9-26-2018

# Using Abrasive Grit for Weed Management in Field Crops

Michael Carlson
*South Dakota State University*, michael.carlson@jacks.sdstate.edu

Frank Forcella
*USDA, Agricultural Research Service*

Sam Wortman
*University of Nebraska - Lincoln*

Sharon A. Clay
*South Dakota State University*, sharon.clay@sdstate.edu

Chapter 5

# Using Abrasive Grit for Weed Management in Field Crops

Michael Carlson, Frank Forcella, Sam Wortman and Sharon A. Clay

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.76875

**Abstract**

Abrasive grit, applied at high pressure and directed at plant base, can control weeds and increase yield. We evaluated fertilizer [pelletized turkey (*Meleagris gallopavo*) litter] and non-fertilizer [walnut (*Juglans regia*) shell] grits for maize and soybean in-row (IR) weed management. Grits were applied at V1 and V5 of maize, and V1 and V3 of soybean. Between-row weed cultivation was done alone (BR), or in combination with grit (I/B), after grit application. Small weeds (<4 cm) were controlled after grit treatment, but, larger broadleaf weeds, grass weeds (treated when growing points were below ground), and later emerging weeds resulted in IR weed biomass similar between season-long weedy (SLW) and IR treatments by August. In maize, fertilizer and nonfertilizer I/B treatments averaged 44 and 14% greater yields, respectively, than SLW ($p<0.01$) but each was similar to BR which averaged 23% greater yield ($p=0.63$). Maize grain had 16% higher N content in the fertilizer I/B treatment than SLW or nonfertilizer I/B ($p<0.003$). In soybean, I/B increased yield by 17% ($p=0.009$) over SLW yield, but was similar to the BR increase of 22% ($p=0.13$). Maize had a greater positive response to fertilizer than nonfertilizer grit, whereas soybean was less influenced by I/B treatment.

**Keywords:** maize (Zea mays), soybean (Glycine max), air-propelled grit, weed control

## 1. Introduction

The number and acreage of organic certified farms across the United States has increased [1] due to expanding organic foods sales [2], which has created premiums for organically grown commodities [3, 4] and alternative income streams for farmers. Crop fertility and weed management, within the confines of the certified organic regulations [5], are major concerns in organic production systems, as methods other than synthetic chemicals must be utilized. Alternative organic-approved nutrient sources include manures [6–9] and seed meals [9–11], when derived from certified organic materials.

Weed control repeatedly has been ranked as very to extremely problematic [12–14] and as a top research priority [15] in organic producer surveys. Flexible systems that rely on cultural and mechanical methods are needed to prevent the creation of specialized weed communities [16, 17]. Cultural methods enhance the crop's competitive ability [16], reducing weed impact. Methods include alternating crops that vary in seasonal growth, fertilizing differentially [18], or speeding canopy closure by planting in narrow rows or at high densities [19–24]. Dense cover crop mulches, such as those created by rye grass (*Lolium* sp.) or hairy vetch (*Vicia villosa*), suppress weeds [25–29], although these may become major weed problems or immobilize N, negatively impacting yield, if not carefully managed [26, 28].

The most important time for weed control is during the early growth stages of a crop, also known as the critical weed free period, so that yield is not reduced [30–39]. Careful timing of physical and mechanical weed control operations [40–42], including deeper tillage or seedbed preparation that disturbs newly emerging weed seedlings (i.e. stale seedbed) [43–45] can provide weed control and lower in-season weed density [46, 47]. Burying the weeds to at least 1 cm deep, through rotary hoeing or rod weeding, or mowing the weeds at the surface also provides control [48, 49].

Cultivation, or flaming at high temperatures [50], are effective methods to control between-row weeds, however, in-row weed control is still a problem for organic growers [51]. In-row weeders, including harrows, finger and torsion weeders, and weed blowers, have been developed [52–55]. However, crop burial or injury [56] can result in yield reduction [57] so that accurate steering and slow driving are needed to minimize crop damage [51]. Despite advances in physical weed management, organic growers are not satisfied with the tools available nor the amount of weed suppression achieved [58]. Additional methods would provide alternatives to support these 'traditional' weed control techniques [51, 59–61].

Air-propelled abrasive grit application for weed control by tissue abrasion was proposed by Nørremark et al. [62]. Numerous types of grits made from agricultural (e.g., maize cobs and walnut shells), non-agricultural (e.g., sand), and organic fertilizer (e.g., soybean meal and corn gluten meal) materials controlled weeds in greenhouse and field settings [63–70] when sprayed at high pressure (800 kPa). In the field, two or three in-row grit applications, applied from V1 to V5 growth stage of maize, could reduce weeds and increase grain or silage yields [65, 69, 70].

Although Forcella [66] demonstrated that soybean could tolerate grit applications after the cotyledon (VC) growth stage, the influence of in-row grit application on weed control has not been field tested in this crop. In addition, organic fertilizers, such as pelletized turkey litter [71], have not been tested as abrasive grits for weed control in maize or soybean field studies. The hypotheses of this study were that 1) grits derived from different sources would result in similar weed control when applied at early crop/weed growth stages; and 2) crop yield would be increased by grits containing nitrogen [68, 72, 73].

## 2. Air propelled abrasive grit influence on in-row weed control and crop yield

### 2.1. Materials and methods

#### *2.1.1. Grits*

Two grits, made from materials that are approved for organic production and that differ in fertilizer value, were used for in-row application and control of weeds. Sustane® (Sustane Corp., Cannon Falls, MN), is made from pelletized aerobically composted turkey litter [71], and had a fertilizer grade of 8-2-4 (N-$P_2O_5$-$K_2O$). Agra Grit (AgraLife), made from walnut shells, which has a high C:N ratio with little immediate nitrogen availability, provided a low N content comparison. Sustane and Agra Grit products have a hardness value of 3 on the Mohs scale of mineral hardness and varied in size from 0.56 to 0.85 mm.

#### *2.1.2. Field experiments*

Maize and soybean were planted from 2015 to 2017 in organic certified production fields at the SDSU Southeast Research Farm (Beresford, SD), in a non-certified transition area at the SDSU Research Field Station at Aurora, SD; and in conventionally managed fields at the at the Swan Lake Research Farm (Morris, MN). Soil types were silt loam complexes (Morris and Beresford) and a silty clay loam at Aurora.

Varieties used, relative maturity (RM), planting and harvest dates varied by year and location (**Table 1**). Swan Lake was the northernmost location and used shorter RM varieties. Southeast was the southernmost location and used longer RM varieties. Maize was seeded at 3.5-cm depth, when soil temperatures were 14°C. Soybean seeding rate varied by location and year (**Table 1**) and was planted at 2.4-cm depth when soil temperatures were 18°C. Row spacing was 0.76 m with four crop rows per treatment (~3-m width). Plot length varied from 3 to 9 m.

Sustane 8-2-4 and Agra Grit were applied in all trials. In-row (IR) grits were applied twice, at the V1 and V5 maize growth stages, and the V1 and V3 soybean growth stages (**Table 1**). About 800 kg $ha^{-1}$ of grit was used for each application, which was applied using a propelled abrasive grit applicator [PAGMan] that sprays four rows simultaneously, with a nozzle on each side of the row [69, 70]. Distance of the nozzle tip to the base of the maize plants was between 10 and 15 cm, at a 45° contact angle. Spray pressure was 690 kPa and tractor speed was 2.5 km $hr.^{-1}$. After the final grit treatment each year, a single cultivation was used for between-row (BR) weed control using a John Deere® 866 spring tine cultivator at 5 km $hr.^{-1}$. In addition, other treatments all years included a single between-row cultivation, as described previously, to determine yield potential with only cultivation, season-long weedy (SLW) to estimate yield in nontreated conditions, and weed-free (hand-weeded weekly until canopy closure) to estimate maximum yield potential under weed-free conditions.

Weed species and density were recorded in each plot prior to and about 1 week after final grit applications. In mid-July to early September depending on crop and year (**Table 1**), weeds,

| Year | Location | Crop | Relative maturity | Planting | | Grit application | | Weed biomass | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Date | Rate | First | Second | Greenness | Harvest date |
| | | | | | (*1000) | | | | |
| 2015 | Aurora | Soybean | 1.4 | June 9 | 395 | June 30 | July 8 | September 8 | October 22 |
| | Beresford | Soybean | 2.1 | June 9 | 395 | June 26 | July 10 | September 2 | October 20 |
| | Morris | Corn | 93 d | April 16 | 79 | May 16 | June 2 | August 27 | October 1 |
| 2016 | Aurora | Corn | 99 d | May 7 | 79 | May 17 | June 15 | July 15 | October 5 |
| | Aurora | Soybean | 1.4 | May 19 | 395 | June 8 | June 23 | July 20 | October 14 |
| | Morris | Soybean | 1.1 | May 4 | 431 | June 1 | June 17 | July 19 | September 9 |
| 2017 | Aurora | Corn | 95 d | May 5 | 79 | June 2 | June 23 | August 1 | November 5 |
| | Aurora | Soybean | 1.7 | May 30 | 395 | June 15 | June 29 | July 31 | October 11 |
| | Beresford | Soybean | 1.9 | May 24 | 420 | June 16 | June 27 | July 28 | October 17 |
| | Morris | Corn | 93 d | May 11 | 86 | June 6 | June 26 | July 25 | October 31 |

**Table 1.** Locations, crops, relative crop maturity rating, planting dates and rates, dates of weed control applications, and measurements.

in- and between-rows, were harvested from 1/10 $m^2$ areas, separated by functional group (grass vs. broadleaf) and dried at 60°C until constant weight to quantify biomass by treatment. Relative greenness of the newest fully expanded maize leaf (SPAD meter, Konica Minolta, Japan) (10 to 20 plants per plot) was measured in 2016 and 2017 during this sampling time. At crop physiological maturity, the middle two rows of each treatment were harvested, and yield determined. Yield was corrected to 15.5% moisture for maize, and 13% moisture for soybean. Maize grain was tested for % N content, and soybean was analyzed for oil and protein contents.

#### *2.1.3. Statistical analysis*

Treatments [grit type followed by between-row treatment (I/B), between-row (BR) only, SLW, and hand-weeded] were replicated four times for each crop, year, and location in randomized complete block designs. Yields in hand-weeded and SLW treatments varied considerably among locations and years. To analyze main effect of grit treatments, the SLW treatment average yield by crop, location, and year was used as the 'base' yield, with grit type and BR treatment average yields for the crop, location, and year divided by the SLW value, providing a relative yield comparison with the SLW. This relative yield approach assisted in evaluating treatment comparisons among years and locations. The treatments by crop were the fixed effects, whereas location, blocks, and years were random effects. One-way ANOVAs (i.e., was the relative treatment yield greater than its SLW?) were calculated with significance of $p = 0.1$. In addition, a sign test for paired comparisons also was used as a non-parametric measure to determine if treatments differed.

## 2.2. Results

### *2.2.1. Influence of treatments on in-row (IR) and between-row (BR) weed control*

Broadleaf weeds observed in plots during the time of grit applications included common lambsquarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus*), common purslane (*Portulaca oleracea*); and grass weeds included green and yellow foxtail (*Setaria viridis* and *S. pumila*, respectively). Weed size ranged from <1 cm (V1 maize application), 2- to 6-cm tall (V1 soybean), and >10 cm tall (V3 soybean or V5 maize). Broadleaf weeds were greater in number, making up >60% (and at times, nearly 100%) of the weed profile.

In general at all locations, grit treatments tended to control all weeds in maize after the first (V1) application (data not shown) as weed densities were low, and most were small (<3 cm). When grit was applied in soybean, plots at Aurora and Beresford already had high weed densities (~700 plants $m^{-2}$) and weed height ranged from 2- to 6-cm at V1 and, while grits abraded leaf tissue, control ranged from 0- to 50%. Plots at Morris were rotary hoed prior to grit application and no weeds were present. Examining weeds before and after the second application indicated that emerged broadleaf weeds again were injured by abrasion, but if >4-cm tall, they were not controlled. Grass weeds, if emerged, were injured, but growing points were still below the soil surface, so that although defoliated, they were not controlled well.

Grit application, generally, did not influence IR weed biomass measured at R4, with weights similar to those recorded in SLW plots. At Aurora IR weed biomass was found to be nearly 100% grass in 2016 and averaged 300 kg $ha^{-1}$ (SLW averaged 400 kg $ha^{-1}$), and in 2017, was about 60% grass and averaged about 4500 kg $ha^{-1}$ (SLW averaged 4300 kg $ha^{-1}$). In Morris maize plots, nearly 100% of biomass was attributed to broadleaf species and averaged 100 kg $ha^{-1}$ (SLW averaged 140 kg $ha^{-1}$) in 2015, and 2200 kg $ha^{-1}$ (SLW averaged 2600 kg $ha^{-1}$) in 2017.

Total IR weed biomass in soybean treated with grit did not differ from the location/year SLW treatment except at Aurora in 2016, where grit treatments had reduced broadleaf biomass that ranged from 20 to 80% less (220 kg $ha^{-1}$ in SLW) and about 50% less grass biomass (1100 kg $ha^{-1}$ in SLW).

The BR cultivation in maize and four of six soybean site-years had few if any weeds remaining between rows and remained nearly weed-free through harvest. The exceptions were the 2015 soybean plots in Aurora where the BR treatment had 11,000 kg ha $^{-1}$ between row weed biomass with grass weeds contributing about 80% of the total biomass, and 2015 soybean plots in Beresford, where BR weed biomass was 105 kg $ha^{-1}$ with grass weeds accounting for all the biomass.

### *2.2.2. Crop yield*

Maize yields in weed-free areas differed by location and year and ranged from 7588 (Aurora, 2017) to 12,690 (Morris, 2015) kg $ha^{-1}$ in weed-free treatments. Yield losses in SLW compared

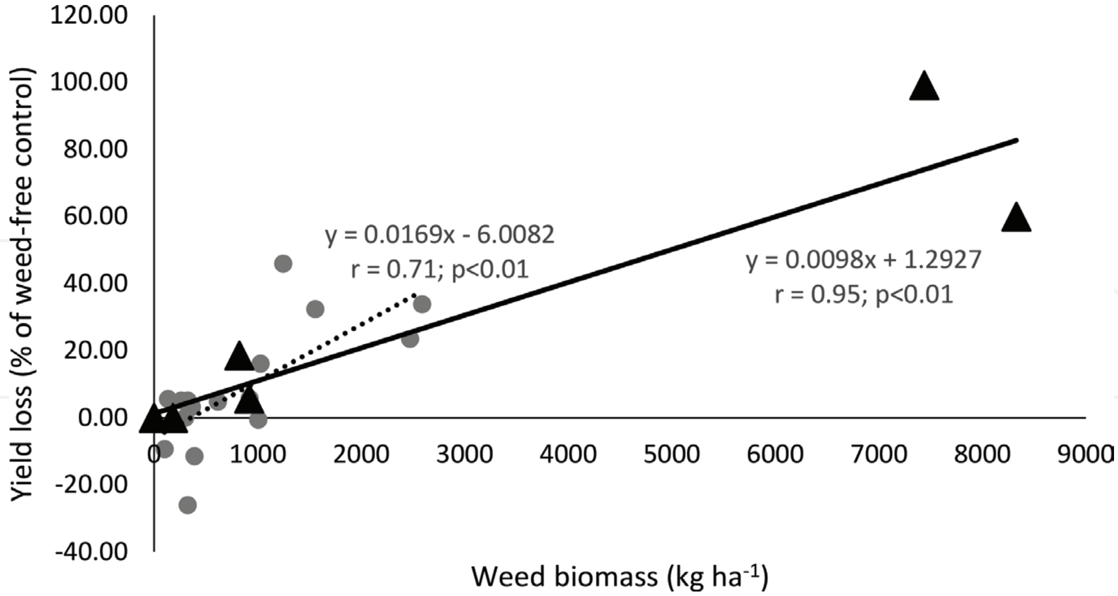


**Figure 1.** Maize yield loss (% of weed-free control) by total weed biomass at all locations and treatments. Triangles represent the season-long weedy treatments and the regression is shown by the solid black line (r = 0.95; p < 0.01). Circles represent yield loss based on weed biomass compared with the weed-free control plots of the I/B and BR treatments with the regression shown in the dotted line (r = 0.71; p < 0.01).

to the weed-free check ranged from 5% to nearly 100%. Maize yields in the SLW, I/B, and BR treatments were almost all lower than the weed-free check. In the SLW vs. weed-free treatments, the percent yield loss was positively correlated with total weed biomass (in-row plus between-row weeds) when examined across all studies (r = 0.93; p = 0.008) (**Figure 1**). Because the I/B and BR treatments had few between row weeds, the yield losses in these treatments were positively correlated with in row weed biomass (r = 0.71; p = 0.001). The slopes of each regression line were similar (m ~ 0.01), which indicated that percent yield loss was about 1% for each 100 kg ha$^{-1}$ of weed biomass present at R4.

Although weeds were present in the row after I/B treatments, maize yields across years and locations were greater than the SLW, except in one case. On average, there was a 30% yield increase in grit application treatments compared within a year and location to its companion SLW treatment. Sustane treatments averaged 44% greater yield than SLW, whereas Agra Grit averaged 14% greater yield (p = 0.1). In addition, maize grain had 16% higher N content than grain from either the SLW or Agra Grit treatments (p<0.003). Sustane appeared to provide some nitrogen to the crop [74], as relative greenness, measured at R4 of maize, was similar to the weed-free check, and averaged 44% (p < 0.01) higher than greenness of plants in the SLW treatment. Agra Grit has a high C/N ratio, and actually slowed soil nitrogen mineralization in laboratory studies [74], although greenness values at R4 were about 30% greater than SLW plants. The BR treatment and I/B treatments averaged over all grits, however, had similar maize yield increases (23% vs. 30%, respectively; p = 0.63) compared to the SLW.

Soybean yield in weed-free treatments ranged from 1626 (Aurora, 2015) to 4856 (Aurora, 2016) kg ha$^{-1}$. Yield losses compared to weed-free treatments within location and year ranged from 2 to 43%. However, unlike maize yield losses, which were linearly related to total weed biomass, soybean yield loss in SLW compared with weed-free was not correlated to total weed biomass ($r = 0.16$; $p = 0.69$), but was more correlated to in-row weed biomass ($r = 0.58$; $p = 0.12$). When examining relative yield compared with the SLW treatment, I/B treatments increased yield on average by about 16% ($p = 0.004$), which was similar to the BR treatment alone ($p = 0.48$). Soybean yield increases due to Agra Grit treatments compared with Sustane treatments were similar. Protein and oil content of soybean grain were similar among treatments as well. These data indicate that grit applications applied at V1 and V5 of soybean had minimal impact on soybean yield and weed biomass. Indeterminate growth of soybean may have been partially responsible for the inconsistency between weed biomass and soybean yield loss.

## 3. Conclusion

Weed management using grits was more effect on small broadleaf weeds than larger broadleaf or grass weeds. While the larger weeds and grasses were defoliated with the grit treatment, these regrew and by late season, biomass was similar in-row as the season-long weedy treatment. The in-row treatment, followed by cultivation between rows, tended to increase maize yield compared to no management, and grit with a higher N content tended to increase maize yield and nitrogen content more than a low N grit. Weed control in soybean was more challenging and, due to the size of the weeds even at V1 (one expanded trifoliate leaf), did not control weeds well, and by the second application (V5), weeds were likely too large for meaningful injury. Soybean yield loss was more related to in-row weed biomass than between row weed biomass. Thus, more research is needed to better control in-row weeds in soybean to limit yield loss.

## Acknowledgements

South Dakota State University; South Dakota Ag Experiment Station; USDA NIFA OREI #2014-51300-22233.

## Author details

Michael Carlson[1], Frank Forcella[2], Sam Wortman[3] and Sharon A. Clay[1]*

*Address all correspondence to: sharon.clay@sdstate.edu

1 Department of Agronomy, Horticulture, and Plant Science, South Dakota State University, Brookings, SD USA

2 USDA-ARS, Morris, MN, USA

3 University of Nebraska-Lincoln, Lincoln, NE USA

## References


[1] USDA. Certified Organic Survey [Internet]. 2017. Available from: http://usda.mannlib.cornell.edu/usda/current/OrganicProduction/OrganicProduction-09-20-2017_correction.pdf [Accessed: November 27, 2017]

[2] Organic Trade Association (OTA). U.S. Organic: State of the Industry. 2016

[3] CME. Corn Futures – CME Group. Corn Futures Quotes. [Internet]. 2017. Available from: http://www.cmegroup.com/trading/agricultural/grain-and-oilseed/corn.html [Accessed: April 4, 2017]

[4] CME. Soybean Futures - CME Group. Soybean Futures Quotes [Internet]. 2017. Available from: http://www.cmegroup.com/trading/agricultural/grain-and-oilseed/soybean.html [Accessed April 4, 2017]

[5] Greene C. Organic provisions in the 2014 Farm Act. [Internet]. 2016. Available from: https://www.ers.usda.gov/topics/natural-resources-environment/organicagriculture/organic-provisions-in-the-2014-farm-act/ [Accessed: November 12, 2017]

[6] Gordillo RM, Cabrera ML. Mineralizable nitrogen in broiler litter: I effect of selected litter chemical characteristics. Journal of Environmental Quality. 1997;**26**:1672-1679

[7] Cooperband L, Bollero G, Coale F. Effect of poultry litter and composts on soil nitrogen and phosphorus availability and corn production. Nutrient Cycling in Agroecosystems. 2002;**62**:185-194

[8] Sistani KR, Sikora FJ, Rasnake M. Poultry litter and tillage influences on corn production and soil nutrients in a Kentucky silt loam soil. Soil and Tillage Research. 2008;**98**:130-139

[9] Gagnon B, Berrouard S. Effects of several organic fertilizers on growth of greenhouse tomato transplants. Canadian Journal of Plant Science. 1994;**74**:167-168

[10] Mikkelsen R, Hartz TK. Nitrogen sources for organic crop production. Better Crops. 2008;**92**:16-19

[11] Sexton P, Jemison J. Comparison of soybean, canola, and mustard meals as organic sources of nitrogen for potatoes in northern New England. Crop Management. 2011;**10**. DOI: 10.1094/CM-2011-0127-01-RS

[12] Peigne J, Casagrande M, Payet V, David C, Sans FX, Blanco-Moreno JM, Cooper J, Gascoyne K, Antichi D, Barberi P, Bigongiali F, Surbock A, Kranzler A, Beeckman A, Willekens K, Luik A, Matt D, Grosse M, Hess J, Clerc M, Dierauer H, Mader P. How organic farmers practice conservation agriculture in Europe. Renewable and Agriculture Food Systems. 2015;**31**:72-85

[13] Moynihan M. Status of organic agriculture in Minnesota, 2015. A report to the Minnesota Legislature. [Internet]. 2016. Available from: http://www.mda.state.mn.us/~/media/Files/news/govrelations/legrpt-organic2015.pdf [Accessed November 26, 2017]

[14] Walz E. Fourth National Organic Farmers' Survey. [Internet] 2004. Available from: http://ofrf.org/sites/ofrf.org/files/docs/pdf/4thsurvey_results.pdf [Accessed: November 26, 2017]

[15] Jerkins D, Ory J. 2016 National organic research agenda. Outcomes and recommendations from the 2015 national organic farmer survey and listening sessions. Organic farming research foundation. [Internet]. 2016. Available from: https://ofrf.org/sites/ofrf.org/files/staff/NORA_2016_final9_28.pdf. [Accessed: November 26, 2017]

[16] Barberi P. Weed management in organic agriculture: Are we addressing the right issues? Weed Research. 2002;**42**:177-193

[17] Buhler DD. Expanding the Context of Weed Management. 1999. Pg 1-7. New York: Haworth

[18] Welsh R. The economics of organic grain and soybean production in the Midwestern United States. Report from Henry A. Wallace Institute for Alternative Agriculture. 34 p. [Internet]. 1999. Available from: https://www.hawiaa.org [Accessed: November 26, 2017]

[19] Malik VS, Swanton CJ, Michaels TE. Interaction of white bean (*Phaseolus vulgaris* L.) cultivars, row spacing and seeding density with annual weeds. Weed Science. 1993;**41**:62-68

[20] Yelverton FH, Coble HD. Narrow row spacing and canopy formation reduces weed resurgence in soybeans (*Glycine max*). Weed Technology. 1991;**5**:169-174

[21] Mohler CL. A model of the effects of tillage on emergence of weed seedlings. Ecological Applications. 1993;**3**:53-73

[22] Wiener J, Griepentrog HW, Kristenses L. Suppression of weeds by spring wheat (triticum aestivum) increases with crop density and spatial uniformity. Journal of Applied Ecology. 2001;**313**:31-51

[23] Rich AM, Renner KA. Row spacing and seeding rate effects on eastern black nightshade (*Solanum ptycanthum*) and soybean. Weed Technology. 2007;**21**:124-130

[24] Place GT, Reberg-Horton SC, Dunphy JE, Smith AN. Seeding rate effects on weed control and yield for organic soybean production. Weed Technology. 2009;**23**:497-502

[25] Carr PM, Gramig GG, Liebig MA. Impact of organic zero tillage systems on crops, weeds and soil quality. Sustainability. 2013;**5**:3172-3201

[26] Clark KM, Boardman D, Staples JS, Easterby S, Reinbott TM, Kremer RJ, Kitchen HR, Veum KS. Crop yield and soil organic carbon in conventional and no-till organic systems on a claypan soil. Agronomy Journal. 2017;**109**:588-599

[27] Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL. Timing of cover crop management effects on weed suppression in no-till planted soybean using a roller–crimper. Weed Science. 2011;**59**:380-389

[28] Mischler R, Duiker SW, Curran WS, Wilson D. Hairy vetch management for no-till organic corn production. Agronomy Journal. 2010;**102**:355-362

[29] Teasdale JR, Coffman CB, Mangum RW. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. Agronomy Journal. 2007;**99**:1297-1305

[30] Bosnic AC, Swanton CJ. Influence of barnyardgrass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). Weed Science. 1997;**45**:276-282

[31] Cowan P, Weaver SE, Swanton CJ. Interference between pigweed, barnyardgrass, and soybean. Weed Science. 1998;**46**:533-539

[32] Knezevic SZ, Weise SF, Swanton CJ. Interference of redroot pigweed (*Amaranthus retroflexus*) in corn (*Zea mays*). Weed Science. 1994;**42**:568-573

[33] Knezevic SZ, Evans SP, Mainz M. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technology. 2003;**17**:666-673

[34] Zimdahl RL. The concept and application of the critical weed-free period. In: Altieri A, Liebman M, editors. Weed Management in Agroecosystems: Ecological Approaches. Boca Raton, FL: CRC Press; 1988. pp. 145-155

[35] Swanton CJ, Weise SF. Integrated weed management: The rationale and approach. Weed Technology. 1991;**5**:648-656

[36] Mulugeta D, Boerboom CM. Critical time of weed removal in glyphosate-resistant *Glycine max*. Weed Science. 2000;**48**:35-42

[37] Clay SA, Kleinjan J, Clay DE, Forcella F, Batchelor W. Growth and fecundity of weed in species in corn and soybean. Agronomy Journal. 2005;**97**:294-302

[38] Moriles J, Hansen S, Horvath DP, Reicks G, Clay DE, Clay SA. Microarray and growth analyses identify differences and similarities of early corn response to weeds, shade, and nitrogen stress. Weed Science. 2012;**60**:158-166

[39] Norsworthy JK, Oliveira MJ. Comparison of the critical period of weed control in wide- and narrow-row corn. Weed Science. 2004;**52**:802-807

[40] Turner R, Lennartsson MK, Bond W, Grundy AC, Whitehouse D. Organic weed control – Getting it right in time. In: Proceedings 1999 Brighton Conference – Weeds, Brighton, UK, 1999. p. 969-974

[41] Pullen DM, Cowell PA. An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. Journal of Agricultur Engineering Research. 1997;**67**:27-34

[42] Baerveldt S, Ascard J. Effect of soil cover on weeds. Biological Agriculture & Horticulture. 1999;**17**:101-111

[43] Leblanc ML, Cloutier DC. Effect of the stale seedbed technique on annual weed emergence in maize. In: Proceedings 10th International Symposium on the Biology of Weeds. Dijon, France: Association Nationale pour la Protection des Plantes; 1996. pp. 29-34

[44] Boyd NS, Brennan EC, Fennimore SA. Stale seedbed techniques for organic vegetable production. Weed Technology. 2006;**20**:1052-1057

[45] Forcella F. Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch. Renewable Agriculture and Food System. 2014;**29**:92-99

[46] Melander B, Rasmussen IA, Bertelsen I. Integration of *Elymus repens* control and post-harvest catch crop growing in organic cropping systems. Abstracts 13th EWRS (European Weed Research Society) Symposium. 2005. session 5 abstract no. 163

[47] Cirujeda A, Aibar J, Zaragoza C, Anzalone A, Gutierrez M, Fernandez-Cavada S, Pardo A, Suso ML, Royo A, Martın L, Moreno MM, Moreno A, Meco R, Lahoz I, Macua JI. Evaluacion de acolchados para el control de la flora arvense en un cultivo de tomate. In: Proceedings of the 2007 Spanish Weed Science Congress. Albacete, Spain: Spanish Weed Science Society. 2007. p.217-221

[48] Jones PA, Blair AM, Orson J. The effects of different types of physical damage to four weed species. In: Proceedings 1995 Brighton Crop Protection Conference – Weeds, Brighton, UK, 1995. p. 653-658

[49] Jones PA, Blair AM, Orson J. Mechanical damage to kill weeds. In: Proceedings Second International Weed Control Congress, Copenhagen, Denmark. 1996. p. 949-954

[50] Ascard J. Effects of flame weeding on weed species at different developmental stages. Weed Research. 1995;**35**:397-411

[51] Van Der Weide RY, Bleeker PO, Achten V, Lotz LP, Fogelberg F, Melander B. Innovation in mechanical weed control in crop rows. Weed Research. 2008;**48**:215-224

[52] Lampkin N. Organic Farming. Ipswich, UK: Farming Press Books; 1990

[53] Kurstjens DG, Bleeker P. Optimising torsion weeders and finger weeders. In: Proceedings of the 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control, 20-22 March 2000; Elspeet, The Netherlands. 2000. p. 30-32

[54] Bleeker P, Van Der Weide RY, Kurstjens DA. Experiences and experiments with new intra-row weeders. In: Proceedings 2002 5th EWRS Workshop on Physical Weed Control, Pisa, Italy. 2002. p. 97-100

[55] Lutkemeyer L. Hydropneumatische unkrautbekampfung in reihenkulturen. Z. Pflan zenkr. Pflanzenschutz Sonderh. 2000;**17**:661-666

[56] Kurstjens DG, Perdok UD. The selective soil covering mechanism of weed harrows on sandy soil. Soil and Tillage Research. 2000;**55**:193-206

[57] Rasmussen J. Weed harrowing in winter wheat. In: Proceedings 15th Danish Plant Protection Conference/Weeds. Nyborg, Denmark: Danish Institute of Agricultural Sciences. 1998. p. 179-189

[58] Baker BP, Mohler CL. Weed management by upstate New York organic farmers: Strategies, techniques and research priorities. Renewable Agriculture and Food System. 2014;**30**:418-427

[59] Cloutier DC, Leblanc M, Johnson E. Non-inversion production techniques in North America. In: Cloutier, D editor. 7th European Weed Research Society Workshop on Physical and Cultural Weed Control. Rostock, Germany: Universitat Rostock. 2007. p. 3-14

[60] Harker KN, O'Donovan JT. Recent weed control, weed management and integrated weed management. Weed Technology. 2013;**27**:1-11

[61] Liebman M, Davis AS. Managing weeds in organic farming systems: An ecological approach. In: Francis CA, editor. Organic Farming: The Ecological System. Madison, WI: American Society of Agronomy; 2009. pp. 173-196

[62] Nørremark M, Sørensen CG, Jørgensen RN. HortiBot: comparison of present and future phytotechnologies for weed control— part III. In: ASABE Annual International Meeting Papers. St. Joseph, MI: American Society of Agricultural and Biological Engineers, 2006. Paper 067023. 14 p

[63] Forcella F. Potential use of abrasive air-propelled agricultural residues for weed control. Weed Research. 2009;**49**:341-345

[64] Forcella F. Potential of air-propelled abrasives for selective weed control. Weed Technology. 2009;**23**:317-320

[65] Forcella F. Air-propelled abrasive grit for postemergence in-row weed control in field corn. Weed Technology. 2012;**26**:161-164

[66] Forcella F. Soybean seedlings tolerate abrasion from air-propelled grit. Weed Technology. 2013;**27**:631-635

[67] Wortman SE. Air-propelled abrasive grits reduce weed abundance and increase yields in organic vegetable production. Crop Protection. 2015;**77**:157-162

[68] Braun E. Abrasive grit application for integrated weed and nitrogen management in organic vegetable cropping systems. [Thesis]. Urbana, Il: University of Illinois Urbana-Champaign; 2017

[69] Erazo-Barradas M, Friedrichsen CN, Forcella F, Humburg D, Clay SA. Propelled abrasive grit applications for weed management in transitional corn grain production. Renewable Agriculture and Food System. 2017:1-8. DOI: 10.1017/S174217051700031X

[70] Erazo-Barradas M, Humburg D, Forcella F, Clay SA. Propelled abrasive grit for weed control in organic silage corn. Agronomy Journal. DOI: 10.2134/agronj2017.08.0454

[71] Sustane. How Sustane is made. [Internet] 2016. Available from: http://www.sustane.com/overview/how-sustane-is-made. [Accessed: November 30, 2017]

[72] Blackshaw RE. Nitrogen fertilizer, manure, and compost effects on weed growth and competition with spring wheat. Agronomy Journal. 2005;**97**:1612-1621

[73] Evans SP, Knezevic SZ, Lindquist JL, Shapiro CA, Blankenship EE. Nitrogen application influences critical period for weed control in corn. Weed Science. 2003;**51**:408-417

[74] Carlson M. Selected agricultural grits for weed control, effect on corn and soybean yield, weed growth, and soil mineralization. [Thesis]. Brookings, SD: South Dakota State University; 2018