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Propelled abrasive grit applications for weed management in transitional corn grain production

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Abstract

Weed control is challenging to farmers who are transitioning from production systems that use synthetic herbicides to organic systems. A 2-year field study examined air-propelled corncob grit abrasion for in-row weed control efficacy and effect on corn yield. Grit was applied based on corn vegetative developmental stages with one (V1, V3 or V5), two (V1 + V3, V1 + V5, or V3 + V5), or three (V1 + V3 + V5) applications. Flame-weeding or cultivation was used after the V5 application for between-row weed control. Grit applications decreased in-row weed densities by about 60% ($\alpha = 0.05$) and biomass up to 95% ($\alpha = 0.001$). Between-row treatments provided similar control, and reduced weed biomass by 55% in 2013 ($\alpha = 0.01$) and 86% ($\alpha = 0.001$) in 2014. In-row grit treatments increased corn yield up to 44%, and yield was more influenced by in-row weeds than between row weeds. These results indicate that abrasive corncob grit for in-row weed control, supplemented with cultivation or flaming, can reduce weed biomass substantially and help maintain corn yield. However, timing and frequency of grit application need further refinement based on weed growth as influenced by climate, as treatments at similar corn growth stages did not consistently provide adequate weed control between years.

Nomenclature: corn *Zea mays* L.

Key Words: *Zea mays*, corncob grit, sustainability

Introduction

Before the discovery and use of synthetic auxin-like herbicides in the late 1940s (Vats, 2015), farmers relied on numerous non-chemical methods for weed control. These included mechanical practices such as hand pulling or hoeing, cultural control that used crop rotations and prevention measures such as planting clean seed (Hay, 1974; Radosevich et al., 1997; Timmons, 2005). Herbicide use reduced the labor needed for farming, increased long-term crop productivity (Aktar et al., 2009), and helped increase the adoption of zero- or reduced-tillage production systems (Lee et al., 2014). However, the USDA-administered National Organic Program prohibits the use of synthetic chemicals for commodities that are certified organic (Greene, 2016). Accordingly, organic growers depend upon alternatives to herbicides.

Alternative weed control strategies also are desirable for conventional growers due to increases in weed biotypes resistant to multiple herbicides (Heap, 2017), the lack of new mode-of-action herbicides (Duke, 2012), environmental impacts of most weed management systems, (Barbash et al., 1999; Johnson, 2004) and general consumer concerns (Greene, 2016).

Effective weed control is challenging to organic producers, and to those who are transitioning into organic systems, when farmland must be free of synthetic chemicals for 36 months (Bond and Grundy, 2001; Walz, 2004; Kruidhof et al., 2008; Baier and Ahramjian, 2012). After conversion, the land must remain free of synthetic chemicals, be in compliance with other accreditation standards, and be recertified annually to maintain organic status. In addition, producers must develop and maintain an organic system plan that describes the practices and substances that will be used for fertility and pest management.

The Organic Farming Research Foundation ranked weed management as one of the top priorities for research (Jerkins and Ory, 2016), and this issue has ranked high on the list of needs for organic system sustainability for many years in both Europe (Peigne et al., 2015) and North America (Jerkins and Ory, 2016; Moynihan, 2016). Many weed control techniques can be used in organic cropping systems, such as crop rotation, cover crops, natural products (e.g., corn gluten meal), steaming, flaming and micro-waving. Stand-alone techniques and even integrated strategies have resulted, at times, in unacceptable weed control and crop yield loss (Johnson et al., 2013). The high application rates of some products or labor intensity to obtain effective weed control make some of the alternative methods prohibitively expensive (Boyd and Brennan, 2006). Weed control research needs to continue to focus on the implementation of efficacious integrated approaches (Liebman and Davis, 2009) and update existing weed management strategies (Cloutier et al., 2007; Van Der Weide et al., 2008; Harker and O'Donovan, 2013) for better weed control in organic and transitional crop production.

Nørremark et al. (2006) conceived the idea of using air-propelled grits to abrade tissue of small weeds, and Forcella (2009a, b; 2010; 2012) demonstrated that grits derived from crop residues such as walnut shells can control small weed seedlings (at one- or two-true leaf stages of growth) in greenhouse and field experiments. In field experiments, Forcella (2012) reported that two applications of air-propelled corncob grit aimed at the row, combined with inter-row cultivation reduced weed presence in corn and increased yield. Erazo-Barradas (2016) demonstrated that in certified organic silage corn, early in-row grit applications (V1 and V3 stages of corn growth) effectively controlled weeds and maintained high crop yields, but later applications (V5 and V7) reduced corn yields due to prolonged crop–weed interference. Thus, in-row grit applications at optimum timings, combined with between-row weed control techniques, may provide unique weed management tools for post-emergence weed control in organic corn.

The objective of this 2-year field study was to assess the efficacy of air-propelled abrasive corncob grit applications for in-row weed control at different frequencies and timings in a transitional corn production field. Tillage or flame-weeding was done once for between-row weed control. The treatment effects were quantified through measuring weed densities and biomass, and corn grain yield.

Materials and Methods

Field experiment

A commercially available 97-day corn hybrid was planted on May 28, 2013 and May 25, 2014 at about 79,000 plants ha^{-1} in rows spaced 0.76 m apart at the Aurora Research Field Station of South Dakota State University (Brookings County, SD). The prior crop each year was soybean (*Glycine max* [L.] Merr.). Plots were chisel plowed about 2 weeks prior to corn planting. The soil parent materials were loess over glacial outwash, and the soil series was a Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludolls) (https://soilseries.sc.egov.usda.gov/OSD_DOCS/B/BRANDT.html; Clay et al., 2009). The soil has high water availability and is well drained. Field capacity (−0.03 MPa) and permanent wilting point (−1.5 MPa) of this soil are about 0.3 and 0.1 g g^{-1}, respectively. The growing degree day (base 10° C) accumulation from May to September was similar each year: 1385 for 2013; 1240 for 2014; 1299 as the 25-yr average. Rainfall during the May–September period was 34.3 cm for 2013, 43.4 cm for 2014 and 39.3 cm for the 25-yr average. Thus, the 2013 season was slightly warmer and drier, and the 2014 season had average temperatures and 10% more rainfall than average.

The study consisted of 16 treatments (see Table 1) that were replicated four times in a randomized complete block design. Plots were 3-m long × 3-m wide and consisted of four corn rows spaced about 76-cm apart. In-row grit applications were performed based on corn phenology, with applications completed at various vegetative growth stages (described by Ritchie et al., 1997). The growth stages were V1 (~June 15), V3 (~June 21) and V5 (~July 5). Double applications were applied at V1 + V3, V1 + V5 and V3 + V5. The triple grit application was accomplished by treating at V1 + V3 + V5. All grit treatments received either a between-row treatment of flaming or cultivation that was completed after the V5 grit application (July 5, 2013 and July 9, 2014). Alongside the rows where corncob grit was applied, four between-row areas were either cultivated or flamed once at V5 to allow for matched pair *t*-tests to compare weed control and corn yield with and without the in-row grit treatment. A season-long weedy (SLW) treatment (no weed control attempted) provided information on maximum weed growth and yield reduction, whereas a hand-weeded (HW) treatment quantified the maximum corn yield potential each year with no weeds present.

Corncob grit (Green Products Company, Conrad, IA) with a commercial standard particle size of the grit of about 0.5 mm diameter (Forcella, 2009b) was applied on both sides of the corn row. The grit was applied with a sand blasting unit whose grit tank was pressurized to about 625 kPa as described by Forcella (2012). The unit had a porcelain nozzle that emitted grit at about 40 g s^{-1} in a full-cone pattern. The nozzle tip was about 30 cm from the top of the weeds and was aimed in a downward 45° angle at the base of the corn plants. The sand blasting unit was positioned on a four-wheeled cart. A person walked alongside the cart at 3.1 km hr^{-1} holding the nozzle and treating each side of the corn row. Grit was applied at about 480 kg ha^{-1} at each application date. Emerged plants typically were defoliated, and in

Table 1. Grit application dates at corn vegetative corn growth stages for 2013 and 2014 at Aurora, SD.

	2013	2014
Growth stages	**Dates**	**Dates**
V1[1]	June 15	June 16
V3	June 21	June 22
V5	June 29	July 2
V1 + V3	June 15 + June 21	June 16 + June 22
V1 + V5	June 15 + June 29	June 16 + July 2
V3 + V5	June 21 + June 29	June 22 + July 2
V1 + V3 + V5	June 15 + June 21 + June 29	June 16 + June 22 + July 2

[1] For each grit treatment, a between-row flaming was done July 5, 2013 and July 9, 2014. Cultivation was done on July 6, 2013 and July 10, 2014. In addition, the single flaming or cultivation treatments with no grit application were established at this same time.

the case of dicotyledons, often the apical meristem was damaged or destroyed.

For between-row weed control, cultivation or flaming was performed in four rows for each treatment. Flaming was applied after the V5 grit application utilizing a hand-pushed, single-wheeled, propane-fueled flamer (http://flameweeders.com). A 4.5-kg propane tank was carried in a backpack and was attached to the flamer via a rubber hose and steel tube (flamer handle). The flame-emitting deck was 75-cm wide with five torches mounted 15-cm apart. The torches were covered by a hood that was positioned 18-cm above soil surface over the row middle and angled back at 30° to the soil. Flaming was done at 3.1 km hr^{-1} and delivered about 50 kg propane ha^{-1}. Cultivation was performed on July 6, 2013 and July 10, 2014 using a John Deere® 886 4-row cultivator mounted on the three-point hitch driven at 5 km hr^{-1}. The cultivator was equipped with three 15-cm wide sweeps between each pair of rows.

Weed densities were quantified by species in each plot in three permanent 15×40 cm^2 quadrats (within rows and between rows) 1 day before treatment and 3 days after treatment. Weed biomass was collected just prior to corn harvesting (October 16, 2013 and October 10, 2014). Weeds within these quadrats were clipped at soil level, bagged as in-row and between-row weeds, dried at 40°C to constant weight, and weighed.

Corn ears from 1-m long sections of the middle two rows of each plot were hand-harvested. The ears were dried at 40°C to constant weight, and shelled. Grain yield was adjusted to 15% moisture content.

Statistical analysis

Analysis of variance (ANOVA) was used to examine data for total weed biomass, in-row and between-row weed biomass, broadleaf and grass biomass, weed density and corn yield. A linear statistical model for a randomized complete block design (Steel and Torrie, 1996) was used. To estimate the mean squares for weed biomass, data from weedy, but not weed-free, checks were included and ANOVA was performed using the library agricolae (de Mendiburu, 2014) in R (R Core Team, 2014).

Results and Discussion

Weed species

Broadleaf weeds were the predominant species present in both years in both in-row and between-row areas. At V1 and V3, redroot pigweed (*Amaranthus retroflexus* L.) at the 2- and 3-leaf stage and common lambsquarters (*Chenopodium album* L.) at the 3- and 4-leaf stage were most prevalent. At V5, redroot pigweed was at the 5- to 6-leaf stage, common lambsquaters at the 6- to 7-leaf stage, and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) at the 3- and 5-leaf stage were present. Grass presence was first noted at V5. The grass species included green and yellow foxtails [*Setaria viridis* (L.) P. Beauv. and *S. pumila* (Poir.) Roem. &Schult.], barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and large crabgrass [*Digitaria sanguinalis* (L.) Scop.].

In-season weed control (weed density)

In-row weeds. The grit from the sprayer abraded the in-row weeds and reduced their densities each year (Fig. 1). In 2013, weed densities before the grit application averaged 35 plants m^{-2} at V1, 50 plants m^{-2} at V3 and 60 plants m^{-2} at V5 (Erazo-Barradas, 2016). Densities after the single application at V1 and V3 were reduced by 50% [to 17 plants m^{-2} for V1 treatment and 25 plants m^{-2} for V3 treatment ($\alpha < 0.05$)]. The single V5 application reduced weed density by 70% to 18 plants m^{-2} ($\alpha < 0.05$). The double V1 + V3 application had an initial density of 35 plants m^{-2} at V1 and 18 plants m^{-2} at V3, and these were reduced to 9 plants m^{-2} after the V3 application ($\alpha < 0.05$). The V5, V1 + V5 and V3 + V5 treatments had similar densities after the last treatment averaging 16 plants m^{-2}, whereas the V1 + V3 + V5 treatment averaged 9 plants m^{-2}, all of which were significantly lower than the untreated check plot (Fig. 1). In 2014, weed densities before the grit applications were greater than those in 2013, and averaged about 50, 70 and 60 plants m^{-2} at V1, V3 and V5, respectively (Erazo-Barradas, 2016, Fig. 1). Grit applications at V1 or V3 significantly reduced in-row weed density to about 30 and 40 plants m^{-2}, respectively, or about a 40% reduction from the initial densities. The single V5 grit application reduced weed density to 25 plant m^{-2}, a 58% reduction ($\alpha < 0.05$). The double application at V1 + V3 had a starting density of 50 plants m^{-2} prior to the V1 application and 38 plants m^{-2} prior to the V3

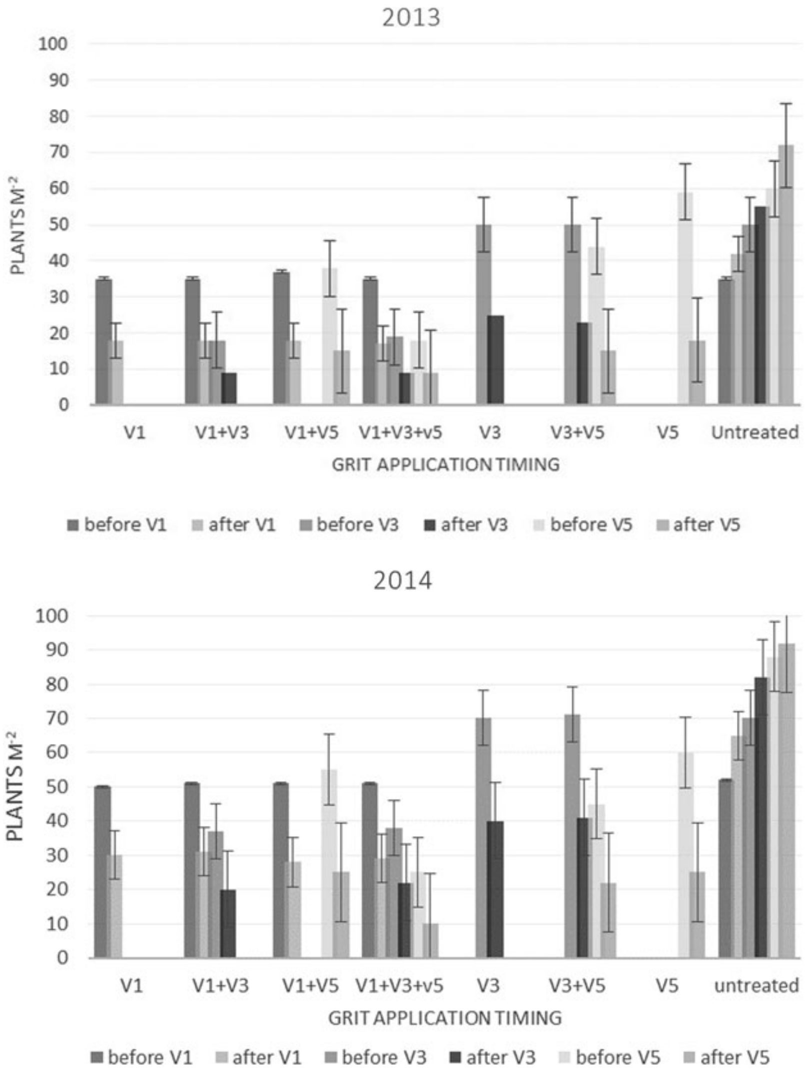

Figure 1. Weed densities before and three days after grit applications in 2013 and 2014. Note that densities of living weeds may not reflect total damage to the plants.

application, which was reduced to 20 plants m^{-2} following the V3 application ($\alpha = 0.10$). The V5, V1 + V5 and V3 + V5 treatments had similar densities of about 25 plants m^{-2} after the V5 application, whereas the V1 + V3 + V5 treatment averaged 10 plants m^{-2}. At V5, grass weeds, while defoliated, recovered and grew later in the season as their growing points were still below the soil surface at the time of application.

Applying grit at any timing (corn growth stage) or frequency (one, two, or three applications) reduced weed densities when compared with densities prior to application or the untreated control (Fig. 1). A single application at V1 controlled 50% of the weeds present. Single grit application at the V3 or V5 stage started with greater weed densities prior to application, but weed control, as a percentage of the initial density, was about 50%, similar to V1 applications. Applying grit two or three times further reduced weed density, but none of the treatments resulted in 100% control.

Between-row weeds. Between-row weed densities before the flaming or cultivation treatments averaged 53 plants m^{-2} in 2013 and 65 plants m^{-2} in 2014. Broadleaf weed species at this time were redroot pigweed, common lambsquarters, and Pennsylvania smartweed at the 5-, 4- and 4-leaf stages, respectively. Grasses included green and yellow foxtails, barnyardgrass and large crabgrass. Cultivation and flaming had a similar effect on weed densities, with reductions averaging 50%.

End-of-season weed control (weed biomass)

Weeds from the in-row and between-row quadrats were harvested just prior to corn harvest. Broadleaf and grass species included redroot pigweed, common lambsquarters, and Pennsylvania smartweed, green and yellow foxtails, barnyardgrass and large crabgrass, which were also the most prevalent species observed at V5. The ratio of broadleaf to grass biomass in the SLW treatment were

1.2:1 (2575 and 2068 kg ha^{-1}, respectively) in 2013, whereas in 2014, the ratio was 4.4:1 (6037 and 1366 kg ha^{-1}, respectively).

Total weed biomass. Total weed biomass was reduced from 60 to 89% when treated with the in-row + between-row treatments both years ($P \leq 0.01$) (Table 2). All treatments had less weed biomass than the season long weedy treatment, and statistically were similar to each other.

In-row weed biomass. In-row weed biomass accounted for 56 and 44% of the total biomass in the SLW treatment in 2013 and 2014, respectively (Table 2). When averaged across between-row treatments, all grit timings and application frequencies reduced in-row weed biomass by an average of 88% compared with biomass of the SLW in 2013 ($P < 0.01$). All grit timings and frequencies had statistically similar weed biomasses. In 2014, in-row treatments did not reduce weed biomass compared with the SLW ($P = 0.22$).

Between-row weed biomass. The between-row treatments (flaming and cultivation) averaged across grit applications had similar and significant reductions of weed biomass ($P < 0.02$) (Table 2) when compared with the SLW treatment. Weed biomass between-rows was reduced by 56% in 2013 and 86% in 2014.

Corn yield

The growing point of corn does not emerge from the soil until about V6 (Ritchie et al., 1997; Ransom, 2013), so even if leaves are damaged or destroyed, plant regrowth can occur and often will not affect final yield. In this study, grit was sprayed toward the base of the corn plant and while some pitting on the lower leaves was observed at times, the plants continued to grow. In addition, the leaf pitting did not influence disease presence, as no diseases were noted in any plot.

Yields in the HW treatments were similar between years, averaging 18400 and 19400 kg ha^{-1} for 2013 and 2014, respectively (Table 2). Weeds reduced yields in the SLW treatments by 22% in 2013 and 40% in 2014. These results indicated that weed interference was greater in 2014 compared with 2013, which was reflected by differences in weed biomass between the 2 years. Corn yield losses were strongly correlated with weed biomass (Fig. 2), with the relationship for in-row weed biomass more distinct (higher R^2) and more intense (steeper slope) than these parameters for total weed biomass. Consequently, treatments that reduced weed biomass, especially in-row weed biomass, tended to maintain corn yields equivalent to those in the HW check treatment.

The between-row treatments of flaming and cultivation alone had yields that were similar within years. These between-row treatments increased average yields by about 20% in 2013 and 28% in 2014 compared with yields of their respective SLW treatments.

In 2013, only the V3 + V5 treatment had a yield significantly lower than the HW treatment (i.e., 15% yield reduction). In contrast, in 2014 the V3 + V5 and V5 treatments were similar to the HW check while all other treatments had yields similar to the SLW treatment. This may indicate that weed flushes that occurred beyond V1 were most responsible for yield loss, and because the V3 single treatment also had reduced yield, grasses, which should have been better controlled at V5, may have had the most influence on yield loss in 2014.

Comparing yields using only between-row techniques with between and in-row treatments indicated that adding an in-row treatment increased yield 50% of the time (7 out of 14 applications) with in-row applications yielding 5–15% greater yield than a between-row treatment alone. In addition, the grit applications reduced weed biomass at the end of the season.

The timing of grit application(s), just like that of herbicides, needs to be carefully implemented. In 2013, the early applications had the greatest positive effect on yield. This was expected as early stages of corn growth and development are greatly reduced when weeds are present (Oliver, 1988; Radosevich et al., 1997; Zimdahl, 2008). In 2014, however, while in-row treatments reduced weed densities, the large number of remaining weeds and the end-of-season biomass, resulted in yield reductions. The V1 + V5 treatment in 2014 may have been too long a time period to let weed escapes after V1 grow prior to V5 treatment. The highest yielding treatments in 2014 were when grit was applied at V5 or at V3 + V5. The V5 treatments, especially in 2014, may have helped with grass control, as the weed biomass ratio was 4.4:1 broadleaf:grass in 2014 compared with only 1.2:1 in 2013. Rainfall in 2013 in August totaled 3.6 cm, whereas in 2014 rainfall was nearly doubled at 6.7 cm. These later rains may have facilitated greater weed biomass accumulation. It is unclear why the 2014 V1 + V3 + V5 in-row treatment had poor weed control (31%) but the consequences were observed in lower yield as well.

The critical weed-free period for corn in this study was from emergence until at least the V5 corn growth stage in both years. Complete season-long weed control typically is not necessary to achieve maximum yield because late-emerging weeds often do not reduce yield (Knake and Slife, 1965; Oliver, 1988; Cardina et al., 1995; Radosevich et al., 1997). However, weeds that escape control and grow to maturity are likely to add to the soil weed seed bank and intensify weed competition in following years. While any weed control timing or method increased yield above the SLW in 2013, results from 2014 did not follow this pattern. Thus, careful field scouting to know weed species composition and the dynamics of seedling emergence of expected species should be used to help anticipate and modify the timing of grit applications to achieve the best results for weed control with this new management technique.

Table 2. Total (in-row + between-row) and in-row weed biomass averaged across between-row treatments, % control, corn yield, and between-row weed biomass and yield with flame and cultivation treatments after V5 grit application for Aurora, SD 2013 and 2014. SLW, season-long weedy check; V1, V3 and V5 represent 1-, 3- and 5-leaf stages of corn growth when grit applications were made.

	2013					2014				
	Weed biomass					Weed biomass				
In-row treatment	**Total[1] kg ha^{-1}**	**Control %**	**In-row kg ha^{-1}**	**Control %**	**Corn yield kg ha^{-1}**	**Total kg ha^{-1}**	**Control %**	**In-row kg ha^{-1}**	**Control %**	**Corn yield kg ha^{-1}**
SLW	4643a[2]		2582a		14269b	7403a		3181		11492c
V1	1129b	76	373b	86	18427a	2450b	67	1864	41	13086c
V1 + V3	1260b	73	319b	88	18590a	1323b	82	737	77	15658bc
V1 + V5	1129b	76	282b	89	17352a	2749b	63	2163	32	12517c
V1 + V3 + V5	1260b	73	453b	83	18651a	2792b	62	2206	31	14380bc
V3	527b	89	167b	94	16432ab	1432b	81	846	73	15042bc
V3 + V5	1879b	60	463b	82	15649b	2221b	70	1635	49	16429ab
V5	1382b	70	129b	95	16389ab	1491b	80	905	72	16531ab
Handweeded					18388a					19381a
Pr > F	0.0007		0.001		0.02	0.012		0.22		0.0004
Between-row treatment										
SLW	2060a[1]				14269b	4222a				11492b
Flame	1039b	50			17587a	617b	85			15248a
Cultivate	785b	62			17128a	556b	87			14365a
Pr > F	0.014				0.001	0.0002				0.001

[1] Total weed biomass in the in-row treatment portion of the table is the total biomass of the weeds in-row plus between-row. Total weed biomass in the between-row portion of the table refers to only the weed biomass present between the rows.

[2] Letters denote significant differences among treatments at $\alpha = 0.05$ level.

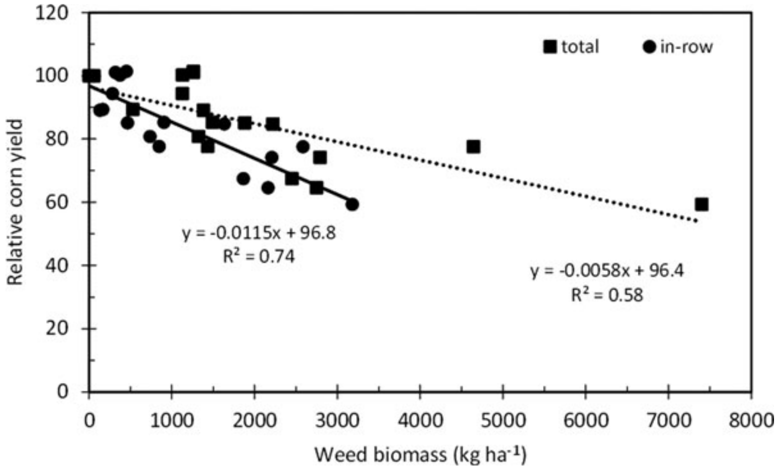

Figure 2. Effects of in-row weed biomass (circles) and total weed biomass (squares) on relative corn yields (percentages of weed-free checks in both 2013 and 2014). Steepness of slope and magnitude of R^2 indicate intensity of relationship for weed-crop interference.

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