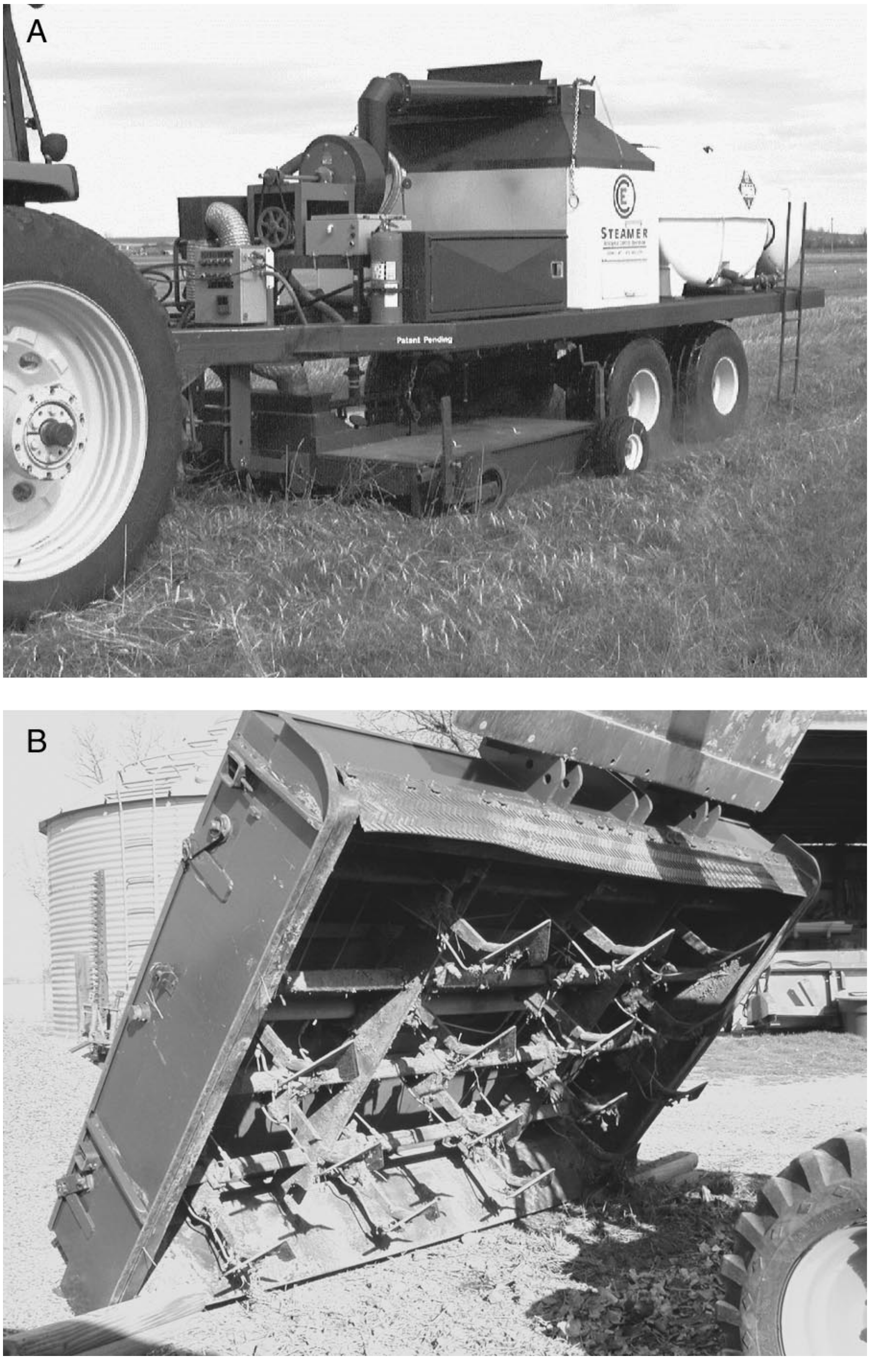

Figure 1. Prototype steam generator–applicator machine used in the present study with surface applicator (A) and the underside of the combination tillage–steam applicator (B).

burner to the applicator. Output of the hydraulically driven water pump was adjusted so that the in-line water temperature just prior to application averaged 175 C. Dosage levels were varied with the speed of travel. Two applicator attachments were used to apply the steam. The surface applicator measured 1.9-m long by 2.4-m wide and comprised six rows of eight nozzles (30-cm spacing) per row. Nozzles were standard spray nozzles[4] arranged 12 cm above the soil surface in a staggered pattern. Nozzles were completely enclosed in a steel housing to pre-

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[4] TeeJet 11003, Spraying Systems Co., Wheaton, IL 60188. Mention of particular companies or commercial products does not imply recommendations or endorsement by USDA over other companies or products not mentioned.

Table 1. Treatments applied to test the effect of steam application, tillage, and auxiliary heat on weed emergence (experiment 4).

Treatment	Tillage	Steam	Auxiliary heat[a]	Speed[b]
		kg/ha		
1	Yes	3200	Yes	Low
2	Yes	3200	No	Low
3	Yes	0	No	Low
4	Yes	1600	Yes	High
5	Yes	1600	No	High
6	Yes	0	No	High
7	No	0	No	Low
8	No	0	No	High
9	No	0	No	—

[a] Exhaust heat from the propane burner was or was not diverted to the applicator unit.

[b] Low speed = 0.8 m/s; high speed = 1.6 m/s.

vent the rapid escape of heat and steam. The second applicator applied steam in conjunction with tillage (Figure 1B). This applicator consisted of fifteen 23-cm-wide sweeps configured in a staggered pattern in four rows (three sweeps in the front row). Two nozzles were positioned with each sweep: one located above the sweep point sprayed toward soil moving past and one underneath the sweep-injected steam toward the sweep point. Average depth of tillage was 9 cm.

Field Experiments. Four field experiments were conducted to evaluate the effect of steam application on standing weeds and seedling emergence.

Experiment 1. Three species of weeds, common lambsquarters, redroot pigweed, and green foxtail, were planted on a Williams loam soil near Sidney, MT in July 1997. The experimental design was a randomized complete block with a split-plot treatment arrangement in three replications. Weed species was the main plot (36 by 15 m^2) with subplots (3 by 15 m^2) containing growth stage and application treatment. Approximately 200 seeds were scattered in each of six, evenly spaced microplots (0.25 m^2 each) within the subplot. Three treatments were compared: control (no application), steam (3,200 kg/ha), and glyphosate (560 g ai/ha, 47 L/ha total spray volume without adjuvant). Redroot pigweed and common lambsquarters were treated at three growth stages: seedling, four- to six-leaf, and anthesis. Depending on the emergence patterns, weed stands were thinned during the first 2 wk of August to a maximum of 30 plants per microplot for the two younger growth stages and to a maximum of 15 plants per microplot for the last growth stage. Weed densities were recorded just prior to application and 4 wk after application. Weed densities were not identical across all treatments at application; however, ANOVA showed no differences ($\alpha = 0.05$). Therefore, treatment effects were compared using the postapplication weed count.

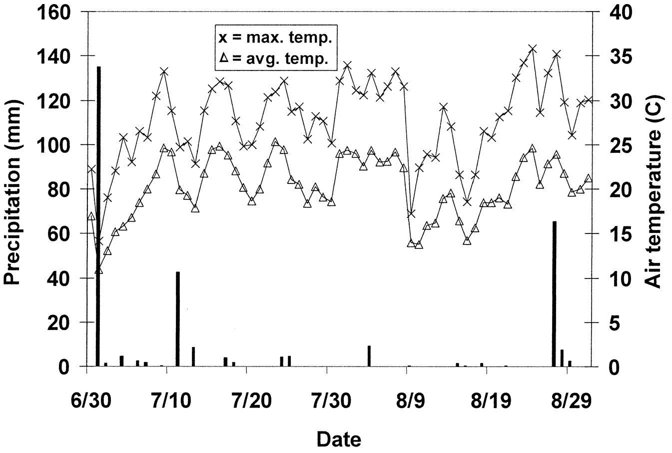

Figure 2. Precipitation and maximum and mean daily air temperature during the study period near Sidney, MT.

For green foxtail, spray treatments were applied only after head emergence. Above-ground weed biomass was collected 2 wk after application when an oven-dry (60 C) weight was recorded. Seed heads of green foxtail were also collected and germination tested. Two hundred seeds were counted from each treatment, kept moist between paper towels over a 4-wk period, and the number of viable seeds recorded.

Experiment 2. Four treatments were applied to a thick natural stand of downy brome: control (no application), steam (3,200 kg/ha), glyphosate + pelargonic acid (280 g ai/ha + 2% solution + surfactant),[5] and glyphosate (560 g ai/ha + surfactant). Treatments were applied at four growth stages: seedling, four- to six-leaf stage, anthesis, and 50% seed maturity. Weed biomass was measured 4 wk after application at the seedling stage and 2 wk after application for the remaining growth stages. Samples were taken from six areas (0.25 m^2 each) along the length of each plot. Plot size was 4 by 60 m^2. The experimental design was a randomized complete block with four replications. The site was near that of experiment 1. Inclusion of glyphosate + pelargonic acid was done because previous research suggested a synergistic effect of the two chemicals (Savage and Zorner 1996).

Experiment 3. Steam treatments only were applied to a mixed stand of weeds. Steam was applied at two speeds (0.8 m/s equal to 3,200 kg/ha and 1.6 m/s equal to 1,600 kg/ha) in combination with and without the use of aux-

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[5] Scythe, Mycogen, Corp., San Diego, CA 92121.

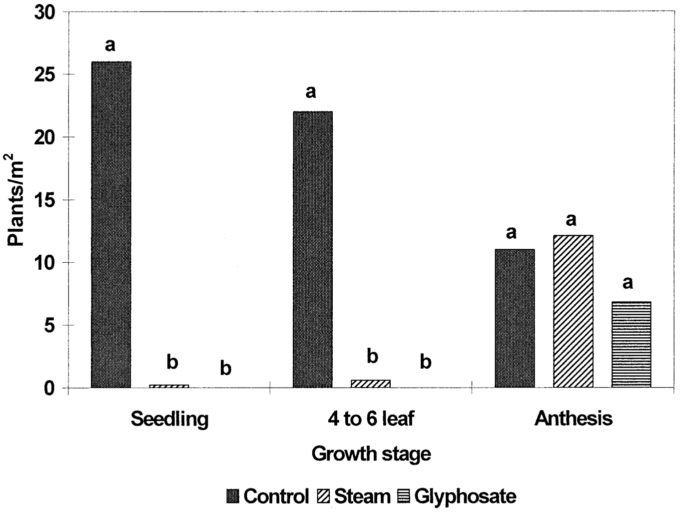

Figure 3. Effect of steam, herbicide, and no application on common lambsquarters at three growth stages measured 4 wk after treatment.

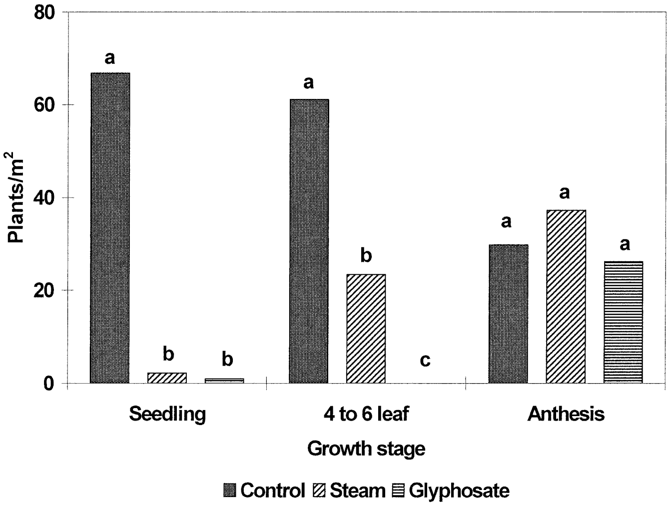

Figure 4. Effect of steam, herbicide, and no application on redroot pigweed at three growth stages measured 4 wk after treatment.

iliary hot air for a total of five treatments including the control. Steam was applied when the weeds were an average height of 3 cm. Species included Russian thistle (*Salsola iberica* Sennen & Pau), kochia (*Kochia scoparia* L. Schrad.), black nightshade, redroot pigweed, and common lambsquarters. Weed biomass was measured 9 wk after application (1 m^2), and comparisons were made with a control treatment. Plots (3 by 15 m^2) were arranged in a randomized complete block with four replications and located near Fort Collins, CO, on certified organic farmland.

Experiment 4. Because the machine can apply steam in conjunction with tillage, the effect of steam application on weed seedling emergence was studied at the Fort Collins site. Steam would be expected to decrease weed emergence, but tillage can increase it (Roberts 1984). In order to understand how the machine might affect emergence of the native weed seed bank with these contrasting effects, we applied the following four machine treatments: (1) driving over the plots to determine if tractor and applicator travel affected weed emergence, i.e., another type of control; (2) tillage alone; (3) tillage with steam; and (4) tillage with steam and auxiliary hot air. Each machine treatment was applied at two traveling speeds with an additional control treatment (see Table 1). Plots (3 by 15 m^2) were arranged in a randomized complete block with four replications. Emerged weeds were counted in eight subplots of 0.25 m^2 within each plot. At 3 and 7 wk after application, the emerged weeds were identified and counted, and during the first count, removed.

The effect of the machine on weed seedling emergence was assessed by analyzing the sum of the two weed counts using generalized linear models (Statistical Analysis Systems Institute 1988). First, weed counts of the eight machine-by-speed treatments were analyzed as a factorial design, which included the two traveling speeds and four machine treatments. The appropriate error term from this analysis was used to calculate a least significant difference (LSD) to compare the weed counts of these eight treatments with those of the control.

RESULTS AND DISCUSSION

Experiment 1. Precipitation and air temperature during the study are given in Figure 2. From July 1 to the first

Table 2. Downy brome fresh weight (relative units) of four application treatments at four growth stages (2 to 4 wk after application).

Treatment	Seedling	Four to six leaf	Anthesis	50% seed maturity
	% Fresh wt[a]			
Control	100 a[b]	100 a	100 a	100 a
Steam	95 a	101 a	72 c	114 a
Glyphosate	72 b	71 b	68 c	94 a
Glyphosate+Pelargonic acid	94 a	90 a	86 b	109 a

[a] Actual values of the control treatment were 428, 514, 482, and 379 g/m^2.

[b] Mean of four replications. The same letter within each growth stage indicates a lack of significance at the 0.05 level. Analysis done on biomass fresh weight.

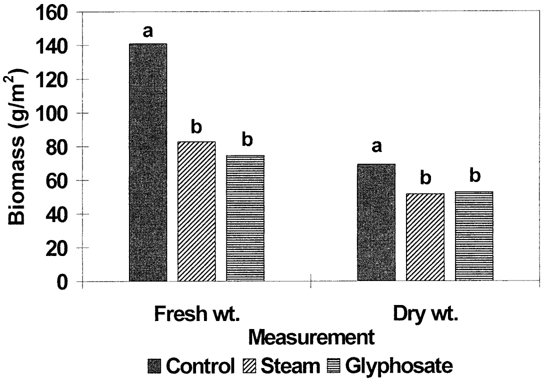

Figure 5. Fresh and dry weights of green foxtail under three treatments applied after head emergence.

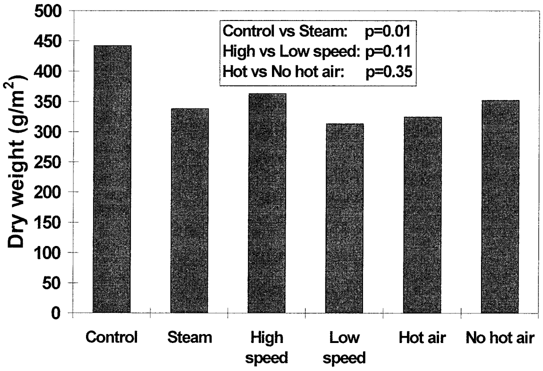

Figure 6. Dry weight of a mixed stand of weeds 9 wk after application using steam at two speeds, with and without auxiliary heat. ‘‘Steam’’ refers to the average of these four treatment combinations. Data within each level of ‘‘speed’’ and ‘‘hot air’’ are averaged over the two levels of their opposing factor.

treatment application (5 wk), 220 mm of precipitation was received, of which 135 mm occurred in one event on July 1 (Figure 2). Daily maximum air temperature over the same period averaged 28 C, with a mean temperature of 21 C. Weeds were actively growing at the time of application.

Weed densities were lowest for the steam and glyphosate treatments applied to common lambsquarters and redroot pigweed at the seedling stage and to common lambsquarters at the four- to six-leaf stage (Figures 3 and 4). All the applications on redroot pigweed and common lambsquarters at anthesis were similar to the control treatment.

Steam and glyphosate significantly reduced biomass of green foxtail compared with the control (Figure 5). The difference in the oven-dry weights of the control and the average of the spray treatments (~ 16 g/m^2) represents a 24% reduction in biomass during the 2-wk interval from application to sampling. A similar pattern was seen in the germination of green foxtail seeds. Steam (18%) and glyphosate (4%) treatments significantly reduced the percentage of green foxtail seeds that germinated when compared with the control (45%).

Experiment 2. Fresh weights of downy brome 4 wk after application at the seedling and four- to six-leaf stages were reduced relative to the control only by glyphosate (Table 2). This indicates that growth was not retarded by steam or glyphosate plus pelargonic acid.

At anthesis, biomass of the spray treatments was less than that of the control (Table 2). Fresh weight of steam was similar to that of glyphosate, indicating that it hindered the growth of downy brome at this stage as well as the herbicide; however, the weight of glyphosate + pelargonic acid was considerably higher. Fresh weights of all treatments were similar at 50% seed maturity.

Experiment 3. Looking at orthogonal comparisons, the average biomass of all steam treatments was about 100 g/m^2 less than that of the control (Figure 6). Comparison of the high dosage rate to the low rate approached significance ($P = 0.11$), with the former being relatively more effective in reducing total weed biomass. Supplementing the steam application with auxiliary hot air did not reduce the total weed biomass when compared with the use of steam alone. The borderline response of weed growth to steam may have resulted from measuring weed biomass 9 wk after treatment. In a cropping situation, where good crop establishment is attained, impaired weed growth early in the season can be adequate to allow the crop to gain a competitive advantage and to suppress later-emerging weeds.

Experiment 4. Only four species were abundant enough for analysis of the effect of the machine on weed emergence. These species were pigweed, nightshade, lambsquarters and kochia, and most emergence occurred after the first evaluation. Speed had no effect on weed emergence ($P \geq 0.42$) for any species, therefore the data presented are averaged across speed (Table 3). The four machine treatments approached significance in their effect on nightshade ($P = 0.06$) and pigweed ($P = 0.09$) emergence. Differences among treatments were difficult to detect because of spatial variability in the natural weed populations of this study, as indicated by a large sampling error. Despite this variability, some trends are observed and inferences made. For both these species, emergence was greatest for tillage with steam and lowest when the machine was just driven over the plot (Table 3). As steam cannot be applied without tillage with this applicator, it is difficult to separate their individual effects. Steam in combination with tillage may have in-

Table 3. Effect of a prototype steam generator–applicator machine on weed emergence near Fort Collins, CO.[a]

Machine use	Black nightshade	Redroot pigweed
	plants/quadrat	
Tillage and steam	13.2 a	17.7 a
Tillage only	8.6 b	13.1 ab
Tillage, steam, and hot air	7.9 b	8.6 b
Just driving	7.0 b	7.5 b
Control	10.3	13.0
LSD_{10} (''Machine use'' means vs. control)	4.9	8.8

[a] Means are for use of the machine at two traveling speeds. Means for the machine treatments followed by the same letter within a species do not differ significantly using paired tests at P = 0.10.

creased emergence. Steam alone stimulated the fully exposed seeds of other weed species to germinate in an unrelated study (data not shown). Stimulation of weed seed germination via light induction from tillage in the present study was possible only to the extent that seeds were left exposed after the applicator passed because the applicator unit was completely enclosed. Emergence was not increased when hot air was used with steam and tillage. For all species and treatments where the machine was used, emergence was not significantly different from that of the control. Noling (1995) observed that for the effective control of nematodes, 2.75 to 6.5×10^5 L/ha of hot water needed to be applied in order to reach the required soil temperature. These application levels range from 85 to 200 times higher than those used in the present study.

The effectiveness of steam was dependent on weed species and plant growth stage. Younger plants were generally more susceptible for the species tested. However, downy brome, which has a high degree of pubescence, was more resistant to steam during younger stages than during mature stages.

Speed of travel or rate of application is also a factor in the weed control effectiveness of steam. Both the quantity of steam and the amount of time that the heat is effectively in contact with the plant determine the extent of damage to the plant. In comparison with routine commercial herbicide applications, our fastest speed was easily half of that used, which may limit the application of steam on large areas.

Adding auxiliary hot air to the enclosed applicator did not increase weed control effectiveness and may have served to further dissipate the steam and possibly cancel any added benefit from the additional heat energy. This raises the question of whether the added energy needed to change water to steam (2.26 kJ/g, which is over six times the energy needed to increase the water temperature from 15 to 100 C) can be effectively transferred to the plant as opposed to the use of hot water. It appears that a means of preventing rapid dissipation of heat from the plant surface after application could increase steam application effectiveness; however, this could prove difficult in terms of applicator design and for use in windy conditions. An accurate measure of propane use per unit area was not obtained in these studies; however, based on an energy equivalent of 25,600 kJ/L of propane and 70% conversion efficiency, the cost of propane per hectare at our high rate of application would be $52 (US $0.15/L). Further research would be needed to assess the effectiveness and cost of using hot water.

Steam application in combination with tillage did not inhibit the emergence of weed seeds. Rates of application that can raise soil temperatures sufficiently to affect seed germination most likely need to be increased significantly from those used in this study. If weed control efficacy could be improved with this method, an opportunity may then exist for organic producers to practice conservation tillage methods. Greater soil and water conservation could then be realized in organic production which is by necessity tillage intensive.

In addition, a combination of steam or hot water with reduced rates of herbicide could prove useful. Other possibilities include using species-specific weed pathogens in combination with steam.

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