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High-Residue Cultivation Timing Impact on Organic No-Till Soybean Weed Management

Gladis M. Zinati, Rita Seidel, Alison Grantham, Jeff Moyer, Victoria J. Ackroyd, and Steven B. Mirsky*

A cereal rye cover crop mulch can suppress summer annual weeds early in the soybean growing season. However, a multi-tactic weed management approach is required when annual weed seedbanks are large or perennial weeds are present. In such situations, the weed suppression from a cereal rye mulch can be supplemented with the use of high-residue cultivators which can prolong the weed-free period during soybean growth. Research trials were conducted to determine the optimum timing of high-residue cultivation for weed control in rolled-crimped cereal rye mulches. Treatments included three cultivation timings with a high-residue cultivator: early (3-4 wk after soybean planting (WAP)), intermediate (5-6 WAP), and late (7-8 WAP), a weed-free and no-cultivation control. Crop and weed measurement included cereal rye biomass, weed biomass, soybean population and biomass, and yield. Cereal rye biomass was 50% lower and weed biomass was three times greater in 2011 than in 2010 and 2012 due to 2011 being a dry year. There was no significant effect of cultivation timing on soybean population when compared to no-cultivation or hand-weeded treatments. While cultivation reduced weed biomass by 67% compared to no-cultivation, soybean yield was only improved by 12% in early and late cultivation treatments and 22% in intermediate cultivation treatment when compared to no-cultivation. Effective strategies for improving weed management by integrating the use of a high-residue cultivator in no-till organic systems could help existing organic field crop producers to reduce tillage while also encourage adoption of organic crop production by conventional growers who prefer reduced-tillage systems. Unlike traditional organic cultivation equipment, therefore, optimal timing of cultivation should be delayed several weeks in organic cover crop-based no-till planted soybean production as compared to the typical tillage-based approach to ensure both weed control and optimal yield.

Nomenclature: Cereal rye, *Secale cereale* L.; soybean, *Glycine max* L.

Key words: Cover crops, cereal rye, rolled mulches, post-soybean planting weed cultivation, weed biomass.

Los residuos de un cultivo de cobertura de centeno pueden suprimir malezas anuales de verano temprano durante la temporada de crecimiento de la soja. Sin embargo, se requiere un manejo de malezas con tácticas múltiples cuando el banco de semillas de malezas anuales es grande o malezas perennes están presentes. En tales situaciones, la supresión de malezas por parte de los residuos del centeno pueden ser complementados con el uso de cultivadores especiales para condiciones de altos residuos, lo cuales pueden prolongar el período libre de malezas durante el crecimiento de la soja. Se realizaron ensayos de investigación para determinar el momento óptimo para cultivar con el objetivo de controlar malezas en residuos de centeno cortados y aplastados con rodillo (rolled-crimped) que formaron un acolchado sobre el suelo. Los tratamientos incluyeron tres momentos de cultivo con un cultivador para altos residuos: temprano (3 – 4 semanas después de la siembra de la soja (WAP)), intermedio (5 – 6 WAP), y tarde (7 – 8 WAP), un testigo libre de malezas y un testigo sin cultivo. Las mediciones del cultivo y de malezas incluyeron biomasa del centeno, biomasa de malezas, y biomasa, población y rendimiento de la soja. La biomasa del centeno fue 50% menor y la biomasa de las malezas tres veces mayor en 2011 que en 2010 y 2012 debido a que el 2011 fue un año seco. No hubo un efecto significativo del momento del cultivo sobre la población de la soja cuando se comparó con los tratamientos sin cultivo y con deshierba manual. Mientras que el cultivar redujo la biomasa de las malezas en 67% al compararse con el tratamiento sin cultivo, el rendimiento de la soja fue solamente mejorado en 12% en los tratamientos con cultivo temprano y tarde y 22% con el tratamiento con cultivo intermedio, cuando se compararon con el tratamiento sin cultivo. Estrategias efectivas para la mejora del manejo de malezas que integren el uso de un cultivador para altos residuos y sistemas orgánicos con cero labranza podrían ayudar a productores orgánicos de cultivos extensivos existentes a reducir la labranza mientras que también se

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*First, second, third, and fourth authors: Associate Research Scientist, former Farming System Trial Leader, former Research Manager, and Executive Director, Rodale Institute, Kutztown, PA 18031; Fifth and sixth authors: Visiting Scientist and Ecologist, United States Department of Agriculture - Agricultural Research Service, Beltsville Agricultural Research Center, Baltimore, Maryland 20705; Current address of second author: Berks County Conservation District, Leesport, PA 19533; Current address of third author: Blue Apron, New York, NY 10031. Corresponding author's E-mail: Steven.Mirsky@ars.usda.gov

promueve la adopción de producción orgánica de cultivos por parte de productores convencionales quienes prefieren sistemas de labranza reducida. A diferencia de cuando se usan equipos tradicionales de labranza para sistemas orgánicos, en sistemas de cero labranza para la producción de soja que incorporan cultivos de cobertura, el momento óptimo del cultivo debería ser retrasado varias semanas en comparación con el sistema típico basado en labranza, para asegurar tanto el control del malezas como el rendimiento óptimo.

Mechanical cultivation is commonly used to control weeds in organic soybean production. In fields with large weed seedbanks, farmers cultivate frequently and intensively during the first 30 d after soybean planting (the critical weed-free period) (Gunsolus 1990; Halford et al. 2001) to improve weed control and grain yield. However, frequent cultivation degrades soil quality, resulting in reduced soil organic matter and soil aggregate stability (Stenberg et al. 2000), greater soil erosion (Holland 2004), and increased fuel and labor costs (Bernstein et al. 2011; Mirsky et al. 2012).

No-till production has gained popularity among organic farmers because of potential reduction in energy use and labor (Lal et al. 2007) and soil quality benefits such as increased soil organic matter levels, improved soil structure, and decreased soil erosion (Carter 2002; Hobbs 2007). No-till crop production has increased about 2.5-fold, from 45 million ha worldwide in 1999 to 111 million ha in 2009 (Derpsch et al. 2010). The increased interest of organic farmers in reduced tillage has created a need for innovative, strategic weed management that does not rely on herbicides (Sooby et al. 2007). These tactics could include diverse crop rotations, cover crops, and high-residue cultivation (HRC).

Cover crops are a major component of weed management in organic agriculture. Cover crops comprise a broad range of plant species and provide numerous ecosystem services that improve cash crop performance (Kasper and Singer 2011; Snapp et al. 2005). Cover crops protect surface- and groundwater quality by decreasing soil erosion, nitrogen (N) leaching, and phosphorus (P) runoff (Adeli et al. 2011; Qi and Helmers 2009), in addition to improving weed suppression (Liebman and Davis 2000) and providing habitat for beneficial insects (Tillman et al. 2004). The use of cover crops to improve N retention through scavenging (Kaspar et al. 2007) and biological N fixation (Reicosky and Forcella 1998) can lower fertilizer costs (Dabney et al. 2010).

Interest in organic rotational no-till farming has increased substantially with the widespread availability of relatively inexpensive roller-crimpers that efficiently terminate cover crops, creating a weed-suppressive mulch (Davis 2010; Mirsky et al. 2009; Mischler et al. 2010). In organic rotational no-till cropping systems, cash crops are no-till planted into winter annual cover crops that were established with tillage the preceding fall (Mirsky et al. 2009; Mischler et al. 2010).

The flexible establishment date, residue persistence (Mirsky et al. 2011; Ruffo and Bollero 2003), winter hardiness, large biomass production (Clark 2007), and provision of a wide range of ecosystem services has made cereal rye the primary cover crop used in organic soybean production (Bernstein et al. 2011; Davis 2010; Delate et al. 2012; Moore et al. 1994). When managed properly, the physical and chemical attributes of cereal rye cover crop mulch can combine to provide substantial weed management (Barnes and Putnam 1983; Teasdale and Mohler 1993). The physical effects of cereal rye residue include limiting light and reducing surface soil temperatures, which influence weed seed germination and emergence (Mohler and Teasdale 1993). Research has shown that cereal rye aboveground dry matter above 9,000 kg ha^{-1}, creating a mulch at least 10 cm deep, will effectively suppress annual weeds (Teasdale and Mohler 2000; Smith et al. 2011). Annual weed species with relatively small seed sizes are more sensitive to suppression by surface residue than are larger-seeded species, which have greater energy and nutrient reserves (Mohler and Teasdale 1993; Teasdale and Mohler 2000). While cereal rye residue releases allelochemicals that accumulate in the rhizosphere and further inhibit weed germination and growth, such active phytotoxic compounds may not be present in the soil more than two weeks after cereal rye termination (Rice et al. 2012). Physical, rather than allelopathic, influences have been shown to be the primary mechanism by which cereal rye inhibits weed germination and growth processes of annual broadleaf weeds (Teasdale et al. 2012), providing early season weed control that diminishes through the season as the residue decomposes. A cereal rye mulch is likely to be most effective as a weed control tactic in reduced-till systems, since these systems minimize residue disturbance and thus decomposition. Unfortunately, perennial weeds are a particular challenge to control in reduced-till systems (Mirsky et al. 2013) because they are often unaffected by surface mulches (Mirsky et al. 2011).

Efficacy of weed suppression by surface mulch is affected by initial weed seedbank densities. At low seedbank densities (<200 seeds m^{-2}), the cereal rye mulch alone can be sufficient (Nord et al. 2011). At higher weed seedbank densities, greater cover crop biomass is required to help suppress weeds, and cover crop residue alone may not achieve effective weed control. Cereal rye biomass production varies from year to year, as it is affected by soil fertility, weather conditions, and management decisions such as planting date. When the weed seedbank is large, cereal rye mulch should be viewed as one component of a multi-tactic approach. Supplemental weed control using technology such as HRC is necessary, particularly at lower mulch levels (e.g., <9,000 kg ha^{-1}). A high-residue cultivator has a series of horizontal sweeps attached to vertical shanks. The sweeps travel approximately 2 to 5 cm underneath the soil surface between crop rows and sever weed shoots from their roots with minimal disturbance to the cover crop residue (Nord et al. 2011). Unlike traditional cultivation techniques, HRC more effectively terminates large weeds rather than small weeds (Keene and Curran 2016). The timing of HRC prior to onset of competition is critical to prevent depressed cash crop yield. The goal of this study was to identify the optimal timing of HRC to maximize both weed control and grain yield.

Materials and Methods

Study Site and Experimental Design. The field experiments were conducted from 2009 to 2012 at Rodale Institute Research Farm in Berks County, southeastern Pennsylvania (40°37'97''N, 75°56'98''W), on a moderately well-drained Berks shaley silt loam (loamy-skeletal mixed active mesic Typic Dystrochrept). The research farm is certified organic and has a history of weed problems. Mean annual growing degree accumulation is 1554 (base 10 C) and mean annual rainfall is 1150 mm. Daily weather data from September through December were collected from a weather station at the Rodale Institute. Distribution of precipitation (mm) and minimum and maximum air temperatures (C) from 2009 to 2012 are presented in Figure 1. The 30-yr climate averages (1981 to 2010) were accessed from the US National Oceanic and Atmospheric Administration climate data website. Individual plots measured 6 m by 30 m and were arranged in a randomized complete block design with four replications. The five treatments consisted of hand-weeded (weed-free), no-cultivation (standard practice), early at HRC at 3 to 4 wk after planting (WAP) (soybean growth stage V2 to V3), intermediate HRC at 5 to 6 WAP (soybean growth stage V4 to V5), and late HRC at 7 to 8 WAP (soybean growth stage V6 to V7). The cultivator used in this study was a four-row Hiniker high-residue cultivator (model 6000, Mankato, MN) equipped with 53 cm wide sweeps, and was operated at 8 km h^{-1}. HRC was done with two passes for minimal disturbance of surface residue (Nord et al. 2011).

Different fields were used each year. The field in 2009 was previously cropped with cereal rye, whereas the fields in 2010 and 2011 had been cropped with oats (*Avena sativa* L.). All fields were fertilized with manure compost at 22,500 kg ha^{-1} in late summer (August 10, 2009, August 2, 2010, and August 1, 2011). The fields were moldboard-plowed using an International 145 three bottom plow (Case International, Racine, WI), disked using a John Deere 210 disk (John Deere, Moline, IL) and an Unverferth soil leveler (Unverferth, Kalida, OH) and packed with a Brillion ML 1483 pulvi-mulcher (Brillion Farm Equipment, Brillion, WI) prior to cover crop seeding. Cereal rye 'Aroostook' was drilled with a John Deere 450 grain drill (John Deere, Moline, IL) in 19-cm rows at 188 kg ha^{-1} on October 6, 2009, October 22, 2010, and October 6, 2011. On May 20, 2010, May 25, 2011, and May 31, 2012, the cover crop was rolled and crimped at 50% anthesis using a front-mounted 3 m wide roller-crimper (I&J Manufacturing LLC, Gap, PA) with a chevron pattern. The soybean cultivar 'Blue River 2A 71' (Blue River Hybrids, Ames, IA) was no-till planted at 543,000 seeds ha^{-1} into cereal rye residue in 76-cm rows on the same day the cover crop was rolled. The soybean was planted with a Monosem® NG Plus 4-row no-till planter (Monosem Inc., Edwardsville, KS) in the same direction as the rye was rolled.

Data Collection and Analysis. One 0.5-m^2 quadrat of rolled cereal rye cover crop biomass per treatment per replicate was collected after rolling on May 20, 2010, May 25, 2011, and May 31, 2012, oven dried at 65 C, and weighed. Subsamples were ground and analyzed for total carbon (C) and N. Weed biomass was collected in one 0.5-m^2 quadrat

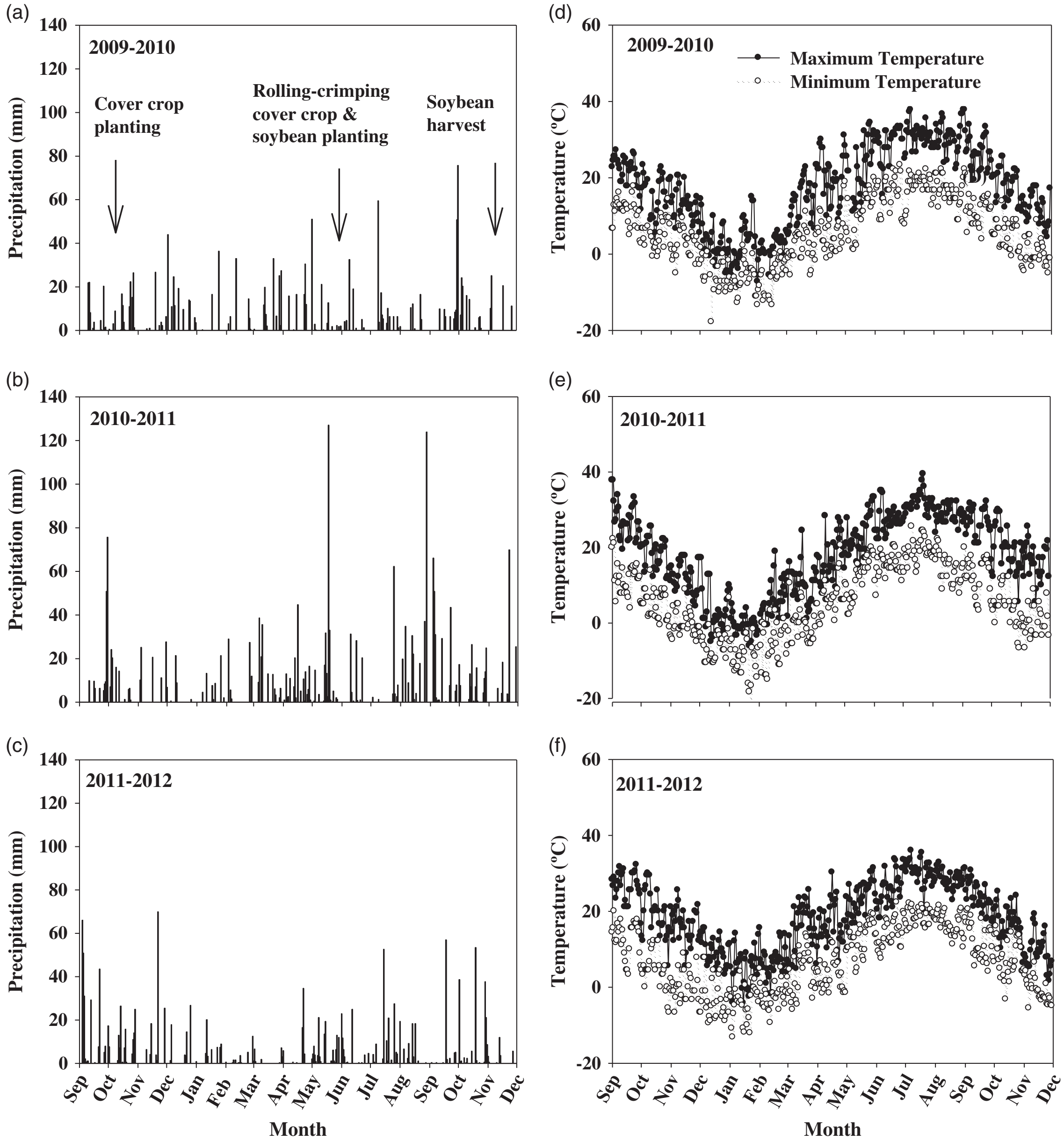

Figure 1. (a–c) Distribution of precipitation in millimeters and (d–f) maximum and minimum temperatures in degrees Celsius during the growing period of cereal rye and soybean in 2009/2010, 2010/2011, and 2011/2012 at Rodale Institute, Kutztown, PA.

per plot in late summer (September 9, 2010, August 24, 2011, and September 13, 2012) and handled as previously described for cover crop biomass. Soybean crop biomass and population were collected at the same time as weed biomass. Soybean plants from a 0.5-m^2 quadrat per plot were counted and cut at soil level and handled as previously described for weed biomass. Soybean grain yield was determined on November 8, 2010, November 9, 2011, and October 18, 2012 by mechanically harvesting the three center rows in each plot; yield was adjusted to 13% moisture.

Data were subjected to analysis of variance and analyzed using the PROC MIXED procedure in SAS® version 9.3 (SAS Institute Inc., Cary, NC, 2004). Mean comparisons were performed using the Tukey-Kramer method ($P < 0.05$) to test the effects of year and cultivation timing on cereal rye biomass, C and N, weed biomass, and soybean stand and yield. Weed biomass data were log (x + 1) transformed

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before analysis to better meet the assumption of homogeneity of variance across treatments.

Results and Discussion

Cereal Rye Cover Crop Biomass and C:N Ratio. Cereal rye cover crop biomass varied across years and was lower ($P < 0.0001$) by about 50% in 2011 than it was in either 2010 or 2012 (Figure 2). Biomass production in 2011 was less than the mean biomass (10,800 kg ha^{-1}) typically achieved at Rodale Institute (Mirsky et al. 2012). The precipitation that fell between October and December 2010 amounted to 230 mm and was well below the 30-yr average precipitation (279 mm) (US Climate Data 2016) for that period, which might have resulted in plant water stress. Despite the large amount of rain (697 mm) received between January and May 2011 (Figure 1b), cereal rye never achieved the typical mean biomass. This suggests that precipitation above 230 mm in the fall is required to ensure cereal rye establishment and accumulation of biomass before overwintering. Cereal rye received a total of 322 and 347 mm of precipitation between October and December of 2009 and 2011, respectively (Figure 1a, c), and produced concomitantly more biomass (Figure 2a) than the cereal rye in 2010, which received only a total of 230 mm of precipitation.

While air temperatures (>5 C) (Figure 1d–f) were conducive to cereal rye growth during the fall and spring seasons (Leonard and Martin 1963) in our study, it appears that rainfall, rather than temperature, influenced cereal rye cover crop biomass accumulation. The two-week-later planting date of cereal rye in fall 2010 may have been a factor for lower cover crop biomass in 2011. Prior to planting the cover crop, the sites were fertilized by manure compost and thus nitrogen nutrient deficiency is not a factor for lower biomass.

Cereal rye C:N ratios ranged between 50:1 and 67:1, and were not significantly different across years (Figure 2b). In this study the C:N ratio of cereal rye biomass was lower than the 83:1 ratio reported by Poffenbarger et al. (2015) when cereal rye was planted as a monoculture cover crop. This difference could be attributed to the early termination of cereal rye, which occurred at anthesis (Mirsky et al. 2009) in our study rather than at the soft dough stage.

Weed Biomass. There was no significant year by management interaction in weed biomass at soybean maturity. The hand-weeded treatment was omitted when weed biomass data were analyzed. Weed biomass varied across years and was greater ($P < 0.0001$) by 82% and 62% in 2011 than it was in either 2010 or 2012, respectively (Figure 3a). The low cover crop biomass production in 2011 (Figure 2a) with a mulch thickness of 7.4 cm may have provided minimal physical or chemical interference with weed emergence and growth (Barnes and Putnam 1987; Macias et al. 2005; Reberg-Horton et al. 2005; Teasdale and Mohler 1993). For effective suppression of annual weeds, a minimum of 9,000 kg ha^{-1} of cereal rye aboveground dry biomass is needed to create a mulch at least 10 cm deep (Smith et al. 2011; Teasdale and Mohler 2000). Two out of three years, optimal levels of cereal rye aboveground dry

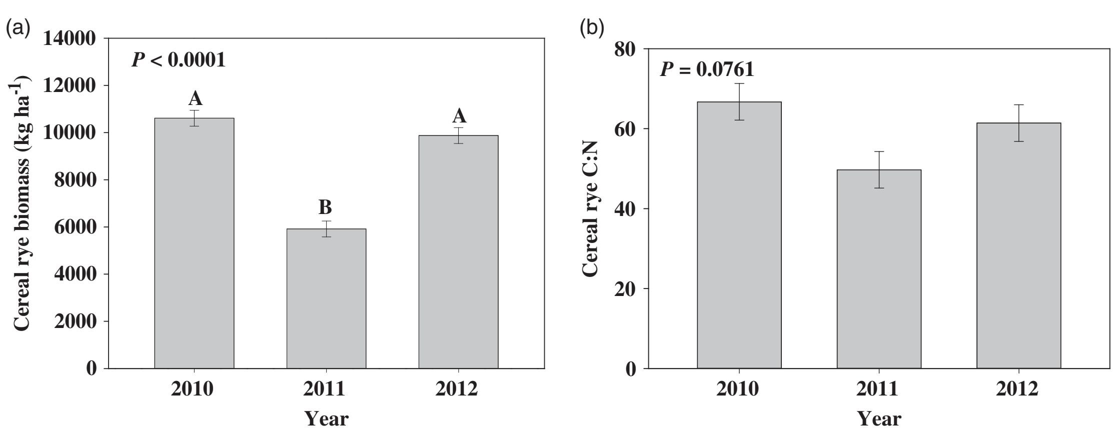

Figure 2. (a) Mean (± SE) cereal rye aboveground dry biomass and (b) cereal rye C:N ratio at rolling-crimping on May 20, 2010, May 25, 2011, and May 22, 2012 at Rodale Institute, Kutztown, PA, as affected by year. Different letters indicate significant differences across years. Means were separated using Tukey's significant difference ($P < 0.05$).

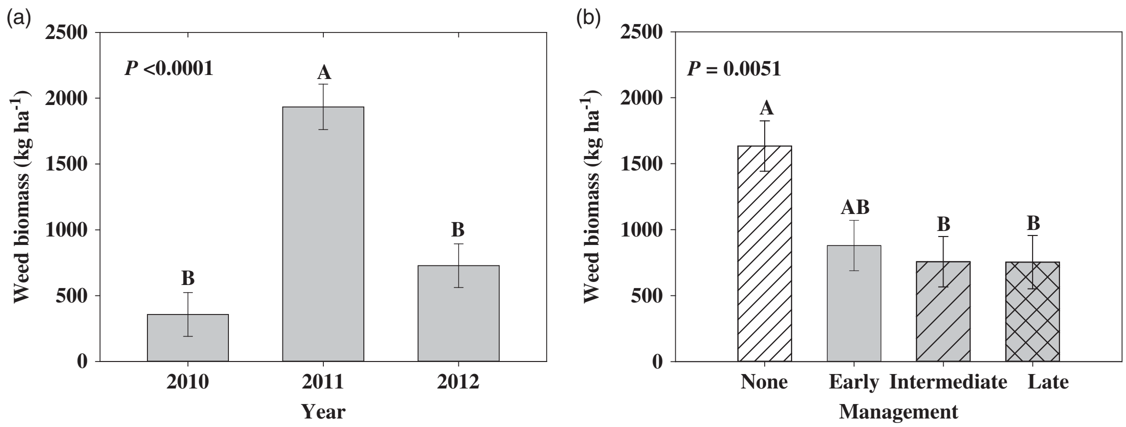

Figure 3. (a) Mean (± SE) weed aboveground dry biomass (kg ha^{-1}) at soybean maturity in 2010, 2011, and 2012, and (b) weed biomass as affected by management treatment (with data from the three years combined) at Rodale Institute, Kutztown, PA. Early: cultivation 3 to 4 weeks after soybean planting; Intermediate: cultivation 5 to 6 weeks after soybean planting; and Late: cultivation 7 to 8 weeks after soybean planting. Different letters indicate significant differences across years (a) and between management treatments (b). Means were separated using Tukey's significant difference ($P < 0.05$).

biomass (Figure 2a), with mulch of 8.7 to 9.5 cm deep, kept weed biomass below 730 kg ha^{-1} (Figure 3a). Furthermore, the soybean row spacing of 76 cm might have compounded the effect by providing additional space for early-season weed growth due to later soybean canopy closure (Harder et al. 2007). In addition, dry soil due to a combination of drought conditions during the first seven WAP (from June 1 to July 24, 2011) (Figure 1b) and relatively high air temperatures in the first 24 days of July 2011 (Figure 1e), may have prevented the horizontal sweeps of the high-residue cultivator from penetrating the soil surface to properly sever weeds and reduce weed biomass.

Across treatments, the no-cultivation treatment, which is the standard weed management regime in no-till organic soybean, had the most weed aboveground dry biomass, about 1,634 kg ha^{-1} ($P = 0.0051$) (Figure 3b). On average, all treatments decreased weed biomass by 67% when compared to the no-cultivation control. Giant foxtail (*Setaria faberi* Herm.) and common ragweed (*Ambrosia artemisiifolia* L.) were the major weed species and constituted 95% of the total weed community. To our knowledge, there are no published records of the critical weed-free period for organic no-till soybean. However, in no-till conventional soybean cropping systems, it is recommended that soybean plots be kept free of weeds between V1 (first trifoliate or node, 11 to 22 d after soybean planting) and R1 (flowering stage, 48 to 69 d after soybean planting) to avoid substantial yield loss (Halford et al. 2001). The intermediate cultivation treatment in our study met the requirements of this recommendation. It is important to note that the above recommendations were made based on no-till herbicide trials and not under cover crop-based no-till conditions. Thus, the critical weed-free period for soybean in organic no-till conditions may shift from V1 and become critical between V2 or V3 and R1, when the soil is covered with dense, rolled cover crop mulch.

Soybean Plant Population. There were no significant effects of management treatment or year by management treatment interaction on soybean plant stand density at maturity. However, soybean stand density was larger ($P = 0.008$) in 2011 compared with that in 2010 and 2012, at 456,000 plant ha^{-1} vs. 334,000 and 316,000 plants ha^{-1}, respectively (Figure 4). The greater soybean plant stand density may have been the result of a combination of plentiful rainfall (214 mm) in May 2011 (Figure 1b) prior to cover crop rolling-crimping, which resulted in sufficient moisture for germination, and the moderate cereal rye biomass production of 5,916 kg ha^{-1}, which allowed for greater seed-to-soil contact after no-till drilling.

Soybean Crop Biomass. There was no significant year by management treatment interaction effect on soybean crop biomass at maturity. Across years, however, there was 29% greater ($P = 0.051$)

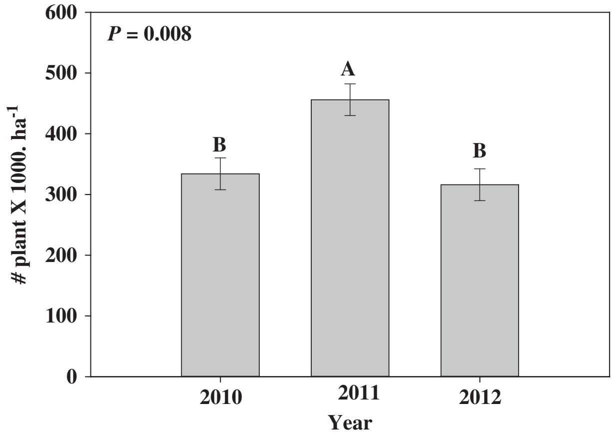

Figure 4. Mean (± SE) soybean plant population per hectare (×1000) at Rodale Institute, Kutztown, PA, counted at soybean plant maturity in Augusts of 2010, 2011, and 2012. Different letters indicate significant differences between years. Means were separated using Tukey's significant difference (P < 0.05).

soybean biomass on average in 2012 than there was in either 2010 or 2011 (Figure 5a). The moderate maximum air temperatures (Figure 1f) combined with steady rainfall amounts totaling 180 mm during the first two months after soybean planting (Figure 1c) may have resulted in greater soybean biomass in 2012. Despite the larger plant stand in 2011, there was a reduction in soybean crop biomass (Figure 5a) as a result of weed competition (Figure 3a) and scant rainfall amounts (94 mm) between June 1 and July 24, 2011 (Figure 1b) that were compounded by higher maximum air temperatures (Figure 1e). It has been reported that drought stress between initial flowering (R1) and seed filling (R5 to R7) decrease vegetative growth, seed number, and yield (Frederick et al. 2001).

HRC did not affect soybean crop biomass and resulted in a similar soybean crop biomass as did the no-cultivation treatment (Figure 5b). However, soybean biomass was 26% (P = 0.0368) lower in the late cultivation treatment compared to that in the hand-weeded treatment (Figure 5b), which suggests that earlier cultivation (early and intermediate) would improve soybean biomass more than cultivating later in the season would. This finding underscores how crucial it is to determine the optimum timing for HRC, balancing the need to cultivate weeds when they are large enough to be efficiently terminated by HRC with the need to not negatively impact soybean yield through competition or by inadvertent damage to the crop.

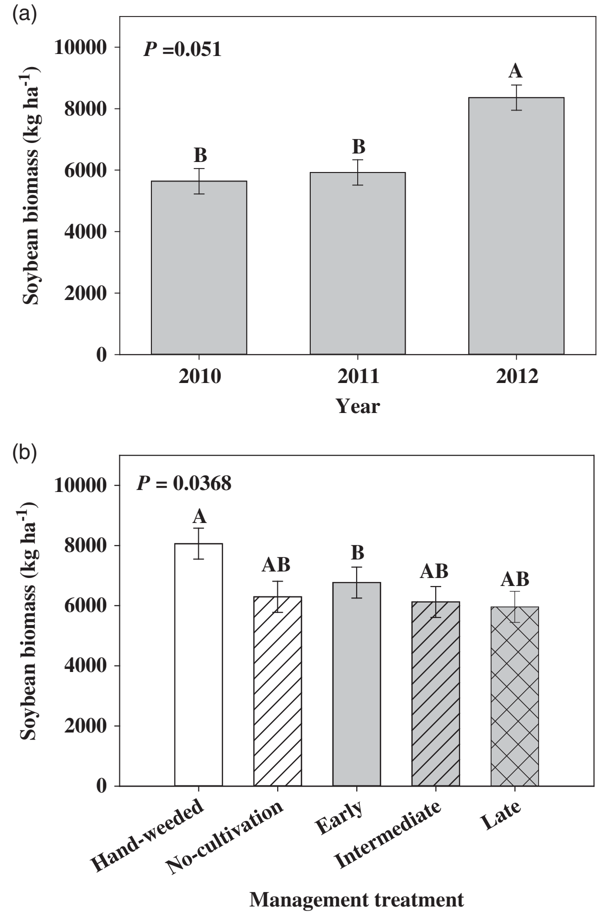

Figure 5. (a) Mean (± SE) soybean aboveground dry biomass (kg ha^{-1}) at maturity in 2010, 2011, and 2012 and (b) the effect of management treatment on soybean aboveground dry biomass at maturity (with data from the three years combined) at Rodale Institute, Kutztown, Pennsylvania. Early: cultivation 3 to 4 weeks after soybean planting; Intermediate: cultivation 5 to 6 weeks after soybean planting; and Late: cultivation 7 to 8 weeks after soybean planting. Different letters indicate significant differences between years (a) and management treatment (b). Means were separated using Tukey's significant difference (P < 0.05).

Grain Yield. There was no significant year by management treatment interaction. Soybean grain yield varied (P < 0.0001) over the three-year project and was 2.4 times greater in 2012 than it was in 2011, and was 1.5 times greater in 2012 than it was in 2010 (Figure 6a). The greater grain yield in 2012 was in accordance with the findings of Ruffo et al. (2004), and fell within the mean soybean yield of 2,800 kg ha^{-1} found in that study. Temperature and precipitation in fall 2011 and 2012 (Figure 1c,f) were favorable for the production of larger cover crop biomass and subsequent thicker mulches (Figure 2a),

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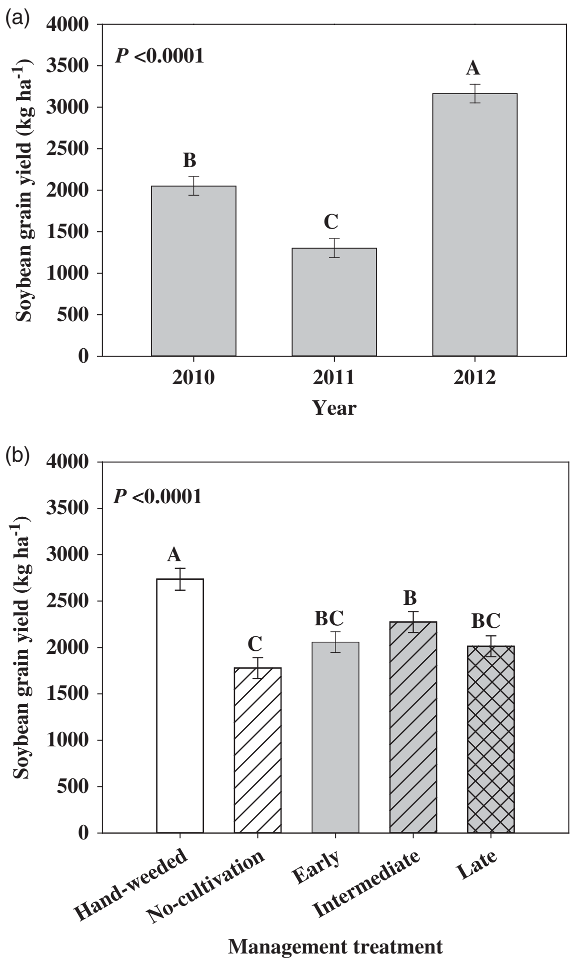

Figure 6. (a) Mean (± SE) soybean grain yield (kg ha^{-1}) in 2010, 2011, and 2012, and (b) the effect of management treatment on soybean grain yield (with data from the three years combined by treatment) at Rodale Institute, Kutztown, Pennsylvania. Early: cultivation 3 to 4 weeks after soybean planting; Intermediate: cultivation 5 to 6 weeks after soybean planting; and Late: cultivation 7 to 8 weeks after soybean planting. Different letters indicate significant differences between years (a) and between management treatments (b). Means were separated using Tukey's significant difference ($P < 0.05$).

greater soybean growth (Figure 5a), and improved weed control (Figure 3a) (Williams et al. 2000). All these factors contributed to enhanced soybean biomass and grain yield. Conversely, the drought during cereal rye growth in fall 2010 and summer 2011, combined with high temperatures, resulted in less cover crop mulch (Figure 2a), larger amounts of weed biomass (Figure 3a), less soybean growth and biomass, and smaller grain yield (Figure 6a). It has been reported that water stress before or during flowering increased the rate of soybean flower and pod abortion (Westgate and Peterson 1993), and the most critical time for water stress is thought to be from late flowering to early seed development (Calvino et al. 2003). Thus, in this project, the drought stress during the first two months after soybean planting might have negatively impacted soybean plant growth, node formation, flowering, and pod formation, and consequently, grain yield. In our study, water stress likely occurred during June and July 2011 (Figure 1b), was the most severe as soybean plants reached the R1 growth stage (initial flowering occurred on July 7), and continued through late July 2011.

Soybean grain yield was highest ($P < 0.0001$) in the hand-weeded treatment, moderate in the intermediate (5 to 6 WAP) HRC treatment, and lowest in the no-cultivation treatment (Figure 6b). Soybean yield was 35% lower in the no-cultivation treatment than it was in the hand-weeded treatment. This corroborated the findings of Delate et al. (2012), who observed a 32% reduction in soybean grain yield over two years in a no-till system. Irrespective of the timing of integration of HRC into a cover crop-based rotational no-till system, the use of HRC improved soybean yield on average by 18% when compared to the no-cultivation treatment. While early and late cultivation slightly increased soybean yield, on average by 12%, a larger increase of 22% was observed in the intermediate HRC treatment when compared to the no-cultivation treatment.

Cover crop–based organic rotational no-till soybean production systems balance the trade-offs between soil conservation and weed management (Mirsky et al. 2013). Currently, there are organic feed grain shortages in the United States (Oberholtzer et al., 2012), resulting in the importation of large amounts of organic grain. Effective strategies for improving weed management by integrating HRC in cover crop–based no-till organic systems could encourage more farmers to adopt these methods, increasing domestic organic grain production.

Cereal rye biomass exceeded the recommended level for weed suppression in two out of three years in our study, suppressing weed emergence and growth. Precipitation was the primary factor affecting cover crop biomass and soybean growth and yield in our study. Cover crop mulch alone (no-cultivation) did not provide effective season-long weed control. The decrease in soybean grain yield of 35% in the no-cultivation treatment compared to the hand-weeded treatment suggests that a combination of different weed management strategies, which include cereal rye mulch followed by HRC, should be integrated to manage weeds and allow for profitable crop production (Chauhan et al. 2012).

In our study, while there were no differences in weed control between cultivation treatments, early HRC was less effective at severing small weeds, as they can re-root with timely rainfall. However, there was a grain yield increase of 22% in the intermediate HRC treatment at 5 to 6 WAP compared to no-cultivation. The use of a two-pass soybean cultivation system was a key because the first pass made a cut in the soil, while the second pass crumbled the soil and severed the weeds. It is critical to time HRC to target larger weeds without waiting so long that grain yield is negatively impacted. Keene and Curran (2016) reported that two HRC passes provided better weed control than one-pass treatments in soybean. In our study, delaying HRC to 5 to 6 WAP resulted in optimal weed control and economical grain yield. Future work will focus on determining the critical weed-free period in rolled cereal rye to further fine-tune timing of cultivation in cover crop–based no-till organic soybean production.

Acknowledgements

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Literature Cited

Adeli A, Tewolde H, Jenkins JN, Rowe DE (2011) Cover crop use for managing broiler litter applied in the fall. Agron J 103: 200–210

Barnes JP, Putnam AR (1983) Rye residues contribute weed suppression in no-tillage cropping systems. J Chem Ecol 9:1045–1057

Bernstein ER, Posner JL, Stoltenberg DE, Hedtcke JL (2011) Organically-managed no-tillage rye-soybean systems: agronomic, economic, and environmental assessment. Agron J 103: 1169–1179

Calvino PA, Sadras VO, Andrade FH (2003) Development, growth and yield of late-sown soybean in the southern Pampas. Eur J Agron 19:265–275

Carter MR (2002) Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron J 94:38–47

Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture. Crop Prot 38:57–65

Clark A (2007) Managing cover crop profitably. 3rd edn. Beltsville, MD: Sustainable Agriculture Network

Dabney SM, Delgado JA, Meisinger JJ, Schomberg HH, Liebig MA, Kaspar T, Mitchell J, Reeves W (2010) Using cover crops and cropping systems for nitrogen management. Pages 231–282 *in* Delgado JA & Follett RF, eds. Advances in Nitrogen Management for Water Quality. Ankeny, IA: Soil and Water Conservation Society

Davis A (2010) Cover crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300–309

Delate K, Cwach D, Chase C (2012) Organic no-till system effects on organic soybean, corn, and tomato production and economic performance in Iowa. Renew Agric. Food Syst. 27(Spec. Issue 01):49–59

Derpsch R, Friedrich T, Kassam A, Li H (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3:1–25

Frederick JR, Camp CR, Bauer PJ (2001) Drought-stress effects on branch and mainstem seed yield and yield components of determinate soybean. Crop Sci 41:759–763

Gunsolus JL (1990) Mechanical and cultural weed control in corn and soybeans. Am J Altern Agric 5:114–119

Halford C, Hamill AS, Zhang J, Doucet C (2001) Critical period of weed control in no-till soybean and corn. Weed Technol 15:737–744

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield and economic return. Weed Technol 21:744–752

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production. J Agric Sci 145:127–137

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103:1–25

Kaspar TC, Jaynes DB, Parkin TB, Moorman TB (2007) Rye cover crop and gramagrass strip effects on NO_3 concentration and load in tile drainage. J Environ Qual 36:1503–1511

Keen CL, Curran WS (2016) Optimizing high-residue cultivation timing and frequency in reduced-tillage soybean and corn. Agron J 108:1897–1906

Lal R, Reicosky DC, Hanson JD (2007) Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res 93:1–12

Leonard WH, Martin JH (1963) Cereal Crops. New York: The Macmillan Co. 478 p

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

Macias FA, Marin D, Oliveros-Bastidas A, Castellano D, Simonet AM, Molinillo JMG (2005) Structure-activity relationship (SAR) studies of benzoxazinones, their degradation products, and analogues. Phytotoxicity on standard target species (STS). J Agric Food Chem 53:538–548

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2009) Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J 101:1589–1596

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

Mirsky SB, Ryan MR, Curran WS, Teasdale JR, Maul J, Spargo JT, Moyer J, Grantham AM, Weber D, Way TR, Camargo GG (2012) Conservation tillage issues: cover crop-based organic rotational production in the mid-Atlantic region, USA. Renew Agric Food Syst 27:31–40
Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern US. Weed Technol 27:193–203
Mischler RA, Curran WS, Duiker SW, Hyde JA (2010) Use of a rolled-rye cover crop for weed suppression in no-till soybeans. Weed Technol 24:253–261
Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res 33:487–499
Moore MJ, Gillespie TJ, Swanton CJ (1994) Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol 8: 512–518
Nord EA, Curran WS, Mortensen DA, Mirsky SB, Jones BP (2011) Integrating multiple tactics for managing weeds in high residue no-till soybean. Agron J 103:1542–1551
Oberholtzer L, Dimitri C, Jaenicke EC (2012) International trade of organic food: evidence of US imports. Renew Agric Food Syst 28:255–262
Poffenbarger HJ, Mirsky SB, Weil RR, Maul JE, Kramer M, Spargo JT, Cavigelli MA (2015) Biomass and nitrogen content of hairy vetch–cereal rye cover crop mixtures as influenced by species proportions. Agron J 107:2069–2082
Qi Z, Helmers MJ (2009) Soil water dynamics under winter rye cover crop in central Iowa. Vadose Zone J 9:53–60
Reberg-Horton SC, Burton JD, Danehower DA, Ma G, Monks DW, Murphy JP, Ranells NN, Williamson JD, Creamer NG (2005) Changes over time in the allelochemical content of ten cultivars of rye. J Chem Ecol 31:179–193
Reicosky DC, Forcella F (1998) Cover crop and soil quality interactions in agroecosystems. J Soil Water Conserv 53: 224–229
Rice CP, Cai G, Teasdale JR (2012) Fate of benzoxazinoids in soil treated with rye cover crop. J Agric Food Chem 60:4471–4479
Ruffo ML, Bollero GA (2003) Modeling rye and hairy vetch residue decomposition as a function of degree days and decomposition days. Agron J 95:900–997
Ruffo ML, Bullock DG, Bollero GA (2004) Soybean yield as affected by biomass and nitrogen uptake of cereal rye in winter cover crop rotations. Agron J 96:800–805
Smith AN, Reberg-Horton SC, Place GT, Meijer AD, Arellano C, Mueller JP (2011) Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci 59:224–231
Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97:322–332
Sooby J, Landeck J, Lipson M (2007) National Organic Research Agenda: Outcomes from the Scientific Congress on Organic Agricultural Research. Santa Cruz, CA: Organic Farming Res. Foundation. 76 p
Stenberg M, Stenberg B, Rydberg T (2000) Effects of reduced tillage and liming on microbial activity and soil properties in a weakly-structured soil. App Soil Ecol 14:135–145
Teasdale JR, Mirsky SB, Spargo JT, Cavigelli MA, Maul JE (2012) Reduced-tillage organic corn production in a hairy vetch cover crop. Agron J 104:621–628
Teasdale JR, Mohler CL (1993) Light transmittance, soil–temperature, and soil–moisture under residue of hairy vetch and rye. Agron J 85:673–680
Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385–392
Tillman G, Schomberg H, Phatak S, Mullinix B, Lachnicht S, Timper P, Olson D (2004) Influence of cover crops on insect pests and predators in conservation tillage cotton. J Econ Entomol 97:1217–1232
US Climate Data (2016) The US NOAA Climate Data, version 2.2. http://www.usclimatedata.com/climate/allentown/pennsylvania/united-states/uspa0025/2015/1. Accessed January 30, 2016
Westgate ME, Peterson CM (1993) Flower and pod development in water deficient soybeans (*Glycine max* (L.) Merr.). J Exp Bot 44:109–117
Williams MM 2nd, Mortensen DA, Doran JW (2000) No-tillage soybean performance in cover crops for weed management in the western corn belt. J Soil Water Conserv 55:79–84

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