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Note

Soybean Seedlings Tolerate Abrasion from Air-Propelled Grit

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New tools for controlling weeds would be useful for soybean production in organic systems. Air-propelled abrasive grit is one such tool that performs well for in-row weed control in corn, but crop safety in soybean is unknown. Responses to abrasion by corn-cob grit of soybean seedlings were examined at VE, VC, VU, V1, V2 (emergence, cotyledon, unifoliate, first trifoliate, and second trifoliate, respectively) and combinations of these growth stages, in both greenhouse and field settings. Seedling leaf areas and dry weights in greenhouse experiments were reduced by treatments that included abrasion at VC, with the primary effect expressed through reductions in the size of the unifoliate leaf. In the field, soybean stand also was reduced by grit applications at VC, especially if followed by a second application at VU or V1. However, soybean yield was not reduced by grit applied at any soybean stage of growth. End-of-season weed dry weights did not differ from hand-weeded checks, and weeds did not impact soybean yields. Thus, abrasive grit for in-row weed control can be applied at least twice at VE through V2 growth stages without lowering soybean yield, but applications at VC probably should be avoided.
Nomenclature: Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.
Key words: Herbicide-free, nonchemical, organic, physical weed control, stale seedbed.

Nuevas herramientas para el control de malezas serían útiles para los sistemas de producción orgánica de soya. La aplicación de partículas abrasivas con aire forzado es una herramienta cuyo desempeño es bueno para el control de malezas sobre la línea de siembra en maíz, pero la seguridad de esta práctica en soya es desconocida. En estudios de invernadero y campo, se examinó la respuesta a la abrasión causada por partículas de mazorcas de maíz en plántulas de soya a VE, VC, VU, V1, V2 (emergencia, cotiledón, hoja unifoliada, primera hoja trifoliada y segunda hoja trifoliada, respectivamente) y combinaciones de estos estados de desarrollo. En los experimentos de invernadero, el área foliar y el peso seco de las plántulas fueron reducidos por los tratamientos que incluyeron abrasión a VC, siendo el efecto primario reducciones en el tamaño de la hoja unifoliada. En el campo, el establecimiento de la soya también se redujo debido a las aplicaciones de partículas a VC, especialmente si fueron seguidas por una segunda aplicación a VU o V1. Sin embargo, el rendimiento de la soya no se redujo producto de la aplicación de partículas en ninguno de los estados de desarrollo. Al final de la temporada el peso seco de las malezas no difirió de los testigos con deshierba manual, y las malezas no impactaron el rendimiento de la soya. De esta forma, se puede aplicar partículas abrasivas para el control de malezas en la línea de siembra al menos dos veces entre los estados de desarrollo VE y V2, sin reducir el rendimiento de la soya, pero las aplicaciones a VC probablemente deberían ser evitadas.

Although many weed control tactics are appropriate for organic soybean, effective weed management remains the universal enigma for this crop in organic production systems. An example of an organically approved broad-spectrum tactic for weed control is the stale seedbed technique, wherein soybean is purposefully sown late after two or more soil disturbances aimed at stimulating flushes of emerged weed seedlings and then destroying them (Forcella 2013; Rasmussen 2003).

In-row weed control in soybean is challenging even with stale seedbeds. Various mechanical tools can be helpful if used during specific windows of opportunity, which depend strongly upon weed and crop developmental stages (Bowman 1997; Gunsolus 1990; Mohler 1996). Nonetheless, additional tools are needed to manage in-row weeds. One such tool, whose utility is still under investigation, is an air-propelled abrasive grit applicator (Forcella 2012). This technique uses grit derived from agricultural products (crop residues, seed meals, fertilizers, etc.) under air pressures of about 600 kPa to abrade small weed seedlings within crop rows while leaving larger crop plants, such as corn, relatively unscathed. The grit is emitted from nozzles that are angled so that weed seedlings are abraded within a 10-cm swath centered on the crop row. If aimed properly, the grit damages just the bases of the corn plants, but only slightly. In fact, if grit is applied at both the 1-leaf and 5-leaf stages of corn, season-long control of annual weeds results without any abrasion-induced reduction in corn yield (Forcella 2012). However, the effectiveness and safety of this technique in crops other than corn are unknown. The goal of the current study was to determine if abrasive grit could be used safely in soybean. Thus, the specific objective of this research was to examine soybean seedling responses to abrasive grit applications under controlled greenhouse conditions and in relatively weed-free field settings.

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Materials and Methods

Greenhouse Study. Two experiments were performed within the greenhouse facilities of the USDA-ARS North Central Soil Conservation Research Laboratory, Morris, MN. Experiments were identical, differing only in dates: April and May 2012. Greenhouse conditions were approximately 25/15 C day/night with natural sunlight, which reached maximum intensities of about 800 μmol $m^{-2}s^{-1}$. Single soybean plants (Croplan RT0043) were reared in 0.5 L pots in a potting mix consisting of 1 : 1 : 1 (v/v/v) of Barnes loam, peat, and sand. Pots were watered daily and fertilized weekly with a commercially available complete nutrient solution.

When soybean seedlings were at various stages of development they were exposed to applications of 5 g of commercially available corn cob grit (particle size averaging 0.5 mm) over the course of 1 to 2 s. Grit was delivered through a pistol-type sand blaster with a single full-cone nozzle (5-mm-wide orifice) at about 550 kPa air pressure (see photograph and description in Forcella [2009a]). The device was affixed to a burette stand, and the nozzle was aimed at the base of the soybean seedling, which was 60 cm from the nozzle tip and angled about 30° from vertical. At this distance, the grit was delivered in a narrow bell-shaped distribution, with most of the grit creating a 10-cm-wide slightly oval pattern at the point of impact (see Figure 2 in Forcella [2009b]), which approximated the surface area of the pots (81 cm^2). Although the nozzle was aimed so that the apex of the bell-shaped grit pattern was focused on a small area at the base of the soybean plant, these plants still were affected by the grit. The intention was to simulate a field situation wherein small weed seedlings growing near soybean would be abraded, but excessive damage to crop plants could be minimized. Previous work (Forcella 2012) showed that two to three well-timed grit applications at the 1- to 5-leaf stages of corn growth near the bases of corn plants growing in rows provided season-long control of weeds such foxtails (*Setaria* spp.), common lambsquarters (*Chenopodium album* L.), and redroot pigweed (*Amaranthus retroflexus* L.), but negligibly affected corn.

Each of five soybean seedlings (replications) was abraded with grit in one of the following treatments, which represented differing stages of growth or combinations thereof: VE, VC, VU, V1, VE.VC, VE.VU, VC.VU, VC.V1, VE.VC.VU, and VC.VU.V1. For clarity, the last treatment refers to three abrasion events, the first at VC, followed by another at VU, followed by a third at V1. A nonabraded control, with 10 replications, completed the treatments. Abbreviations VE, VC, VU, and V1 correspond to emergence, cotyledon, unifoliate, and first trifoliate stages of soybean growth, respectively (Ulloa et al. 2010).

Two weeks after the last grit application (V1), when plants were at the V3 stage (third trifoliate), they were clipped at soil level, and areas of individual leaves (unifoliate, and first, second, and third trifoliates) and green stems were determined with a leaf-area meter immediately after clipping. All plant parts were then combined and dried at 65 C for one week, and total dry weights determined.

Arrangement of pots before and after treatments in both experiments was random. Preliminary AVOVA indicated significant experiment x treatment interactions and, therefore, data for each experiment were analyzed separately using the Completely Random Design option in Statistix 9 software (Anonymous 2008). Dunnett's two-sided multiple comparison test was used to distinguish treatment means from those of the controls at $\alpha = 0.05$.

Field Study. Two field experiments were performed at the USDA-ARS Swan Lake Research Farm, Stevens County, MN (45.68°N, 95.80°W) on a Barnes loam soil (fine-silty, mixed, super-active, frigid Calcic Hapludoll). Treatments were arranged in a completely random experimental design with three replications. Treatments were soybean stages at times of abrasive grit application (see below).

Seedbeds were tilled, residues from previous wheat (*Triticum aestivum* L.) crops buried, and fertilizer (ammonium nitrate at 112 kg N ha^{-1}) incorporated with a low-residue field cultivator (Bowman 1997) in the autumn (2010 and 2011). Synthetic fertilizer was used to eliminate plant nutrition as a source of subsequent variation in experimental results. Seedbeds were field-cultivated again and harrowed on June 14, 2011 and May 31, 2012. These late seedbed preparations would have been expected to control $>$ 90% of potential seedling populations of common annual weeds typical for this area compared to seedbed preparation in late April to early May (Forcella et al. 1992). A relatively weed-free experimental area was needed to test soybean tolerance to abrasive grit without the confounding effects of interference by dense weed populations. Within one day after field-cultivation, Croplan RT0043 soybean (0.04 relative maturity) was sown with a no-till planter at 387,000 seeds ha^{-1} in rows spaced 76 cm apart. For comparison, target planting dates for conventional soybean (1.0 RM) are early to mid-May in this area.

Twelve treatments included ten times of abrasion by corn-cob grit as well as a nontreated check and a nontreated/hand-weeded control. Plots were 3.1 m long and two rows (1.5 m) wide and randomized within the entire experiment. Times of grit application corresponded to the following stages of soybean growth: VC, VU, V1, V2, VC.VU, VC.V1, VU.V1, VU.V2, VC.VU.V1, and VU.V1.V2. Corn cob grit was applied to each side of both soybean rows in a manner nearly identical to that described previously (Forcella 2012). Briefly, an all-terrain vehicle was used to carry an air compressor and a tank that contained the grit. The grit tank was pressurized to about 600 kPa and connected to a single hand-held full-cone nozzle via a high-pressure hose. The distance from the nozzle tip to the base of soybean plants was kept at about 60 cm, vehicle speed was about 1 m s^{-1}, and delivery rate was about 37 g grit s^{-1}. Weed populations between rows were managed through inter-row cultivation.

In-row weeds were sampled at the end of the growing season (September 12, 2011 and August 24, 2012) by clipping all plants in a 1-m row length (10 cm wide) in each row of each plot. Between-row weed samples came from a single 2-m long (10 cm wide) area between the two rows used for in-row weed sampling. Weeds were sorted by species, dried for one week at 65 C, and weighed.

Soybean plants were harvested by hand on October 4, 2011 and September 10, 2012 in two 1-m row-lengths in each plot. Plants were threshed, seed moisture determined with a capacitance meter, and seeds weighed. Yields were adjusted to 13% seed moisture content. Soybean stand was determined by counting cut stems in the same two 1-m row lengths.

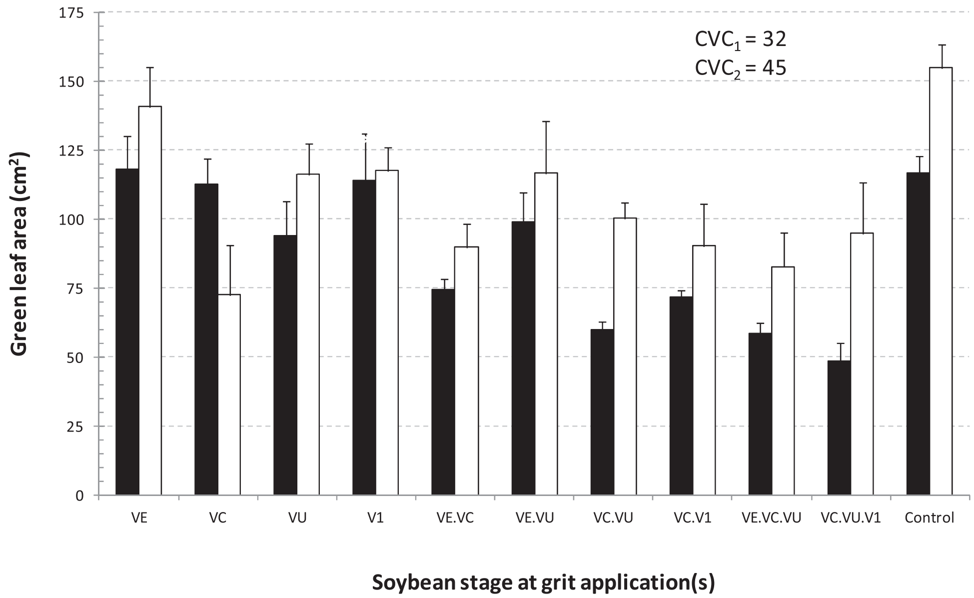

Figure 1. Total area of green leaf tissue of soybean plants at the third trifoliate stage of growth as influenced by abrasion by grit applied at differing growth stages or combinations of growth stages. Solid columns, Experiment 1; open columns, Experiment 2. Vertical bars atop columns are standard errors. $CVC_{1,2}$, critical value for comparison ($\alpha = 0.05$) to the untreated check from Dunnett's two-sided test for Experiment 1 and Experiment 2; VE, emergence, VC, cotyledon, VU, unifoliate; V1, first trifoliate; and V2, second trifoliate.

Statistical evaluations included preliminary ANOVA that assumed soybean stages at grit application as fixed effects. Year and interactions were random effects. If year effects or interactions with year were significant, then yearly data were examined separately using the Completely Random Design option available in Statistix 9 software (Anonymous 2008).

Results and Discussion

Greenhouse Study. Results for seedling dry weights and leaf areas from greenhouse experiments mimicked one another closely, thus only analyses for leaf areas are discussed. Two weeks after the last treatment with abrasive grit, average total seedling leaf area differed ($P < 0.01$) between experiments (90 ± 4.1 vs. 111 ± 4.9 cm^2 $plant^{-1}$ in Experiment 1 vs. Experiment 2), probably because the longer daylengths during Experiment 2 enhanced leaf expansion (Zhang et al. 2001). A significant experiment x treatment interaction also occurred ($P = 0.03$), although the trends in the two experiments were similar (Figure 1). Based upon the critical value for comparison ($CVC_{0.05}$) from Dunnett's two-sided multiple comparison test, treatments that differed from the control in Experiment 1 were: VE.VC, VC.VU, VC.V1, VE.VC.VU, and VC.VU.V1. Similarly, for Experiment 2, these treatments were: VC, VE.VC, VC.VU, VC.V1, VE.VC.VU, and VC.VU.V1. Thus, treatments that included seedling abrasion at VC tended to have lower leaf areas than the controls, which suggested that VC is a more sensitive stage of growth than other seedling stages in terms of tolerance of abrasion.

At the time of sampling, soybean was at the V3 stage of growth, and leaf area data were collected separately for unifoliate, and first, second, and third trifoliate leaves. Separate analyses of the leaf classes (Figure 2) allowed identification of where abrasion by grit exerted its greatest level of influence on total leaf area. For ease of presentation, data from both experiments were combined despite significant experiment and experiment x treatment interactions for some leaf classes. The unifoliate leaf showed the most sensitivity to abrasion. Only when grit was applied at VE or V1 was unifoliate leaf area not affected, otherwise it declined significantly ($P < 0.01$) from that of control plants when grit was applied in all other treatments. First trifoliate leaf areas were influenced negatively ($P < 0.01$) by grit only at the VC.VU, VC.V1 and VC.VU.V1 stages of growth, and that of second trifoliates ($P < 0.01$) only at VE.VC, VC.V1, and VE.VC.VU stages of growth. Leaf areas of third trifoliates never were impacted by abrasion treatments ($P = 0.95$).

Lack of treatment effects on third trifoliates and visual inspection of plants suggested that all plants were recovering from abrasion by grit at the time of sampling, which was two weeks after the last abrasion treatment on V1 plants. Given sufficient time perhaps all treated plants would recover fully. This possibility was tested in the field experiments.

Field Study. Soybean stage at grit application affected soybean stand significantly ($P < 0.01$), but stand was not influenced by year ($P = 0.51$) nor by the interaction between stage and year ($P = 0.73$). Consequently, soybean densities as influenced by growth stage at grit application were aggregated over years (Figure 3). Using the hand-weeded check, which was not abraded by grit, as the basis for comparison with Dunnett's two-sided test ($\alpha = 0.10$), only two treatments, VC.VU and VC.V1, reduced soybean stands, by 23% and 25%, respectively. Other treatments that included VC also had somewhat lower stands, but not significantly so ($\alpha > 0.10$); for instance VC and VC.VU.V1 had 14% and 13% reductions compared to the hand-weeded check. Thus,

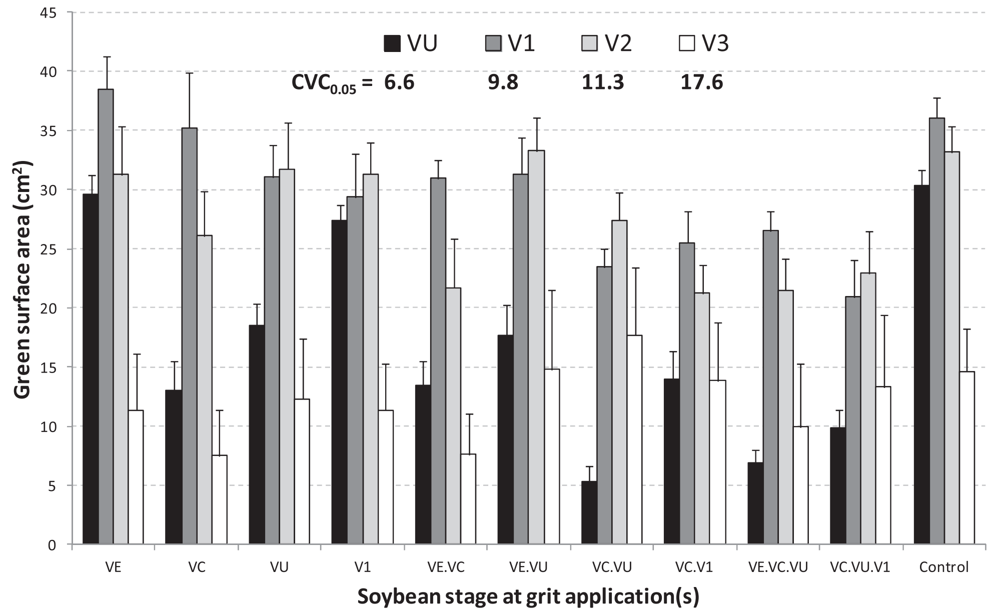

Figure 2. Areas of green leaf tissue for specific leaves (VU, V1, V2, and V3) when soybean plants were at the third trifoliate stage of growth. Abrasive grit was applied at differing growth stages or combinations of growth stages. Values are averaged over two experiments. Vertical bars atop columns are standard errors. CVC, critical value for comparison ($\alpha = 0.05$) to the untreated check from Dunnett's two-sided test; VE, emergence, VC, cotyledon, VU, unifoliate; V1, first trifoliate; V2, second trifoliate, and V3, third trifoliate.

in field settings soybean at the VC stage of growth generally appeared to be more sensitive to abrasion by grit than other stages in terms of final stand densities. Reduced stands likely were not caused by abrasion directly, but by loss of unifoliate leaf area, which led to reduced growth rates, and thinning of these slower-growing plants because of faster-growing neighbors.

Yields were affected by year ($P < 0.01$), but not by growth stage ($P = 0.90$) or a year by stage interaction ($P = 0.41$, data not shown). Average yields were 1.6 $\pm$ 0.07 Mg ha^{-1} in 2011 and 2.9 $\pm$ 0.09 Mg ha^{-1} in 2012. The low yields in 2011 were because of early frost on September 13, which preceded full maturity of the crop. Despite reduced stands in the VC treatments, these plants apparently compensated for low densities by producing higher seed yields per plant. Whatever the case, soybean yield of field-grown plants appeared immune from the timing of grit abrasion of seedlings at the VC through V2 stages of growth.

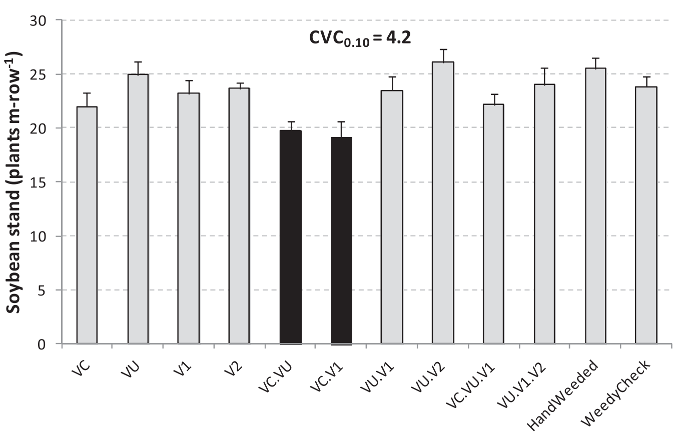

Figure 3. Soybean stand as influenced by one, two, or three abrasive grit applications at various stages of growth. A black column indicates significant difference ($\alpha = 0.10$) with hand-weeded check according to the critical value for comparison (CVC) of Dunnett's two-sided comparison test. Plants in hand-weeded and weedy check treatments were not abraded with grit. Data aggregated over two years. Stages of soybean growth: VC, cotyledon; VU, unifoliate; V1, first trifoliate; V2, second trifoliate. (Multiply by 13158 for plants ha^{-1}.)

Year influenced in-row weed dry weights ($P < 0.01$), but dry weight was not affected by soybean growth stage ($P = 0.75$) nor a year x stage interaction ($P = 0.56$, data not shown). When averaged across all treatments, weed dry weights were 4 $\pm$ 1.1 g m-row^{-1} in 2011 and 39 $\pm$ 6.9 g m-row^{-1} in 2012. Although both of these dry weights are low, the higher value in 2012 likely reflects the 2-wk earlier seedbed preparation that year compared to 2011, which may have nullified partially the "stale seedbed effect" in terms of weed control. Nonetheless, the late seedbed preparations kept weed densities sufficiently low that grit applications at varying soybean growth stages had no influence on weed dry-weights at the end of the growing season. Because the primary intent of the experiments was to examine soybean tolerance to grit applications, the lack of appreciable interference by weeds enabled more reliable interpretation of soybean stand and yield results.

As expected, between-row weed weights were not impacted by any treatment or interaction ($P > 0.39$, data not shown). Dry weights of between-row weeds were 0.4 $\pm$ 0.25 g m-row^{-1} when averaged across years and treatments. Such low values indicated the effectiveness of between-row cultivation for suppressing weeds.

In conclusion, soybean was most sensitive to abrasion by grit at the VC stage of growth. This response exerted itself primarily through size reduction of the unifoliate leaf.

Presumably at the VC stage the developing bud of the unifoliate leaf was either injured directly by grit, or grit-induced injury to cotyledons impeded nutrient export to the unifoliate bud. Exposure of soybean seedlings at all other stages of seedling growth that were tested did not have measurable effects on soybean leaf area or dry weight. In field settings, stand also was reduced if grit was applied at VC, but yield of soybean was not reduced by grit abrasion at any soybean growth stage. Thus, assuming abrasive grit is effective for POST control of small annual weeds within soybean rows, as it is in corn (Forcella 2012), the technique appears to be safe for use in soybean with the caveat that applications at the VC stage of growth probably should be avoided.

Acknowledgments

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