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Corn Density Effect on Interseeded Cover Crops, Weeds, and Grain Yield

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ABSTRACT

A field experiment was conducted at three sites (New York, Pennsylvania, and Maryland) in 2016 to test the effects of drill interseeding a cover crop mixture consisting of cereal rye (*Secale cereale* L.), annual ryegrass (*Lolium multiflorum* Lam.), hairy vetch (*Vicia villosa* Roth), and red clover (*Trifolium pratense* L.) into organically managed corn (*Zea mays* L.). We quantified the effects of corn density on weed biomass, cover crop biomass, and corn grain yield. Increasing corn density had a direct negative effect on interseeded cover crop biomass as well as indirect effects that were mediated by light transmission and weeds. At two sites, corn grain yield at the low corn density (3.71 plants m^{-2}) did not differ from corn grain yield at the standard density (7.41 plants m^{-2}). We also compared plots with and without interseeded cover crops at the same standard corn planting density. Corn grain yield did not differ, but weed biomass at the October sample date was 31% lower in plots with interseeded cover crops compared to plots without. Our results suggest that organic farmers may be able to (i) improve weed suppression in corn by interseeding cover crops and (ii) optimize cropping system performance by planting corn at a slightly lower rate (e.g., 5–10%) than what is typically used when interseeding cover crops. Additional research should be conducted across a wider range of environments to determine corn planting rate recommendations that optimize corn yield, cover crop growth, weed suppression, and profitability in organic cropping systems.

Core Ideas

- Observed trade-off between corn planting density and drill interseeded cover crop biomass.
- Effect of corn density on cover crop biomass was mediated by light and weed biomass.
- Interseeded cover crops suppressed weeds in the fall and did not affect corn grain yield.

Cover crops are an underutilized tool that can provide a variety of benefits including increased soil health and enhanced pest suppression (Schipanski et al., 2014). Some benefits such as weed suppression and soil nitrate scavenging are correlated with cover crop biomass production (Bybee-Finley et al., 2017, Finney et al., 2016). Despite the different benefits that cover crops can provide, few farmers in the United States actually use cover crops (Wallander, 2013). According to a 2014 survey of U.S. farmers ($n = 2814$), 21% reported problems with establishment and 18% reported that the time and labor needed for management were the main reasons to not grow cover crops (SARE et al., 2015). Often the window to plant cover crops is narrow and may compete with other vital field operations (Roesch-McNally et al., 2017). Challenges with limited time after crop harvest in the fall to establish a cover crop before winter is more problematic in northern regions with shorter growing seasons. This might partially explain why cover crops were used on 16% of cropland in Pennsylvania, but only 10% of cropland in New York in 2012 (Hamilton, 2016).

Farmers can overcome cover crop establishment obstacles associated with limited time in the fall by interseeding cover crops during the summer. Interseeding is a form of relay intercropping where cover crops are planted while the primary crop is still growing. Early establishment of interseeded cover crops is important for maximizing cover crop biomass, and is particularly important for maximizing nitrogen scavenging so as to reduce nitrate leaching over the winter (Staver and Brinsfield, 1998; Feyereisen et al., 2006; Hashemi et al., 2013). Furthermore, interseeding enables the use of legume cover crop species [e.g., hairy vetch and crimson clover (*Trifolium incarnatum* L.)], as they require early planting dates to successfully overwinter. Cover crop interseeding in corn is typically accomplished by broadcasting seed either with a tractor-mounted spreader or aerially with an airplane or helicopter. Aerial broadcasting is relatively fast and allows farmers to plant seeds over large areas very quickly, even when field conditions are too wet for tractor operations (NRCS Iowa, 2010). However, broadcasting seed can also have drawbacks (Hively and Cox, 2001). This seeding method leaves seeds on the soil surface and results in minimal seed-to-soil contact, and thus under dry conditions seeds can desiccate, resulting in poor establishment (Baker and

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Griffis, 2009). Seeds can also get stuck in the canopy of the cash crop (Baker and Griffis, 2009), be blown off target prior to landing on the soil surface, or be transported out of the field with surface water flow (Fisher et al., 2011).

One potential solution to the problems associated with broadcasting seed is drill interseeding cover crops. Similar to standard grain drills, high clearance drill interseeders plant cover crop seeds into a seed furrow between rows of cash crops that are actively growing. Advantages of drill interseeding compared with broadcast seeding are twofold: (i) it ensures seed-to-soil contact so seeds are buffered from wind and desiccation; and (ii) cover crops are seeded uniformly at a specific seeding rate. High clearance interseeders allow better placement of seeds, and lay them in rows between the rows of cash crops. In previous research, Fisher et al. (2011) found drilled cover crops had up to 10 times greater seedling emergence per m^2 than broadcast cover crops, depending on site and sample date.

Although drill interseeding cover crops can potentially overcome some of the challenges that limit cover crop adoption, relatively little research has been conducted on this method of establishment to date. To realize the benefits of drill interseeding, farmers need guidelines and recommendations as the management of the host cash crop can affect cover crop establishment and performance. For example, residual herbicides that are commonly used to control weeds in corn, such as atrazine, have extended plant-back restrictions and can be problematic for cover crop establishment (Wallace et al., 2017). In organic cropping systems, farmers often plant cash crops at relatively high seeding rates to hasten canopy closure and enhance weed suppression (Bond and Grundy, 2001; Bastiaans et al., 2008). Even with increased seed costs, high cash crop planting rates can be more profitable if the enhanced weed suppression leads to increased crop yields (Liebert and Ryan, 2017). However, increased shading by a dense crop canopy can also reduce the establishment and growth of interseeded cover crops.

The aim of this experiment was to determine the effect of corn planting density on drill interseeded cover crop performance, weed suppression, and corn grain yield during the transition to certified organic production. We hypothesized that (i) light transmission, cover crop biomass, and weed biomass would all decrease as corn planting density increased; (ii) the effect of corn planting density on cover crop biomass would be mediated by light transmission and weed biomass; and (iii) weed biomass would be suppressed by interseeded cover crops.

MATERIALS AND METHODS

Site Descriptions and Experimental Design

This experiment was conducted in 2016 at three locations in the northeastern United States. The first site was at the Cornell Musgrave Research Farm near Aurora, NY (42.73° N, 76.65° W.). The soils are classified as a Lima silt loam, fine-loamy Oxyaquic Hapludalf; cover crops were grown in the previous year at this site. The second site was at the Penn State Russell E. Larson Agricultural Research Center near Pennsylvania Furnace, PA (40.73° N, 77.93° W). The soils are classified as a Hagerstown silt loam, mesic Typic Hapludalfs, and the previous crop at this site was soybean. The third site was at the USDA Beltsville Agricultural Research Center in Beltsville, MD (39.03° N, 76.93° W). The soils are classified as Codorus-Hatboro a fine-loamy, mixed, mesic Typic Endoaquults, and the previous crop was organic soybean at this site. Soil organic matter was 3.0% at the New York site, 2.5% at the Pennsylvania site, and 2.9% at the Maryland site. Fields at each site were managed using organic production methods for the duration of the experiment (Table 1).

Table 1. Dates of field operations and sampling events in 2016. Photosynthetically active radiation (PAR) 1 and 2 are the dates PAR was measured. Biomass 1 and 2 are the dates weed and cover crop biomass were sampled.

Activity	New York	Pennsylvania	Maryland
Field operation			
Manure application	11 May	18 May	24 May
Moldboard plowing & disking	12 May	18 May	25 May
Corn planting	12 May	27 May	26 May
Blind cultivation 1	25 May	31 May	27 May
Blind cultivation 2	2 June	10 June	–
Inter-row cultivation 1	16 June	21 June	6 June
Inter-row cultivation 2	21 June	1 July	27 June
Interseeding	22 June	1 July	27 June
Irrigation	–†	1 Aug.	–
Sampling event			
PAR 1	21 June	31 June	27 June
PAR 2	9 Aug.	12 Aug.	15 Aug.
Biomass 1	10 Aug.	12 Aug.	15 Aug.
Biomass 2	12 Oct.	11 Nov.	20 Oct.
Corn density	14 Nov.	15 Nov.	31 Aug.
Corn harvest	15 Nov.	15 Nov.	2 Nov.

† Dash indicates that operation or sampling event did not occur.

The experiment was arranged as a randomized complete block design with four replication blocks at each site. At all sites, each block had five treatment plots that measured 12 by 14 m with blocks spaced 12 m apart. Five treatments were compared in each block: (i) ‘No Corn’ (no corn planted + interseeded cover crops); (ii) ‘Low’ (corn planting density of 37,050 plants ha^{-1} + interseeded cover crops); (iii) ‘Medium’ (corn planting density of 74,100 plants ha^{-1} + interseeded cover crops); (iv) ‘High’ (corn planting density of 111,150 plants ha^{-1} + interseeded cover crops); and (v) ‘Medium Control’ (corn planting density of 74,100 plants ha^{-1} + no interseeded cover crops).

Field Operations

In late spring 2016, manure was applied at each site prior to tillage to ensure adequate corn growth (Table 1). The nutrient amendment employed at each location was based on availability and the typical organic corn production practices for each location. In New York, 5600 kg of poultry manure (5–4–3, Kreher’s Farm Fresh Eggs, Clarence, NY) was applied to the field. In Pennsylvania, dairy manure was applied to the field at a rate of 51,450 L ha^{-1} and supplemented with 224 kg ha^{-1} of sodium nitrate (16–0–0). As of 2012, sodium nitrate can be used in certified organic crop production as long as it is used in a manner that maintains or improves the natural resources of the operation, including soil and water quality, and complies with crop nutrient and soil fertility requirements (McEvoy 2012). In Maryland, 9330 kg of poultry manure (3–2–3, Purdue Agricycle LLC, Seaford, DE) was applied to the whole field. All experimental fields were plowed and disked after manure application, and cultimulched immediately before planting (Table 1).

Fig. 1. Interseeding the cover crop mixture in corn at the New York site. The high-clearance drill interseeder has a coulter and double disc opener that deposits seed in a furrow creating three rows spaced 19-cm apart between 76-cm rows of corn.

Untreated conventional corn seed (*Zea mays* L.; cv. 'Viking 69–99' 99 d relative maturity) was planted in late May at all sites (Table 1). This variety is marketed as a hybrid with excellent ear flex, meaning that ear size can vary with population. Corn was planted at all sites with a four-row planter on 76 cm row spacing. A total of 16 rows of corn were planted in each plot. Planters were calibrated to specific planting rates (Low = 3.71 plants m^{-2}, Medium = 7.41 plants m^{-2}, High = 11.12 plants m^{-2}) and tested after each new calibration to verify seed planting rate. The 'Medium' planting rate (7.41 plants m^{-2}) was selected to represent a standard corn planting density for organic farmers (White et al., 2015).

Weeds were controlled by blind and inter-row cultivation at each location (Table 1). A tine weeder was used twice in New York and Pennsylvania; once before and once after the corn had emerged. Only the first blind cultivation event occurred in Maryland due to rain events that prevented additional operations. The tine weeder was tested prior to the second blind cultivation to ensure its pressure was aggressive enough to uproot weeds without damaging corn seedlings. An S-tine cultivator was used to complete two inter-row cultivations events at each site. One interrow cultivation occurred when the corn was at the V2 to V3 stage, the other occurred when the corn was at the V4 to V5 stage.

Once corn reached the V5 growth stage, a cover crop mixture was drill interseeded. The mixture contained 51% (by weight) cereal rye, 25% annual ryegrass, 14% hairy vetch, and 10% red clover and was seeded at 33.7, 16.5, 9.2, and 6.6 kg ha^{-1} respectively (King's AgriSeeds Inc., Ronks, PA). These species were chosen based on previous research (Curran et al., 2018). The cover crop was interseeded into corn with a high-clearance drill interseeder (InterSeeder Technologies, Woodward, PA) at each site (Fig. 1). The cover crop mixture was seeded in three rows that were spaced 19-cm apart between each 76-cm corn row. Legume cover crop seeds were inoculated with appropriate *Rhizobium leguminosarum* strains immediately prior to seeding.

Across all sites, the corn-growing season in 2016 was hotter and drier than the 30-yr average (Table 2). The Pennsylvania site was irrigated on 1 August due to extreme drought conditions (Table 2). A total of 2.5 cm of water was applied to the entire field on this date. Irrigation was not used at the other two sites.

Sampling

Photosynthetically active radiation (PAR) was measured with a line quantum sensor (LI-190, Li-Cor, Inc., Lincoln, NE), point sensor (LI-191, Li-Cor, Inc.), and data logger (LI-1400, Li-Cor, Inc.) to determine light transmission through the corn canopy. At each site, PAR was measured twice, once immediately preceding cover crop interseeding and the other immediately preceding the first cover crop biomass collection (Table 1). Photosynthetically active radiation measurements were taken between 10 am and 2 pm under minimal cloud cover. The point sensor was held level directly above the corn canopy and line quantum sensor was held level on the soil surface. PAR was measured at four locations in each plot. In previous research, four unique PAR locations provided a reliable estimate of PAR for an entire corn field (Singer et al., 2011). Three readings were taken at each of the four locations per plot from each sensor, and data from the different locations and readings were aggregated at the plot level prior to conducting analyses. Light transmission was quantified by dividing the PAR measurement of the line sensor by the PAR measurement of the point sensor. At the Maryland site, PAR was sampled at two instead of four locations in each treatment.

Weed biomass and cover crop biomass were sampled approximately 50 and 110 d after cover crop interseeding (Table 1). At each date, biomass was sampled from within two separate 0.5 m^2 quadrats in each plot. Cover crop biomass was harvested from all three rows along a 65 cm length between each corn row by cutting vegetation (i.e., cover crops and weeds) at ground level and placing the cover crop biomass in paper bags. Weeds taller than 2.5 cm within the 0.5 m^2 quadrat were placed in separate paper bags. Plant material was oven dried at 60 °C for two weeks, then weighed. Grain yield was collected from the center 7.6 m of rows 6, 7, 10, and 11 in each plot using a small plot combine. Grain weight and moisture content were recorded by the harvester for each row pair and an adjusted weight at 15.5% moisture was calculated. Biomass and yield data were converted to g m^{-2} prior to conducting analyses.

Statistical Analyses

Several statistical analyses were used including ANOVA, linear and nonlinear regression, path analysis, and partial correlation analysis. All analyses were done with R version 3.2.2 (R Core Team, 2015). Weed and cover crop biomass data were log-transformed to satisfy assumptions of normality and homogeneous variance, using the natural log + 1 to account for zeros in the data. Back transformed means are presented in text and tables.

Linear mixed effect models (packages lme4 and lmerTest) with block as a random effect were used to test for differences across sites, treatments, and sample times. Site and corn density treatment were fixed effects for all models, and sample date was also used as a fixed effect for light transmission, weed biomass, and cover crop biomass models. Data used for light transmission and biomass analyses were from 'No Corn', 'Low', 'Medium', and 'High' treatments, whereas only data from 'Low', 'Medium', and 'High' treatments were used for corn density and corn grain yield analyses. The effect of interseeded cover crops on weed biomass and corn grain yield was also analyzed using linear mixed effect models (packages lme4 and lmerTest) with block as a random effect and both site and treatment as fixed effects. Only data from 'Medium' and 'Medium Control' treatments were used for these analyses. Means were compared with Tukey HSD using the lsmeans function (package lsmeans), and were considered significantly different at $P \le 0.05$.

Nonlinear regression was used to test the effects of measured corn density within each site. An asymptotic model modified to pass through the origin was fit using the nls function (package MASS):

$$Y = asym\left(1 - e^{\left(-e^{lrc \times CD}\right)}\right)$$

where Y is the corn yield (g m^{-2}); *asym* is the asymptote (i.e., the maximum grain yield when corn density approaches infinity); *lrc* is the natural log of the rate constant (i.e., the corn density to reach half of the asym); and CD is the corn density (plants m^{-2}). Data used for nonlinear regression analyses were from 'No Corn', 'Low', 'Medium', and 'High' treatments. Linear regression was used to test the relationship between measured corn density and light transmission, weed biomass, and cover crop biomass within each site. Data used for these regression analyses were from 'No Corn', 'Low', 'Medium', and 'High' treatments.

Path analysis (lavaan package) was used to analyze the network of relationships between all response variables. The advantage to using path analysis instead of multiple regression is that path analysis incorporates mediating effects of model variables (Grace and Bollen, 2005). Data from all sites were pooled and only data from 'No Corn', 'Low', 'Medium', and 'High' treatments at the August sample date were used for the path analysis. Corn density, light transmission, and biomass had different units, so coefficients were standardized using:

$$\text{Standardized variable} = \frac{X_i - \bar{X}}{S_X}$$

where X_i is the i^{th} observation, $\bar{X}$ is the mean of the variable, and S_x is the standard deviation of the variable. This standardization allows the relationships between variables to be expressed as changes in standard deviation units, and makes it possible for direct comparisons across paths (Grace and Bollen, 2005). The error terms associated with light transmission, weed biomass, and cover crop biomass were calculated as $\sqrt{1 - R^2}$. The coefficient of determination (R^2) was calculated for each variable in the model.

Partial and semipartial R^2 values were calculated with the spcor and pcor functions (package ppcor) to assess the proportion of variance in cover crop biomass that was explained by corn density, light transmission, and weed biomass. Path analysis and partial and semi-partial correlation are complementary analyses that can be used to determine if trends in the magnitude of effect and explained variance are consistent across predictors. Similar to the path analysis, data used for partial and semipartial correlation were pooled across sites and only data from the August sample date in 'No Corn', 'Low', 'Medium', and 'High' treatments were used for the analysis. Multicollinearity of the predictor variables can be quantified with the *vif* function (package car), which calculates the variance inflation factor (VIF) for each predictor as:

$$\text{VIF}_i = \frac{1}{1 - R_i^2}$$

where R^2 is the multiple correlation coefficient of a predictor variable regressed on the remaining predictor variables (Belsley et al., 1980). A predictor variable that is uncorrelated to any other predictor variable will yield a VIF_i of 1 (Fox and Monette, 1992). Severe multicollinearity is evident when VIF > 10 (Kutner et al., 2005). Partial and semipartial R^2 values were calculated to determine the proportion of variance in cover crop biomass accounted for by each predictor variable. Partial R^2 is the amount of variance of the response variable explained by a predictor variable from which the explained variance of the other predictors has been partialed or controlled (Cohen et al., 2003; Kim, 2015). Semipartial R^2 is the amount variance of a response variable that is uniquely explained by a predictor variable, and is independent of the other predictor variables (Cohen et al., 2003; Kim, 2015).

Table 2. Cumulative growing degree days (GDD) and monthly precipitation in 2016 and 30-yr long-term averages in parentheses at each site. GDDs are base 10 °C and were calculated for the period from corn planting to harvest (CPH), cover crop interseeding to first cover crop sample date (CC 1), and cover crop interseeding to second cover crop sample date (CC 2).

	New York	Pennsylvania	Maryland
Period	GDD†		
CPH	1445 (1231)	1466 (1196)	1968 (1729)
CC 1	593 (516)	526 (453)	783 (708)
CC 2	1154 (941)	1082 (888)	1518 (1328)
Month	Precipitation (cm)		
May	1.6 (8.0)	1.6 (8.8)	11.0 (13.1)
June	1.4 (9.5)	6.7 (10.4)	9.4 (12.0)
July	4.4 (8.9)	4.1 (8.9)	10.0 (14.9)
Aug.	5.5 (8.0)	0.8 (9.8)	8.3 (10.7)
Sept.	5.3 (10.2)	1.2 (9.1)	10.4 (7.6)
Oct.	20.5 (8.7)	4.3 (7.7)	9.3 (1.9)

† The 30-yr GDD averages were calculated from http://climatesmart-farming.org/tools/csf-growing-degree-day-calculator/. Precipitation data were complied from on-site weather stations, 30-yr averages were found at https://www.ncdc.noaa.gov/cdo-web/datatools/normals.

RESULTS AND DISCUSSION

Effects of Crop Density Treatments on Corn Density and Yield across Sites

A corn density gradient was successfully established by the different planting rates at each site. ANOVA was used to test for differences in corn density and corn yield across sites and corn planting rate treatments (i.e., 'Low', 'Medium', and 'High') (Table 3). In general, mean corn density was lower across the corn planting rate treatments in Pennsylvania (5.23 plants m^{-2}) compared with New York (6.59 plants m^{-2}) and Maryland (6.70 plants m^{-2}), but a significant interaction between site and treatment occurred (Table 3). Despite dry conditions (Table 2), average yield at the New York site (1066 g m^{-2}) exceeded the 2016 Cayuga County, NY average yield (886 g m^{-2}) (USDA NASS, 2017). Average yield at the Pennsylvania site (703 g m^{-2})

Table 3. The effect of site and treatment on corn density (plants m^{-2}) and corn grain yield (g m^{-2}) using data from the 'Low', 'Medium', and 'High' corn planting rate treatments in all sites. Similar letters within a site (NY, PA, and MD) indicate no significant difference (α = 0.05) between treatments.

Effect	Corn density	Corn grain yield
	P-value	*P*-value
Site (*S*)	<0.001	<0.001
Treatment (*T*)	<0.001	<0.001
S × *T*	<0.001	0.02
	plants m^{-2}	g m^{-2}
NY Low	3.69 c	969 a
NY Medium	6.50 b	1108 a
NY High	9.54 a	1122 a
PA Low	2.67 c	517 b
PA Medium	5.61 b	784 a
PA High	7.41 a	809 a
MD Low	3.68 c	702 a
MD Medium	6.55 b	781 a
MD High	9.90 a	722 a

was similar to the 2016 Centre County, PA average yield (699 g m^{-2}) (USDA NASS, 2017). Average yield at the Maryland site (734 g m^{-2}) was lower than the 2016 Anne Arundel County, MD average yield (910 g m^{-2}) (USDA NASS, 2017). A significant interaction between site and treatment was observed for corn yield (Table 3). Corn yield did not differ across corn planting rate treatments (i.e., 'Low', 'Medium', and 'High') in New York or Maryland (Table 3). The lack of differences in corn yield across corn planting rate treatments in New York and Maryland was probably because of the flex-ear corn hybrid, which has an indeterminate ear size that can compensate for variation in plant density (Thomison and Jordan, 1995). Thus, corn plants in the 'Low' treatments in New York and Maryland were likely able to produce a larger ear. The 'Low' treatment in Pennsylvania had a lower yield than other treatments (Table 3), which could have been partially due to a lower corn density in this treatment at this site compared to the 'Low' treatment at the other sites.

The relationship between corn grain yield and measured corn density as well as the maximum grain yield was also assessed for each site separately using nonlinear regression (Fig. 2). In New York, the maximum predicted corn grain yield was 1132 g m^{-2} (Table 4). Corn grain yield in New York was relatively high, especially considering the drought conditions early in the season. In Pennsylvania, the maximum predicted corn grain yield was 928 g m^{-2} (Table 4). Corn density in Pennsylvania did not exceed 8 plants m^{-2}, so it is possible that asymptotic yield could have been achieved had the corn population densities better reflected the intended planting rates. In Maryland, the maximum predicted corn grain yield was 754 g m^{-2} (Table 4). Corn grain yield at the Maryland site was relatively low, which was likely due to dry conditions through corn pollination.

Effect of Corn Density on Light Transmission, Weed Biomass, and Cover Crop Biomass within Each Site

ANOVA was used to test for differences in light transmission, weed biomass, and cover crop biomass using data from the 'No Corn', 'Low', 'Medium', and 'High' treatments. An interaction between site, sample date, and treatment was observed for light transmission (Table 5). This interaction is likely the result of differences in corn densities and corn growth rates across sites. Weed biomass varied by site and we observed an interaction between treatment and sample date (Table 5). In general, when pooled across the four crop density treatments and two sample dates, mean weed biomass was greatest in the PA site (78.83 g m^{-2}), intermediate at the MD site (21.42 g m^{-2}), and lowest at the NY site (1.01 g m^{-2}). We observed a site by treatment interaction and a site by sample date interaction for cover crop biomass (Table 5). In general, when pooled across the four crop density treatments and two sample dates, mean cover crop biomass was greatest in the NY site (11.52 g m^{-2}), intermediate at the PA site (10.00 g m^{-2}), and lowest at the MD site (5.68 g m^{-2}). Site differences in cover crop biomass could be due to different soil and weather conditions.

The relationships between measured corn density and light transmission, weed biomass, and cover crop biomass were tested with linear regression within each site for each sample date. Overall, results support our hypothesis that light transmission, cover crop biomass, and weed biomass would decrease as corn density increased. However, in Pennsylvania we found no relationship between weed biomass and corn density at either sample date (Table 6).

We observed a negative relationship ($P < 0.001$) between corn density and light transmission at all sites and at both sample dates (Table 6, Fig. 3). The effect of corn density on light transmission strengthened from the first to the second sample date, which can be seen in the slope of the regression lines at the two sample dates. These results are consistent with previous research showing significant reductions in light transmission at ground level from increased corn planting rates (Tollenaar et al., 1994; Westgate et al., 1997; Teasdale, 1998; Andrade et al., 2002). In high density corn, most light is captured by young leaves at the top of the canopy, and in low density corn the light that is not captured by the top leaves can be captured by those lower on the plant (Loomis et al., 1968). Similar to our findings at the August sample date, Rajcan and Swanton (2001) reported that corn planted at recommended planting rates resulted in approximately 10% light transmission below the top 1 m of the corn canopy at corn tasseling. Tollenaar et al. (1994) found light transmission at corn silking varied from 14.9% at 4 plants m^{-2} to 8.1% at 7 plants m^{-2} to 4.2% at 10 plants m^{-2}.

Dominant weed species varied by site. In New York, the most frequently occurring species (occurrence > 50%) in decreasing order were common lambsquarters (*Chenopodium album* L.), pigweeds (*Amaranthus* spp.) and common ragweed (*Ambrosia artemisiifolia* L.). In Pennsylvania, the most frequently occurring species (occurrence > 50%) in decreasing order were giant foxtail (*Setaria faberi* R. A. W. Herm.), velvetleaf (*Abutilon theophrasti* Medik), common lambsquarters and pigweeds. In Maryland, the most frequently occurring species (occurrence > 50%) in decreasing order were barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and pigweeds. A negative relationship was observed between corn planting density and weed biomass in New York and Maryland, but not in Pennsylvania (Table 6, Fig. 3). Higher weed biomass at the Pennsylvania site could partially explain the lower corn yield that was observed in the 'Low' at this site (Table 3).

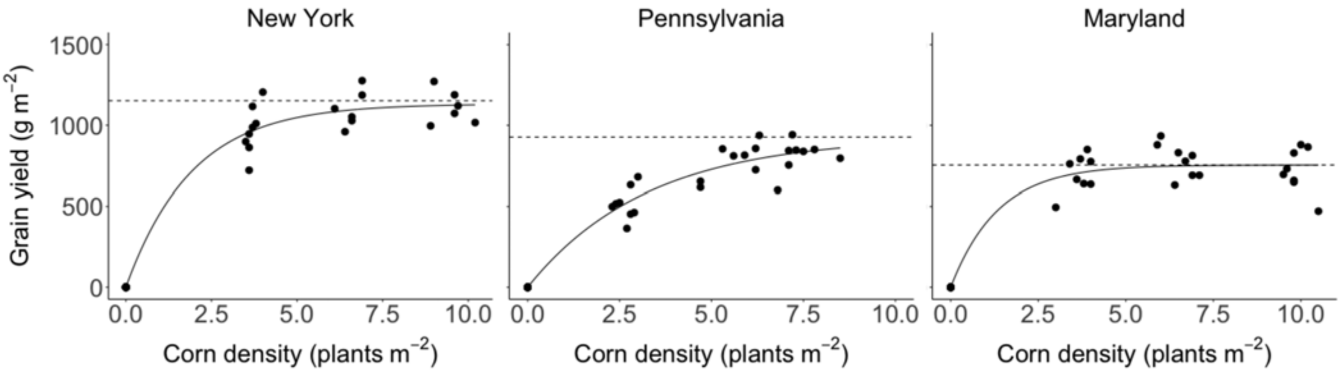

Fig. 2. The effect of corn density on grain yield at each site. The dashed line corresponds to the predicted asymptote from the model, which can be interpreted as the maximum predicted yield.

Table 4. Results from nonlinear regressions of corn yield as a function of corn density. Parameter estimates, standard errors (SE), and *p*-values (*P*) for the asymptotic yield (asym; g m^{-2}) and the natural log of the rate constant (lrc) are provided for each site. R^2 were calculated from the predicted Pearson residuals of each model.

Site	R^2	Parameter	Estimate	SE	*P*
New York	0.84	asym	1132	38.8	<0.001
		lrc	–0.7	0.17	<0.001
Pennsylvania	0.90	asym	928	59.5	<0.001
		lrc	–1.2	0.16	<0.001
Maryland	0.75	asym	754	28.2	<0.001
		lrc	–0.3	0.34	0.4

Table 5. The effect of site, treatment, and sample date on light transmission, weed biomass (g m^{-2}), and cover crop biomass (g m^{-2}) using data from the 'No Corn', 'Low', 'Medium', and 'High' corn planting rate treatments in all sites.

Fixed effects	Light transmission	Weed biomass†	Cover crop biomass†
Site (S)	0.05	<0.001	0.083
Treatment (T)	<0.001	<0.001	<0.001
S × T	<0.001	0.87	<0.001
Sample date (SD)	0.12	<0.001	<0.001
S × SD	<0.001	0.11	0.03
T × SD	<0.001	0.006	0.25
S × T × SD	0.02	0.50	0.81

†Dry weight biomass data were ln(*x* + 1) transformed for analyses.

The regressions for New York and Maryland are congruent with previous research (Teasdale, 1995; Teasdale, 1998; Weiner et al., 2001). Tollenaar et al. (1994) found that increasing corn plant density from 4 to 10 plants m^2 reduced weed biomass by up to 50%. The regressions for New York and Maryland show lower weed biomass when corn density is higher. This result should be interpreted cautiously, as the trend was influenced by high weed biomass in 'No Corn' treatments. The regression between corn planting density and weed biomass in Pennsylvania showed no relationship (Table 6, $P > 0.05$). It is likely that drought at this site slowed the development of the corn and so canopy closure was delayed (Çakir, 2004). Reduced competition from the corn may have allowed the weeds in Pennsylvania to be more competitive and evenly distributed across treatments. It is also possible that the lack of weed suppression was due to the lower corn density at this site compared with the other sites.

A negative relationship between corn planting density and cover crop biomass was observed at all sites for both sampling dates (Table 6, Fig. 3). Unlike the relationship between measured corn density and light transmission, the slope of the relationship with cover crop biomass was fairly consistent across the two sampling dates. Baributsa et al. (2008) drilled interseeded red clover (*Trifolium pratense* L.) or chickling vetch (*Lathyrus sativus* L.) into a corn planting density gradient ranging from 3.75 to 7.50 plants m^{-2} and found a negative relationship between corn planting density and fall cover crop biomass. In this experiment, fall cover crop biomass in the lowest corn planting rate treatment (3.75 plants m^{-2}) was more than double the biomass in the highest corn planting rate treatment (7.50 plants m^{-2}) for both cover crops when averaged across the 3 yr of the experiment (Baributsa et al., 2008). Few, if any, other studies have examined drill interseeded cover crops across a corn density gradient. However, research with cover crops that were broadcast seeded into a cereal crop showed that cover crop biomass decreased with increased planting density of the cereal crop. For example, Ross et al. (2003) found biomass of interseeded berseem clover (*Trifolium alexandrinum* L.) was reduced by 58 to 60, 68 to 75, and 80 to 82% in oat densities of 25, 50, and 100 live seeds m^{-2}, respectively, compared with a no oat control. In our experiment, all four cover crop species emerged and contributed to cover crop biomass, with no one species dominating the mixture. However, samples were not separated by species and thus we cannot report on the exact species composition of cover crop biomass.

Direct and Indirect Effects on Cover Crop Biomass

Linear regression analyses showed a strong negative relationship between corn density and light transmission, corn density and weed biomass at two of three sites, and corn density and cover crop biomass. However, due to the confounding effect of corn density, the relationships between light transmission and cover crop biomass, light transmission and weed biomass, and cover crop and weed biomass were not analyzed using the same linear regression approach. Instead path analysis was used to parse out the effects of corn density, light transmission, and weed biomass on cover crop biomass, and to test if the effect of corn density on cover crop biomass was mediated through light transmission and weed biomass.

In our path model, measured corn density, light transmission, and weed biomass each had a direct effect on cover crop biomass (Fig. 4). Corn density had three indirect effects on cover crop biomass: one mediated by light transmission, one mediated

Table 6. Regression equations and associated R^2 and P-values for six response variables as a function of corn density (CD; plants m^{-2}). Response variables include June light transmission (JLT), August light transmission (ALT), August weed biomass (AWB; g m^{-2}), October weed biomass (OWB; g m^{-2}), August cover crop biomass (ACCB; g m^{-2}), and October cover crop biomass (OCCB; g m^{-2}).

Response variable	New York			Pennsylvania			Maryland		
	Equation	R^2	P	Equation	R^2	P	Equation	R^2	P
JLT	$-0.02x + 0.93$	0.74	<0.001	$-0.04x + 0.82$	0.69	<0.001	$-0.04x + 0.91$	0.79	<0.001
ALT	$-0.08x + 0.74$	0.68	<0.001	$-0.09x + 0.64$	0.77	<0.001	$-0.07x + 0.73$	0.74	<0.001
AWB†	$-0.12x + 1.10$	0.2	0.006	$-0.09x + 4.22$	0.02	0.21	$-0.24x + 4.39$	0.25	0.002
OWB†	$-0.24x + 2.10$	0.29	<0.001	$-0.10x + 4.59$	0.01	0.27	$-0.39x + 4.98$	0.46	<0.001
ACCB†	$-0.43x + 4.18$	0.84	<0.001	$-0.45x + 3.79$	0.83	<0.001	$-0.28x + 3.18$	0.75	<0.001
OCCB†	$-0.47x + 5.30$	0.87	<0.001	$-0.53x + 4.88$	0.66	<0.001	$-0.28x + 3.44$	0.51	<0.001

† Dry weight biomass data were $\ln(x + 1)$ transformed for analyses.

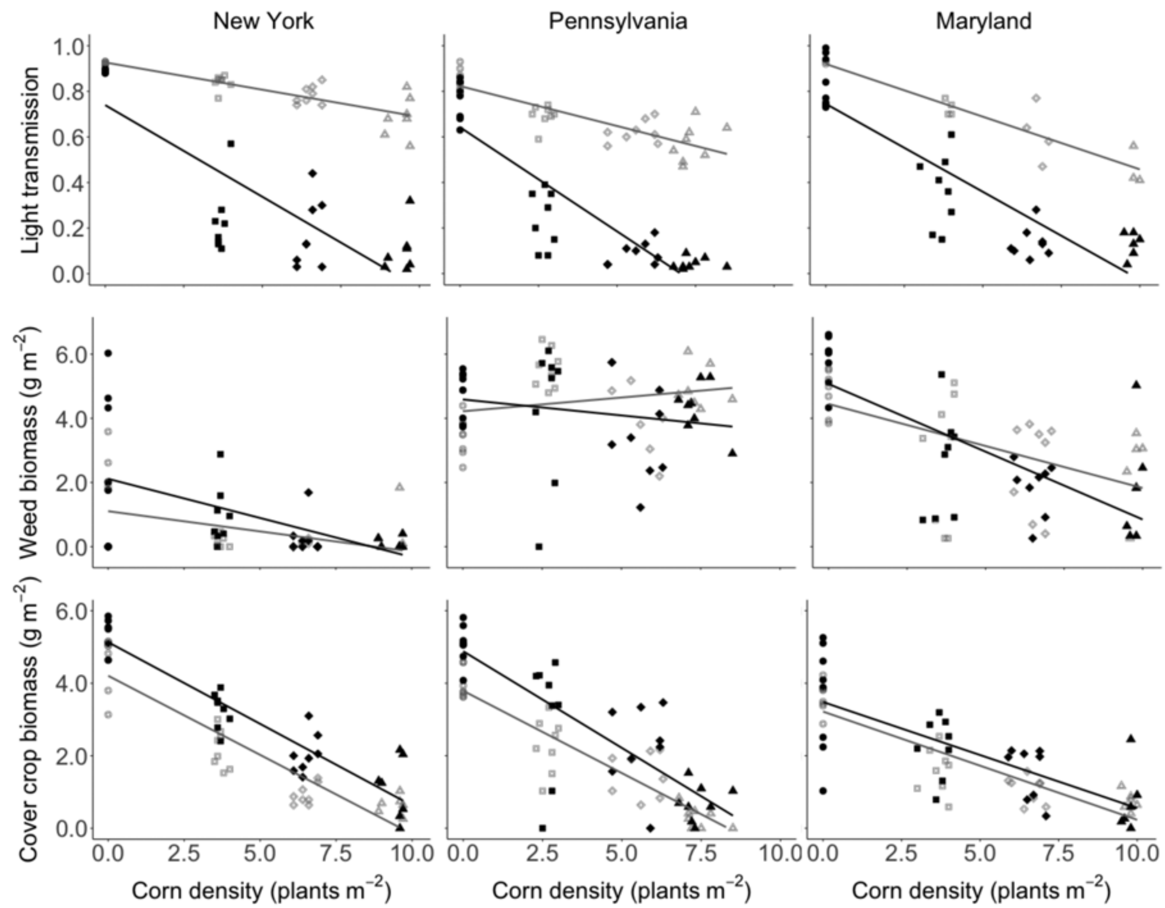

Fig. 3. The effect of corn density on light transmission, interseeded cover crop biomass, and weed biomass in the three experimental sites. All dry weight biomass data were [$\ln(x + 1)$] transformed. The gray points and regression line are data from the June sample date for PAR, and the August sample date for weed and cover crop biomass. The black points and regression line are data from the August sample date for PAR and the October sample date for weed and cover crop biomass. Circles are data from the 'No Corn' density treatments, squares are data from the 'Low' corn density treatments, diamonds are data from the 'Medium' treatments, and triangles are data from the 'High' treatments. Equations for each regression line and associated R^2 and P-values are presented in Table 6.

by weed biomass, and one mediated by light transmission and weed biomass (Fig. 4). The path coefficient corresponding to the arrow between corn density and light transmission represents a standardized simple regression relation. The path coefficients corresponding to the arrows between corn density and cover crop biomass, between light transmission and cover crop biomass, and between weed biomass and cover crop biomass represent partial coefficients. A partial coefficient is the expected change in the dependent variable associated with a unit change in a given predictor that controls for the covarying effect of another predictor (Grace and Bollen, 2005).

An indirect effect is calculated as the product of component direct effects. For example, the direct effect of corn density on light transmission is −0.82, and the direct effect of light transmission on cover crop biomass is 0.29, so the indirect effect of corn density on cover crop biomass as mediated by light transmission is −0.24. The total effect of corn density on cover crop biomass can be calculated from the sum of all the direct and indirect path coefficients of corn density on cover crop biomass (−0.88). An example of model interpretation is as follows: a one standard unit increase in corn density would directly change cover crop biomass by −0.68 standard deviation units,

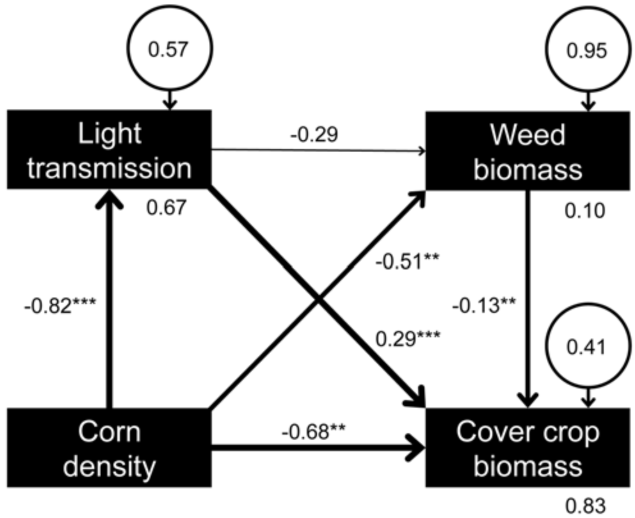

Fig. 4. Path diagram of factors influencing interseeded cover crop biomass. Arrows indicate a direct effect of one variable on another. R^2 values are on the bottom right of the variable and error terms associated with the variable are in circles in the upper right. Asterisks next to coefficients refer to significance level where ** = $P < 0.01$, *** = $P < 0.001$.

and indirectly (mediated through light transmission) by −0.24 standard deviation units.

Results from the path analysis support our second hypothesis that the effect of corn planting density on cover crop biomass is mediated by light transmission and weed biomass. Specifically, path analysis showed that corn density, light transmission, and weed biomass had significant direct effects on cover crop biomass, but corn density had the greatest effect (Table 7). The indirect effect of corn density on cover crop biomass, as mediated by either light transmission or weed biomass, was significant but not when mediated by light transmission and weed biomass. Light transmission did not have a significant direct effect on weed biomass (Table 7). Considering the dry conditions across all sites (Table 2), competition for water between the interseeded cover crops and the host cash crop could potentially explain why crop density was a stronger predictor of cover crop biomass than light transmission. However, soil moisture was not measured and thus other factors may have also contributed to this result.

To assess the proportion of variance in cover crop biomass that was explained by corn density, light transmission, and weed biomass, we used multiple linear regression and compared the partial R^2 (pr^2) and semipartial R^2 (sr^2) for each predictor variable (Table 8). Corn density explained 44% of the variance in cover crop biomass when the effect of the other two variables was controlled. Light transmittance explained 13% of the variance in cover crop biomass when the effect of the other two variables was controlled. Weed biomass explained 8% of the variance in cover crop biomass when the effect of the other two variables was controlled. Corn density, light transmission, and weed biomass uniquely accounted for 13%, 4%, and 7% of the variance in cover crop biomass, respectively.

The results from path analysis and partial and semipartial correlation reinforce the same trends. For example, path analysis showed that corn density had the greatest effect on cover crop biomass, while partial and semipartial correlation showed that corn density accounted for the most variance in cover crop biomass. These analyses are independent but complementary ways of understanding the interrelations of a network of variables; path analysis quantifies the effects of predictor variables, and partial and semipartial correlation quantify the explained variance by each predictor variable.

Table 7. Direct and indirect path coefficients of the path diagram from Fig. 4. Variables were corn density (CD; plants m^{-2}), August light transmission (LT), August cover crop biomass (CCB; g m^{-2}), and August weed biomass (WB; g m^{-2}). For direct effect path types, path coefficients are the effect of the variable to the left of the ➔ (*x*) on the variable to the right of the ➔ (*y*). For indirect effect path types, path coefficients are effect of the leftmost variable on the rightmost variable, as mediated by the variable(s) between ➔'s. *P* is the *p*-value for the path coefficient. The estimate for the path coefficient can be interpreted as the expected change in standard deviation units of *y* with an increase of one standard deviation unit of *x*.

Path type	Path	Coefficient	*P*
Direct	CD ➔ LT	–0.82	<0.001
	CD ➔ WB†	–0.51	0.003
	CD ➔ CCB†	–0.68	<0.001
	LT ➔ WB	–0.29	0.08
	LT ➔ CCB	0.29	<0.001
	WB ➔ CCB	–0.13	0.004
Indirect	CD ➔ LT ➔ CCB	–0.24	<0.001
	CD ➔ LT ➔ WB	0.24	0.09
	CD ➔ WB ➔ CCB	0.07	0.04
	LT ➔ WB ➔ CCB	0.04	0.14
	CD ➔ LT ➔ WB ➔ CCB	–0.03	0.14
Error	LT	0.57	<0.001
	WB	0.95	<0.001
	CCB	0.41	<0.001

† Dry weight biomass data were ln(x + 1) transformed for analyses.

Effects of Interseeded Cover Crops on Weed Biomass and Corn Grain Yield

Weed biomass in August and October and corn grain yield were compared between the 'Medium' and 'Medium Control' treatments to determine if interseeded cover crops suppressed weeds or corn yield. We expected the 'Medium' treatment to have a lower weed biomass than the 'Medium Control' treatment because interseeded cover crops have been shown to suppress weeds (Uchino et al., 2015). Uchino et al. (2015) found interseeded cover crops suppress inter-row weeds in corn throughout the growing season. We expected there to be no yield difference between the treatments because cover crops were interseeded after the V5 stage of corn when there is little competition between corn and the cover crop (Caswell, 2017).

Results from ANOVA showed an interaction between site and treatment for August weed biomass, a difference in mean October weed biomass in both site and treatment, and a difference in mean yield between sites (Table 9). There was no suppressive effect by interseeded cover crops on August weed biomass, but there was a suppressive effect in October, where weed biomass was lower in the 'Medium' than the 'Medium Control' treatments averaged across sites. Uchino et al. (2012, 2015) found interseeded cover crops suppressed weeds as early as 150 GDD (°C) after interseeding (approximately 40 d after interseeding) in a cool summer growing season where maximum temperatures ranged from 16.6 to 23.8 °C. Cover crops

Table 8. The proportion of variance in cover crop biomass explained by bivariate (R^2), partial (pr^2) and semipartial (sr^2) coefficients of determination for the predictor variables corn density, light transmission, and weed biomass at the August sample date. Multicollinearity was assessed with variance inflation factors (VIF), where a value > 10 indicates severe multicollinearity.

Predictor	VIF	R^2	pr^2	sr^2
Corn density	3.4	0.78	0.44	0.13
Light transmission	3.2	0.69	0.13	0.04
Weed biomass	1.1	0.01	0.08	0.07

perform better in systems where they do not compete for water and nutrients (Snapp et al., 2005), so it is possible that the weed suppressive ability of the cover crop in this experiment was inhibited by the drought conditions that prevailed during the early part of the 2016 growing season. We found support for our hypothesis that weed biomass would be suppressed by interseeded cover crops for only the October sampling date.

Summary and Management Implications

We determined the effect of corn planting density on interseeded cover crop performance in an organically managed system. A negative relationship between corn density and cover crop biomass was observed; however, corn yield was not different between the 'Low', 'Medium', and 'High' corn planting rates at two of the three sites, which could be partially due to the flex ear corn hybrid that was used. High crop planting rates are often recommended for organic farmers because of the ability of crop plants to suppress weeds by shading. However, our research suggests that organic farmers may be able to reduce corn planting rates while maintaining good weed suppression by drill interseeding cover crops. Results from this experiment should be interpreted cautiously because the experiment was conducted during a dry year and only one corn variety was used. Additional research should be conducted across a wider range of environments using different flex ear and fixed ear varieties, to determine the economic optimum corn planting density that maximizes profitability and cover crop biomass. Future research should also determine how costs (e.g., cover crop seed, equipment, labor, etc.) and benefits (e.g., improved soil health, reduced fertilizer requirements, lower weed seed production, etc.) related to drill interseeding a grass-legume cover crop mixture compares with standard post-harvest cover crop seeding and broadcast interseeding.

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Table 9. Results of ANOVA and LSmeans to determine the effect of presence/absence of interseeded cover crops on August and October weed biomass and corn yield. Site refers to the three experimental sites New York (NY), Pennsylvania (PA), and Maryland (MD). Treatment refers to the 'Medium Cover Crop' (CC) and 'Medium No Cover Crop' (NCC) treatments, which were planted with corn at 7.41 plants m^{-2}, with and without interseeded cover crops, respectively. *P*-values refer to the *F*-test in the ANOVA. Similar letters next to means within a column indicate no significant difference (α = 0.05).

Effect†	August weed biomass		October weed biomass	Corn grain yield
	P-value			
Site (*S*)	<0.001		<0.001	0.02
Treatment (*T*)	0.4		0.01	0.56
S × *T*	0.04		0.24	0.96
	$g\ m^{-2}$			
NY	–‡		1.88 b	1026 a
PA	–		62.18 a	745 b
MD	–		7.24 b	830 b
NCC	–		13.87 a	–
CC	–		6.42 b	–
NY × NCC	1.40		–	–
NY × CC	1.06	NS	–	–
PA × NCC	89.12		–	–
PA × CC	67.36	NS	–	–
MD × NCC	3.60 b		–	–
MD × CC	13.20 a		–	–

† Weed biomass data were ln(*x* + 1) transformed for analyses; back-transformed means are presented.

‡ Dash indicates effect or interaction should not be interpreted.

NS Indicates no significant difference.

REFERENCES

Andrade, F.H., P. Calvino, A. Cirilo, and P. Barbieri. 2002. Yield responses to narrow rows depend on increased radiation interception. Agron. J. 94:975–980. doi:10.2134/agronj2002.0975

Baker, J.M., and T.J. Griffis. 2009. Evaluating the potential use of winter cover crops in corn–soybean systems for sustainable co-production of food and fuel. Agric. For. Meteorol. 149:2120–2132. doi:10.1016/j.agrformet.2009.05.017

Baributsa, D.N., E.F. Foster, K.D. Thelen, A.N. Kravchenko, D.R. Mutch, and M. Ngouajio. 2008. Corn and cover crop response to corn density in an interseeding system. Agron. J. 100:981–987. doi:10.2134/agronj2007.0110

Bastiaans, L., R. Paolini, and D.T. Baumann. 2008. Focus on ecological weed management: What is hindering adoption? Weed Res. 48:481–491. doi:10.1111/j.1365-3180.2008.00662.x

Belsley, D.A., E. Kuh, and R.E. Welsch. 1980. Regression diagnostics: Identifying influential data and sources of collinearity. Wiley, Hoboken, NJ. p. 85–191. doi:10.1002/0471725153

Bond, W., and A.C. Grundy. 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383–405. doi:10.1046/j.1365-3180.2001.00246.x

Bybee-Finley, K.A., S.B. Mirsky, and M.R. Ryan. 2017. Crop biomass not species richness drives weed suppression in warm-season annual grass–legume intercrops in the Northeast. Weed Sci. 65:669–680. doi:10.1017/wsc.2017.25

Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89:1–16. doi:10.1016/j.fcr.2004.01.005

Caswell, K. 2017. Incorporating cover crops and diversified weed management to improve cropping system productivity. MA. Thesis. Penn State Univ., University Park, PA.

Cohen, J., P. Cohen, S.G. West, and L.S. Aiken. 2003. Applied multiple regression/correlation analysis for the behavioral sciences, 3rd edn. Erlbaum, Mahwah, NJ. p. 64–100.

Curran, W.S., R.J. Hoover, S.B. Mirsky, G.W. Roth, M.R. Ryan, V.J. Ackroyd, M.J. Wallace, M.A. Dempsey, and C.J. Pelzer. 2018. Evaluation of cover crops interseeded into corn (*Zea mays* L.) across the mid-Atlantic region. Agron. J. (in press). doi:10.2134/agronj2017.07.0395

Feyereisen, G.W., B.N. Wilson, G.R. Sands, J.S. Strock, and P.M. Porter. 2006. Potential for a rye cover crop to reduce nitrate loss in Southwestern Minnesota. Agron. J. 98:1416–1426. doi:10.2134/agronj2005.0134

Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron. J. 108:39–52. doi:10.2134/agronj15.0182

Fisher, K.A., B. Momen, and R.J. Kratochvil. 2011. Is broadcasting seed an effective winter cover crop planting method? Agron. J. 103:472–479. doi:10.2134/agronj2010.0318

Fox, J., and G. Monette. 1992. Generalized collinearity diagnostics. J. Am. Stat. Assoc. 87:178–183. doi:10.1080/01621459.1992.10475190

Grace, J.B., and K.A. Bollen. 2005. Interpreting the results from multiple regression and structural equation models. Bull. Ecol. Soc. Am. 86:283–295. doi:10.1890/0012-9623(2005)86[283:ITRFMR]2.0.CO;2

Hamilton, A.V. 2016. Maximizing the on-farm benefits of cover crops: Comparing management intentions and ecosystem service provisioning. MS ths. The Pennsylvania State Univ., University Park, PA.

Hashemi, M., A. Farsad, A. Sadeghpour, S.A. Weis, and S.J. Herbert. 2013. Cover crop seeding-date influence on fall nitrogen recovery. J. Plant Nut. Soil Sci. 176:69–75.

Hively, W.D., and W.J. Cox. 2001. Interseeding cover crops into soybean and subsequent corn yields. Agron. J. 93:308–313. doi:10.2134/agronj2001.932308x

Kim, S. 2015. ppcor: An R package for a fast calculation to semi-partial correlation coefficients. Commun. Stat. Appl. Methods 22:665–674.

Kutner, M.H., C.J. Nachtsheim, J. Neter, and W. Li. 2005. Applied linear statistical models. 5th ed. McGraw-Hill/Irwin, New York. p. 406– 414.

Liebert, J.A., and M.R. Ryan. 2017. High planting rates improve weed suppression, yield, and profitability in organically-managed, no-till—planted soybean. Weed Technol. 31:536–549. doi:10.1017/wet.2017.35

Loomis, R.S., W.A. Williams, W.G. Duncan, A. Dovrat, and F. Nunez. 1968. Quantitative descriptions of foliage display and light absorption in field communities of corn plants. Crop Sci. 8:352–356. doi:10.2135/cropsci1968.0011183X000800030027x

McEvoy, M. 2012. Sodium nitrate use in organic crop production. National Organic Program Notice 12-1. USDA Agricultural Marketing Service, Washington, D.C. https://www.ams.usda.gov/sites/default/files/media/NOP-Notice-12-1-SodiumNitrate.pdf (accessed 25 July 2018).

NRCS Iowa. 2010. Aerial seeding of cover crops. Technical notes, Agronomy #36. U.S. Department of Agriculture, Des Moines, IA.

Rajcan, I., and C.J. Swanton. 2001. Understanding maize–weed competition: Resource competition, light quality and the whole plant. Field Crops Res. 71:139–150. doi:10.1016/S0378-4290(01)00159-9

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Roesch-McNally, G.E., A.D. Basche, J.G. Arbuckle, J.C. Tyndall, F.E. Miguez, T. Bowman, and R. Clay. 2017. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renewable Agriculture and Food Systems 33:322–333.

Ross, S.M., J.R. King, J.T. O'Donovan, and R.C. Izaurralde. 2003. Seeding rate effects in oat-berseem clover intercrops. Can. J. Plant Sci. 83:769–778. doi:10.4141/P02-130

SARE, CTIC, and ASTA. 2015. 2014–2015 SARE cover crop report. Sustainable Agriculture Research and Education Program, Conservation Technology Information Center, American Seed Trade Association, West Lafayette, IN.

Schipanski, M.E., M. Barbercheck, M.R. Douglas, D.M. Finney, K. Haider, J.P. Kaye, A.R. Kemanian, D.A. Mortensen, M.R. Ryan, J. Tooker, and C. White. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125:12–22. doi:10.1016/j.agsy.2013.11.004

Singer, J.W., D.W. Meek, T.J. Sauer, J.H. Prueger, and J.L. Hatfield. 2011. Variability of light interception and radiation use efficiency in maize and soybean. Field Crops Res. 121:147–152. doi:10.1016/j.fcr.2010.12.007

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97:322–332.

Staver, K., and R. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. J. Soil Water Conserv. 53:230–240.

Teasdale, J.R. 1995. Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance. Weed Technol. 9:113–118. doi:10.1017/S0890037X00023046

Teasdale, J.R. 1998. Influence of corn (*Zea mays*) population and row spacing on corn and velvetleaf (*Abutilon theophrasti*) yield. Weed Sci. 46:447–453.

Thomison, P.R., and D.M. Jordan. 1995. Plant population effects on corn hybrids differing in ear growth habit and prolificacy. J. Prod. Agric. 8:394–400. doi:10.2134/jpa1995.0394

Tollenaar, M., A.A. Dibo, A. Aguilara, S.F. Weise, and C.J. Swanton. 1994. Effect of crop density on weed interference in maize. Agron. J. 86:591–595. doi:10.2134/agronj1994.00021962008600040003x

Uchino, H., K. Iwama, Y. Jitsuyama, K. Ichiyama, E. Sugiura, T. Yudate, and J. Gopal. 2012. Effect of interseeding cover crops and fertilization on weed suppression under an organic and rotational cropping system. Field Crops Res. 127:9–16. doi:10.1016/j.fcr.2011.10.007

Uchino, H., K. Iwama, Y. Jitsuyama, T. Yudate, S. Nakamura, and J. Gopal. 2015. Interseeding a cover crop as a weed management tool is more compatible with soybean than with maize in organic farming systems. Plant Prod. Sci. 18:187–196. doi:10.1626/pps.18.187

USDA NASS. 2017. Quick stats. USDA National Agricultural Statistics Service, Washington, D.C. https://quickstats.nass.usda.gov/#0070BD79-60FE-3110-882E-9BEBAA697B95 (accessed 19 Dec. 2017).

Wallace, J., W. Curran, S. Mirsky, and M. Ryan. 2017. Tolerance of interseeded annual ryegrass and red clover cover crops to residual herbicides in mid-Atlantic corn cropping systems. Weed Tech. 31:1–10. doi:10.1017/wet.2017.48

Wallander, S. 2013. While crop rotations are common, cover crops remain rare. In: USDA-ERS, editor, AmberWaves: The economics of food, farming, natural resources, and rural America. USDA ERS, Washington, D.C.

Weiner, J., H.W. Griepentrog, and L. Kristensen. 2001. Suppression of weeds by spring wheat *Triticumaestivum* increases with crop density and spatial uniformity. Journal of Applied Ecology 38:784–790.

Westgate, M.E., F. Forcella, D.C. Reicosky, and J. Somsen. 1997. Rapid canopy closure for maize production in the northern US Corn Belt: Radiation-use efficiency and grain yield. Field Crops Res. 49:249–258. doi:10.1016/S0378-4290(96)01055-6

White, C., M. Barbercheck, and W. Curran. 2015. Penn State organic crop production guide. The Pennsylvania State University, University Park, PA.