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Integrating Weed and Vegetable Crop Management with Multifunctional Air-Propelled Abrasive Grits

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Abrasive weed control is a novel weed management tactic that has great potential to increase the profitability and sustainability of organic vegetable cropping systems. The objective of this study was to determine the effect of air-propelled organic abrasive grits (e.g., organic fertilizers) on weed seedling emergence and growth and vegetable crop growth. A series of thirteen greenhouse trials were conducted to determine the susceptibility of weeds to abrasive weed control with one of six organic materials including: corn cob grits, corn gluten meal, greensand fertilizer, walnut shell grits, soybean meal, and bone meal fertilizer. In addition, crop injury was quantified to determine the potential utility of each organic material as abrasive grits in tomato and pepper cropping systems. Of the six organic materials, corn gluten meal, greensand fertilizer, walnut shell grits, and soybean meal provided the broadest range of POST weed control. For example, one blast of corn gluten meal and greensand fertilizer reduced Palmer amaranth (one-leaf stage) seedling biomass by 95 and 100% and green foxtail (one-leaf stage) biomass by 94 and 87%, respectively. None of the organic materials suppressed weed seedling emergence when applied to the soil surface, suggesting that residual weed control with abrasive grits is unlikely. Tomato and pepper stems were relatively tolerant of abrasive grit applications, though blasting with select materials did increase stem curvature in tomato and reduced biomass (corn cob grit) and relative growth rate (corn gluten meal and greensand) in pepper. Results suggest that organic fertilizers can be effectively used as abrasive grits in vegetable crops, simultaneously providing weed suppression and supplemental crop nutrition. Field studies are needed to identify cultural practices that will increase the profitability of multifunctional abrasive weed control in organic specialty crops.

Nomenclature: Common lambsquarters, *Chenopodium album* L., CHEAL; common purslane, *Portulaca oleracea* L., POROL; green foxtail, *Setaria viridis* (L.) P. Beauv. SETVI; Palmer amaranth, *Amaranthus palmeri* S. Wats., AMAPA; pepper, *Capsicum annuum* L.; tomato, *Solanum lycopersicum* L.

Keywords: Ecological weed management, organic farming, physical weed control, weed blasting, weed control, specialty crops.

El control abrasivo de malezas es una táctica novedosa para el manejo de malezas que tiene gran potencial para incrementar la rentabilidad y la sostenibilidad de los sistemas de cultivos de vegetales orgánicos. El objetivo de este estudio fue determinar el efecto de la aplicación de partículas abrasivas orgánicas (e.g. fertilizantes orgánicos) con aire a alta presión en la emergencia y crecimiento de plántulas de malezas y en el crecimiento de cultivos de vegetales. Se realizó una serie de trece experimentos de invernadero para determinar la susceptibilidad de las malezas al control abrasivo de malezas con uno de seis materiales orgánicos incluyendo: partículas de mazorca de maíz, harina de gluten de maíz, fertilizante de arena verde, partículas de cáscara de nuez, harina de soya, y fertilizante de harina de hueso. Adicionalmente, se cuantificó el daño del cultivo para determinar la utilidad potencial de cada material orgánico como partícula abrasiva en sistemas de cultivos de tomate y pimentón. De los seis materiales orgánicos, la harina de gluten de maíz, el fertilizante de arena verde, las partículas de cáscara de nuez y la harina de soya brindaron el mayor rango de control POST de malezas. Por ejemplo, una aspersión de harina de gluten de maíz y el fertilizante de arena verde redujeron la biomasa de *Amaranthus palmeri* (estado de una hoja) en 95 y 100% y de *Setaria viridis* (estado de una hoja) en 94 y 87%, respectivamente. Ninguno de los materiales orgánicos suprimió la emergencia de plántulas de malezas cuando se aplicó a la superficie del suelo, lo que sugiere que el control de malezas residual con partículas abrasivas es poco probable. Los tallos del tomate y del pimentón fueron relativamente tolerantes a las aplicaciones de partículas abrasivas, aunque la aplicación con aire a presión de los materiales seleccionados incrementó la curvatura del tallo en tomate y redujo la biomasa (partículas de mazorca de maíz) y la tasa de crecimiento relativo (harina de gluten de maíz y arena verde) del pimentón. Los resultados sugieren que los fertilizantes orgánicos pueden ser usados efectivamente como partículas abrasivas en cultivos de vegetales, brindando simultáneamente supresión de malezas y nutrición suplementaria al cultivo. Se necesitan estudios de campo para identificar prácticas culturales que incrementen la rentabilidad del control abrasivo de malezas multifuncional en cultivos de vegetales orgánicos.

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Significant research progress has been made toward improved integrated weed management strategies, yet weeds remain a top management concern among specialty crop and organic farmers. Most farmers and researchers agree that a successful weed management plan depends on a diverse, multi-tactical approach consisting of "many little hammers" (Liebman and Davis 2009). Chemical, cultural, and biological approaches to integrated weed management are well developed (e.g., registered herbicides, crop rotation, and cover crops), but many of the physical approaches are outdated and there is a strong need for technical innovation. The development of air-propelled abrasive weed control is one example of recent innovation in physical weed control that could contribute to a more diversified weed management portfolio at the disposal of specialty crop and organic farmers (Forcella 2009a). Air-propelled abrasive weed control, or "weed blasting," is the application of existing sand-blasting technology (typically used for industrial cleaning or etching applications) to physically abrade leaf, stem, and meristematic tissue to induce weed mortality within cropping systems.

Norremark et al. (2006) first suggested the use of abrasive grits to control weeds, and Forcella (2009a) later demonstrated that granulated walnut shells could be used to kill small common lambsquaters seedlings. This initial proof-of-concept has led to rapid development of the technology (Forcella 2009b; Forcella 2012). In initial greenhouse trials, Forcella (2009b) found that one split-second blast of corn cob grit delivered from a sand blaster at 517 kPa pressure was enough to achieve greater than 85% mortality of common lambsquarters. In a more recent field study, Forcella (2012) demonstrated that two hand-held applications of air-propelled corn cob grit coupled with interrow cultivation was successful in preventing weed-induced reductions in corn yield.

The development of abrasive weed control has many specialty crop farmers excited, but further research is needed to determine the suitability, practicality, and profitability for a broader range of crops including high value fruits and vegetables. Moreover, there are unexplored possibilities for using fertilizers (e.g., soybean meal) and organic PRE herbicides (e.g., corn gluten meal) as abrasive grits. Though this possibility has been suggested as a means for increasing the profitability of abrasive weed control (Forcella 2012), only one previous study has explored the potential (Forcella et al. 2011). Granulated corn gluten meal, an organic fertilizer containing up to 10% N, applied as an abrasive grit reduced grass weed biomass by 84 to 94% at 4 wk after treatment (Forcella et al. 2011). However, this is the only organic fertilizer or herbicide that has been tested as an abrasive grit and it was only tested on one weed species and one grain crop species.

Abrasive weed control has potential to serve as a multifunctional tool for integrated crop and weed management. For example, the POST timing and placement of organic fertilizer grit may serve to minimize in-row weed competition by delaying nitrogen availability until periods of peak crop demand (Liebman and Davis, 2000; Mesbah and Miller 1999). Moreover, some organic fertilizers may have herbicidal properties that can aid in the inhibition of weed seed germination and growth. Previous studies have demonstrated significant reductions in weed emergence and biomass following soil application of mustard seed meal and corn gluten meal (Bingaman and Christians 1995; Boydston et al. 2011; Webber, III et al. 2008). Despite the fertility benefits and herbicidal potential of some organic fertilizers, none have been tested as abrasive grits in vegetable crops. The objectives of this study were to (1) determine the efficacy of various organic materials as grits for POST abrasive weed control and (2) measure their potential to reduce subsequent weed seed emergence and growth, and (3) characterize tomato and pepper crop response to abrasive weed control with various organic materials and application rates.

Materials and Methods

To accomplish study objectives, a series of thirteen greenhouse trials were conducted between November 2012 and April 2013 at the University of Illinois Plant Care Facility. Details of factors and treatment levels included in each trial are provided in Table 1. Greenhouse light and temperature day / night cycles were set at 16 / 8 h and 27 / 19 C, respectively. Natural light was supplemented with 250 μE PAR m^{-2} s^{-1} artificial light during the 16 h photoperiod when outdoor light intensity dropped below 700 W m^{-2}.

Table 1. Details of factors and treatment levels included in each of thirteen greenhouse trials in 2012 and 2013. An (x) indicates that a treatment level was included for comparison in the respective trial.

	Trial												
Factor	1	2	3	4	5	6	7	8	9	10	11	12	13
Weed													
Palmer amaranth	x	x	x	x									x
Green foxtail					x	x	x	x					x
Common purslane													x
Common lambsquarters													x
Growth stage													
Seed													x
Seedling (< 2 leaf)	x	x			x	x							
Juvenile (> 2 leaf)			x	x			x	x					
Crop													
Tomato									x	x			
Pepper											x	x	
Organic material													
Corn cob grits	x		x		x		x		x		x		x
Corn gluten meal	x		x		x		x		x		x		x
Greensand fertilizer	x		x		x		x		x		x		x
Walnut shell grits		x		x		x		x		x		x	x
Soybean meal		x		x		x		x		x		x	x
Bone meal fertilizer		x		x		x		x		x		x	x
Application rate													
1, 2, 3, 4, 5, & 6 blasts	x	x			x	x							
1, 2, 4, 6, 8, & 10 blasts			x	x			x	x	x	x	x	x	
2, 4, 6, & 10 blasts													x

Abrasive Weed Control. The first eight trials were conducted to study the effectiveness of six organic materials as abrasive grits applied at varying application rates on two weed species at two growth stages (Table 1). Two separate trials were conducted for each weed species and growth stage and each trial compared two different groups of three organic materials to a nontreated control. Organic materials in group one included granulated forms of corn cob grits (CC), greensand fertilizer (GS) and corn gluten meal (CGM), while group two included walnut shell grits (WS), bone meal fertilizer (BM), and soybean meal (SM). Each experiment was a randomized complete block factorial design with organic material and application rate as factors and four replicate blocks. Organic materials were either purchased as 20/40 mesh grit (or smaller) or reduced to the 20/40 mesh size in a soil grinder (Humboldt Mfg. Co., Schiller Park, IL). Application rates for weeds in the seedling growth stage experiments (< 2 leaf; trials 1, 2, 5, and 6) included 1, 2, 3, 4, 5, or 6 blasts of the organic material propelled at 517 kPa air pressure. Weeds in the juvenile growth stage experiments (> 2 leaf; trials 3, 4, 7, and 8) were exposed to 1, 2, 4, 6, 8, or 10 blasts of the organic material at the same pressure. Individual blasts were rapid, lasting less than one second, and the mass of grit delivered in one average blast is reported in Table 2.

Palmer amaranth and green foxtail were planted in 12.7 cm diam pots filled with a commercial potting mix (Sunshine Mix #1 / LC1). Fifteen seeds of each species were planted to a depth of 0.5 cm in respective experimental units, and thinned to one plant per pot after emergence. Weeds were watered daily and fertilized twice per week with a nutrient solution (20–20–20, Jack's Professional; JR Peters, Inc.) until weeds reached the appropriate experimental growth stage. Each of the eight trials resulted in a total of 76 experimental units consisting of one weed species at one growth stage, three organic materials, six application rates, four replications, and four nontreated controls.

Table 2. Application rates of organic material applied to the soil surface of experimental units in residual weed control experiment (trial 13) based on mean output for one blast of each organic material at 517 kPa air pressure.

Organic material	Density	One blast	Application rate			
			2×	4×	6×	10×
	g cm^{-3}	g	g pot^{-1}			
Corn cob grits (CC)	0.47	0.31	0.62	1.25	1.87	3.12
Corn gluten meal (CGM)	0.69	0.34	0.68	1.36	2.05	3.41
Greensand fertilizer (GS)	1.41	1.20	2.39	4.79	7.18	11.97
Walnut shell grits (WS)	0.69	0.35	0.70	1.40	2.10	3.50
Bone meal fertilizer (BM)	0.76	0.31	0.62	1.23	1.85	3.08
Soybean meal (SM)	0.69	0.38	0.76	1.52	2.28	3.80

Weeds were blasted with an experimental gravity-fed sand-blasting unit as described by Forcella (2009b). The blasting nozzle was aimed at the top of the weed in a downward 45° angle and weeds were placed approximately 30 cm from the tip of the blasting orifice. Grit was delivered in a conical pattern and aimed at the top of the weed in an effort to defoliate the plant, and in the case of dicotyledons, destroy the apical meristem. Blasting distance, angle, and pressure all influence efficacy of this technology (Forcella 2009a), so each of these factors was held constant across all trials. Prior to blasting, weeds were staged based on the number of fully emerged leaves (e.g., one-leaf, two-leaf, etc.). Weeds were cut at the soil surface at 7 d after treatment (DAT) and weighed to record final fresh biomass. Percent biomass reduction for treated experimental units was calculated relative to the average biomass of the four nontreated control plants in each trial as:

$$\textit{Percent biomass reduction} = \left((\bar{C} - B)/\bar{C}\right)100 \quad [1]$$

where $\bar{C}$ is the mean biomass of the four nontreated control replicates, and B is the biomass of an individual experimental unit after blasting treatment.

Values for biomass reduction were log-transformed to improve normality and homogeneity of variances when necessary. After transformation (if necessary), values were compared among factorial treatments with a linear mixed model analysis of variance in the GLIMMIX procedure of SAS 9.3 (SAS Institute Inc., Cary, NC). Fixed effects in the model included organic material, application rate, and the interaction between the two, and block was the random effect. Least square (LS) means and standard errors were calculated for all significant fixed effects at an alpha level of 0.05. LS means obtained from analyses of transformed values were back-transformed for presentation in all tables and figures. However, transformation of data does not allow for back-transformation of error terms.

Crop Tolerance. Four additional trials (9, 10, 11, and 12; Table 1) were conducted to study the tolerance of tomato (cv. 'Better Boy') and pepper (cv. 'Bell Boy') crops to abrasive weed control with the same six organic materials applied at varying application rates (1, 2, 4, 6, 8, and 10 blasts). Similar to weed control trials, each experiment was a randomized complete block factorial design with organic material and application rate as factors and four replicate blocks. Crop seedlings were transplanted from germination flats into 12.7 cm diameter pots with a commercial potting mix (Sunshine Mix #1 / LC1). Crops were watered daily and fertilized twice per week with a commercially available complete nutrient solution before and after blasting treatment. Also similar to the weed control trials, each crop tolerance trial resulted in 76 experimental units (one crop, six application rates, three organic materials, four replications, and four nontreated controls). Crops were blasted similar to weeds (517 kPa air pressure with nozzle at 45° angle and placed 30 cm from the tip of the blasting orifice), except the nozzle was aimed at the base of the crop stem instead of the apical meristem. In field situations, susceptible weeds are those growing beneath the crop canopy (e.g., seedlings emerging through crop holes of a plastic mulch); thus, tolerance of crop stems to blasting is essential for the success of this weed management tactic. Prior to blasting, crops were staged based on the number of fully emerged leaves

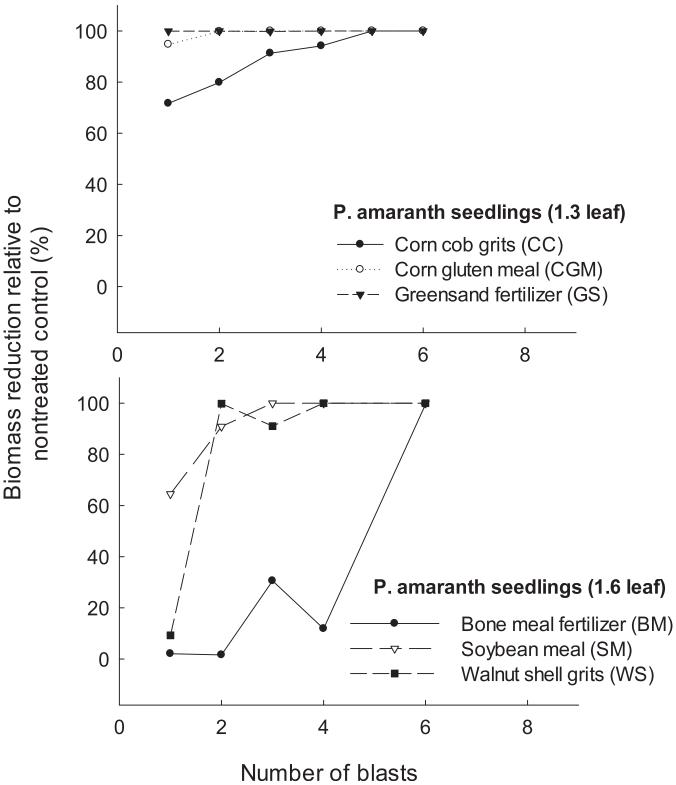

Figure 1. Percent biomass reduction (relative to nontreated control) of Palmer amaranth seedlings in trial 1 (top; 1.3 leaf stage) and trial 2 (bottom; 1.6 leaf stage) one week after application of 1, 2, 3, 4, 5, or 6 blasts with one of six different organic materials.

and plant heights were measured from the soil surface to the top of the newest fully emerged leaf (vertically extended). Plant height was measured again at 7 and 12 or 14 DAT. In addition, tomato stem angles were measured with a protractor to quantify stem curvature following blasting at 12 DAT. Lastly, tomato and pepper plants were clipped at the soil surface and weighed to determine fresh aboveground biomass. Relative growth rates for each experimental unit were calculated based on plant heights over time as:

$$RGR_{Height}=\Big(Ln(Ht_2) - Ln(Ht_1)\Big)/(t2 - t1) \quad [2]$$

where Ht_2 is the height of a plant at the second sampling interval and Ht_1 is the height of the plant at the first sampling interval. The difference of the natural log (Ln) of each value was then divided by the difference of time (days) between sampling intervals. Consistent with weed data, values for crop height, relative growth rate, stem angle, and fresh biomass were log-transformed when necessary and analyzed with the same linear mixed model analysis of variance.

Residual Weed Control. The final trial (trial 13; Table 1) was conducted to determine the PRE herbicidal activity of the six organic materials. This experiment was setup as a randomized complete block factorial design with three factors, five replicate blocks, and twenty nontreated control experimental units. The first factor was organic material and included the same six materials tested in the abrasive weed control and crop tolerance trials. The second factor was application rate, including rates typical of 2, 4, 6, and 10 blasts of each organic material based on a calibration trial (Table 2). The third factor was weed species and included Palmer amaranth, green foxtail, common lambsquarters, and common purslane. There were five replicated nontreated controls for each of the four weed species. Experimental design resulted in a total of 500 experimental units. Each experimental unit (12.7 diameter pots) was filled with a steam pasteurized 3 : 1 : 1 mixture of field soil : coarse sand : vermiculite, and 30 seeds of each weed were planted to a depth of 0.5 cm. After planting, organic materials were weighed and applied evenly to the soil surface, as would be observed following a blasting application. Soil was watered lightly two times per day to avoid surface erosion and pooling of the organic materials on the surface of each experimental unit. Emergence of weeds was counted daily for a 2-wk period beginning the day of first weed emergence. Values for cumulative weed seedling emergence of each species were analyzed with the linear mixed model analysis of variance used for the abrasive weed control and crop tolerance trials, though data did not require transformation.

Results and Discussion

Organic Materials Effective as Abrasive Grits. Palmer amaranth seedlings were susceptible to a broad range of organic materials at relatively low application rates. Trial 1 included a comparison of CC, CGM, and GS on 1.3 leaf stage (on average) Palmer amaranth seedlings. Of these materials, CGM and GS were the most effective and one blast reduced biomass relative to the nontreated control by 95 and 100%, respectively (Figure 1). In

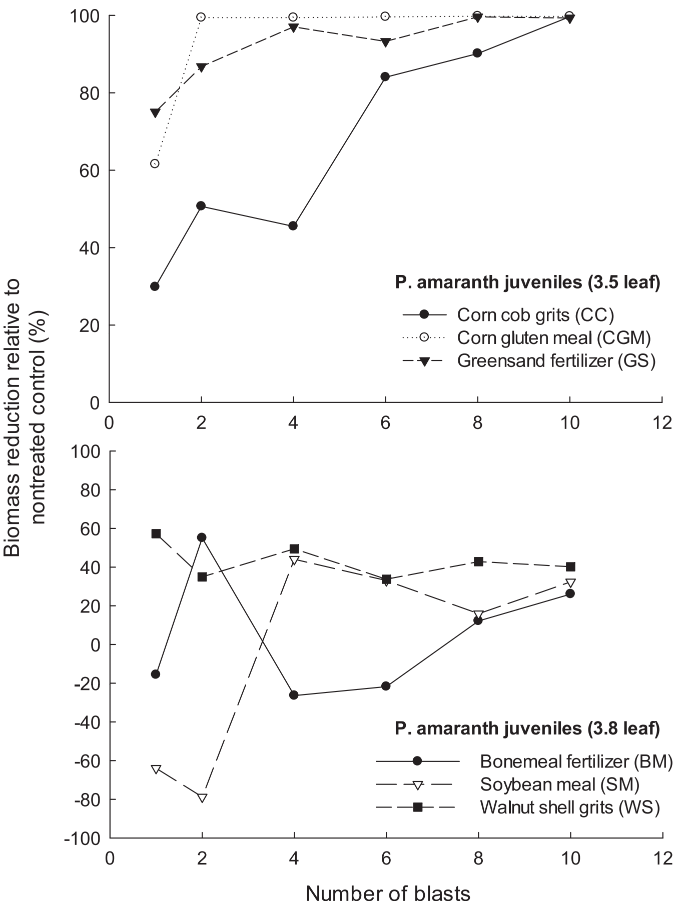

Figure 2. Percent biomass reduction (relative to nontreated control) of Palmer amaranth juveniles in trial 3 (top; 3.5 leaf stage) and trial 4 (bottom; 3.8 leaf stage) one week after application of 1, 2, 4, 6, 8, or 10 blasts with one of six different organic materials.

contrast, one and two blasts of CC only provided 72 and 80% biomass reduction, respectively. Trial 2 compared WS, BM, and SM on 1.6 leaf stage Palmer amaranth seedlings. The level of biomass reduction achieved in this trial was reduced, likely caused by the slightly advanced growth stage of Palmer amaranth. However, among these organic materials, WS and SM provided the greatest weed control reducing biomass by 100 and 91% after two blasts, respectively. BM was relatively ineffective against Palmer amaranth seedlings as six blasts were required to achieve 100% biomass reduction (Figure 1). Suppression of Palmer amaranth seedlings with air-propelled abrasive grits is significant because it is a problematic weed species in vegetable cropping systems and has demonstrated herbicide resistance (Culpepper et al. 2006; Norsworthy and Meehan 2005).

As Palmer amaranth seedlings progressed to the juvenile growth stage (three to four leaf stage), abrasive weed control with organic materials became less effective. This is consistent with the results of Forcella (2009), who found that the number of blasts required to achieve weed mortality increased as the leaf stage of the weed increased. However, consistent with effects on seedlings, CGM, GS, and WS were most effective in reducing biomass relative to a nontreated control (Figure 2). In trial 3 (3.5 leaf stage), one and two blasts of CGM reduced Palmer amaranth biomass by 62 and 99%, respectively. Similarly, one and two blasts of GS reduced biomass by 75 and 87%, respectively. In trial 4 (3.8 leaf stage), only WS consistently reduced weed biomass across all application rates; however, the level of weed suppression was modest with biomass reductions ranging from 34 to 57%. SM and BM reduced weed biomass by as much as 44 and 55%, but results were inconsistent across application rates and in some cases applications stimulated weed biomass (e.g., two blasts of SM increased biomass by 79%; Figure 2). Similar to results for Palmer amaranth seedlings, the relative efficacy of WS, BM, and SM may have been reduced because of the slightly advanced growth stage of weeds in trial 4 compared to trial 3 (3.8 vs. 3.5 leaf stage).

Abrasive weed control with organic materials was less effective in achieving 100% suppression of green foxtail, but substantial biomass reductions were possible when foxtail was still at the one-leaf growth stage. In trial 5 (1.3 leaf stage), a single blast of GS and CGM provided biomass reductions of 87 and 94%, respectively. However, 100% biomass reduction (i.e., complete weed mortality) was only achieved with CGM after four blasts (Figure 3). Consistent with the results of Forcella et al. (2011), complete suppression of grasses was difficult to achieve with abrasive weed control. In trial 6 (1.6 leaf stage), three blasts was necessary to achieve green foxtail biomass reductions of at least 70%. Consistent with the results for Palmer amaranth, WS were most effective in suppressing green foxtail where three blasts provided an 89% reduction in biomass relative to the nontreated control (Figure 3). As in previous trials, a small increase in leaf stage in trial 6 compared to trial 5 (1.6 vs. 1.3 leaf stage) seemed to reduce the overall effectiveness of abrasive weed control. However, it was not possible to

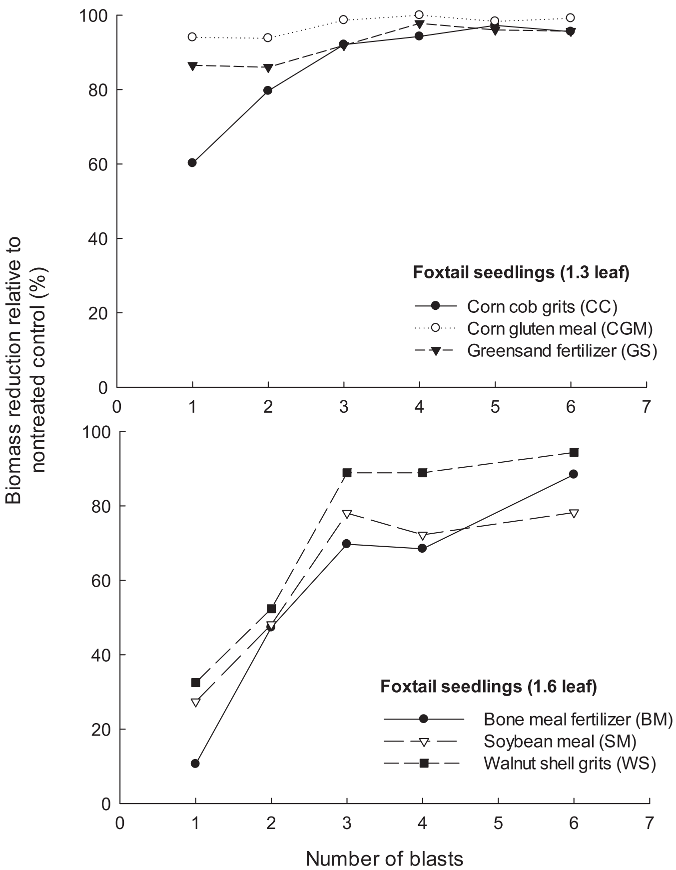

Figure 3. Percent biomass reduction (relative to nontreated control) of green foxtail seedlings in trial 5 (top; 1.3 leaf stage) and trial 6 (bottom; 1.6 leaf stage) one week after application of 1, 2, 3, 4, 5, or 6 blasts with one of six different organic materials.

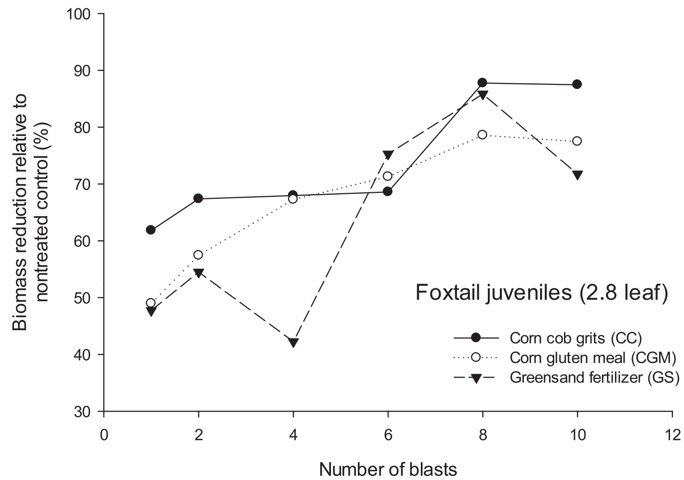

Figure 4. Percent biomass reduction (relative to nontreated control) of green foxtail (*Setaria viridis*) juveniles in trial 7 (2.8 leaf stage) one week after application of 1, 2, 4, 6, 8, or 10 blasts with one of three different organic materials.

directly compare growth stages because there were no common materials tested in both trials.

Suppression of green foxtail with air-propelled abrasive grits was much less effective at more mature growth stages (2.8 and 2.9 leaf stage relative to 1.3 and 1.6 leaf stage). In fact, at the 2.9 leaf stage, WS, BM, and SM (trial 8) had no effect on biomass reduction of green foxtail (data not shown). Significant reductions in green foxtail biomass were observed in trial 7 after application with CC, CGM, and GS at the 2.8 leaf stage (Fig. 4). In contrast to results for smaller foxtail seedlings ($<$ 2 leaf) and Palmer amaranth, CC was the most effective blasting grit resulting in 62 and 88% biomass reductions after one and eight blasts, respectively. Achieving complete mortality of grass seedlings is difficult with abrasive weed control because of the location of the growing point beneath the soil surface, but biomass reductions may be useful in providing the crop an early competitive advantage (Forcella et al. 2011).

Tomato and Pepper are Tolerant of Blasting in a Greenhouse. The most consistently adverse effect of abrasive weed control on tomato and pepper crops was an increase in stem curvature of tomato after blasting. Tomato stems tended to curve away from the blasting disturbance. Tomato transplants were at the two-leaf growth stage for trial 9 and stem curvature was influenced by the interaction of organic material and application rate ($F = 4.24$; $P < 0.001$; $df_n = 10$, $df_d = 54$). Compared to the nontreated control, stem curvature was greater after blasting with all organic materials across almost all application rates, though the difference was not always significant (Table 3). Tomato stem response was highly variable and did not follow a predictable pattern. For example, one blast of greensand resulted in a stem angle of 39.5°, while two and four blasts resulted in stem angles of 10.8 (less than the nontreated control) and 53.0°, respectively.

Only the number of blasts influenced stem curvature of tomato transplants at the four-leaf growth stage in trial 10 ($F = 3.54$; $P = 0.007$; $df_n = 5$, $df_d = 57$). Excluding results for one blast, stem curvature seemed to increase with the number of blasts to as much as 28.4° after eight blasts (Table 3). Abnormal stem curvature could be problematic

Table 3. Stem curvature angle (degrees) 2 wk after 1, 2, 4, 6, 8, or 10 blasts with one of six different organic materials relative to nontreated controls in trials 9 and 10. On average, tomato transplants were at the two leaf stage for trial 9 (CC, CGM, and GS) and the four leaf stage for trial 10 (WS, BM, and SM).

Organic material	Stem curvature angle (degrees)						
	Number of blasts						
	0	1	2	4	6	8	10
Control[a]	12.8						
Corn cob grits		15.0	19.3	23.5	16.8	32.8*	48.0*
Corn gluten meal		25.3	31.0*	34.0*	25.5	17.0	49.3*
Greensand		39.5*	10.8	53.0*	37.3*	39.5*	25.3
Control[b]	2.8						
Bone meal fertilizer, soybean meal, and walnut shell grits[c]		25.2*	8.9*	10.4*	21.2*	28.4*	24.7*

[a] Standard error for stem curvature angle = ± 6.4.

[b] Standard error for stem curvature angle not calculated because of back-transformed data.

[c] Means pooled across organic materials as factor did not influence stem curvature.

* Values different from nontreated control in respective trials ($P < 0.05$).

for production of many vegetable crops (e.g., pepper), but most tomato varieties are physically supported by stakes, cages, or trellis systems and abnormal stem orientation should not limit the utility of abrasive weed control. One issue that could limit the utility of abrasive weed control is stem and leaf tissue damage incurred during application of abrasive grits. While it was not quantified, blasting did result in visually detectable stem tissue damage in all treatments. Tissue damage did not seem to adversely affect plants in the greenhouse, but it is possible that this condition may increase susceptibility to disease in a field environment.

Despite increases in stem curvature and visible tissue damage, abrasive weed control did not influence relative growth rate during the 2-wk period following application of organic materials in trials 9 or 10. In contrast, fresh biomass of tomato was influenced by organic materials in trial 9 ($F = 18.8$; $P < 0.0001$; $df_n = 2$, $df_d = 54$). Tomato biomass was greatest following abrasive weed control with CGM (15.4 ± 0.5 g plant^{-1}), followed by GS (13.6 ± 0.5 g plant^{-1}), and CC (11.2 ± 0.5 g plant^{-1}) and the nontreated control (10.9 ± 1.2 g plant^{-1}). However, tomato biomass was not affected by organic material or application rate when comparing among organic materials in trial 10.

CGM and GS are both common organic fertilizers and would have provided additional nutrients to tomatoes after application, but all plants were fertilized twice per week with a complete nutrient solution to avoid this potentially confounding effect. Increased biomass following application of these two materials is most interesting because, along with WS, they represent the most dense and potentially abrasive materials. As a result, we hypothesized that these materials would result in the greatest level of weed suppression but also the greatest level of crop damage. In contrast to this hypothesis, it is possible that the tomato plants experienced compensatory growth following abrasive weed control. Compensatory plant growth following insect herbivory is not uncommon and moderate stem tissue damage from blasting may have stimulated a similarly beneficial growth response in tomato (McNaughton 1983).

Overall, pepper transplants at the eight-leaf growth stage were more resistant to the adverse effects of blasting in trials 11 and 12. Most importantly, stem curvature was not visually evident in pepper suggesting that plant lodging should not be problematic following abrasive weed control applications. Unlike tomato, pepper plants are not physically supported in typical field production systems; thus, any increase in stem curvature or plant lodging would have limited the potential for abrasive weed control in this crop. Among organic materials, only those tested in trial 11 (CC, CGM, and GS) had adverse effects on pepper. Specifically, select organic materials reduced relative growth rate ($F = 7.56$; $P = 0.001$; $df_n = 2$, $df_d = 53$) and fresh biomass ($F = 3.67$; $P =$

0.03; $df_n = 2$, $df_d = 53$). Abrasive weed control with CC, independent of application rate, reduced pepper biomass (25.0 ± 0.9 g plant^{-1}) relative to the nontreated control (28.5 ± 2.1 g plant^{-1}), CGM (27.6 ± 0.9 g plant^{-1}), and GS (27.8 ± 0.9 g plant^{-1}). While CC application reduced fresh biomass of pepper, relative growth rates were lowest following application with CGM (0.021 ± 0.002 cm cm^{-1} d^{-1}) and GS (0.021 ± 0.002 cm cm^{-1} d^{-1}), relative to the nontreated control (0.029 ± 0.004 cm cm^{-1} d^{-1}). In contrast to tomato, compensatory growth was not evident in pepper plants following abrasive weeding disturbance.

Organic Materials Stimulate, Not Inhibit, Weed Emergence. None of the six organic materials tested in this experiment (trial 13; Table 1) reduced seedling emergence of Palmer amaranth, green foxtail, common purslane, or common lambsquarters when applied to the soil surface at rates typical of 2, 4, 6, and 10 blasts (Table 2). In fact, cumulative seedling emergence of Palmer amaranth ($F = 3.15$; $P = 0.01$; $df_n = 5$, $df_d = 96$) and common lambsquarters ($F = 3.17$; $P = 0.01$; $df_n = 5$, $df_d = 96$) were actually stimulated by the application of certain organic materials. Cumulative seedling emergence of Palmer amaranth was 108% greater after soil application with either CGM or GS, and application of CC increased common lambsquarters seedling emergence by 102% relative to the nontreated control. The lack of herbicidal effects for CGM, WS, and SM was unexpected and seems to contradict previous studies demonstrating the utility of these plant byproducts for weed management (Bingaman and Christians 1995; Lee and Campbell 1969).

Stimulation of weed seed emergence following application of corn gluten meal and greensand may be related to increases in available soil nutrients, as experimental units in this trial did not receive supplemental fertility. Increases in soil fertility, especially soil nitrates, have been shown to stimulate germination and emergence of dormant weed seeds (Dyer 1995). The lack of herbicidal effects in the soil observed for these organic materials seems to limit the multifunctional capacity of abrasive weed control, but the stimulation of weed emergence highlights the potential to supplement crop nutrition through abrasive grit application. The most immediate need for weed control in organic vegetable cropping systems is often within the crop row or in the crop holes of plastic mulches (Bonanno 1996); thus, abrasive weed control in these areas with organic fertilizers (e.g., SM, BM, GS, or CGM) would result in strategic fertilizer placement that may give crops a further competitive advantage over weeds (Mesbah and Miller 1999).

Conclusions and Recommendations for Future Directions. Of the organic materials tested in this study, corn gluten meal, soybean meal, greensand fertilizer, and walnut shell grits demonstrated the greatest potential as air-propelled abrasive grits for weed control in vegetable cropping systems. These four materials provided the best POST abrasive weed control across both weeds and growth stages. Despite a few observed negative effects on crop growth, low application rates of most organic abrasive grits were compatible with tomato and pepper. Abnormal stem growth in tomato (i.e., stem curvature) following blasting application suggests that future research will be needed to establish optimum field application rates and materials that maximize weed suppression and minimize crop injury. However, results for tomato also suggest that certain grit–crop combinations may result in compensatory growth that could be beneficial to farmers if diseases can be mitigated in field systems.

A preliminary field trial is currently underway to evaluate abrasive weed control on a field scale in an organic plasticulture tomato production system. This field study aims to determine optimum application rates and timing intervals and to quantify weed suppression, crop physiological response, yield, and fruit quality, and mulch durability in response to abrasive weed control within plant holes and along interrow edges of plastic mulch. Abrasive weed control has great potential to increase the profitability and sustainability of organic fruit and vegetable production, but field research trials are needed in a variety of cropping systems to improve the technical and economic efficiency of this novel tactic prior to on-farm adoption.

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Literature Cited

Bingaman BR, Christians NE (1995) Greenhouse screening of corn gluten meal as a natural control product for broadleaf and grass weeds. HortSci 30:1256–1259

Bonanno AR (1996) Weed management in plasticulture. HortTech 6:186–189

Boydston RA, Morra MJ, Borek V, Clayton L, Vaughn SF (2011) Onion and weed response to mustard (*Sinapis alba*) seed meal. Weed Sci 59:546–552

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, York AC, Davis JW, Hanna WW (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54:620–626

Dyer WE (1995) Exploiting weed seed dormancy and germination requirements through agronomic practices. Weed Sci 43:498–503

Forcella F (2009a) Potential use of abrasive air-propelled agricultural residues for weed control Weed Res 49:341–345

Forcella F (2009b) Potential of air-propelled abrasives for selective weed control. Weed Technol 23:317–320

Forcella F (2012) Air-propelled abrasive grit for postemergence in-row weed control in field corn. Weed Technol 26:161–164

Forcella F, James T, Rahman A (2011) Post-emergence weed control through abrasion with an approved organic fertilizer. Renew Agr Food Syst 26:31–37

Lee KC, Campbell RW (1969) Nature and occurrence of juglone in *Juglans nigra* L. Hort Sci 4:297–298

Liebman M, Davis AS (2000) Integration of soil, crop and weed management in low-external-input farming systems. Weed Res 40:27–47

Liebman M, Davis AS (2009) Managing weeds in organic farming systems: an ecological approach. Pages 173–195 *in* Francis C, ed. Organic Farming: The Ecological System. Agronomy Monograph 54, ASA-CSSA-SSSA, Madison, WI

McNaughton SJ (1983) Compensatory plant growth as a response to herbivory. Oikos 40:329–336

Mesbah AO, Miller, SD (1999). Fertilizer placement affects jointed goatgrass (*Aegilops cylindrica*) competition in winter wheat (*Triticum aestivum*). Weed Technol 13:374–377

Norremark M, Sorensen CG, Jorgensen RN (2006) Hortibot: feasibility study of a plant nursing robot performing weeding operations – Part III. ASABE Annual International Meeting Paper 067023, 14 p

Norsworthy JK, Meehan JT (2005) Use of isothiocyanates for suppression of Palmer amaranth (*Amaranthus palmeri*), pitted morningglory (*Ipomoea lacunosa*), and yellow nutsedge (*Cyperus esculentus*). Weed Sci 53:884–890

Webber CL III, Shrefler JW, Taylor MJ. 2008. Corn gluten meal as an alternative weed control option for spring-transplanted onions. Intern J Veg Sci 13:17–33

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