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Cover Crop Impact on Weed Dynamics in an Organic Dry Bean System

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Weed suppression is one possible benefit of including cover crops in crop rotations. The late spring planting date of dry beans allows for more growth of cover crops in the spring. We assessed the influence of cover crops on weed dynamics in organic dry beans and weed seed persistence. Medium red clover, oilseed radish, and cereal rye were planted the year before dry beans; a no-cover-crop control was also included. After cover-crop incorporation, common lambsquarters, giant foxtail, and velvetleaf seeds were buried in the red clover, cereal rye, and no-cover control treatments and then retrieved 0, 1, 2, 4, 6, and 12 mo after cover-crop incorporation. Dry beans were planted in June and weed emergence and biomass measured. Eleven or more site-years of data were collected for each cover-crop treatment between 2011 and 2013, allowing for structural equation modeling (SEM), in addition to traditional analyses. Cereal rye residue increased giant foxtail and velvetleaf seed persistence by up to 12%; red clover decreased common lambsquarters seed persistence by 22% in 1 of 2 yr relative to the no-cover-crop control. Oilseed radish and incorporated cereal rye rarely reduced weed densities. When red clover biomass exceeded 5 Mg ha^{-1}, soil inorganic N was often higher (5 of 6 site-years), as were weed density and biomass (5 and 4 of 12 main site sample times, respectively). Using SEM, we identified one causal relationship between cover-crop N content and weed biomass at the first flower stage (R1), as mediated through soil N at the time of dry bean planting and at the stage with two fully expanded trifoliates. Increasing cover-crop C : N ratios directly reduced weed biomass at R1, not mediated through changes in soil N. Cover crops that make a significant contribution to soil N may also stimulate weed emergence and growth.

Nomenclature: Dry bean, *Phaseolus vulgaris* Herrm.; medium red clover, *Trifolium pratense* L.; oilseed radish, *Raphanus sativus* L.; cereal rye, *Secale cereale* L.; common lambsquarters, *Chenopodium album* L.; giant foxtail, *Setaria faberi* L.; velvetleaf, *Abutilon theophrasti* Medik.

Key words: Cover-crop nitrogen dynamics, soil amendments, structural equation modeling (SEM), weed density, weed seed persistence.

Cover crops are planted on approximately 1.8 million ha of grain and oilseed production land in the United States, 2% of total cropland (USDA-NASS 2014). This number is expected to increase as producer interest grows (CTIC and NCR-SARE 2013) and efforts to improve soil quality and mitigate surface water pollution continue. Producers use cover crops to reduce soil compaction and erosion, scavenge N, and provide weed control (CTIC and NCR-SARE 2013). The weed control provided by cover crops is of particular interest to organic producers who cannot use genetically modified crop technologies or synthetic herbicides.

Organic dry beans are produced on over 11,000 ha in the United States, 33% of which are in Michigan (USDA-ERS 2013). Beans are typically planted between early and mid-June in Michigan and harvested in late September or October. The late planting date and short growing season of dry beans increases the time between cover-crop winter kill and planting and expands time for spring growth of overwintering cover crops compared with other warm-season field crops in the state such as corn, soybeans, and sugar beets.

Cover crops have the potential to influence weed competition in dry beans in several ways, including direct competition, allelopathy, and alterations to the soil environment, which can influence weed seed persistence, weed emergence, and growth (Conklin et al. 2002; Creamer et al. 1996; Dyck and Liebman 1994; Fisk et al. 2001; Snapp et al. 2005). Direct competition with weeds occurs from the time of cover-crop emergence through termination and may result in reduced inputs to the weed seed bank, and therefore fewer weeds in the dry bean crop (Gallandt 2006; Ross et al. 2001; Teasdale 1998). Allelochemicals, or compounds that become allelopathic through microbial degradation, have been identified in several cover-crop species, and detailed accounts of the allelopathic impact of cover crops on weeds have been published in the literature (Hill 2006; Kelton et al. 2012).

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Any suppression of weed emergence or growth from allelochemicals is usually short-lived (Kruidhof et al. 2009) and would occur shortly after cover-crop termination. Last, weeds may be affected by cover-crop alterations to the soil environment both during active growth and after termination. These alterations include physical and light barriers to weed emergence due to cover-crop surface residue (Blum et al. 1997; Teasdale 1996, 1998), changes in soil biology both at the soil surface and within the soil matrix (Gallandt 2006; McDaniel et al. 2014; Teasdale 1998), and changes in soil moisture and nutrient availability (Teasdale 1998). Cover crops that increase N availability could stimulate the germination and growth of weedy species and reduce seed persistence (Blackshaw et al. 2003; Shem-Tov et al. 2005; Sweeney et al. 2008). Conversely, cover crops with high C : N ratio inputs have the potential to increase weed seed persistence (Davis 2007; Davis et al. 2005, 2006; Shem-Tov et al. 2005).

Medium red clover and cereal rye are popular cover crops among midwestern producers because the seeds of these two cover crops are readily available and relatively inexpensive. Typically medium red clover is interseeded into or planted after a small grain the year before corn (*Zea mays* L.) is planted. Small grains interseeded with red clover can increase weed seedling recruitment compared with the corn and soybean [*Glycine max* (L.) Merr.] portions of a crop rotation (Heggenstaller and Liebman 2006) and can also increase fall weed seed rain when the establishment of the cereal or clover is slow (Mirsky et al. 2010). However, Davis and Liebman (2003) showed higher predation rates of giant foxtail in wheat (*Triticum aestivum* L.) interseeded with red clover compared with wheat alone both before and after wheat harvest. Red clover reduced the root growth of wild mustard (*Sinapsis arvensis* L.) up to 12 d after clover incorporation (Conklin et al. 2002; Ohno et al. 1999); however, the potential allelopathic properties of this cover crop and other influences on weed dynamics in the following cash crop are not well understood.

Cereal rye is most often planted after corn in fields that will be rotated to soybeans or dry beans the subsequent season. Rye can reduce the growth of weeds in the fall through competition (Kruidhof et al. 2008). Rye also has well-characterized allelochemicals that can reduce weed emergence and growth after termination (Clark 2007; Hill 2006; Putnam 1988; Rice et al. 2012; Teasdale et al. 2012). Conflicting findings have been reported for the impact of rye on weeds during the growth of the subsequent cash crop, with some reporting reduced weed pressure and others reporting no influence (Peachey et al. 2004; Reddy 2001; Reddy et al. 2003).

Oilseed radish is usually planted in late summer after wheat harvest, and has the potential to reduce weed densities in the fall because of rapid growth and light interception (Kruidhof et al. 2008; O'Reilly et al. 2011). Reports of the impact on weed densities the following spring have been mixed, with some reporting suppression (Wang et al. 2008; Weil and Kremen 2007) and others reporting no impact (Kruidhof et al. 2008; O'Reilly et al. 2011). The proposed primary mechanism of weed suppression of oilseed radish is fall competition with winter and summer annual weeds (Lawley et al. 2012; O'Reilly et al. 2011; Wang et al. 2008). Wang et al. (2008) showed reduced total weed seed banks in the spring after fall *Brassica* cover crops compared with a no-cover-crop control. Though extensive work has been done on the biologically inhibitory properties of glucosinolates found in *Brassicaceae* species, limited research has been done on the allelopathic potential of oilseed radish, with only one study showing inhibitory effects on the germination and growth of downy brome (*Bromus techtorum* L.) (Machado 2007) and one study showing no allelopathic activity (Lawley et al. 2012).

All of the previous studies were limited in the number of site-years and therefore none was able to examine how the network of measured variables might influence weed communities. The scope and scale of this study allow us to utilize structural equation modeling (SEM) to address more complex hypotheses. SEM is increasingly being incorporated into the natural sciences to quantify direct and indirect causal relationships among a network of observed and latent variables (Grace et al. 2010; Kane et al. 2015; Lamb et al. 2011; McLeod et al. 2015).

The objectives of our research were to analyze how red clover, cereal rye, and oilseed radish influence weed communities and weed seed persistence in organic dry bean systems. We hypothesized that cover-crop quality would affect soil N availability, which would indirectly affect weed biomass through weed seedling recruitment and growth. For example, cover crops that increase soil N availability would promote weed emergence and growth, particularly for annual weed species highly responsive to N; conversely, cover crops that reduce N may suppress weeds. We also hypothesized that cover-crop N content and C : N ratio would affect weed seed persistence; cover crops with C : N ratios lower than 25 : 1

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would decrease weed seed persistence, and cover crops with higher C : N ratios would increase weed seed persistence. Our null hypotheses were that cover-crop biomass would directly suppress weed density and biomass and have no influence on weed seed persistence.

Materials and Methods

Two types of experimental sites (main and satellite) were utilized to study the effects of cover crops on weeds in organic dry beans. The main sites were located on certified organic or transitional fields at two Michigan State University (MSU) research stations for 3 yr. The MSU campus locations were in Lansing, MI at the Horticultural Teaching and Research Center (42.67°N, 84.48°W; 2011 and 2012) and the Agronomy Farm (42.71°N, 84.47°W; 2013). The other location was at the Kellogg Biological Station (KBS) (42.40°N, 85.38°W) in Hickory Corners, MI. Soil types at these locations were loam or clay loam, with soil organic matter averaging 2.8%. Additional satellite sites were located throughout Michigan on the certified organic farms of cooperating growers in Alma, Caro, Columbiaville, Millington, and Sandusky, MI. Over the 3-yr period 18 total site-years of data were collected among these locations (5 to 7 per cover-crop species). Soil types ranged from sandy loam to clay loam with organic matter averaging 3.1%, excluding two sites in Sandusky, MI where soil organic matter was higher.

At each site, a split-plot design was used with three to four replications. The main plot factor was cover crop and the subplot factor was dry bean variety. At the main sites there were four cover-crop treatments: medium red clover, oilseed radish, cereal rye, and no cover. All cover crops were planted into or after the harvest of a small grain in the calendar year preceding dry bean planting. Medium red clover 'Marathon' was spring seeded (11 kg ha^{-1}) into the small grain usually around March, with the exception of MSU 2011 when red clover was seeded in August of 2010. Following the harvest of the small grain, Groundhog™ oilseed radish (Ampac Seed Company, Tangent, OR) was planted (12 kg ha^{-1}) in mid-August and cereal rye 'Wheeler' was planted (100 to 125 kg ha^{-1}) in mid-September. At the main sites, the subplot factor consisted of four dry bean varieties, two each in two classes. Black bean varieties included 'Zorro' and 'Black Velvet' and navy bean varieties included 'Vista' and a nonnodulating line 'R99' (Park and Buttery 1992). Information regarding the effects of the cover crops on dry bean yield and a more detailed account of soil N availability for each cover crop are published in Hill et al. (2016). Each cover-crop plot at the main sites was 12.2 m wide and a minimum of 15.2 m long. During the dry bean season, four 3-m-wide bean subplots were planted within each main cover-crop plot. Each subplot consisted of four rows of one dry bean variety at 76-cm spacing.

At the satellite sites there were two cover-crop treatments: one of the cover crops (i.e., medium red clover, oilseed radish, or cereal rye) and a no-cover-crop control. Medium red clover (7 site-years) and cereal rye (5 site-years) varieties were chosen on the basis of what the growers were already using on their farms, typically "variety not stated." GroundHog oilseed radish was provided to growers interested in oilseed radish (6 site-years). Cover-crop planting times were more variable at satellite sites than at the main sites (Supplemental Tables 1 and 2; http://dx.doi.org/10.1614/WS-D-15-00114.S1). At the satellite sites the subplot factor consisted of two dry bean varieties, Zorro black beans and Vista navy beans. Plot dimensions at the satellite sites were based on the grower's equipment size, with minimum plot lengths of 30.5 m. Most growers planted rows at a 76-cm spacing; however, three sites were planted at 56-cm spacing. Target bean planting populations ranged from 262,000 to 296,000 seeds ha^{-1} for both main and satellite site locations. No external N sources were added to fields in this study. In general, the red clover and cereal rye cover crops were terminated using one to two passes with a primary tillage tool (e.g., moldboard plow, chisel plow, or disk) followed by a field cultivator (termination dates, Supplemental Tables 1 and 2; http://dx.doi.org/10.1614/WS-D-15-00114.S1). All oilseed radish and no-cover control plots also received primary tillage in the spring. After dry bean planting, weed management was uniform across all treatments at each location (Supplemental Tables 1 and 2 for the main and satellite sites, respectively; http://dx.doi.org/10.1614/WS-D-15-00114.S1). The total number of weed control operations ranged from two to eight in any given site-year (Supplemental Tables 1 and 2; http://dx.doi.org/10.1614/WS-D-15-00114.S1). Precipitation data were collected at the main sites by utilizing MSU's Enviro-weather online database (MSU Enviroweather 2014) (Supplemental Table 3; http://dx.doi.org/10.1614/WS-D-15-00114.S1).

Cover-Crop Quantity and Quality. Cover-crop measurements included percent cover, dry biomass, C and N content, and C : N ratio of the plant tissue. Parameters were all measured at the time of peak production: mid- to late November before winter kill of oilseed radish, and in spring at the time of incorporation for red clover, rye, and no cover. Percent cover was determined using line transects (Laflen et al. 1981) laid diagonally across the main cover-crop plots, 15 m (main sites) or 30 m (satellite sites). Incidents of cover crop, weed, or no vegetation were recorded along transects at 50 and 100 points at 30-cm spacing for the main and satellite sites, respectively. Two 0.25-m^2 quadrats of whole plant material (i.e., shoots and roots) were collected for each cover-crop plot. Samples were separated into cover crop and weed material and were then dried at 66 C for 7 d and weighed. The C and N contents of the tissue (and C : N ratios) were determined by grinding dried biomass samples using a Christy Mill (Suffolk, U.K.) fitted with a $\leq$ 2-mm sieve and sending 2-g samples to Midwest Laboratories, Inc. (Omaha, NE) for total carbon and N analysis.

Plant-available N in the soil was measured at three times during the dry bean growing season (at planting, two fully expanded trifoliates [V2], first flower [R1]) by sampling 8 to 10 soil cores (2.5 cm) to a depth of 20 cm in each cover-crop plot. Samples were homogenized within each plot, dried at room temperature, and ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) fitted with a 1-mm sieve. After grinding, samples were extracted with 1 M KCl and filtered through #2 Whatman filter paper (GE Healthcare Bio-Science, Pittsburg, PA). Extracts were sent to the Michigan State University Soil and Plant Nutrient Laboratory to determine NH_4^+-N and NO_3^--N concentrations via the ammonium salicylate and cadmium reduction methods, respectively, using a Lachat rapid flow injection autoanalyzer (Hach Co., Loveland, CO) (Mulvaney 1996).

Weed Seed Banks. In 2012 and 2013, the weed seed bank at each research site was estimated using a germination method similar to that of Forcella (1992). Research at the Long Term Ecological Research at KBS showed that estimating seedbanks via germination as compared with elutriation has the advantage of detecting more species and avoiding the possible inclusion of nonviable seeds (Gross 1990). Ten to 12 soil samples were collected across each site (i.e., across all treatments and replications) in the spring before dry bean planting using a Miltona PowerStroke cup cutter (Maple Grove, MN) set to a 15-cm depth (for a total of approximately 18 L of soil). After the samples were collected they were mixed, spread out, and allowed to dry in a greenhouse. After drying, 0.95 L of soil was spread on top of a soilless potting media (Suremix Perlite, Michigan Grower Products, Inc., Galesburg, MI) in flats measuring 26 by 53 cm; three subsamples were planted for each site-year. Flats were placed outdoors under irrigation during the early summer and weeds were identified, counted, and removed weekly until emergence ceased.

Weed Density and Biomass. Weed density and biomass within the dry bean row were measured at V2 and R1 in each dry bean variety subplot. At V2 (July), beans have two fully expanded trifoliates and it is at this stage that many growers switch from tined weeders or rotary hoes to an implement targeting interrow cultivation only. At R1 (mid-July to mid-August), dry beans first begin to flower and plants are often too large for mechanical cultivation to continue; hand labor may be utilized during the reproductive stages of dry beans. At each sampling time, three 0.1-m^2 quadrats (15 cm wide by 76 cm long) were placed directly over one of the center dry bean rows, weed were counted by species, and all aboveground weed biomass was harvested. Weed biomass was dried at 66 C and weighed after 7 d. The bean rows sampled were alternated between the V2 and R1 sample timings to avoid sampling the same area twice.

Weed Seed Persistence. To determine the influence of cover crops on weed seed persistence, a subexperiment was conducted in 2012 and 2013 at the MSU research farm sites. The cover-crop treatments assessed were medium red clover, cereal rye, and no cover. Fresh seed of common lambsquarters, giant foxtail, and velvetleaf were collected from the MSU and KBS farms in the early fall of each year. Initial viability of the seed lots was determined through tetrazolium chloride testing (Peters 2000). Two hundred weed seeds were buried with 100 g of white silica sand in no-seeum mesh bags (Outdoor Wilderness Fabrics, Nampa, ID), 10 by 10 cm. Bags were buried in the cover-crop plots in the fall at a depth of 15 cm. Burial at this time exposed seeds to seasonal fluctuations in temperature and soil moisture and any cover-crop root leachates. Sufficient bags were buried to allow for six removal times at 0, 1, 2, 4, 6, and 12 mo after cover-crop incorporation (MAI), with four replications for each weed species and removal time combination. In the spring, all bags were excavated immediately before cover-crop incorporation. One set of bags was analyzed for overwinter seed persistence (0 MAI), whereas the other sets of seed bags were mixed with a high rate of the cover-crop biomass (fresh, chopped shoot and root material, equivalent to 6.2 g of dry biomass per bag) and placed in new mesh bags, identical to the original bags. A more typical quantity of dry biomass added to 100 g of sand in each bag would have been 0.3 g, on the basis of the assumptions that (1) 600 g m^{-2} dry cover-crop biomass can be produced by clover and rye, (2) cover crops can be uniformly incorporated into the soil profile, and (3) a 15-cm-depth hectare furrow slice of soil weighs approximately 2,240 Mg. The high rate was chosen to mimic the activity at microsites with high cover-crop concentrations, as we considered uniform cover-crop incorporation to be unlikely. Samples in the no-cover treatment were also repackaged in new mesh bags. All repackaged seed bags were buried for temporary storage adjacent to the study site in the same field to allow for soil preparation and planting of the dry bean crop. Immediately after dry bean planting, the seed bags were returned to their respective cover-crop plots and buried individually to a depth of 15 cm using the cup cutter mentioned above. Bags were placed in the dry bean row to avoid damage due to cultivation; bean plants emerging adjacent to the seed bags were terminated at cotyledon stage. At each removal time, bags were excavated and air dried in the laboratory. Samples were then sieved and sorted by hand to separate seeds from the sand and organic debris. Intact seeds retrieved were counted and viability was determined using a combination of germination (dark, 25 C) (Hill et al. 2014) and tetrazolium chloride testing. Seed persistence percentages were calculated as follows (Equation 1):

$$\%\ \text{Seed persistence}_{x\,\text{MAI}} = (\#\ \text{viable seed}_{x\,\text{MAI}}/200 \times \text{initial seed viability fraction}) \times 100 \qquad [1]$$

Statistical Analysis. To test the direct influence of cover crops on soil N and weed density, biomass, and seed persistence, data were first analyzed in SAS 9.3 (SAS Institute Inc., Cary, NC) using the MIXED procedure. All cover-crop parameters, soil N extractions, and weed seed persistence were measured at the main plot level; therefore cover crop, year, and location were treated as fixed effects and replication was treated as a random effect nested within site-year. Weed density and biomass data were taken at the subplot level; therefore dry bean variety was also treated as a fixed effect for these analyses. Weed density and biomass data were averaged over the three subsamples in each subplot before analysis. Variance assumptions were checked using the UNIVARIATE procedure. All weed density and biomass were normalized using log 10 transformation after adding a constant (1.1); back-transformed data are presented. Mean separation was conducted using Fisher's protected LSD ($P \leq 0.05$). For weed parameters measured at the subplot level, interactions between cover crop and dry bean variety were rare; therefore main effects of cover crop and bean variety are presented and discussed separately. Variations in management and weather led to many interactions among locations, years, and measurement timings; therefore within each fixed effect site-years and timings are presented separately.

The relationships between cover-crop quantity and quality and weed density and biomass as mediated through changes in soil inorganic N were analyzed using SEM. All red clover, cereal rye, and weedy no-cover treatment data (i.e., spring terminated) from all main and satellite site-years were combined and standardized (standard score, *z*) for backward elimination SEM. Oilseed radish data were not included as the cover-crop biomass (included in the total biomass) winter killed and thus did not reflect biomass at the time of spring incorporation. It was not modeled alone as the number of observations (38) was too low. The combined data set (excluding oilseed radish) had a total of 182 observations.

SEM was conducted using the lavaan package (Rosseel 2012, 2013) in R version 3.2.2 (R Development Core Team 2015). SEM models were based on variance–covariance matrices generated by lavaan for the variables specified in each candidate model, and models were fit using maximum likelihood procedures. Variances were modeled for all parameters, and covariances among exogenous variables were modeled for those relationships denoted by double-headed arrows in the figures showing the three SEM models compared in our analysis (Figures 1–3). We started with an initial global model (Figure 1) analyzing all the relationships between cover-crop measurements (exogenous variables: biomass, C : N ratio, N content), soil N availability during the dry bean growing season (endogenous), and weed density and biomass for a total of 42 pathways (including one for the latent error of R1 weed biomass). Weed seed bank assessments and seed persistence were not included in the model because of the reduced number of observations. The global model was refined into a more parsimonious model by assessing the fit using Akaike information

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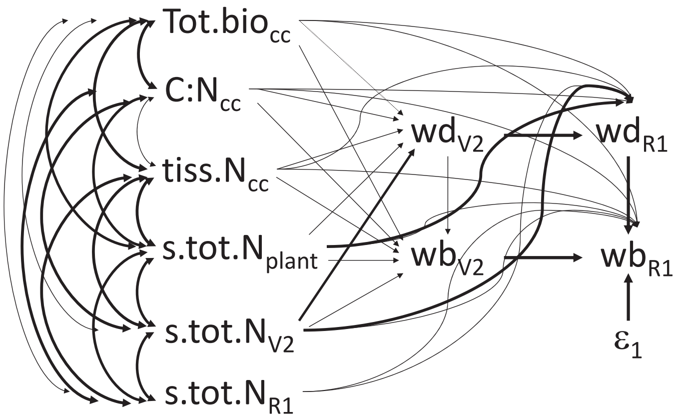

Figure 1. Initial global structural equation model with 42 pathways assessed between cover crop/weed attributes (CC) ($Tot.bio_{cc}$ = cover crop + spring weed biomass at the time of spring termination, $C:N_{cc}$ = C : N ratio of the cover crop/no-cover weeds, and $tiss.N_{cc}$ = total nitrogen content within the cover crop/weed tissue), total inorganic nitrogen (s.tot.N) availability in the soil based on dry bean stage (Plant = planting, V2 = two fully expanded trifoliates, R1 = first flower), and the weed parameters (w) density (d) and biomass (b) at V2 and R1. This model represents the red clover, cereal rye, and weedy no-cover treatments combined and does not include oilseed radish. Regression relationships are represented as single-headed arrows, whereas covariance relationships are represented by double-headed arrows. Bold arrows represent significant relationships and thin arrows represent nonsignificant relationships. ε_1 represents the latent error of R1 biomass.

criterion and comparative fit index values (Grace 2006; Kane et al. 2015; Lamb et al. 2011).

Results and Discussion

Cover-Crop Quantity and Quality. The medium red clover, oilseed radish, and cereal rye cover crops at the main sites (i.e., MSU and KBS, excluding the 2012 MSU poor radish stand) added 800 to nearly 4,000 kg C ha^{-1} and 30 to 230 kg N ha^{-1} compared with contributions of 400 to 1,300 kg C ha^{-1} and 20 to 50 kg N ha^{-1} in the weedy no-cover control treatment (Hill et al. 2016; Table 1). C : N ratios of 25 : 1 or greater lead to N immobilization (Clark et al. 1997; Kuo and Jellum 2002), and the maximum C : N ratios observed for oilseed radish, cereal rye, and weeds in the no-cover control were 31 : 1, 52 : 1, and 29 : 1, respectively (Table 1). For red clover, the maximum C : N ratio was 18 : 1 (Table 1). Unlike the main MSU research sites, organic farmer cooperators were not always able to plant cover crops after a small grain. This and other production considerations often resulted in later cover-crop planting dates at the satellite sites compared with the main sites (Supplemental Tables 1 and 2; http://dx.doi.org/10.1614/WS-D-15-00114.S1). Later planting dates resulted in lower cover-crop biomass production and C and N content and sometimes C : N ratios (data not shown) compared with the main sites. C : N values are affected by differences in development and relative plant component composition (i.e., leaves, stems, roots) at the time of incorporation (Clark et al. 1997; Schomberg et al. 2006; USDA-NRCS 2011).

Cover-Crop Influence on Weeds at Cover-Crop Termination. Weed species present at the time of cover-crop incorporation in the spring varied by year and location. The most commonly observed weeds included the winter annuals: common chickweed [*Stellaria media* (L.) Vill.], field pennycress (*Thlaspi arvense* L.), mayweed chamomile (*Anthemis cotula* L.), annual bluegrass (*Poa annua* L.), and henbit (*Lamium amplexicaule* L.), and occasionally volunteer wheat. Weed ground cover and biomass in the no-cover control treatments at the main sites ranged from 59 to 95% (data not shown) and 1.5 to 7.1 Mg ha^{-1}, respectively (Table 1). Volunteer wheat was the dominant species in the high-biomass site-year, 2011 KBS.

The average percent ground cover for red clover and cereal rye stands before incorporation was 91% (data not shown) at the main sites, with little to no weed biomass (Table 1). Many studies have reported low weed biomass in vigorous cover crops (Bárberi and Mazzoncini 2001; Blackshaw et al. 2001; Brennan and Smith 2005; Creamer and Baldwin 2000; Peachey et al. 2004; Teasdale et al. 2007). For example, Peachey et al. (2004) found that over 5 Mg ha^{-1} rye biomass in the spring reduced spring weed biomass by 94 to 99% compared with the bare ground control. In our study, oilseed radish only covered 21 to 74% of the ground at the main sites before winter kill (2012 and 2013 only; 2011 not measured); weedy ground cover within radish ranged from 0 to 67% in the fall (data not shown). In three of the six main site-years, spring weed biomass following oilseed radish was less than the no-cover control; in 2 site-years it was equivalent, and in 1 site year (2012 MSU) there were more weeds following oilseed radish than in the no-cover-crop control because fall competition with volunteer oat (*Avena sativa* L.) reduced oilseed radish growth (Table 1). This risk of reduced oilseed radish growth due to competition with volunteer small grain after harvest is not uncommon (Sandler et al. 2015). Overall there was no clear relationship between fall radish biomass or percent cover and spring weed biomass in this research. In New York, early plantings of oilseed radish (late August/early September) resulted in no measureable weed biomass

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Table 1. Summary of cover crop biomass, N content, C : N ratio, and influence on soil N at the main sites from 2011 to 2013.

Year	Location[a]	Cover crop treatment[b]	Dry weight: Cover crop	Dry weight: Weed[c]	Dry weight: Total	N content[d]	C : N ratio	Soil inorganic N: Planting	Soil inorganic N: V2	Soil inorganic N: R1
			Mg ha^{-1}			kg ha^{-1}		kg ha^{-1}		
2011	KBS	Clover	7.1	0.4	7.6	154	15 : 1	49	82	77
		Radish	4.5	2.2	6.7	54	31 : 1	38	67	54
		Rye	9.7	0.0	9.7	53	29 : 1	35	70	55
		No cover	—	7.1	7.1	53	24 : 1	36	54	63
		LSD[e]	NS	1.9	NS	33	1[f]	4	NS	NS
	MSU	Clover	2.3	1.3	3.6	44	18 : 1	35	57	39
		Radish	6.1	0.9	7.0	164	14 : 1	43	72	39
		Rye	12.8	0.0	12.8	136	26 : 1	22	39	26
		No cover	—	3.4	3.4	34	23 : 1	42	59	33
		LSD	2.3	1.4	2.4	35	3	13	14	10
2012	KBS	Clover	10.3	0.0	10.3	196	18 : 1	63	99	69
		Radish	4.5	2.3	6.8	61	24 : 1	33	59	39
		Rye	12.0	0.0	12.0	66	52 : 1	29	40	22
		No cover	—	4.2	4.2	43	29 : 1	30	44	36
		LSD	1.9	1.0	1.8	30	5	4	12	10
	MSU	Clover	11.6	0.0	11.6	232	17 : 1	48	74	57
		Radish	0.8	2.8	3.6	10	18 : 1	23	42	32
		Rye	7.9	0.0	7.9	42	30 : 1	25	37	25
		No cover	—	1.9	1.9	24	27 : 1	26	46	29
		LSD	2.2	0.8	2.0	31	5	8	5	12
2013	KBS	Clover	8.6	0.8	9.4	115	17 : 1	46	69	54
		Radish	5.2	2.4	7.6	68	23 : 1	30	51	50
		Rye	10.5	0.0	10.5	60	31 : 1	23	42	39
		No cover	—	1.5	1.5	18	23 : 1	25	40	42
		LSD	2.2	1.3	2.1	41.1	4	13	6	NS
	MSU	Clover	5.7	0.6	6.4	145	17 : 1	45	67	48
		Radish	2.9	2.3	5.2	33	25 : 1	31	54	36
		Rye	11.8	0.0	11.8	73	29 : 1	23	38	29
		No cover	—	1.9	1.9	22	22 : 1	29	54	37
		LSD	4.2	1.1	2.8	36	3	4	10	11

[a] Abbreviations: KBS, Kellogg Biological Station, Hickory Corners, MI; MSU, Michigan State University Horticulture Teaching and Research Center (2011 and 2012) and Agronomy Farm (2013), Lansing, MI.
[b] Clover = medium red clover; radish = oilseed radish; rye = cereal rye; no cover = weedy control.
[c] Weed biomass was taken during the spring at the time of cover-crop incorporation, even for oilseed radish, which winter killed.
[d] For clover, radish, and rye the N content and C : N ratio represent the cover crop biomass alone; for the no-cover treatment these values come from the weed biomass collected in the spring.
[e] Fisher's protected LSD (P ≤ 0.05).
[f] LSD values for the C : N ratios were calculated on the basis of the carbon fraction alone.

in early spring (March/April), whereas later plantings (early–mid-Sept) with reduced radish biomass (i.e., 32% less in 1994) still suppressed spring weed growth by 80 to 87% compared with the bare ground treatment (Stivers-Young 1998).

Rye and clover cover crops generally had very little weed biomass in the spring at the satellite locations (data not shown), similar to the main sites. However, when red clover biomass at the satellite sites was less than 4 Mg ha^{-1} (as was the case in four of seven clover satellite site-years), weed biomass exceeded clover biomass at the time of incorporation. Farmer cooperators usually tilled the no-cover control treatments in the fall and both the no-cover control and winter-killed oilseed radish treatments early in the spring to remove weed biomass; therefore there was usually no spring weed biomass recorded in these plots (data not shown).

Cover-Crop Effects on Weed Density and Biomass after Termination. Weed densities and biomass were not influenced by dry bean variety, with the exception of grass weeds at KBS in 2011 and V2 total weed density at KBS in 2013. Therefore, varieties are pooled for the remaining analyses and interactions for the 2011 and 2013 KBS locations are indicated within the table footnotes (Table 2). There was no difference in weed densities or biomass in dry beans after the incorporation of a rye

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Table 2. Weed densities and biomass recorded at bean stages V2 (two fully expanded trifoliates) and R1 (first flower) as influenced by cover crop at the main sites from 2011 to 2013. Values are averaged over all four dry bean varieties and within each site-year different letters represent differences as determined by Fisher's protected LSD ($P \leq 0.05$).

			V2				R1			
			Weed density				Weed density			
Year	Location[a]	Cover crop[b]	CHEAL[c]	Grasses	Total	Weed biomass	CHEAL[c]	Grasses	Total	Weed biomass
			plants (10-m row)$^{-1d}$			g (10-m row)$^{-1}$	plants (10-m row)$^{-1d}$			g (10-m row)$^{-1}$
2011	KBS	Clover	1.1	53.6[e]	62.7a	3.5[f]	0.0	20.7[g]	21.9	28.9
		Radish	1.8	5.5	12.4b	0.5	0.4	1.1	3.3	31.0
		Rye	0.7	0.0	5.1b	0.3	0.7	1.0	1.8	7.9
		No cover	3.3	4.4	19.0ab	2.4	0.4	0.7	1.1	2.6
	MSU	Clover	0.5	1.6	3.8	0.4	0.8	0.0	1.6b	10.1
		Radish	0.3	0.0	0.6	0.0	0.8	0.0	1.6b	43.0
		Rye	0.5	0.0	1.6	0.1	2.5	0.0	3.8ab	35.5
		No cover	1.1	0.0	1.9	0.6	4.9	0.3	9.0a	57.6
2012	KBS	Clover	25.6	35.3a	70.5a	1.9	2.2	41.0	46.2a	157.6
		Radish	5.8	45.9a	59.3a	3.5	0.5	14.2	15.9bc	43.9
		Rye	0.6	6.0b	7.9b	0.7	0.3	2.2	3.6c	20.1
		No cover	7.1	42.9a	57.7a	2.6	0.5	16.7	18.9ab	78.3
	MSU	Clover	95.4a	6.8	127.9a	2.2a	66.2a	2.7	94.9a	173.0a
		Radish	4.6b	0.8	15.9b	0.2b	2.5b	1.1	13.4b	23.2b
		Rye	3.3b	1.1	12.0b	0.2b	3.0b	0.8	10.1b	39.2b
		No cover	3.6b	0.6	20.5b	0.4b	1.9b	1.1	14.5b	35.9b
2013	KBS	Clover	0.0	6.0a	9.6	0.8[h]	0.8	12.6a	18.8a	22.5
		Radish	0.0	2.2b	5.2	0.8	0.0	3.3b	5.5b	6.3
		Rye	0.6	1.1b	5.2	0.7	0.3	1.6b	4.9b	13.9
		No cover	0.0	1.1b	4.4	0.6	0.8	1.6b	6.0ab	7.5
	MSU	Clover	0.0	16.4	22.6a	3.1a	0.0	20.0a	22.6a	36.5a
		Radish	0.0	2.2	4.7b	0.3b	0.0	2.2b	2.9b	3.8b
		Rye	0.4	1.5	2.9b	0.1b	0.0	1.5b	3.3b	2.8b
		No cover	0.0	0.4	2.6b	0.3b	0.0	1.1b	1.5b	1.5b

[a] Abbreviations: KBS, Kellogg Biological Station, Hickory Corners, MI; MSU, Michigan State University Horticulture Teaching and Research Center (2011 and 2012) and Agronomy Farm (2013), Lansing, MI.

[b] Clover = medium red clover; radish = oilseed radish; rye = cereal rye; no cover = weedy control.

[c] CHEAL = common lambsquarters.

[d] The plant (10-m row)$^{-1}$ measurement is 15 cm in width. Weed densities and biomass were only recorded within the row as most interrow weeds were effectively removed via cultivation.

[e] Cover crop × dry bean variety interaction: Vista and Zorro show red clover to be significantly higher than no cover and rye; Black Velvet and R99 show no significant differences.

[f] Cover crop × dry bean variety interaction: Black Velvet, Zorro, and R99 show significant differences, with red clover being higher than oilseed radish and cereal rye; Vista showed no difference among cover-crop treatments.

[g] Cover crop × dry bean variety interaction: Black Velvet and R99 show significant differences, with red clover being higher than all other cover-crop treatments; Vista and Zorro show no difference among cover-crop treatments.

[h] Cover crop × dry bean variety interaction: Zorro showed a significant difference among cover-crop treatments, with red clover being higher than all other cover-crop treatments; the other dry bean varieties showed no difference among cover-crop treatments.

cover crop compared with no cover crop at the main (Table 2) or satellite sites, with one exception: 2012 KBS, when rye reduced grass weed density at V2 and total weed density at V2 and R1, relative to the no-cover control. These results concur with Reddy (2001) and Peachey et al. (2004), where rye usually had no effect on weeds compared with a no-cover control in no-till soybeans and no-till and conventionally tilled sweet corn, respectively. In a later publication by Reddy et al. (2003), rye reduced weed densities and biomass in the following soybean crop compared with no cover. Cover-crop biomass and C : N ratio were not reported in these references so it is unclear if the differences in the results are biomass or C : N related.

Similar to our results with cereal rye, there were no differences in weed populations or biomass following oilseed radish compared with the no-cover control treatment with one exception: 2011 MSU (Table 2). In the Netherlands, oilseed radish (4 to 7 Mg ha^{-1}) reduced the weed density of the summer annual weed common lambsquarters and the winter annual

Table 3. Structural equation models (global and reduced) for the combined treatments of red clover, cereal rye, and the weedy no cover for all site-years, highlighting model performance indicators for the global and reduced structural equation models and standardized parameter estimates for significant paths for the reduced model (P ≤ 0.05).

	Model performance[a]				Independent variables[b]			
Model	*k*	AIC	CFI	SRMR	Variable 1	Variable 2	Standardized parameter estimate	P-value
Global	42	4,062	1.00	0.01	Total biomass	C : N ratio	0.50	0.00
					Total biomass	N content	0.51	0.00
					Total biomass	Soil N @ planting	−0.27	0.00
					C : N ratio	Soil N @ planting	−0.56	0.00
					C : N ratio	Soil N @ V2	−0.38	0.00
					C : N ratio	Soil N @ R1	−0.40	0.00
					N content	Soil N @ planting	0.39	0.00
					N content	Soil N @ V2	0.52	0.00
					N content	Soil N @ R1	0.39	0.00
					Soil N @ planting	Soil N @ V2	0.81	0.00
					Soil N @ planting	Soil N @ R1	0.61	0.00
					Soil N @ planting	R1 weed density	−0.31	0.03
					Soil N @ V2	Soil N @ R1	0.71	0.00
					Soil N @ V2	V2 weed density	−0.34	0.03
					Soil N @ V2	R1 weed density	0.38	0.02
					V2 weed density	R1 weed density	0.61	0.00
					V2 weed biomass	R1 weed biomass	0.21	0.00
					R1 weed density	R1 weed biomass	0.30	0.00
					Latent error (ε)	R1 weed biomass	0.81	—
Reduced: N content	7	1,565	1.00	0.00	N content	Soil N @ planting	0.49	0.00
					N content	Soil N @ V2	0.55	0.00
					Soil N @ planting	Soil N @ V2	0.83	0.00
					Soil N @ planting	R1 weed biomass	0.41	0.01
					Soil N @ V2	R1 weed biomass	−0.36	0.02
					Latent error (ε)	V2 weed biomass	0.94	—
Reduced: C : N ratio	4	1,296	1.00	0.00	C : N ratio	Soil N @ V2	−0.32	0.00
					C : N ratio	R1 weed biomass	−0.19	0.04
					Latent error (ε)	R1 weed biomass	0.96	—

[a] Model performance indicators: *k*, path numbers analyzed; AIC, Akaike information criterion; CFI, comparative fit index, SRMR, standardized root-mean-square residual.

[b] Independent variables: N content, N content of the cover crop/weedy biomass present at spring termination; Soil N @ planting, at the time of dry bean planting in June; R1, first flower stage; V2 weed biomass, weed biomass when dry beans had two fully expanded trifoliates.

weeds common chickweed and annual bluegrass in the fall because of early light interception, but differences in weed establishment in the spring were not observed (Kruidhof et al. 2008); a similar trend was observed in Canada (O'Reilly et al. 2011). Contrary to their findings and those of this study, an earlier Michigan study found reduced redroot pigweed densities and biomass following oilseed radish (fall biomass 6.2 Mg ha^{-1}) in a late-April-planted onion crop on muck soil 2 and 2.5 mo after planting (Wang et al. 2008). The differences in oilseed radish influence on spring weed growth may be due to differences in production systems including tillage following oilseed radish, soil type, herbicide use, weed species and density, and cash-crop planting date.

Weed density and biomass were higher in some site years in red clover compared with the no-cover-crop control. At 2012 MSU the seed bank was dominated by common lambsquarters (27 million seeds [ha furrow slice]$^{-1}$, data not shown), which was reflected in the emerged seedlings (Table 2). Common lambsquarters is known to thrive (i.e., increased density or biomass) in N-rich environments (Blackshaw et al. 2003, 2004; Sweeney et al. 2008; Williams and Harper 1965; Wilson and Tilman 1995). In this site-year (2012 MSU) red clover plots had 22 to 28 kg N ha^{-1} more than the no-cover control treatments from planting through R1 (Table 3), equating to a 60 to 96% increase in N. At 2013 MSU, the dominant weed species following clover was giant foxtail, with grass densities averaging 10-fold higher following clover than the other treatments at R1 (Table 2). There was no common lambsquarters seed found in the seed bank samples (data not shown), nor were there any seedlings recorded during the growing season for 2013

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MSU. The increased giant foxtail emergence in the red clover plots at 2013 MSU may have resulted from increased foxtail seed inputs in the fall of 2012 in a less vigorous clover stand, which was not corroborated by the field-wide seed bank assay. Rates of foxtail seedling survival have been shown to be higher in the cereal plus legume intercropped portions of rotations compared with the corn and soybean portions of the rotation (Heggenstaller and Liebman 2006). Mirsky et al. (2010) documented increases in foxtail inputs to the seed bank following a red clover cover crop in 3 of 4 site-years due to poor establishment of the companion oat cash crop and slow initial growth of the clover. The germination or biomass of foxtail species responded positively (Schreiber and Orwick 1978), negatively (Anderson et al. 1998; Sweeney et al. 2008; Wilson and Tilman 1995), or not at all (Fawcett and Slife 1978) to increasing applications of synthetic N fertilizers.

At KBS red clover increased soil N availability compared with the no-cover control at the time of planting, but not later in the growing season in 2011 and 2013. At 2012 KBS, higher total weed densities were recorded following red clover at R1, but uneven distribution of weeds in the field resulted in too much variability to detect differences in biomass. Additionally, soil conditions at 2012 KBS at dry bean planting and throughout most of the growing season were very dry. Monthly precipitation averages were 30 to 67% below the 30-yr averages for June through September (Table 3), which in a location with a reduced water holding capacity compared with 2012 MSU (i.e., 2% less organic matter and nearly 20% more sand) may have been a more stressful environment. In previous Michigan research, red clover did not increase summer annual weed densities or biomass in no-till corn in 3 of 4 site-years 45 to 60 d after terminating the cover crop (late June to early July) (Fisk et al. 2001). In the no-till research of Fisk et al. (2001), the herbicides applied probably masked weed response to cover-crop treatments.

The analysis of our initial global SEM illustrating all 42 pathways analyzed are presented in Figure 1 and Table 3 (182 observations). The parsimonious reduced model exploring cover-crop N content at the time of incorporation (Figure 2; Table 3) supports our initial hypothesis that cover quality influences weeds late in the dry bean season (R1) by means of altering soil inorganic N availability (Figure 2; Table 3). For these cover crops and weeds, higher total N content at the time of spring termination

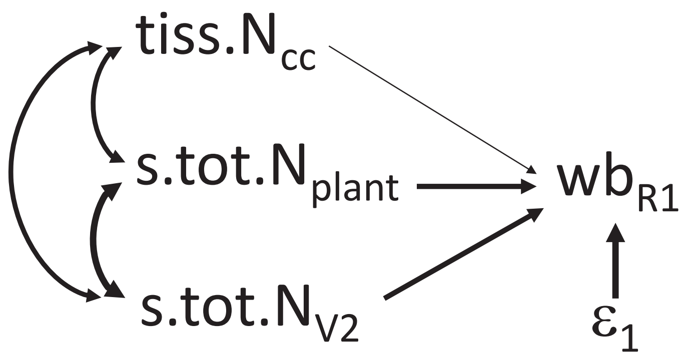

Figure 2. Reduced structural equation model for the total nitrogen content within the cover crop/weed tissue (tiss.N_{cc}), total inorganic nitrogen (s.tot.N) at the time of dry bean planting (Plant) and at V2 dry bean, and weed biomass at R1 dry bean (wb_{R1}). This model represents the red clover, cereal rye, and weedy no-cover treatments combined and does not include oilseed radish. Regression relationships are represented as single-headed arrows, whereas covariance relationships are represented by double-headed arrows. Bold arrows represent significant relationships and thin arrows represent nonsignificant relationships. ε_1 represents the latent error of R1 biomass.

increased soil N availability at planting and at V2. As soil N availability at planting increased so did R1 weed biomass; however, as soil N availability at V2 increased R1 weed biomass decreased. This decrease in weed biomass associated with increased N availability at V2 was unexpected and the cause is unclear, particularly since no relationship with V2 weed density was observed. The other reduced model exploring C : N ratio supported the null hypothesis; increasing C : N ratios in the spring cover crop/weed biomass appear to directly reduce late-season weed biomass (R1; Figure 3; Table 3). It is possible that this direct association is facilitated through other variables not considered. The reduced models proposed require validation with future data sets; a larger data set is needed to conduct SEM of oilseed radish impacts on weed density and biomass. The SEM analysis done in this study and in other agricultural studies now (Lamb et al. 2011; McLeod et al. 2015; Smith et al. 2014) and in the future will continue to further our understanding of systems as a whole.

In this research it appears that the combination of high N availability, a high seed bank of N-responsive weeds, and adequate soil moisture may have been the driving factors behind increased weed density and biomass following a red clover cover crop. Another contributing factor may have been the lack of soil disturbance. The soil in the red clover plots remained undisturbed from the time of spring seeding until May of the subsequent year when the clover was incorporated before dry bean planting. Conversely,

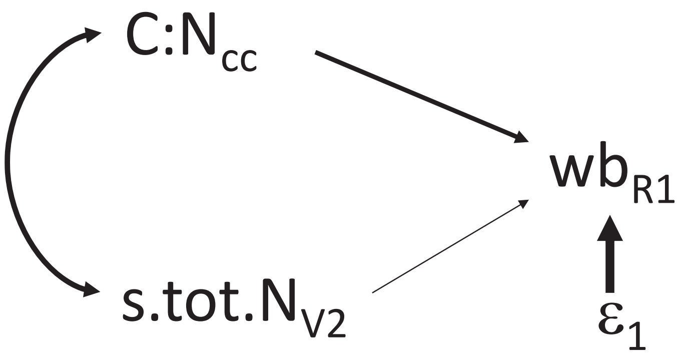

Figure 3. Reduced structural equation model for cover crop/weed C : N ratio (C : N_{cc}), total inorganic nitrogen at the time of V2 dry bean (s.tot.N_{V2}), and weed biomass at the sample time of R1 dry bean (wb_{R1}). This model represents the red clover, cereal rye, and weedy no-cover treatments combined and does not include oilseed radish. Regression relationships are represented as single-headed arrows, whereas covariance relationships are represented by double-headed arrows. Bold arrows represent significant relationships and thin arrows represent nonsignificant relationships. ε_1 represents the latent error of R1 biomass.

the oilseed radish, rye, and no-cover treatments all experienced soil disturbance with a chisel plow and one or two passes with a soil finisher in July or August, after small grain harvest. These disturbances were made to prepare the seedbed for cover-crop planting and killed any weeds present at the time, reducing new weed seed bank inputs in these treatment areas. These disturbances also may have led to different vertical distributions of the weed seeds in the soil profile, and hence differences in emergence that were unrelated to N or seed rain.

Weed Seed Persistence. There was a significant interaction between the main effects and year; thus years are presented separately within each main effect. Part of that interaction occurred because we were unable to recover the 6 MAI bags in 2013 because of the extended period of snow cover (2013 to 2014). The persistence over time data did not fit the exponential decay equation ($R^2 \leq 0.41$); therefore mean separation of the main effects are presented separately.

Weed Seed Persistence over Time. Over the course of our 2-yr experiment the overwinter weed seed persistence (0 MAI), before cover crops were incorporated and added to the seed bags, ranged from 53 to 91% for common lambsquarters and velvetleaf, and from 28 to 79% for giant foxtail (Table 4). In a 2-yr regional study on weed seed persistence, the average overwinter persistence (October through April) of common lambsquarters, giant foxtail, and velvetleaf was 74, 72, and 76% and minimum observed persistence was 5, 5, and 8%, respectively (Davis et al. 2005). Our 2013 giant foxtail seed (i.e., 28% overwinter persistence) was collected at KBS during 2012, when precipitation was low (Table 3), supporting previous research where dry growing conditions of maternal plants reduced giant foxtail seed persistence (Kegode and Pearce 1998; Schutte et al. 2008). The influence of maternal moisture availability on giant foxtail seed development and persistence has not been studied; however, in oats, water stress of maternal plants shortened the period of dormancy in the progeny (Sawhney and Naylor 1982), which under the conditions of our study may have led to fatal germination. In contrast, the 2013 velvetleaf seed had greater overwinter persistence compared with 2012, confirming that maternal effects are species specific (Schutte et al. 2008). The primary dormancy of velvetleaf lasts longer when maternal plants grow in warm and dry conditions (Cardina and Sparrow 1997). An alternative explanation for our observations may be that giant foxtail was more sensitive to overwintering, spring storage conditions, or potential pathogen exposure in 2012 to 2013, increasing the mortality of giant foxtail, but not common lambsquarters and velvetleaf.

Seed persistence of all species, with the exception of 2013 velvetleaf, decreased by 12 to 40% from 0 to 1 MAI (Table 4). The lack of an interaction between cover crop and retrieval time may indicate that soil disturbance during bag retrieval, repackaging with cover crop residue, and bag reburial was more likely the cause of reduced persistence, likely

Table 4. Weed seed persistence over time for 2012 and 2013. Values are averaged across cover-crop treatments (i.e., red clover, cereal rye, and no-cover-crop control treatments).

		Weed species		
Year	Time	Common lambsquarters	Giant foxtail	Velvetleaf
	MAI[a]	Percent persistence		
2012	0	53	79	77
	1	41	29	60
	2	41	22	56
	4	26	21	51
	6	31	17	53
	12	40	13	52
	LSD[b]	10	9	8
2013	0	80	28	91
	1	66	7	95
	2	56	5	90
	4	54	3	90
	6	-	-	-
	12	34	0	93
	LSD	12	10	NS

[a] Abbreviation: MAI, months after cover-crop incorporation.
[b] Fisher's protected LSD (P ≤ 0.05).

by stimulating fatal germination. If the cover-crop amendment decreased seed persistence we would have expected a retrieval time-by-cover-crop interaction for 1 MAI since no amendment was added to the no-cover control bags. In previous research, common lambsquarters germination was positively influenced by exposure to light (Henson 1970), and light and dark tillage in late May in Minnesota increased emergence of common lambsquarters, velvetleaf, and giant foxtail (Buhler 1997). Beyond 1 MAI, weed seed persistence continued to decrease, more so in 2012 than in 2013 despite spring flooding during storage in 2013 (Table 4). Minimum persistence for common lambsquarters, giant foxtail, and velvetleaf was 26, 0, and 51%, respectively.

Cover-Crop Impact on Weed Seed Persistence. When pooled across sampling times, there were no differences in weed seed persistence between the clover and no-cover control treatments in 2012. However, in 2013 red clover decreased the persistence of common lambsquarters by an average of 25% compared with rye and the no-cover control (Table 5). Possible mechanisms responsible for changes in weed seed persistence include the stimulation of microbial activity (Mendes et al. 1999) causing seed decay and the germination of weed seeds. When organic amendments are incorporated into the soil a surge in the populations of fungi, nematodes, and other soil microbes has been observed (Chung et al. 1988; Fennimore and Jackson 2003; Manici et al. 2004; Mohler et al. 2012). Mohler et al. (2012) attributed differences in weed seedling emergence after the incorporation of a different legume, pea (*Pisium sativum* L.), to the increase in pathogenic fungi attack on the weed seeds and seedlings.

Cereal rye increased the persistence of velvetleaf and giant foxtail seed by up to 12 and 6%, respectively, in 2012 compared with the no-cover control. Additions of high C : N plant material such as the rye in our research (30 : 1) to the soil has increased weed seed persistence in other studies (Davis 2007; Davis et al. 2005, 2006; Shem-Tov et al. 2005), possibly because of N limitations that reduce microbial activity (Davis et al. 2006). No effect of rye was observed in 2013; however, seed persistence for giant foxtail was very low (9%) and velvetleaf was high (92%). Abiotic and biotic differences in the soil environment as well as weed seed properties (e.g., seed coat thickness/chemical composition and germination/growth response to N) may all be important factors contributing to the observed changes in weed seed persistence (Davis et al. 2005, 2006; De Cauwer et al. 2011; Kremer 1993); further research is needed on the influence of soil amendments, including cover-crop residues, on weed seed mortality in agroecosystems.

Table 5. Weed seed persistence as influenced by cover crop in 2012 and 2013. Values are averaged across all pull times (i.e., 0 to 12 mo after cover-crop incorporation).

		Weed species		
Year	Cover crop[a]	Common lambsquarters	Giant foxtail	Velvetleaf
		Percent persistence		
2012	No cover	38	27	57
	Clover	35	25	53
	Rye	43	39	64
	LSD[b]	NS	10	6
2013	No cover	64	4	94
	Clover	42	14	91
	Rye	69	8	91
	LSD	9	NS	NS

[a] Clover = medium red clover; radish = oilseed radish; rye = cereal rye; no cover = weedy control.
[b] Fisher's protected LSD ($P \leq 0.05$).

Cover crops are an investment by organic farmers with the goal of recycling nutrients, improving soil health and structure, reducing soil erosion, and improving weed control. Cereal rye and oilseed radish could be added into organic crop rotations before dry beans without affecting weed density or biomass, while still adding carbon to the soil for long-term improvements to soil organic matter and tilth (Hill et al. 2016). Caution should be exercised with cereal rye management, however, to avoid excessive biomass accumulation (> 12 Mg ha^{-1}), which can lead to soil N immobilization and dry bean yield loss in extreme cases (Hill et al. 2016). Spring seeding red clover in the year before dry bean planting, however, presents the risk of increasing weed density and weed biomass and would not be recommended at this time. Our SEM analysis supports the explanation that the stimulation of weed growth following red clover may have been the result of increased soil N at the time of dry bean planting, which did not improve dry bean yields (Hill et al. 2016). In addition to N availability, weed seed inputs in the fall, soil moisture, and differences in seed distribution resulting from fewer tillage passes in the red clover treatment may have contributed to whether or not weeds were problematic in the following dry bean crop. Our seed persistence study showed a decrease in seed persistence following red clover (thus the potential for weed emergence) in one of two burial years. Future research on cover crops and weeds could test the proposed model or build upon this and other existing data sets to facilitate further SEM analysis and improve our understanding of how weed community structure is altered by cover crops.

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Literature Cited

Anderson RL, Tanaka DL, Black AL, Schweizer EE (1998) Weed community and species response to crop rotation, tillage, and nitrogen fertility. Weed Technol 12:531–536

Bárberi P, Mazzoncini M (2001) Changes in weed community composition as influenced by cover crop and management system in continuous corn. Weed Sci 49:491–499

Blackshaw RE, Brandt RN, Janzen HH, Entz T, Grant CA, Derksen DA (2003) Differential response of weed species to added nitrogen. Weed Sci 51:532–539

Blackshaw RE, Molnar LJ, Janzen HH (2004) Nitrogen fertilizer timing and application method affect weed growth and competition with spring wheat. Weed Sci 52:614–622

Blackshaw RE, Moyer JR, Doram RC, Boswell AL (2001) Yellow sweetclover, green manure, and its residues effectively suppress weeds during fallow. Weed Sci 49:406–413

Blum U, King LD, Gerig TM, Lehman ME, Worsham AD (1997) Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. Am J Alternative Agric 12:146–161

Brennan EB, Smith RF (2005) Winter cover crop growth and weed suppression on the central coast of California. Weed Technol 19:1017–1024

Buhler DD (1997) Effects of tillage and light environment on emergence of 13 annual weeds. Weed Technol 11:496–501

Cardina J, Sparrow DH (1997) Temporal changes in velvetleaf (*Abutilon theophrasti*) seed dormancy. Weed Sci 45:61–66

Chung YR, Hoitink HAH, Lipps PE (1988) Interactions between organic matter decomposition level and soilborne disease. Agric Ecosyst Environ 24:183–193

Clark A (2007) Managing cover crops profitably. 3rd edn. Beltsville, MD: Sustainable Agriculture Network. 244p

Clark AJ, Decker AM, Meisinger JJ, McIntosh MS (1997) Kill date of vetch, rye, and a vetch–rye mixture: I. Cover crops and corn nitrogen. Agron J 89:427–434

Conklin AE, Erich MS, Liebman M, Lambert D, Gallandt ER, Halteman WA (2002) Effects of red clover (*Trifolium pretense*) green manure and compost soil amendments on wild mustard (*Brassica kaber*) growth and incidence of disease. Plant Soil 238:245–256

Creamer NG, Baldwin KR (2000) An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortScience 35:600–603

Creamer NG, Bennett MA, Stinner BR, Cardina J (1996) A comparison of four processing tomato production systems differing in cover crop and chemical inputs. J Am Soc Hortic Sci 121:559–568

[CTIC, NCR-SARE] Conservation Technology Information Center and U.S. Department of Agriculture North Central Region Sustainable Agriculture Research and Education (2013) 2012-2013 Cover crop survey. http://www.northcentralsare.org/Educational-Resources/From-the-Field/2012-Cover-Crops-Survey-Analysis. Accessed July 12, 2014

Davis AS (2007) Nitrogen fertilizer and crop residue effects on seed mortality and germination of eight annual weed species. Weed Sci 55:123–128

Davis AS, Anderson KI, Hallett SG, Renner KA (2006) Weed seed mortality in soils with contrasting agricultural management histories. Weed Sci 54:291–297

Davis AS, Cardina J, Forcella F, Johnson GA, Kegode G, Lindquist JL, Luschei EC, Renner KA, Sprague CL, Williams MM II (2005) Environmental factors affecting seed persistence of annual weeds across the U.S. corn belt. Weed Sci 53:860–868

Davis AS, Liebman M (2003) Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. Green manure and tillage timing. Weed Sci 51:919–929

De Cauwer B, D'Hose T, Cougnon M, Leroy B, Bulcke R, Reheul D (2011) Impact of the quality of organic amendments on size and composition of the weed seed bank. Weed Res 51:250–260

Dyck E, Liebman M (1994) Soil fertility management as a factor in weed control: the effect of crimson clover residue, synthetic nitrogen fertilizer, and their interaction on emergence and early growth of lambsquarters and sweet corn. Plant Soil 167:227–237

Fawcett RS, Slife FW (1978) Effects of field applications of nitrate on weed seed germination and dormancy. Weed Sci 26:594–596

Fennimore SA, Jackson LE (2003) Organic amendment and tillage effects on vegetable field weed emergence and seedbanks. Weed Technol 17:42–50

Fisk JW, Hesterman OB, Shrestha A, Kells JJ, Harwood RR, Squire JM, Sheaffer CC (2001) Weed suppression by annual legume cover crops in no-tillage corn. Agron J 93:319–325

Forcella F (1992) Prediction of weed seedling from buried seed reserves. Weed Res 32:29–38

Gallandt ER (2006) How can we target the weed seedbank? Weed Sci 54:588–596

Grace JB (2006) Structural equation modeling and natural systems. Cambridge, UK: Cambridge University Press. 365 p

Grace JB, Anderson TM, Olff H, Scheiner SM (2010) On the specification of structural equation models for ecological systems. Ecol Monogr 80:67–87

Gross K (1990) A comparison of methods for estimating seed numbers in the soil. J Ecol 78:1079–1093

Heggenstaller AH, Liebman M (2006) Demography of *Abutilon theophrasti* and *Setaria faberi* in three crop rotation systems. Weed Res 46:138–151

Henson IE (1970) The effects of light, potassium nitrate, and temperature on the germination of *Chenopodium album* L. Weed Res 10:27–39

https://doi.org/10.1614/WS-D-15-00114.1 Published online by Cambridge University Press

Hill EC (2006) Allelopathic Effects of Hairy Vetch (*Vicia villosa*) and Cowpea (*Vigna unguiculata*) on Weeds and Vegetable Crops. M.S. thesis. East Lansing, MI: Michigan State University. 119 p

Hill EC, Renner KA, Sprague CL (2014) Henbit (*Lamium amplexicaule*), common chickweed (*Stellaria media*), shepherd's-purse (*Capsella bursa-pastoris*), and field pennycress (*Thlaspi arvense*): fecundity, seed dispersal, dormancy, and emergence. Weed Sci 62:97–106

Hill EC, Renner KA, Sprague CL (2016) Cover crop impact on nitrogen availability and dry bean in an organic system. Agron J 108:329–341

Kane DA, Snapp SS, Davis AS (2015) Ridge tillage concentrates potential mineralizable soil nitrogen, facilitating maize uptake. Soil Sci Soc Am J 79:81–88

Kegode GO, Pearce RB (1998) Influence of environment during maternal plant growth on dormancy of shattercane (*Sorghum bicolor*) and giant foxtail (*Setaria faberi*) seed. Weed Sci 46:322–329

Kelton J, Price AJ, Mosjidis J (2012) Allelopathic weed suppression through the use of cover crops. Pages 115–130 *in* Price A, ed. Weed Control. Shanghai, China: InTech China

Kremer RJ (1993) Management of weed seed banks with microorganisms. Ecol Appl 3:42–52

Kruidhof HM, Bastiaans L, Kropff MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Res 48:492–502

Kruidhof HM, Bastiaans L, Kropff MJ (2009) Cover crop residue management for optimizing weed control. Plant Soil 318:169–184

Kuo S, Jellum EJ (2002) Influence of cover crop and residue management on soil nitrogen availability and corn. Agron J 94:501–508

Laflen JM, Amemiya M, Hintz EA (1981) Measuring crop residue cover. J Soil Water Conserv 36:341–343

Lamb EG, Shirtliffe SJ, May WE (2011) Structural equation modeling in the plant sciences: an example using yield components in oat. Can J Plant Sci 91:603–619

Lawley YE, Teasdale JR, Weil RR (2012) The mechanism for weed suppression by a forage radish cover crop. Agron J 104:1–10

Machado S (2007) Allelopathic potential of various plant species on downy brome: Implications for weed control in wheat production. Agron J 99:127–132

Manici LM, Caputo F, Babini V (2004) Effect of green manure on *Pythium* spp. population and microbial communities in intensive cropping systems. Plant Soil 263:133–142

McDaniel MD, Tiemann LK, Grandy AS (2014) Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol Appl 24:560–570

McLeod EM, Banerjee S, Bork EW, Hall LM, Hare DD (2015) Structural equation modeling reveals complex relationships in mixed forage swards. Crop Prot 78:106–113

Mendes IC, Banki AK, Dick RP, Bottomley PJ (1999) Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci Soc Am 4:878–881

[MI Climatologist] Michigan State Climatologist's Office (2014) Climate statistics: Normals and statistics. http://climate.geo.msu.edu/. Accessed September 30, 2014

Mirsky SB, Gallandt ER, Mortensen DA, Curran WS, Shumway DL (2010) Reducing the germinable weed seedbank with soil disturbance and cover crops. Weed Res 50:341–352

Mohler CL, Dykeman C, Nelson EB, DiTommaso A (2012) Reduction in weed seedling emergence by pathogens following the incorporation of green crop residue. Weed Res 52:467–477

[MSU Enviroweather] Michigan State University Enviro-weather (2014) Weather station network. http://www.agweather.geo.msu.edu/mawn/. Accessed September 30, 2014

Mulvaney RL (1996) Nitrogen—inorganic forms. Pages 1123–1184 *in* Sparks DL, ed. Methods of Soil Analysis. Part 3, Chemical Methods Book Series 5. Madison, WI: Soil Science Society of America

Ohno T, Doolan K, Zibilske LM, Liebman M, Gallandt ER, Berube C (1999) Phytotoxic effects of red clover amended soils on wild mustard seedling growth. Agric Ecosyst Environ 78:187–192

O'Reilly KA, Robinson DE, Vyn RJ, Van Eerd LL (2011) Weed populations, sweet corn yield, and economics following fall cover crops. Weed Technol 25:374–384

Park SJ, Buttery BR (1992) Ethyl-methane sulphonate (EMS) induced nodulation mutants of common bean (*Phaseolus vulgaris* L.) lacking effective nodules. Plant Soil 139:295–298

Peachey RE, William RD, Mallory-Smith C (2004) Effect of no-till or conventional planting and cover crops residues on weed emergence in vegetable row crop. Weed Technol 18:1023–1030

Peters J (2000) Tetrazolium Testing Handbook. Contrib. No. 29 to the Handbook on Seed Testing. Lincoln, NE, Association of Official Seed Analysts. 32 p

Putnam AR (1988) Allelochemicals from plants as herbicides. Weed Technol 2:510–518

R Development Core Team (2015) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. Accessed July 7, 2015

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15:660–668

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987–994

Rice CP, Cai G, Teasdale JR (2012) Concentrations and allelopathic effects of benzoxazinoid compounds in soil treated with rye (*Secale cereal*) cover crop. J Agric Food Chem 60:4471–4479

Rosseel Y (2012) lavaan: an R package for structural equation modeling. J Stat Softw 48:1–36

Rosseel Y (2013) The lavaan tutorial. http://lavaan.ugent.be/tutorial/. Accessed July 7, 2015

Ross SM, Ling JR, Izaurralde C, O'Donovan JT (2001) Weed suppression by seven clover species. Agron J 93:820–827

Sandler L, Nelson KA, Dudenhoeffer CJ (2015) Radish planting date and nitrogen rate for cover crop production and the impact on corn yields in upstate Missouri. J Agric Sci (Toronto) 7:1–13

Sawhney R, Naylor JM (1982) Dormancy studies in seed of *Avena fatua*. 13. Influence of drought stress during seed development on duration of seed dormancy. Can J Bot 60:1016–1020

Schomberg HH, Endale DM, Calegari A, Peixoto R, Miyazawa M, Cabrera ML (2006) Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil. Biol Fertil Soils 42:229–307

Schreiber MM, Orwick PL (1978) Influence of nitrogen fertility on growth of foxtail (*Setaria*) taxa. Weed Sci 26:547–550

https://doi.org/10.1614/WS-D-15-00114.1 Published online by Cambridge University Press

Schutte BJ, Davis AS, Renner KA, Cardina J (2008) Maternal and burial environment effects on seed mortality of velvetleaf (*Abutilon theophrasti*) and giant foxtail (*Setaria faberi*). Weed Sci 56:834–840

Shem-Tov S, Klose S, Ajwa S, Fennimore SA (2005) Effect of soil carbon: nitrogen ratio and organic matter amendments on seedbank longevity. Weed Sci Soc Am 45:324 [Abstract]

Smith RG, Davis AS, Jordan NR, Atwood LW, Daly AB, Grandy AS, Hunter MC, Koide RT, Mortensen DA, Ewing P, Kane D, Li M, Lou Y, Snapp SS, Spokas KA, Yannarell AC (2014) Structural equation modeling facilitates transdisciplinary research on agriculture and climate change. Crop Sci 54:475–483

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

Stivers-Young L (1998) Growth, nitrogen accumulation, and weed suppression by fall cover crops following early harvest of vegetables. HortScience 33:60–63

Sweeney AE, Renner KA, Laboski C, Davis A (2008) Effect of fertilizer nitrogen on weed emergence and growth. Weed Sci 56:714–721

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agric 9:475–479

Teasdale JR (1998) Cover crops, smother plants, and weed management. Pages 247–270 *in* Hatfield JL, Buhler DD, Stewart BA, eds. Integrated Weed and Soil Management. Chelsea, MI: Ann Arbor Press

Teasdale JR, Brandsaeter LO, Calegari A, Skora Neto F (2007) Cover crops and weed management. Pages 49–64 *in* Upadhyaya MK, Blackshaw RE, eds. Nonchemical Weed Management: Principles, Concepts and Technology. Reading, UK: Biddles Ltd

Teasdale JR, Rice CP, Cai C, Mangum RW (2012) Expression of allelopathy in the soil environment: soil concentration and activity of benzoxazinoid compounds released by rye cover crop residue. Plant Ecol 213:1893–1905

[USDA-ERS] U.S. Department of Agriculture–Economic Research Service (2013) Organic production: Table 7. Certified organic beans. Acres of soybeans, dry beans, dry peas/lentils by State, 1997 and 2000–2011. USDA-ERS. http://www.ers.usda.gov/data-products/organic-production.aspx#25766. Accessed October 26, 2015

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2014) 2012 United States Summary and State Data. Volume 1. Geographic Area Series. Part 51. http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.txt. Accessed May 5, 2014

[USDA-NRCS] U.S. Department of Agriculture–Natural Resources Conservation Service (2011) Carbon to nitrogen ratios in cropping systems. Available for download at: http://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcs142p2_052823&ext=pdf. Accessed June 4, 2014

Wang G, Ngouajio M, Warncke DD (2008) Nutrient cycling, weed suppression and onion yield following brassica and sorghum sudangrass cover crops. Hort Technol 18:68–74

Weil R, Kremen A (2007) Perspective: thinking across and beyond disciplines to make cover crops pay. J Sci Food Agric 87:551–557

Williams JT, Harper JL (1965) Seed polymorphism and germination I. The influence of nitrates and low temperatures on the germination of *Chenopodium album*. Weed Res 5:141–150

Wilson SD, Tilman D (1995) Competitive responses of eight old-field plant species in four environments. Ecology 76:1169–1180

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