DEVELOPING THE SYSTEM:

CULTURAL PRACTICES TO ENHANCE WEED SUPPRESSION AND PROFITABILITY IN ORGANIC NO-TILL PLANTED SOYBEAN

A Thesis

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ABSTRACT

Cultural practices are an integral component of a multi-tactic approach to weed management. In cover crop-based organic rotational no-till soybean (*Glycine max* [L.] Merr.) production, these practices play a particularly important role in the absence of mechanical weed management. In this system, a fall-planted winter cereal cover crop, such as cereal rye (*Secale cereale* L.), is mechanically terminated with a roller-crimper in the spring to create a layer of mulch. Soybean is then no-till planted through the mulch, which serves as the primary form of weed suppression. Species and cultivar selection, planting date, planting rate, timing of termination, and fertility management are all common cultural practices that can be used to enhance the weed suppression effects provided by these fall-planted cover crops. Previous research has focused on adjusting these practices to maximize cereal rye biomass and create a thick layer of mulch. However, high biomass production can be difficult to achieve, and thick mulch can impede adequate seed-to-soil contact during soybean planting.

To overcome the challenges associated with excessive biomass production, our research investigated cultural practices that enhance shading before and after no-till planting soybean. In this way, our research aimed to optimize both early- and late-season weed suppression, which has the potential to improve soybean performance and economic profitability.

Based on differences in plant height and leaf morphology, our first experiment assessed whether intercropping barley (*Hordeum vulgare* L.) and cereal rye would improve shading prior to termination and reduce weed biomass compared with either species in monoculture. In contrast to previous efforts to improve weed suppression through cover crop management, our approach was predicated on enhanced shading without a concomitant increase in biomass

production. Conducted from 2012 to 2014 in central New York, the two species were seeded in a replacement series (barley:cereal rye, 0:100 , 50:50, and 100:0). Average weed biomass across all treatments in late summer ranged from 0.5 to 1.1 Mg ha^{-1} in 2013 and 0.6 to 1.3 Mg ha^{-1} in 2014. Although weed biomass tended to decrease as the proportion of cereal rye in the mixture increased, soybean population also decreased as the proportion of cereal rye increased in 2013. The results from our partial correlation analyses indicated that shading prior to cover crop termination explained more variation in weed biomass than cover crop biomass.

Our second experiment examined the cultural practice of using high soybean planting rates to improve weed suppression by attaining canopy closure more rapidly and maximizing light interception. This tactic can minimize weed germination, decrease weed competitive ability, and reduce the fecundity of weeds that have emerged prior to terminating a cover crop with a roller-crimper, thereby improving long-term weed seedbank management. The experiment was conducted in 2014 in central (Aurora) and eastern (Hurley) New York, and planting rates of 198,000; 395,000; 595,000; 790,000; and 990,000 seeds ha^{-1} were arranged in a randomized complete block design. Weed biomass decreased and soybean yield increased as soybean population increased at both sites. An asymptotic relationship between increasing soybean population and yield was observed, and the maximum yields were estimated at 2,506 kg ha^{-1} in Aurora and 3,282 kg ha^{-1} in Hurley. Partial returns declined beyond the predicted economically optimal planting rates of 650,000 and 720,000 seeds ha^{-1} in Aurora and Hurley, respectively, as greater seed costs were no longer offset by an increase in soybean yield.

Our research has demonstrated that there are meaningful gains to be made by optimizing cultural practices for both cover crop and soybean management. Enhancing early-season shading with cover crop mixtures has the potential to minimize the challenges associated with excessive biomass production, while still maintaining adequate weed suppression. As a complementary cultural practice, high soybean planting rates can improve late-season shading via earlier canopy closure, which contributes to enhanced weed suppression, higher yields, and greater profitability.

BIOGRAPHICAL SKETCH

Born and raised on Vancouver Island, Jeff is from British Columbia, Canada. He completed his BSc at the University of British Columbia (UBC) in the Global Resource Systems program, specializing in soil science and agroecology. While attending UBC, he helped design and build numerous school and community gardens in Vancouver, BC. Jeff also worked at the 24-hectare organically-managed UBC Farm where he developed perennial crop nutrient management protocols, oversaw the Community-Supported Agriculture (CSA) program, and assisted with rotationally-grazed, integrated crop-livestock research.

Dedicated to Sophia Palmer

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

ROLLED MIXTURES OF BARLEY AND CEREAL RYE FOR WEED SUPPRESSION IN COVER CROP-BASED ORGANIC NO-TILL PLANTED SOYBEAN

ABSTRACT

Maximizing cereal rye biomass has been recommended for weed suppression in cover crop-based organic no-till planted soybean; however, achieving high biomass can be challenging and thick mulch can interfere with soybean seed placement. An experiment was conducted from 2012 to 2014 in New York to test whether mixing barley and cereal rye would (1) increase weed suppression via enhanced shading prior to termination, and (2) provide acceptable weed suppression at lower cover crop biomass levels compared with cereal rye alone. This experiment was also designed to assess high-residue cultivation as a supplemental weed management tool. Barley and cereal rye were seeded in a replacement series, and a split-block design with four replications was used with management treatments as main plots and cover crop seeding ratio treatments (barley:cereal rye, 0:100 , 50:50, and 100:0) as subplots. Management treatments included high-residue cultivation (HRC) and standard no-till management without high-residue cultivation (SNT). Despite wider leaves in barley, mixing the species did not increase shading. Across all treatments, average weed biomass in late summer ranged from 0.5 to 1.1 Mg ha^{-1} in 2013 and 0.6 to 1.3 Mg ha^{-1} in 2014, and weed biomass tended to decrease as the proportion of cereal rye increased. However, soybean population also decreased as the proportion of cereal rye increased in 2013. Soybean yield under no-till management averaged 2.9 Mg ha^{-1} in 2013 and

2.6 Mg ha^{-1} in 2014 and was not affected by cover crop ratio or management treatment. Partial correlation analyses demonstrated that shading from cover crops prior to termination explained more variation in weed biomass than cover crop biomass. Our results indicate that cover crop management practices that enhance shading at slightly lower cover crop biomass levels might reduce the challenges associated with excessive biomass production without sacrificing weed suppression in organic no-till planted soybean.

INTRODUCTION

Challenges with current weed management practices have prompted farmers, agronomists, and agroecologists to explore alternative approaches that reduce environmental degradation and non-target effects. For example, soil tillage and inter-row cultivation, which are common weed management practices in organic cropping systems, can increase soil erosion (Lal 1991; Logan et al. 1991; Pimentel et al. 1995) and greenhouse gas emissions (Lal 2004; Paustian et al. 2000; Reicosky 1997). On the other hand, synthetic herbicides used in conventional management can alter plant communities in adjacent non-crop areas, reduce habitat quality, and depress biodiversity (Boutin et al. 2014; Pleasants and Oberhauser 2013; Relyea 2005). Increasing problems with herbicide-resistant weeds have also stimulated interest in practices that can be used to reduce selection pressure and the development of resistant populations (Beckie 2006; Mortensen et al. 2012; Norsworthy et al. 2012). In addition to these management considerations, concerns about food security have prompted agriculturists to identify and design cropping systems that provide supporting and regulating ecosystem services in addition to simply provisioning agricultural products (Foley et al. 2005). Cover crops are a viable solution to many of the problems with current weed management practices, and cover crop-based systems can increase soil nitrogen (N) and carbon (McDaniel et al. 2014; Poeplau and Don 2015) while providing many other important ecosystem services (Schipanski et al. 2014).

In conventional no-till cropping systems, non-selective, postemergence herbicides are commonly used to terminate cover crops prior to planting a cash crop (Ashford and Reeves 2003; Weston 1990). As synthetic herbicides are not permitted in organic production, growers must instead rely on physical methods for cover crop management. Mowing can be successfully used for cover crop termination (Creamer and Dabney 2002; Wilkins and Bellinder 1996), but only certain types of mowers are compatible with organic no-till systems. For instance, both rotary and flail mowers can unevenly distribute cover crop residue, resulting in poor weed suppression in areas where the mulch layer is thin or absent (Teasdale and Mohler 2000). Mowing prior to anthesis at Zadoks 60 growth stage (Zadoks et al. 1974) can also stimulate some cover crops to regrow, which increases competition with the cash crop for available light, moisture, and nutrients (Raper et al. 2004; Westgate et al. 2005). Additionally, rotary and flail mowing increases the surface area of cover crop residue, thereby accelerating decomposition and diminishing the persistence of the mulch and its ability to physically suppress weeds later in the season (Creamer and Dabney 2002).

As an alternative to mowing, terminating cover crops with a roller-crimper is gaining popularity among organic grain farmers in North America (Mirsky et al. 2012; Raper et al. 2004). The most commonly used roller-crimper model in the United States (U.S.) is a steel cylinder (41- to 51-cm diameter) with blunt metal blades arranged in a chevron pattern (Mirsky et al. 2012). When used at growth stages immediately following anthesis, cover crop termination with a roller-crimper is as effective as herbicides (Ashford and Reeves 2003; Davis 2010; Mirsky et al. 2009) and requires less energy to operate than mowing (Ashford and Reeves 2003). In contrast to rotary and flail mowing, rolling-crimping creates a unidirectional cover crop mulch layer that is oriented in the direction of travel. When growers plant a cash crop parallel to the direction of rolling-crimping, the amount of residue lodged in the furrow (i.e., hair-pinning) is reduced, coulter function is improved, and seed-to-soil contact is enhanced compared with planting after rotary or flail mowing (Ashford and Reeves 2003). Sickle-bar mowers do not shred plant residue, and some research has indicated that it can be a viable substitute for a roller-crimper (Bernstein et al. 2011). However, cut residue can shift under windy conditions, and it can be dragged through the field with planting, high-residue cultivation, and harvesting equipment.

Previous research on cover crop-based organic no-till planted soybean (*Glycine max* [L.] Merr.) systems has often focused on maximizing cereal rye (*Secale cereale* L.) biomass through cultivar selection (Wells et al. 2015), or by manipulating seeding date (Nord et al. 2012; Ryan et al. 2011b), soil fertility (Ryan et al. 2011a), and termination date (Mirsky et al. 2011; Nord et al. 2012; Wayman et al. 2014). Based on work by Teasdale and Mohler (2000), a minimum threshold for cereal rye biomass of 8.0 Mg ha^{-1} at cover crop termination has been recommended for optimal weed suppression in the subsequent cash crop (Mirsky et al. 2012; Mirsky et al. 2013). However, multiple challenges can arise from such high biomass production: (1) soybean seed placement through the thick mulch can be difficult (De Bruin et al. 2005; Liebl et al. 1992; Wagner-Riddle et al. 1994); (2) soil water content can be depleted, reducing soybean germination and decreasing yield (De Bruin et al. 2005; Liebl et al. 1992; Wells et al. 2015); and (3) the amount of soybean lodging can increase (Smith et al. 2011).

Whereas excessive cover crop biomass can present numerous difficulties, insufficient biomass production can be equally challenging to manage. A variety of factors can result in poor cereal rye cover crop growth, including late establishment and low soil N. In these instances, a "rescue cultivation" can effectively control weeds, reducing the risk of soybean yield loss and contributions to the soil weed seedbank (Nord et al. 2011). If soybeans are no-till planted in 76-cm rows, high-residue cultivators with low-angle wide sweeps can be used to slice through the soil just below the surface, severing weed shoots from roots. Under ideal operating conditions, the soil is not inverted and the thin shanks limit the amount of cover crop residue that is disturbed.

In this research, we quantified the effects of intercropping barley (*Hordeum vulgare* L.) and cereal rye on weed suppression and soybean performance. Importantly, relying more on shading prior to cover crop termination than total cover crop biomass production for weed control minimizes the challenges associated with thick cover crop mulches. Barley was selected to complement the well-documented productivity of cereal rye because it is also a winter-hardy small grain, but it is shorter in stature and has broader leaves than cereal rye. These differences in plant height and leaf morphology might increase light interception through resource partitioning. To investigate the potential of barley and cereal rye mixtures to enhance light interception and weed suppression in cover crop-based organic no-till planted soybean, our research consisted of two primary objectives: (1) quantify the impact of cover crop mixtures of barley and cereal rye on shading, weed suppression, and soybean yield; and (2) compare the effect of high-residue cultivation (HRC) and standard no-till (SNT) on weed biomass and soybean yield. These research objectives were framed by the following hypotheses: (1) mixtures of barley and cereal rye will result in greater weed suppression than a monoculture of either cover crop, and (2) weed suppression and soybean yield will be greater in HRC than in SNT.

MATERIALS AND METHODS

Site Description and Experimental Design

We conducted a field experiment from 2012 to 2014 at the Cornell University Musgrave Research Farm in Aurora, New York (42.73°N, 76.66°W). This time frame comprises data collection from two main growing seasons: year 1 (2012 to 2013) and year 2 (2013 to 2014). The dominant soil type is a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs), with partial tile drainage in both field sites. Soft red winter wheat (*Triticum aestivum* L.) was conventionally managed prior to the initiation of the experiment for years 1 and 2. Across both years, the soil pH ranged from 7.7 to 7.8, and the organic matter content (determined by measuring the mass loss on ignition at 500°C) ranged from 3.4 to 3.6%. Due to the previous conventional management, this experiment represents crop production under the first year of organic transition.

A spatially balanced split-block design with four replications was used with management treatments (HRC and SNT) as main plots and cover crop seeding ratio treatments as subplots. In addition to HRC and SNT, a management treatment consisting of no cover crop, tilled soil, and inter-row cultivation (IRC) was included in plots adjacent to the experiment to evaluate soybean performance under typical organic soybean management. Although this management treatment was not included in a formal statistical analysis, it served as an external control that was superior to comparing to the county average because it represented no-herbicide management conditions. In 2012 and 2013, barley and cereal rye were seeded in a replacement series with three seeding ratio treatments. Each cover crop was planted in monoculture (barley:cereal rye, 0:100 and 100:0), as well as in biculture (50:50). Cover crop seeding rates were based on the rate used in cereal rye monoculture (12.6 g m^{-2}). The seeding rates for the barley monoculture and mixtures were determined volumetrically, such that the same volume was seeded in all plots. When a replacement series is used to study metrics of plant competition, such as interference and niche differentiation, interpretations of the results can be limited (Connolly 1986; Connolly et al. 2001; Firbank and Watkinson 1985; Inouye and Schaffer 1981; Jolliffe 2000; Taylor and Aarssen 1989). However, many of these limitations might not apply if the research objective is to compare yields between monocultures and mixtures (Jolliffe 2000). As we are not assessing plant competition and density dependence is not detrimental to testing our hypotheses, we implemented a practical approach to cover crop seeding that is common among farmers. Each subplot measured 6.1 by 9.1 m in size, which was large enough to facilitate farm-scale equipment and destructive sampling of the cover crops.

Field Operations

Prior to planting the cover crops in fall 2012 and 2013, the field was moldboard plowed and prepared with a field cultivator (Unverferth Perfecta II), and poultry litter (5–4–3, $N–P_2O_5–K_2O$ [Krehers Enterprises, Clarence, NY]) was broadcast applied with a box-spreader at 56 kg total N ha^{-1}. After incorporating the poultry litter with a cultimulcher (John Deere 950), ‘Valor’ barley and ‘Aroostook’ cereal rye were seeded with a drill (John Deere 450) on September 17, 2012 in year 1, and September 7, 2013 in year 2. The cover crops were seeded with 19-cm row spacing at a depth of 2.5 cm.

As barley matures earlier than cereal rye, cover crop termination was delayed until after cereal rye had reached anthesis, with rolling occurring on June 19, 2013 and June 16, 2014 for years 1 and 2, respectively (Table 1.1). Front-mounted on a tractor and driven at approximately

Table 1.1. Dates of field operations in 2013 and 2014 for the standard no-till (SNT) and high-residue cultivation (HRC) management treatments, as well as the tillage-based inter-row cultivation (IRC) comparison in the experiment in Aurora, New York.

	Management treatment					
	Standard no-till (SNT)		High-residue cultivation (HRC)		Inter-row cultivation (IRC)	
Field operation	2013	2014	2013	2014	2013	2014
Preplant tillage[a]	—[b]	—	—	—	Jun 1 to 7	May 25 to 31
Rolling-crimping	Jun 19	Jun 16	Jun 19	Jun 16	—	—
Soybean planting	Jun 19	Jun 16	Jun 19	Jun 16	Jun 19	Jun 16
High-residue cultivation	—	—	Jul 16	Aug 11	—	—
Inter-row cultivation	—	—	—	—	Jul 15	Jul 2
	—	—	—	—	Jul 25	Jul 9
	—	—	—	—	—	Jul 16
Soybean harvest	Oct 17	Nov 3	Oct 17	Nov 3	Oct 17	Nov 3

[a] Preplant operations included moldboard plowing, disking, and cultipacking.
[b] A dash (—) indicates that the operation was not conducted.

7 km h^{-1}, the 3-m-wide roller-crimper (I & J Manufacturing) was filled with water for a total mass of 1,195 kg. The cover crops were rolled perpendicular to the direction of sowing to achieve more uniform ground cover and improve soybean seed placement (Kornecki et al. 2005). For IRC management, a field cultivator was used to bury any weeds that had emerged, and then a cultimulcher was used to prepare the seedbed for planting. On the same date as cover crop termination, rhizobium-inoculated 'HS13A11' soybean (maturity group I) was no-till planted through the rolled cover crop mulch (HRC and SNT) or bare soil (IRC) at a depth of 3 cm using a 4-row planter (John Deere 7200 MaxEmerge 2). As the soil was particularly dry at planting in 2014, we added 318 kg of weight to the 4-row planter to increase the down-pressure and ensure seed placement was at the targeted depth. Soybean was planted parallel to the direction of cover crop rolling with 76-cm row spacing, and a high seeding rate of 740,000 seeds ha^{-1} was used as a cultural weed management tactic. Soybean canopy closure is attained earlier at higher seeding

rates, which contributes to weed control through increased shading (Arce et al. 2009; Bastiaans et al. 2008; Place et al. 2009; Ryan et al. 2011b).

For HRC management, a 4-row no-till high-residue cultivator (John Deere 886) was used on July 16, 2013 in year 1 and August 11, 2014 in year 2. The SNT treatment did not include any supplemental weed management. For weed control under IRC management in 2013, an inter-row cultivator was used on July 15 and July 25. In 2014, inter-row cultivation occurred on July 2, July 9, and July 16. A 7- to 10-day interval between cultivation events was used to provide enough time for recently germinated summer annual weeds to emerge, thereby enhancing the efficacy of the following cultivation.

Sampling and Data Collection

On the same day as cover crop termination, photosynthetically active radiation (PAR) transmittance through the canopy was measured prior to rolling-crimping with a line quantum sensor (LI-COR LI-191) linked to a point quantum sensor (LI-COR LI-190) at solar noon. The line sensor was placed on the soil surface between two rows of cover crops, and the point sensor was mounted on a telescoping monopod extended above the canopy to obtain reference values for instantaneous calculation of PAR transmittance. Also before rolling-crimping, aboveground cover crop stem density and biomass were quantified within each plot. Before removing the biomass, cover crop stem density was assessed by counting stems with seed heads by species within the quadrats. To estimate biomass, barley and cereal rye vegetation was clipped at the soil surface within a 0.5-m^2 quadrat, and then samples were oven-dried at 50°C for approximately 1 week and weighed.

Weed biomass samples were collected approximately 11 weeks after planting, just prior to maturation of several dominant weeds in the experiment. Weeds were clipped at the soil surface within a 0.5-m^2 quadrat and separated according to species as follows: (1) common ragweed (*Ambrosia artemisiifolia* L.); (2) giant foxtail (*Setaria faberi* Herrm.) and yellow foxtail (*Setaria pumila* [Poir.] Roemer & J.A. Schultes); and (3) all other weed species. Common ragweed and the two foxtail species were separated from all other weeds because they were identified as the most abundant (i.e., dominant) species in the experiment based on visual estimates of weed cover. Weed biomass samples were dried and weighed as described for the cover crop samples. Soybean population was assessed by counting individual plants within a 0.5-m^2 quadrat at soybean harvest on October 17, 2013 for year 1 and November 3, 2014 for year 2. Soybean yield was determined by harvesting mature plants with a 2-row plot combine (ALMACO SP20) and adjusting grain moisture to 13%.

Statistical Analyses

Data were analyzed using R version 3.1.0 (R Core Team 2014). We used linear mixed-effects models (*lmer* function in the *lme4* package in R; Bates et al. 2015) with block as a random effect to test for relationships among seeding ratio, management treatment, PAR transmittance, cover crop biomass, weed biomass, common ragweed biomass, soybean population, and soybean yield. Interactions between these factors and year were also tested, and year was removed during model simplification if the interaction or main effect of year was not significant ($P > 0.05$).

For linear mixed-effects models, calculating the coefficient of determination (R^2) can lead to numerous issues, such as a decreasing or negative R^2 when additional independent variables are introduced (Nakagawa and Schielzeth 2013). To overcome these deficiencies, we used the *r.squaredGLMM* function (*MuMIn* package; Bartoń 2015) to calculate two types of R^2: the marginal coefficient of determination (R_m^2) and conditional coefficient of determination (R_c^2). The R_m^2 represents the proportion of response variance that is associated with the fixed effects only, whereas the R_c^2 describes the variance explained by both fixed and random effects (Nakagawa and Schielzeth 2013).

When two predictor variables in a model are linearly related, the presence of collinearity (or multicollinearity when there are more than two predictors) can result in unstable parameter estimates and inflated standard errors (Dormann et al. 2013). Particularly problematic is the inability to separate the unique effects of each variable, which in some instances is the primary motivation for using multiple regression. To measure the degree of collinearity between two predictor variables, we used the *vif* function (*car* package; Fox and Weisberg 2011) for the variance-inflation factor (VIF) calculation (Marquardt 1970), which is described as

$$VIF_i = \frac{1}{1-R_i^2} \ , \qquad [1]$$

where R_i^2 is the multiple correlation coefficient of X_i regressed on the remaining predictor variables (Belsley et al. 1980). If the predictor variables are uncorrelated, then $R_i^2 = 0$ and VIF_i will be the minimum value of 1 (Fox and Monette 1992). Widely used as diagnostic measurement, many competing "rules of thumb" have been proposed for identifying severe or excessive collinearity when assessing a VIF (O'Brien 2007). Most commonly, it has been suggested that a VIF > 10 indicates severe collinearity (Kutner et al. 2005; Marquardt 1970; Neter et al. 1996). However, Fox (1997) proposed that the precision of estimation (square root of the VIF) is seriously degraded at a VIF > 4, and it has even been suggested that a VIF as low as 2 can indicate problematic collinearity (Graham 2003). Condition indices (CI) are a complimentary diagnostic tool for identifying collinearity, with a CI > 30 commonly used as an indicator of severe collinearity (Belsley et al. 1980; Rawlings et al. 1998). We used the *colldiag* function (*perturb* package; Hendrickx 2015) to obtain condition indices for the two predictors.

For our multiple regression analysis, we were specifically interested in calculating semipartial and partial R^2 to partition the proportion of variance in weed biomass that each predictor variable (PAR transmittance and cover crop biomass) accounted for. The formulae for the semipartial correlation (sr_i) between each predictor and the response can be described as

$$sr_1 = \frac{r_{Y1} - r_{Y2}r_{12}}{\sqrt{1 - r_{12}^2}} \quad \text{and} \qquad [2.1]$$

$$sr_2 = \frac{r_{Y2} - r_{Y1}r_{12}}{\sqrt{1 - r_{12}^2}} \quad , \qquad [2.2]$$

where sr_1 and sr_2 express the correlation between the entirety of weed biomass (Y) and a predictor variable from which the other predictor has been "partialed" or controlled for (Cohen et al. 2003); r_{Y1} is the bivariate correlation between Y and PAR transmittance (X_1); r_{Y2} is the bivariate correlation between Y and cover crop biomass (X_2); and r_{12} is the bivariate correlation between the two predictor variables, X_1 and X_2. These are considered semipartial correlations because the effects of X_2, for example, have been uncoupled from X_1, but not from Y (Cohen et al. 2003). Squaring the semipartial correlation represents sr_i^2, which can be understood as the proportion of variance in Y explained by a given predictor beyond that which is explained by the partialed predictor (Preacher 2006).

Partial correlation (pr_i) is the correlation between X_i and Y in which the other predictor has been partialed from both X_i and Y. This relationship is given by

$$pr_1 = \frac{r_{Y1} - r_{Y2}r_{12}}{\sqrt{1 - r_{Y2}^2}\sqrt{1 - r_{12}^2}} \quad \text{and} \qquad [3.1]$$

$$pr_2 = \frac{r_{Y2} - r_{Y1} r_{12}}{\sqrt{1 - r_{Y1}^2}\sqrt{1 - r_{12}^2}} \quad , \qquad [3.2]$$

where pr_1 represents the partial correlation between X_1 and Y after controlling for the effect of X_2 on both X_1 and Y, and pr_2 is the corresponding relationship with respect to X_2. Of the variance in Y that is not estimated by the other predictor in the model, the coefficient of partial determination (pr_i^2) represents the amount of that remaining Y variance explained by X_i (Cohen et al. 2003). Semipartial and partial correlations were determined in R with the *spcor* and *pcor* functions (*ppcor* package; Kim 2015), respectively.

Mixed-effects analysis of covariance (ANCOVA) was used to evaluate the effect of management treatment (SNT and HRC) and year (2013 and 2014) on weed biomass, common ragweed biomass, soybean population, and soybean yield while accounting for seeding ratio or cover crop biomass as covariates and block as a random effect. Diagnostic tests were performed to ensure that there was independence of the covariate and the treatment effects, and homogeneity of the regression slopes. Tukey's Honest Significant Difference (HSD) test was performed with the *HSD.test* function (*agricolae* package; Mendiburu 2015) to compare the means of cover crop biomass production. Data for all analyses were tested to ensure that the errors exhibited homogeneity of variance, independence, and normal distribution.

RESULTS AND DISCUSSION

Weather and Field Conditions

The cover crop and soybean growing seasons for years 1 and 2 were characterized by highly variable precipitation (Figure 1.1) and temperatures similar to the long-term average (1956 to 2014) (Northeast Regional Climate Center 2015). Compared with the long-term average, precipitation was greater by 6% or less during the cover crop growing season in years 1 and 2.

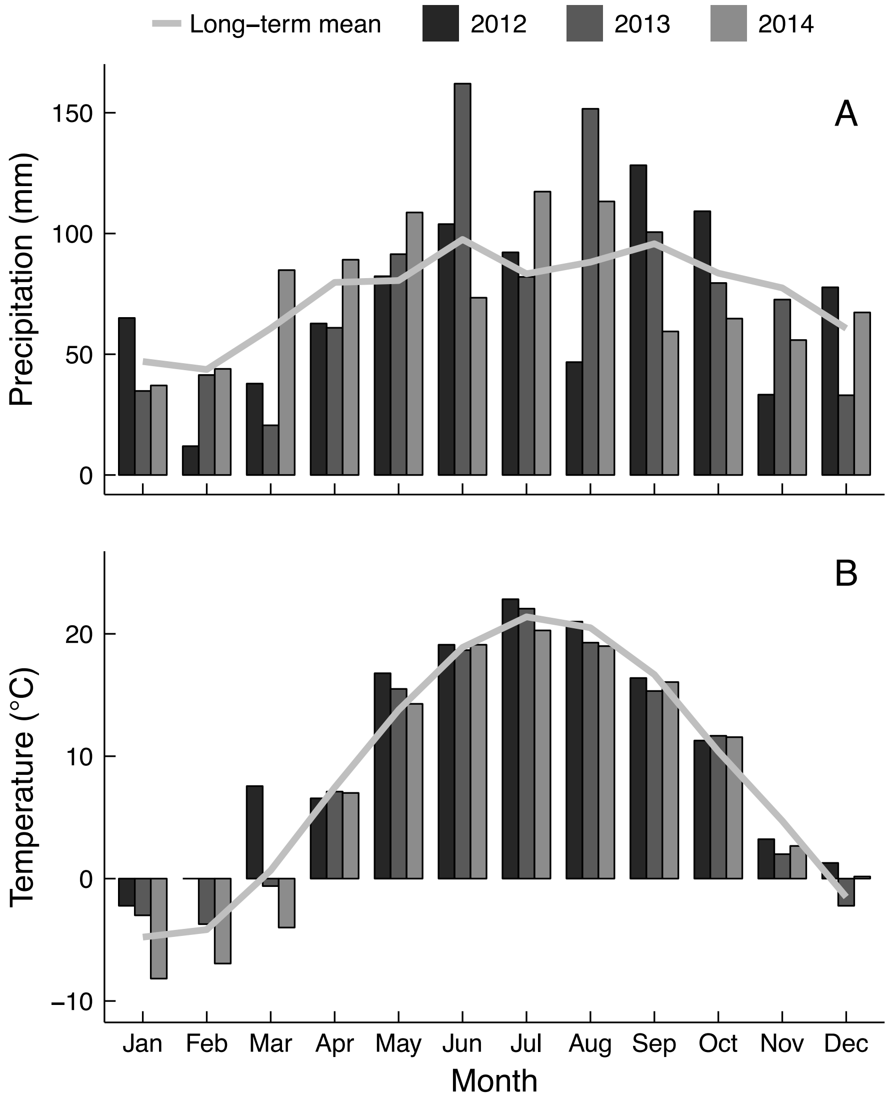

Figure 1.1. Monthly precipitation from 2012 to 2014 and the long-term mean (A), and mean monthly temperatures and the long-term mean (B). Data are from the Northeast Regional Climate Center (2015).

However, there was 28% more precipitation during the 2013 soybean growing season and 7% less precipitation in 2014 compared with the long-term average. Notably, June and August in 2013 were much wetter than the long-term average for each month with 65 and 73% more precipitation, respectively.

Average monthly temperatures were similar to the long-term average during the cover crop growing seasons (September 17, 2012 to June 19, 2013 and September 7, 2013 to June 16, 2014) and soybean growing seasons (June 19, 2013 to October 17, 2013 and June 16, 2014 to November 3, 2014). A total of 2,161 and 2,096 growing degree-days (GDD, base 10°C) accumulated from June 1 to October 31 in 2013 and 2014, respectively (Northeast Regional Climate Center 2015). The long-term average for this site is 2,218 GDD.

In 2014, precipitation was above average from March through May and below average, overall, from June through October. Tile drainage in the 2014 field site did not function as well as the tile drainage in 2013, which exacerbated the effects of above-average rainfall in the spring. In some plots, this resulted in a tenfold increase in biomass production directly above the irregularly spaced tiles compared with adjacent, poorly drained areas. Areas affected by poor tile drainage were mapped, and data from plots within these areas were excluded from analyses after statistical procedures, such as measuring Cook's distance, were used to verify whether the outliers were influential.

Cover Crop Biomass Production and PAR Transmittance

Cover crop biomass production was more variable in 2014 than 2013, which was likely due to poor drainage in the 2014 field site. As the proportion of cereal rye increased in 2013, mean cover crop biomass increased from 2.6 Mg ha^{-1} in the barley monoculture to 5.2 Mg ha^{-1} in the cereal rye monoculture (Figure 1.2). In 2014, mean cover crop biomass was again greatest in the cereal rye monoculture at 4.5 Mg ha^{-1}, but the biculture was the least productive seeding ratio

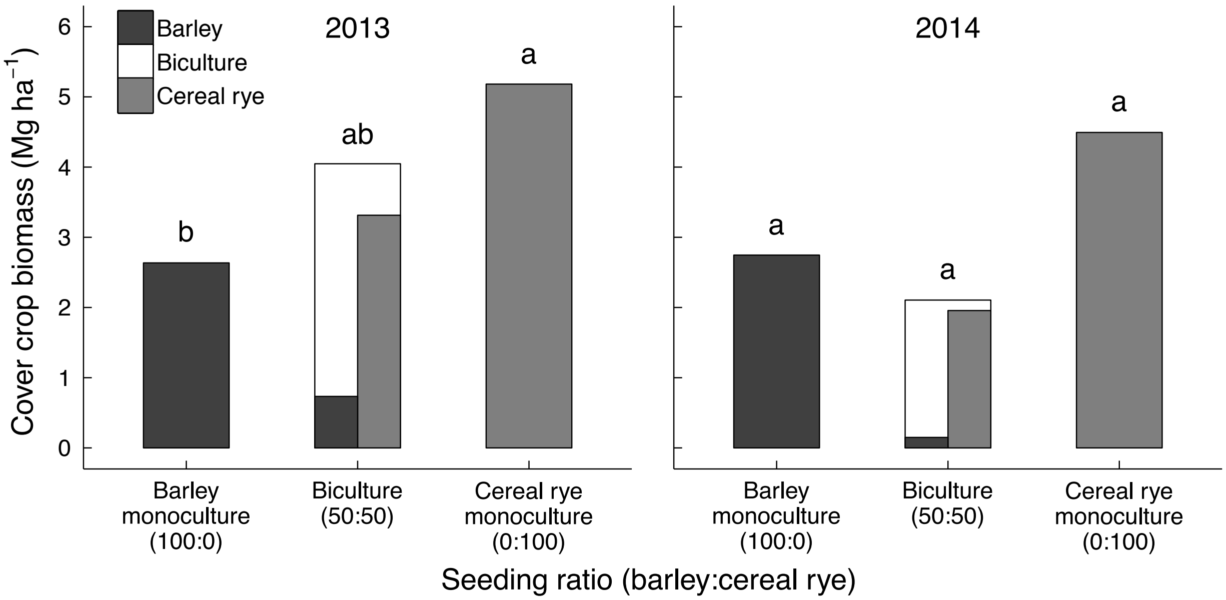

Figure 1.2. Cover crop biomass production of barley and cereal rye in monoculture and biculture in 2013 and 2014. Similar letters above bars indicate no significant difference ($P < 0.05$) among seeding ratios based on Tukey's Honest Significant Difference test.

treatment, accumulating 2.1 Mg ha^{-1} of barley and cereal rye biomass combined. In all cases, total biomass production was substantially less than the recommended 8.0 Mg ha^{-1} threshold for adequate weed suppression. Whereas cover crop biomass increased, PAR transmittance through the cover crop canopy decreased as the proportion of cereal rye in the seeding ratio increased (Figure 1.3). This reduction in PAR transmittance was from 64% in the barley monoculture to 41% in the cereal rye monoculture ($P < 0.001$). Data were pooled over 2013 and 2014 because there was no interaction or main effect of year.

We seeded barley and cereal rye based on volume rather than seed density because cover crop seeding rates are more commonly established on a volume or mass basis by farmers. Although cereal rye is known to be highly competitive (Beres et al. 2010), barley and cereal rye production in the 50:50 mixture was notably uneven. For example, cereal rye comprised 82% of the biomass and 67% of the stem density in the 50:50 mixture in 2013 (density data not shown).

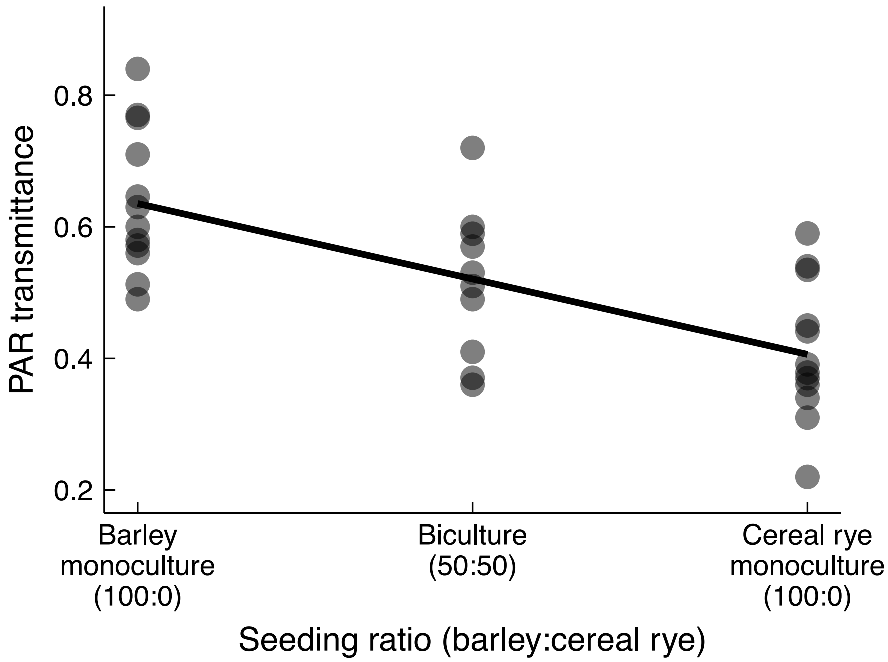

Figure 1.3. Photosynthetically active radiation (PAR) transmittance through the cover crop canopy across seeding ratio treatments. Data were pooled over both years and block was included as a random effect ($y = 0.635 - 0.002x$; $R_m^2 = 0.43$, $R_c^2 = 0.70$, $P < 0.001$).

Biomass production and stem density was even more disproportionate in 2014 with the biculture consisting of 83% cereal rye stems, representing 93% of the biomass in the 50:50 mixture.

The amount of PAR transmittance decreased as the proportion of cereal rye increased, closely mirroring the relationship between cover crop biomass and cereal rye proportion. Although cover crop biomass was statistically equivalent across the three seeding ratios in 2014, the difference between the biculture and the cereal rye monoculture exceeded 2.0 Mg ha^{-1}. Despite this substantial difference in biomass, PAR interception was lowest in the barley monoculture, not the biculture. Minor differences in plant architecture and resource partitioning might help explain this, but it is the cumulative effect on weed suppression that is of practical importance.

Compared with cereal rye, barley is typically less tolerant of wet soil and the increase in ethylene that is associated with anaerobic conditions (Drew and Lynch 1980; Smith and Restall 1971; Smith and Robertson 1971). Non-uniform soil drainage in 2014 coupled with above-average precipitation from March to May (Figure 1.1) might have reduced root growth and the competitive ability of barley more so than cereal rye. Injury is often less severe when short-term flooding occurs during more mature barley growth stages, but recovery is typically limited, resulting in reduced tillering, biomass production, and grain yield (Leyshon and Sheard 1974). This occurrence would help explain the highly disproportionate density and biomass in the 50:50 biculture in 2014, but the mixture was also uneven in 2013. Although we can draw conservative inferences based on field notes, observations, and biomass data to help explain the uneven biculture proportions, our replacement series was not designed to directly assess interspecific plant competition.

Weed Response to Seeding Ratio and Management Treatments

Across all seeding ratios and management treatments, common ragweed was the dominant weed, accounting for 65% of the aboveground biomass among all weed species in 2013 and 84% in 2014. The dominance of this summer annual weed species is illustrated in Figure 1.4 by allowing the symbol size to vary proportionally with the amount of common ragweed biomass. Giant foxtail and yellow foxtail were also prominent at the 2013 study site, comprising 25% of the total weed biomass. In 2014, the proportion of foxtail species was only 7% of the aboveground weed biomass. Based on the ANCOVA (Table 1.2), the interaction between seeding ratio and management treatment was not significant ($P > 0.05$), which indicates that the relationship between weed biomass (response) and seeding ratio (covariate) was similar for the

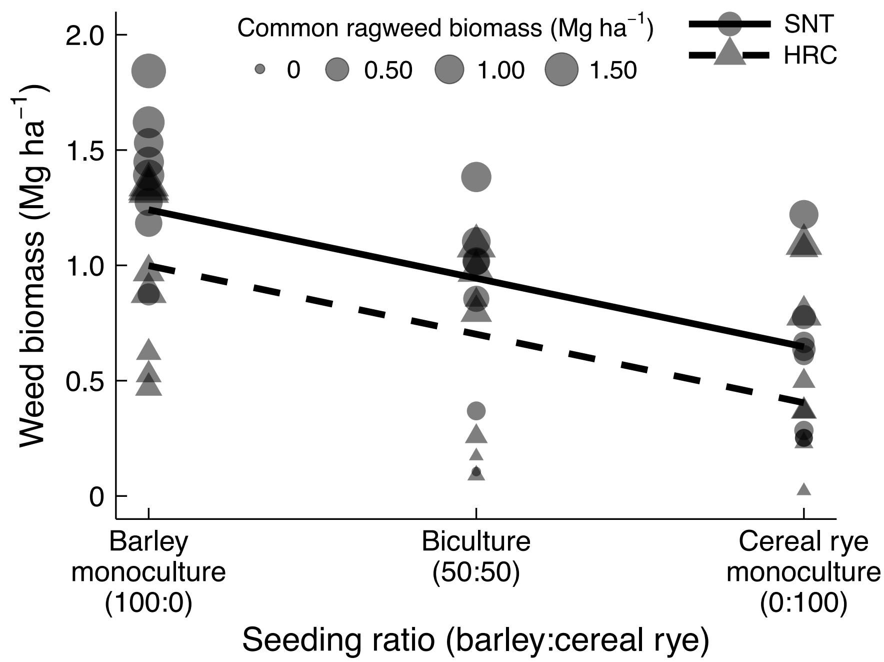

Figure 1.4. Weed biomass production in the standard no-till (SNT) and high-residue cultivation (HRC) management treatments across seeding ratios. The data were pooled over both years, and block was included as a random effect (R_m^2 = 0.35, R_c^2 = 0.35). Interactions were not observed (P > 0.05), but the effects of seeding ratio (P < 0.001) and management treatment (P = 0.04) were significant. For SNT management, $y = 1.241 - 0.006x$; for HRC management, $y = 0.999 - 0.006x$. Symbol size increases as the proportion of common ragweed in total weed biomass increases.

SNT and HRC management treatments. Also, these data were pooled over 2013 and 2014 because the ANCOVA showed no interaction or main effect of year. Mean weed biomass decreased as the proportion of cereal rye increased (Figure 1.4), ranging from 1.2 to 0.6 Mg ha^{-1} under SNT management and 1.0 to 0.4 Mg ha^{-1} under HRC management.

Overall, HRC reduced weed biomass by 26% compared with SNT (P = 0.04). This is congruent with previous research showing the weed suppression benefit of high-residue cultivation in cover crop-based organic no-till planted soybean (Mirsky et al. 2013). Tillage-based IRC management effectively eliminated all weeds in 2013 and 2014, reducing weed

Table 1.2. Results from the mixed-effects analysis of covariance (ANCOVA) on weed biomass and soybean yield.[a] The covariate was seeding ratio treatment (barley:cereal rye, 100:0, 50:50, and 0:100), and the other factors were management treatment (standard no-till and high-residue cultivation) and year (2013 and 2014).

Effect[b]	Weed biomass	Soybean yield
	——— P-value ———	
Seeding ratio	<0.001	0.904
Management	0.036	0.890
Year	—[c]	0.003

[a] Block was included as a random effect.

[b] All three-way and two-way interactions were tested and removed from the models because they were not significant ($P > 0.05$).

[c] Year did not have an effect ($P > 0.05$) on weed biomass, so it was removed from the model.

biomass to 1% or less of the biomass levels found in HRC and SNT (data not shown). In other comparisons between no-till and tillage in organic soybean production (Bernstein et al. 2011; Bernstein et al. 2014), weed suppression was not significantly better under tillage-based management.

Common ragweed produced the greatest proportion of biomass across all treatments, which has been found in other experiments on cover crop-based organic no-till planted soybean systems in the northeastern U.S. (Nord et al. 2012; Ryan et al. 2011a). As common ragweed typically emerges prior to cover crop termination (Myers et al. 2004), the operation of a no-till planter can contribute to low within-row common ragweed abundance by physically cutting, burying, or uprooting seedlings. With common ragweed found primarily between rows in these systems, HRC can provide particularly effective control of this problematic species. The timing of high-residue cultivation, however, presents a trade-off: earlier cultivation can provide better control of species that emerge prior to rolling-crimping, but species that emerge later might actually be stimulated by the disturbance. A separate ANCOVA was used to test for interactions among and effects of seeding ratio, management treatment, and year on common ragweed biomass. No interactions were observed, but the effects of seeding ratio ($P < 0.001$), management treatment ($P = 0.02$), and year ($P = 0.01$) were all significant. Compared with SNT management, HRC reduced common ragweed biomass by 52% in 2013, but only by 22% in 2014 when the operation occurred later in the season (Table 1.1). In general, HRC was not as effective at controlling foxtail species. As giant foxtail and yellow foxtail tend to emerge after rolling-crimping (Myers et al. 2004), HRC might have helped stimulate germination in 2013, resulting in a 113% increase in biomass compared with SNT. Later HRC in 2014 provided more effective control of both foxtail species, which was likely due to a greater proportion of the two species emerging prior to the cultivation event.

As with any weed management tactic, timing is critical to the success of high-residue cultivation. Common ragweed is known to be problematic in these rotational no-till systems in the northeastern U.S., so it might be advantageous to forgo some control of later-emerging species in favor of greater common ragweed suppression. Similar to the relationship between seeding ratio and PAR transmittance, weed biomass tended to be lower in cover crop seeding ratio treatments that were more productive. Our hypothesis that mixtures of barley and cereal rye would provide greater weed suppression than either species in monoculture was not supported by these results.

Relationships among Cover Crops, PAR Transmittance, and Weeds

Comparing the R_i^2 from simple linear regression analyses, PAR transmittance explains a greater proportion of the variance in weed biomass than cover crop biomass in both 2013 and 2014 (Table 1.3). However, this approach does not reveal the degree of redundancy that likely

Table 1.3. The proportion of variance in weed biomass (Y) in 2013 and 2014 as explained by bivariate (R_i^2), partial (pr_i^2), and semipartial (sr_i^2) coefficients of determination for two predictor variables: photosynthetically active radiation (PAR) transmittance (X_1) and cover crop biomass (X_2). Collinearity between the two predictors was assessed with variance-inflation factors (VIF) and condition indices (CI).

				Coefficients of determination		
Year	VIF[a]	CI[b]	Predictor	R_i^2	pr_i^2	sr_i^2
2013	2	19	PAR transmittance, X_1	0.666	0.354	0.174
			Cover crop biomass, X_2	0.600	0.225	0.111
2014	3	17	PAR transmittance, X_1	0.471	0.399	0.135
			Cover crop biomass, X_2	0.192	0.082	0.028

[a] As a general rule, a VIF > 10 signifies severe collinearity.
[b] Severe collinearity is also commonly indicated by a CI > 30.

exists between the two predictors. Although cover crop biomass is intrinsically correlated with the amount of PAR that passes through the cover crop canopy (or inversely, the amount intercepted by the canopy), it also contributes to weed suppression as rolled mulch. This helps differentiate the effect of cover crop biomass on weed biomass from the effect of PAR transmittance prior to cover crop termination. Without the confounding presence of severe collinearity (VIF < 10 and CI < 30 in both years; Table 1.3), we were able to assess the proportion of variance in weed biomass that was uniquely explained by PAR transmittance and cover crop biomass. To do this, we used multiple linear regression and compared the sr_i^2 and pr_i^2 for each predictor variable (Table 1.3).

The sr_i^2 was 0.17 and 0.14 for PAR transmittance and 0.11 and 0.03 for cover crop biomass in 2013 and 2014, respectively. This indicates that PAR transmittance explains 17% of the variance in weed biomass in 2013 and 14% in 2014 when the effect of cover crop biomass has been partialed from PAR transmittance. In comparison, cover crop biomass explains 11% of the variance in weed biomass in 2013 and 3% in 2014 when the effect of PAR transmittance has been partialed from cover crop biomass. In other words, when X_i is added to a model that already contains the other predictor, sr_i^2 represents the incremental increase in explained variance in weed biomass that is uniquely due to X_i.

For the pr_i^2 analysis, PAR transmittance uniquely accounted for 35% of the variance in weed biomass after partialing the effect of cover crop biomass from both PAR transmittance and weed biomass in 2013. Conversely, cover crop biomass uniquely accounted for 23% of the variance in weed biomass after partialing the effect of PAR transmittance from both cover crop biomass and weed biomass in 2013. Similarly in 2014, the amount of variance in weed biomass that was uniquely explained by PAR transmittance was greater than the proportion of variance explained by cover crop biomass.

It is worth reiterating that both PAR transmittance and cover crop biomass were measured prior to cover crop termination, but that the effect of cover crop biomass on weed suppression extends (as mulch) until soybean canopy closure, and to a lesser degree until soybean harvest. Despite influencing weed suppression over a longer period of time, cover crop biomass uniquely explained less of the variance in weed biomass than PAR transmittance. These observations are consistent with previous research demonstrating that the percent ground cover prior to cereal rye jointing (Zadoks 31) was a strong predictor of weed biomass later in the season, after cover crop termination (Ryan et al. 2011a). Acknowledging that adequate cover crop biomass production is critical to the success of organic no-till planted soybean, our results suggest that farmers should consider implementing management practices that optimize shading prior to cover crop termination.

Soybean Population and Yield

In 2013 and 2014, the no-till planter was calibrated to dispense 740,000 seeds ha^{-1}. Final soybean stand counts in 2013 revealed that this high rate was exceeded with an average of 757,000 plants ha^{-1} at harvest. In 2014, average soybean population across treatments was only 545,000 plants ha^{-1}. We tested the effects of cover crop biomass and year on soybean population using ANCOVA and found an interaction between cover crop biomass and year (P = 0.01). Soybean population decreased as cover crop biomass increased in 2013, but soybean population actually increased slightly with increasing cover crop biomass in 2014 (Figure 1.5). Although high soybean seeding rates can cause lodging, this was not observed in our experiment. Within

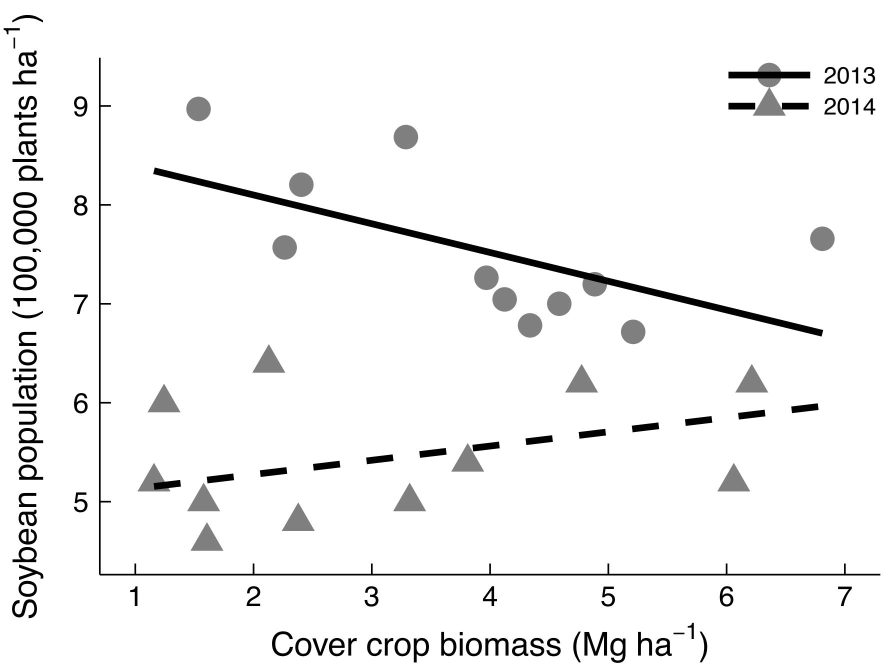

Figure 1.5. Soybean population at harvest as affected by cover crop biomass in 2013 and 2014. The interaction between cover crop biomass and year was significant (P = 0.01), and block was included as a random effect (R_m^2 = 0.75, R_c^2 = 0.82). In 2013, y = 8.682 – 0.291x, and in 2014, y = 4.988 + 0.144x.

year, no differences ($P > 0.05$) in soybean yield between seeding ratio, no-till management treatment, or their interaction were detected in 2013 or 2014 (Table 1.2). However, soybean yield was higher ($P = 0.003$) at 2.9 Mg ha^{-1} in 2013 compared with 2.6 Mg ha^{-1} in 2014. Soybean yield under no-till management (HRC and SNT) was lower than the tillage-based on-site comparison (IRC management) across all seeding ratios, producing 98% of the yield obtained with IRC management in 2013 and 79% in 2014. The low weed biomass across treatments might help explain why we observed no differences in soybean yield within year, but these results were still surprising given the treatment differences among cover crop biomass, PAR transmittance, and weed biomass.

Despite accumulating less than 8.0 Mg ha^{-1} of cover crop biomass in each of the seeding ratio treatments, reduced soybean populations were observed in plots with more cover crop biomass—and thus, more cereal rye biomass—in 2013. This relationship was not observed in 2014, possibly due to more challenging planting conditions and the relatively low soybean populations across all cover crop biomass levels. Other researchers have also reported lower crop populations in high-residue management systems, typically attributing the reduction to a decrease in soil moisture associated with the cover crop (De Bruin et al. 2005; Wells et al. 2015), or as a result of impaired planter function (e.g., hair-pinning) and poor seed-to-soil contact (Eckert 1988; Liebl et al. 1992; Mitchell and Teel 1977). Although soybean population at harvest in 2013 decreased as cover crop biomass increased, yield loss at lower populations can be avoided through increased branching, pod formation, and more seeds per plant (Carpenter and Board 1997; Lueschen and Hicks 1977; Weber et al. 1966). Despite this phenotypic plasticity, soybean yield can be reduced when excessive cover crop biomass prevents adequate planter function and seed placement (Liebl et al. 1992).

Weight was added to the no-till planter in 2014 in an effort to overcome the hard, dry soil conditions, but inadequate seed-to-soil contact and low soil moisture resulted in an average soybean population that was much lower than the targeted planting rate. In addition to a reduced soybean population, the below-average precipitation during June 2014 (Figure 1.1) might help explain the lower soybean yield in 2014 compared with 2013. Previous research has found that soil moisture loss through transpiration before cover crop rolling-crimping and after incomplete termination can substantially reduce soil water content (Ashford and Reeves 2003; Moschler et al. 1967; Munawar et al. 1990). This effect can be more pronounced when precipitation is low, with dry soil conditions resulting in low soybean emergence, seedling mortality, poor stands, and lower yields (De Bruin et al. 2005; Eckert 1988; Helms et al. 1996; Liebl et al. 1992; Wells et al. 2015). Regardless of the suite of factors that affected soybean yield in the experiment, our hypothesis that soybean yield would be greater with the addition of HRC than with SNT management alone was not supported. Considering the similarity in soybean yields between the two no-till treatments and the tillage-based management, organic farmers in the northeastern U.S. can, however, potentially realize greater profits when using the cover crop-based organic no-till planted soybean system due to the associated cost reductions from less labor and fuel use (Mirsky et al. 2012).

Management Implications

Although this experiment was managed without synthetic inputs, routine chemical herbicide use at the research farm in previous years likely contributed to the low weed populations and relative lack of weed species diversity observed. These conditions are not typical of most organically managed cropping systems (Bernstein et al. 2014; Thelen et al. 2004) because the legacy of low weed populations from previous herbicide use would only be present in fields that had recently been transitioned from conventional to organic production practices. Thus, it is important to consider the effects of past management practices, such as crop rotation (Ball 1992; Cardina et al. 2002; Liebman and Dyck 1993; Wortman et al. 2010) and tillage regime (Buhler 1995; Clements et al. 1996; Mohler and Callaway 1995; Murphy et al. 2006), on weed seedbank dynamics, as well as aboveground weed diversity, density, and abundance. Mirsky et al. (2012) found that high-residue cultivation decreased weed biomass by 66% and increased soybean yield by 23% compared with standard no-till. As weed biomass was greater in the Mirsky et al. (2012) study than in our experiment, the weed biomass reduction from high-residue cultivation likely had a greater impact on soybean yield.

Our results suggest that weed biomass can be reduced by enhancing cover crop shading prior to termination; however, mixtures of barley and cereal rye did not intercept more PAR than cereal rye grown in monoculture. Although our barley-cereal rye mixture did not provide increased shading, this objective might be achieved by seeding other species combinations. In the northeastern U.S., cover crops used for mulch in organic no-till planted soybean production must be winter-hardy and early-maturing. In addition to these region-specific traits, an ideal cover crop mixture would include species that matured at approximately the same time to optimize the efficacy of rolling-crimping. Preferably, each cover crop species would also be non-leguminous for greater complementarity with the soybean cash crop, thereby enhancing the relative competitive ability of soybean, compared with weeds, through increased soil N depletion. Mixing a *Brassica* species with cereal rye might provide superior shading as a grass-broadleaf biculture, but research is required to determine optimal management. If a cover crop monoculture is used, selecting a winter cereal species with greater leaf area than cereal rye, such as triticale (× *Triticosecale* Witt.), also has the potential to enhance PAR interception. However, an assessment of any alternative winter cereal species must consider maturation and termination timing as they relate to soybean planting and yield potential.

Until these alternative mixtures or species have been evaluated, farmers can improve cover crop shading by modifying cereal rye monoculture seeding methods. For example, using narrower row spacing or drilling half of the seeding rate and broadcasting the remaining half might provide earlier, more complete ground cover. Increasing cereal rye seeding rates can also be effective for increasing weed suppression without increasing cover crop biomass (Ryan et al. 2011a). Thus, future research should focus on a multi-tactic approach to weed management that reduces the need for high-residue cultivation by enhancing shading prior to cover crop termination, rather than maximizing biomass production.

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CHAPTER 2

HIGH PLANTING RATES IMPROVE WEED SUPPRESSION, YIELD, AND PROFITABILITY IN ORGANIC NO-TILL PLANTED SOYBEAN

ABSTRACT

High soybean populations have been shown to hasten canopy closure, which can improve both weed suppression and soybean yield. In conventional soybean production, the high cost of genetically engineered seed and seed treatments have led growers to plant at lower rates to maximize profitability. For organic farmers, market price premiums are typically double the price received for conventional soybean. Without chemical or mechanical weed management, cultural practices are particularly important for adequate weed suppression in organic no-till planted soybean production. In 2014, an experiment was conducted in Aurora and Hurley, New York, to assess the effects of increasing soybean planting rates on weed suppression, soybean yield, and partial economic return. Planting rates of 198,000; 395,000; 595,000; 790,000; and 990,000 seeds ha^{-1} were arranged in a randomized complete block design. As soybean population increased, weed biomass decreased and soybean yield increased at both sites. An asymptotic model described the relationship between increasing soybean population and yield, and the estimated maximum yield was 2,506 kg ha^{-1} in Aurora and 3,282 kg ha^{-1} in Hurley. Despite high soybean populations, minimal lodging was observed. Partial returns decreased beyond the predicted economically optimal planting rate of 650,000 seeds ha^{-1} in Aurora and 720,000 seeds ha^{-1} in Hurley as higher seed costs were no longer offset by yield gains. Based on our results, planting rates that are more than double the recommended rate of 321,000 seeds ha^{-1} for wide

row (≥76 cm) conventional soybean management in New York can enhance weed suppression, increase yield, and improve profitability in organic no-till planted soybean production.

INTRODUCTION

Cover crop-based organic rotational no-till soybean (*Glycine max* [L.] Merr.) production uses fall-planted winter cereal cover crops, such as cereal rye (*Secale cereale* L.), that are mechanically terminated with a roller-crimper in the spring to create a layer of mulch. Soybean is then no-till planted through the thick mulch, which serves as the primary form of weed suppression. Farmers can combine cover crop termination and planting operations in a single pass by mounting the roller-crimper to the front of their tractor and no-till planting soybean simultaneously. When used to produce food-grade soybean, this system is a model for sustainable agriculture.

Food security challenges associated with dietary shifts toward greater consumption of animal protein (Eisler et al. 2014; Keyzer et al. 2005; Tilman and Clark 2014), combined with environmental problems that include biodiversity loss (Gonthier et al. 2014; Green et al. 2005), water pollution and unsustainable withdrawal rates (Hanjra and Qureshi 2010; Vörösmarty et al. 2000), soil degradation (Lal 2004; Montgomery 2007), and climate change (Schmidhuber and Tubiello 2007; Wheeler and von Braun 2013), all suggest that major changes to our food system are urgently needed. Cover crop-based organic rotational no-till soybean management can be used to minimize the deleterious effects of crop production on the environment (Bernstein et al. 2011; Kaspar et al. 2001; Villamil et al. 2006), while at the same time providing an alternative to animal products for protein. However, management recommendations must be developed specifically for cover crop-based organic rotational no-till soybean production if this system is to be widely adopted among farmers.

Managing weeds is often one of the most challenging aspects of crop production for organic farmers (Bàrberi 2002; Bond and Grundy 2001), and reducing tillage without the use of synthetic herbicides can make it particularly difficult for growers to achieve adequate weed suppression (Peigné et al. 2007; Smith et al. 2011). Weed management typically consists of multiple tillage and cultivation events in traditional organic soybean production, whereas the rolled cover crop mulch suppresses weeds in organic no-till planted soybean production. Although not unique to cover crop-based organic rotational no-till soybean, combining multiple cultural weed management practices is of particular importance in the absence of chemical or mechanical weed control.

Cultural weed management tactics that are compatible with organic soybean production practices include narrow row spacing, high planting rates, and the selection of cultivars that possess strong weed suppressive ability (Jannink et al. 2000; Jordan 1993; Place et al. 2011; Rose et al. 1984). Compared with wide row spacing (≥76 cm), narrow row spacing (<76 cm) generally provides enhanced weed suppression due to more rapid soybean canopy closure (Burnside and Moomaw 1977; Forcella et al. 1992; Légère and Schreiber 1989; Nelson and Renner 1999; Wax and Pendleton 1968; Yelverton and Coble 1991). Of the experiments reviewed by Bradley (2006), a reduction of late-season weed biomass or density was observed in 72 of 113 site-years when narrow row spacing was used compared with wide row spacing.

Increasing crop planting rates can also contribute to weed suppression via faster canopy closure and enhanced weed-crop competition (Doll 1997; Mohler 1996; Murphy et al. 1996). When the relationship between increasing plant density and crop yield is asymptotic (i.e., yield begins to plateau as density increases) rather than parabolic (i.e., yield declines above an optimum density), higher plant populations can be used to improve weed suppression (Weiner et al. 2001). As large-seeded crop seedlings are typically greater in size than weed seedlings immediately following germination (Mohler 1996), increasing crop density can potentially enhance the competitive size-asymmetry (Schwinning and Weiner 1998; Weiner 1990) that exists between the crop and weed population, resulting in greater weed suppression at elevated crop densities compared with lower densities (Weiner et al. 2001). At higher soybean populations, Arce et al. (2009) observed inconsistent effects on weed densities, but end-of-season weed biomass decreased linearly as soybean population increased. Place et al. (2009) found that increased soybean planting rates decreased percent weed cover at three of the five sites in their experiment.

As canopy closure can be considered a prerequisite for maximum soybean yield under certain environmental conditions (Ball et al. 2000a, 2000b; Ball et al. 2001; Shibles and Weber 1966; Tanner and Hume 1978; Wells 1991), management practices that hasten canopy formation provide the benefits of both enhanced weed suppression and greater yield potential. Previous research has suggested that yield gains from narrow row spacing and high plant populations might be associated with increased light interception during reproductive growth (Board et al. 1990; Board and Harville 1993; Parvez et al. 1989; Shibles and Weber 1965). In more northern regions where environments receive a limited number of heat units, a review of field studies indicated that narrow row spacing and higher populations tended to improve soybean yield (Lee 2006). This positive yield response was primarily attributed to the relationship between maximum light interception and rapid canopy development. However, drawbacks to using higher planting rates include higher seed costs, increased lodging (Cooper 1971a, 1971b; Costa et al.

1980; Oplinger and Philbrook 1992), and greater incidence of some diseases, such as Sclerotinia stem rot (*Sclerotinia sclerotiorum* [Lib.] de Bary) (Lee et al. 2005).

Soybean planting rates that maximize yield do not necessarily result in maximum economic return. In conventional soybean production systems, the high costs of genetically engineered seed and increased adoption of fungicide and insecticide seed treatments have prompted researchers to recommend lower planting rates in an effort to increase profitability for farmers (Cox and Cherney 2014; De Bruin and Pedersen 2008b; Epler and Staggenborg 2008; Esker and Conley 2012; Gaspar et al. 2015; Harder et al. 2007; Lee et al. 2008; Norsworthy and Oliver 2001). Under organic management practices, the operational costs and soybean market price can differ substantially from conventional production. Although labor and fuel costs tend to be higher in organic systems (Archer et al. 2007; Crowder and Reganold 2015), the price premium for organic soybean has been approximately double the price received for conventional soybean since national organic soybean prices were recorded and archived in 2008 (USDA-AMS 2016; USDA-NASS 2016). For instance, the average price received for conventional feed-grade soybean in 2014 was \$0.47 kg^{-1} (USDA-NASS 2016), compared with \$0.93 and \$1.04 kg^{-1} for feed- and food-grade organic soybean, respectively (USDA-AMS 2016). Given the differences in organic and conventional soybean management practices and market prices, economically optimal planting rates likely differ as well. Place et al. (2009) noted that previous economic analyses for conventional soybean production are likely inappropriate for organic growers due to the differences in seed costs, weed management practices, on-farm weed pressure, and soybean price received. In addition to price premiums and economic advantages over conventional production, cover crop-based organic rotational no-till soybean management can reduce diesel fuel use by 27% and labor requirements by 33% compared with tillage-based organic soybean production (Mirsky et al. 2012).

In this research, we compared a wide range of planting rates in organic no-till planted soybean. High planting rates of more than double the recommended rate of 321,000 seeds ha^{-1} in 76-cm wide rows for conventional production in New York (Cox and Cherney 2011; Orlowski et al. 2012) were used to overcome potential seed placement challenges that can be common in rolled cover crop systems, and to ensure an asymptotic relationship between planting rate and yield. By reaching a yield plateau (or decline due to lodging or severe intraspecific competition), we can estimate the economically optimal planting rate. Whereas the economically optimal planting rate in conventional soybean production is often lower than the rate associated with the greatest yield (De Bruin and Pedersen 2008b; Lee et al. 2008; Norsworthy and Oliver 2001), we hypothesized that the economically optimal planting rate in organic no-till planted soybean would closely correspond to the rate at which the greatest yield is obtained.

The objectives of this study were to quantify the effect of planting rate on (1) weed suppression, (2) soybean yield, and (3) partial economic return in cover crop-based organic rotational no-till soybean production.

MATERIALS AND METHODS

Site Description and Experimental Design

A field experiment was conducted in 2014 at the Cornell University Musgrave Research Farm in Aurora, New York (42.73°N, 76.66°W), and at the Hudson Valley Farm Hub in Hurley, New York (41.91°N, 74.10°W). The soils are classified as a Honeoye silt loam (fine-loamy, mixed, semiactive, mesic Glossic Hapludalf) with 2.5% organic matter (mass loss on ignition at

500°C) and a pH_{water} of 7.5 in Aurora, and a Unadilla silt loam (coarse-silty, mixed, active, mesic Typic Dystrudept) with 1.7% organic matter and a pH_{water} of 6.1 in Hurley. Prior to this experiment, the fields at both farms were managed conventionally. Commodity grains, including corn, soybean, and wheat, comprised the crop rotation in Aurora, and weeds were managed with synthetic herbicides. The crop rotation and management were similar in Hurley, with the exception of sweet corn being grown rather than grain corn.

In this experiment, we compared five soybean planting rates (198,000; 395,000; 595,000; 790,000; and 990,000 seeds ha^{-1}) that were arranged in a randomized complete block design at both field sites. Five replicate blocks were used in Aurora, and four blocks were used in Hurley. Plots consisting of a single soybean planting rate within a given block measured 3.0 by 9.1 m in Aurora and 6.1 by 91.4 m in Hurley.

In Aurora, a mixture of cereal rye, barley (*Hordeum vulgare* L.), and triticale (× *Triticosecale* Wittm.) was no-till drill-seeded (John Deere 1590) at a rate of 125 kg ha^{-1}, 2.5-cm deep, on October 3, 2013. In Hurley, a mixture of cereal rye and triticale was broadcast (AGCO Willmar S-600) at a rate of 220 kg ha^{-1}, and shallow disking (John Deere 637) was used to improve the seed-to-soil contact and facilitate germination. This seeding operation also occurred on October 3, 2013. Although the seeding method, rate, and species composition of the cover crop mixtures differed between sites, this experiment was not designed to compare cover crop performance.

In cover crop-based organic rotational no-till planted soybean production, the timing of cover crop termination is often based on cover crop phenology. As adequate mechanical control is achieved when winter cereal cover crops are rolled no earlier than anthesis (Ashford and Reeves 2003; Mirsky et al. 2009), termination was delayed until triticale—the later-maturing species in both mixtures—reached at least Zadoks 60 growth stage (Zadoks et al. 1974). At both sites, this occurred in early June 2014. The cover crops were terminated with a 3-m-wide roller-crimper (I & J Manufacturing), which weighed 1,195 kg when filled with water. In Aurora, the cover crops were rolled perpendicular to the direction they were sown to eliminate gaps between rows, thereby creating more uniform ground cover. As the cover crop seed was broadcast in Hurley, rolling was not constrained to a particular direction. On the same day as rolling-crimping (June 8 in Aurora and June 10 in Hurley), 'IA 2053' food-grade soybean (yellow hilum, 2.0 relative maturity) was no-till planted (John Deere 7200 MaxEmerge 2 in Aurora, John Deere 1760 NT MaxEmerge XP in Hurley) through the cover crop mulch in 76-cm rows at a depth of 3.8 cm for all five planting rates. Due to hard, dry soil conditions in Aurora, 318 kg of additional weight was distributed across the no-till planter units in an effort to improve soil penetration and achieve the desired planting depth. Although we targeted the same five rates (198,000; 395,000; 595,000; 790,000; and 990,000 seeds ha^{-1}), actual planting rates differed slightly between sites due to equipment limitations.

Cover crop biomass was assessed by clipping the winter cereal cover crops at the soil surface within a randomly-placed quadrat, oven-drying the samples at 50°C for one week, and then weighing the dried vegetation. In both Aurora and Hurley, one 0.5-m^2 quadrat was harvested per block. Weed biomass samples were collected approximately 11 weeks after soybean planting, which coincided with peak biomass accumulation during the transition from vegetative to reproductive growth stages for the most abundant species based on visual estimates of ground cover. Weed biomass was clipped at the soil surface from within a single 0.5-m^2 quadrat per plot in Aurora, whereas two 0.25-m^2 quadrats were harvested per plot in Hurley for better representation of the larger plot size. Weed biomass samples were dried and weighed as described for the cover crop samples. Soybean population was assessed at the same time as weed biomass collection by counting the number of soybean plants within each quadrat. Soybean yield was measured with a two-row plot combine (ALMACO SP20) in Aurora on November 3, 2014. In Hurley, soybean were hand-harvested within two 0.25-m^2 quadrats per plot on October 29, 2014, and then threshed, weighed, and subsampled to determine moisture content. Soybean yields were adjusted to 13% moisture for both sites.

Statistical Analyses

All data were analyzed using R version 3.2.4 (R Core Team 2016), and diagnostic procedures were performed to ensure that the errors exhibited independence, normality, and homoscedasticity. In Hurley, the data collected in two 0.25-m^2 quadrats per plot were treated as subplots and averaged. To test for relationships between soybean planting rate and population, we used linear mixed-effects models (*lme* function in the *nlme* package in R; Pinheiro et al. 2016) with block as a random effect. For these models, we used the *r.squaredGLMM* function (*MuMIn* package; Bartoń 2015) to calculate marginal (R_m^2) and conditional (R_c^2) coefficients of determination. The proportion of response variance that is associated with fixed effects only is represented by R_m^2, whereas the variance explained by both fixed and random effects is described by R_c^2 (Nakagawa and Schielzeth 2013).

A rectangular hyperbolic model (Baumann et al. 2001; Spitters 1983) was used to assess the relationship between weed biomass and soybean population, and can be described as

$$B_w = \frac{M_w}{1 + i_w P_s} \ , \qquad [1]$$

where B_w is weed biomass (kg ha^{-1}); M_w is mean weed biomass (kg ha^{-1}) at the lowest soybean planting rate; i_w is the reduction in weed biomass per soybean plant (ha $plant^{-1}$), which describes the initial slope of the relationship; and P_s is soybean population (plants ha^{-1}), which has been adjusted by subtracting the lowest soybean population (by site) from the measured population in each plot. The lowest population was 180,000 and 100,000 plants ha^{-1} in Aurora and Hurley, respectively. In the absence of a weedy check (e.g., 0 seeds ha^{-1} planting rate) treatment, this adjusted soybean population allows us to estimate the initial reduction in weed biomass from increasing soybean planting rates above the lowest rate tested.

The rectangular hyperbolic model is more commonly used to assess the relationship between weed density and yield loss (Cousens 1985a, 1985b). To quantify the effect of weed biomass on crop yield, the hyperbolic model can be modified (Ryan et al. 2009) as

$$Y_s = \frac{\frac{1}{a_0} P_s}{1 + i_w B_w} \; , \qquad [2]$$

where Y_s is soybean yield (kg ha^{-1}); a_0 is the reciprocal of the yield of an individual soybean plant (plants kg^{-1}) at the lowest observed weed biomass level, which determines the maximum possible soybean yield (i.e., *y*-intercept); P_s is soybean population (plants ha^{-1}); i_w is the initial soybean yield loss per unit weed biomass (ha kg^{-1}), which determines the slope of the relationship; and B_w is weed biomass (kg ha^{-1}).

An asymptotic model that has been modified to pass through the origin (Pinheiro and Bates 2000) was used to describe the relationship between soybean population and yield,

$$Y_s = a\left(1 - e^{(-e^{b} P_s)}\right) \; , \qquad [3]$$

where Y_s is soybean yield (kg ha^{-1}); a represents the horizontal asymptote; b denotes the natural logarithm of the rate constant; and P_s is soybean population (plants ha^{-1}). Constraining the model through the origin is biologically realistic as there will be no soybean yield at a population of 0 plants ha^{-1}. The *nlme* function in R (*nlme* package; Pinheiro et al. 2016) was used for all three nonlinear mixed-effects models, with block as a random effect.

A partial budget analysis was conducted to assess profitability across the range of soybean planting rates. Partial returns were calculated as

$$P_r = (Y_s \cdot M_p) - (R_s \cdot C_s) \quad , \qquad [4]$$

where P_r is the partial return (\$ ha^{-1}); Y_s is soybean yield (kg ha^{-1}); M_p is the mean market price of \$1.04 kg^{-1} for organic food-grade soybean in 2014 (USDA-AMS 2016); R_s is soybean planting rate (seeds ha^{-1}); and C_s is the soybean seed cost of \$0.0004 seed^{-1} (4,630 seeds kg^{-1} at \$1.85 kg^{-1}, or \$56 for a unit of 140,000 seeds). A quadratic mixed-effects model best described the relationship between soybean planting rate and partial return (*lme* function in the *nlme* package in R; Pinheiro et al. 2016). Estimated changes in partial return were also calculated for a range of soybean seed costs (\$0.00029 to \$0.00051 seed^{-1}) and market prices (\$0.74 to \$1.14 kg^{-1}). The estimated change in partial return reflects the economic loss or gain from planting soybean at 685,000 seeds ha^{-1} (the average of the predicted economically optimal planting rates from both sites), rather than at the recommended rate of 321,000 seeds ha^{-1} for conventional soybean planted at 76-cm row spacing (Cox and Cherney 2011; Orlowski et al. 2012). The predicted yield advantage of 416 kg ha^{-1} when planting at 685,000 seeds ha^{-1} instead of 321,000 seeds ha^{-1} was used for Y_s, and the additional number of seeds (364,000 seeds ha^{-1}) required at the higher planting rate was used for R_s in Equation 4.

RESULTS AND DISCUSSION

Monthly precipitation and temperature in 2014 differed considerably between Aurora and Hurley (Table 2.1) (Northeast Regional Climate Center 2016). Compared with the 15-year average, Aurora received 25% less precipitation during June, with above-average precipitation in July and August. In Hurley, excessive rainfall in June and July were followed by droughty

Table 2.1. Total precipitation and average temperature by month in Aurora and Hurley, New York, during the 2014 soybean growing season.

		Precipitation		Temperature	
Site	Month	2014	15-yr avg.	2014	15-yr avg.
		mm		°C	
Aurora	June	73	97	19.1	19.3
	July	117	88	20.3	21.6
	August	113	93	19.0	20.9
	September	59	98	16.1	17.1
	October	65	91	11.6	10.7
Hurley	June	126	114	19.3	20.5
	July	169	100	25.4	23.4
	August	23	129	21.3	22.4
	September	24	103	17.3	17.9
	October	121	117	13.4	11.5

conditions in August and September. The average temperatures from June through October were 17.2°C in Aurora and 19.3°C in Hurley, which were close to their respective long-term averages of 17.9 and 19.1°C.

Relationship Between Soybean Planting Rate and Population

As a percentage of the targeted planting rates, soybean population in August—representing germination, emergence, and seedling survival—was lower on average in Aurora (75%) compared with Hurley (84%). In Aurora, soybean establishment decreased ($P < 0.001$) from 78% at the lowest planting rate (195,213 seeds ha^{-1}) to 72% at the highest planting rate (905,640 seeds ha^{-1}) (Figure 2.1). Soybean establishment also decreased ($P < 0.001$) from the lowest to the highest rate in Hurley, ranging from 101 to 68%. Transpiration prior to cover crop termination and following inadequate termination can markedly reduce soil moisture (Ashford and Reeves 2003; Liebl et al. 1992; Moschler et al. 1967; Munawar et al. 1990). With below-average

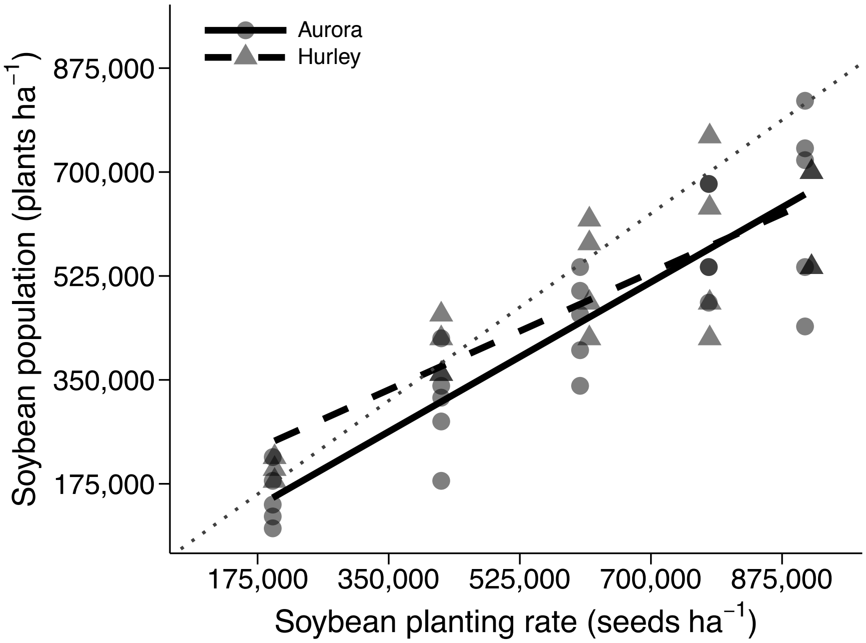

Figure 2.1. Relationship between soybean planting rate (seeds ha^{-1}, x) and population (plants ha^{-1}, y) as described by a linear mixed-effects model with block as a random effect. In Aurora, $y = 0.7x + 11{,}097$ ($R_m^2 = 0.79$, $R_c^2 = 0.85$, $P < 0.001$), and in Hurley, $y = 0.56x + 135{,}596$ ($R_m^2 = 0.69$, $R_c^2 = 0.69$, $P < 0.001$). The diagonal dotted line represents 90% germination, which corresponds to the certified germination test for the IA 2053 soybean seed used in this experiment.

precipitation in June at Aurora (Table 2.1) exacerbated by the impact of pre-termination transpiration losses, dry soil conditions likely inhibited soybean germination and emergence (Ashford and Reeves 2003; Helms et al. 1996; Wells et al. 2015), and increased seedling desiccation and mortality (Eckert 1988). This might help explain the lower soybean populations in Aurora compared with Hurley, which received above-average precipitation in June.

In addition to low soil moisture conditions, no-till planter configuration and poor seed placement can also reduce soybean populations. Despite evenly distributing 318 kg of additional weight among the no-till planter units, it was still difficult to achieve the targeted planting depth due to the hard, dry soil conditions in Aurora. The no-till planter was also outfitted with wavy coulters, which are less effective at penetrating drier soils than other types, such as ripple or smooth coulters (Mirsky et al. 2012). Furthermore, no-till planting through thick cover crop mulch can be particularly challenging due to hair-pinning, which occurs when residue is pressed into the seed furrow and adequate seed-to-soil contact is prevented (Hovermale et al. 1979; Williams et al. 2000). Hair-pinning was observed at both sites, and non-germinated seeds were found on top of cover crop residue, especially when furrow closure was incomplete.

Row cleaners can minimize hair-pinning by shifting the cover crop residue away from the double-disc openers (Wells et al. 2015), but their effectiveness is diminished if the row cleaner wheels become tangled by residue (Mirsky et al. 2012). Although creating a within-row gap in the mulch would reduce the weed suppression provided by the rolled cover crops, faster emergence and higher soybean populations (Mirsky et al. 2012) could potentially compensate by enhancing soybean competitiveness (Place et al. 2009; Wells et al. 2015). Our no-till planter setup did not include row cleaners, but the soybean establishment rates in our experiment were similar to those reported under conventional no-till management in previous research in New York (Cox and Cherney 2011; Orlowski et al. 2012), as well as other studies in the United States (De Bruin and Pedersen 2008a; Ethredge et al. 1989; Lee et al. 2008; Walker et al. 2010). Still, further modifications to no-till planters will be helpful for improving seed placement and potentially lowering recommended planting rates if the performance of such configurations is consistently demonstrated.

Weed Response to Soybean Population

Plot-level weed biomass ranged from 107 to 1,676 kg ha^{-1} in Aurora and from 3 to 2,917 kg ha^{-1} in Hurley. Increasing soybean population effectively reduced weed abundance at both sites.

Using a rectangular hyperbolic model (Equation 1) and setting the lowest observed soybean population at each site to 0 plants ha^{-1}, weed biomass decreased nonlinearly in both Aurora (i_w = 3.45×10^{-6} ha plant^{-1}, $P < 0.001$) and Hurley ($i_w = 8.18 \times 10^{-6}$ ha plant^{-1}, $P = 0.06$) as the adjusted soybean population increased (Figure 2.2). This shows that weed biomass decreased more from the initial increase in soybean density at Hurley compared with Aurora.

Our results are consistent with other studies demonstrating that high soybean planting rates contribute to weed suppression through interspecific competition (Monks and Oliver 1988; Weber and Staniforth 1957). Though shading is the primary mechanism through which weeds are suppressed with this cultural practice (Bastiaans et al. 2008), higher soybean planting rates

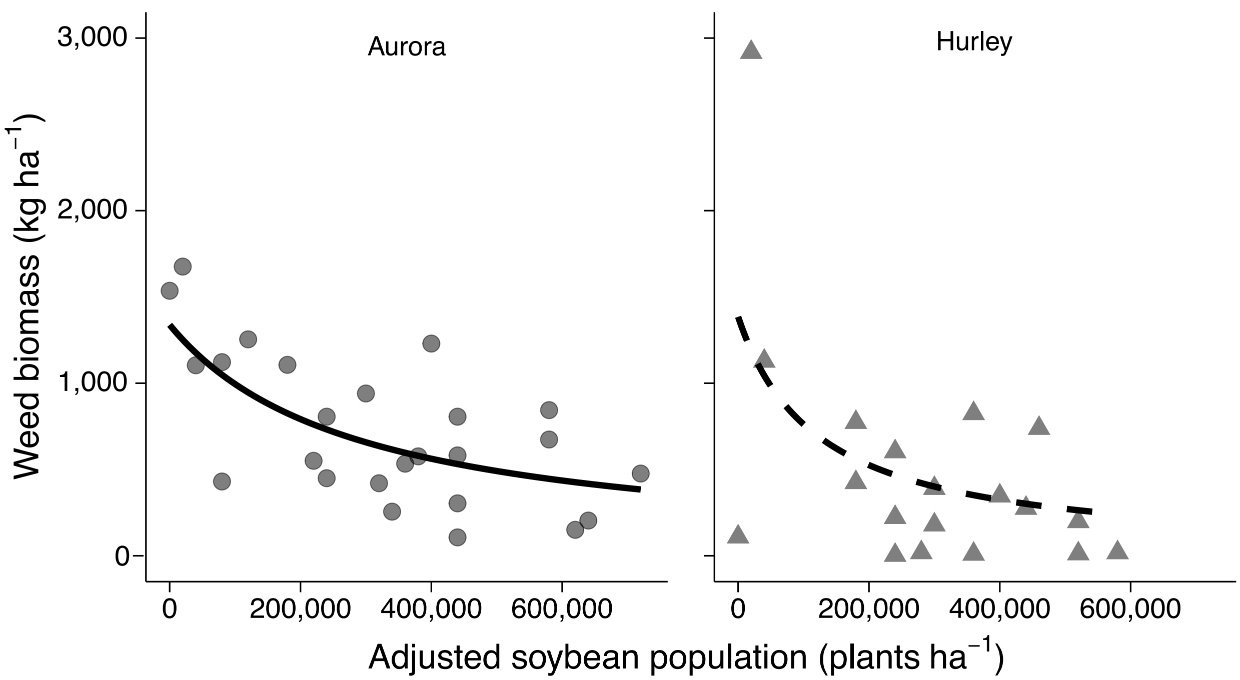

Figure 2.2. Effect of soybean population (plants ha^{-1}) on weed biomass (kg ha^{-1}) at approximately 11 weeks after planting. Using a rectangular hyperbolic model with block as a random effect (Equation 1), the lowest observed soybean population at each site was set to 0 plants ha^{-1}. Mean weed biomass (M_w) at the lowest soybean plating rate was 1,338 and 1,385 kg ha^{-1} in Aurora and Hurley, respectively. Representing the reduction in weed biomass per soybean plant, the initial slope (i_w) was 3.45×10^{-6} ha plant^{-1} ($P < 0.001$) in Aurora and 8.18×10^{-6} ha plant^{-1} ($P = 0.06$) in Hurley.

have the potential to enhance competition for other resources (Arce et al. 2009). In organic no-till planted soybean, increasing planting rates have also been shown to interact synergistically with increasing cover crop mulch rates (Ryan et al. 2011). Often in conjunction with narrower row spacing, high soybean planting rates have long been used to hasten canopy closure and enhance shading (Ball et al. 2000a, 2000b; Place et al. 2009; Wax et al. 1977), which is advantageous for minimizing the germination of later-emerging annual weeds (Burnside and Colville 1964; Mickelson and Renner 1997; Peters et al. 1965; Wax and Pendleton 1968; Yelverton and Coble 1991). As observed in our experiment, shaded sub-canopy conditions can reduce weed biomass (Mohler and Callaway 1995; Tharp and Kells 2001). And, as fecundity is directly correlated with biomass production (Conley et al. 2002; Hartzler et al. 2004), more rapid canopy formation can decrease weed seed production and minimize contributions to the weed seedbank (Arce et al. 2009). Although weed seed production was not measured in our research, high soybean planting rates have the potential to contribute to both short- and long-term weed management.

Influence of Weed Biomass on Soybean Yield

Congruent with previous research showing that weed interference in soybean reduces the number of pods per plant and negatively impacts other yield components (Burnside and Moomaw 1977; Harris and Ritter 1987; Knake and Slife 1969; Krausz et al. 2001; Monks and Oliver 1988; Young et al. 1982), soybean yield decreased as weed biomass increased in our experiment (Figure 2.3). However, we cannot completely separate the effect of increasing weed biomass from the effect of decreasing soybean density on soybean yield. It has been previously reported that broadleaf weeds cause greater reductions in soybean yield compared with grass

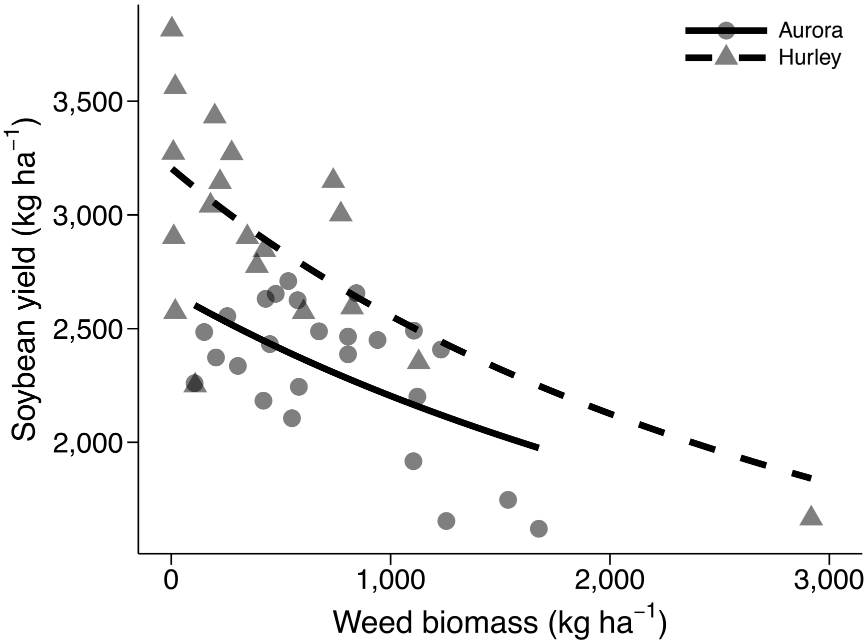

Figure 2.3. Response of soybean yield (kg ha^{-1}) to weed biomass (kg ha^{-1}). A rectangular hyperbolic model with block as a random effect (Equation 2) was used to describe this nonlinear relationship. The parameter estimates for the reciprocal of the weed-free yield of an individual soybean plant (a_0) and the soybean yield loss per unit weed biomass (i_w) were significant in Aurora (a_0 = 161 plant kg^{-1}, $P < 0.001$; $i_w = 2.10\times10^{-4}$ ha kg^{-1}, $P = 0.007$) and Hurley (a_0 = 149 plant kg^{-1}, $P < 0.001$; $i_w = 2.50\times10^{-4}$ ha kg^{-1}, $P = 0.02$).

weeds (McWhorter and Hartwig 1972; Nave and Wax 1971). Based on a visual assessment of ground cover, the dominant weed species in Aurora was a broadleaf, common ragweed (*Ambrosia artemisiifolia* L.), whereas large crabgrass (*Digitaria sanguinalis* [L.] Scop.) was most prevalent in Hurley. However, the initial reduction in soybean yield associated with increasing weed biomass was very similar in Aurora ($i_w = 2.10\times10^{-4}$ ha kg^{-1}, $P = 0.007$) and Hurley ($i_w = 2.50\times10^{-4}$ ha kg^{-1}, $P = 0.02$), indicating that weeds exerted a consistent competitive effect across sites. Despite different weed communities, soybean yield loss from weed biomass did not differ substantially.

Soybean Yield Response to Population

Soybean yield at the plot-level ranged from 1,620 to 2,709 kg ha^{-1} in Aurora and 1,665 to 3,815 kg ha^{-1} in Hurley (Figure 2.4). Soybean yields were comparable to those previously observed in the long-term Cornell Organic Cropping Systems Experiment (Caldwell et al. 2014), indicating little to no yield difference relative to tillage-based soybean production practices. Based on the nonlinear model (Equation 3), the estimated asymptote was 2,506 kg ha^{-1} in Aurora ($P < 0.001$) and 3,282 kg ha^{-1} in Hurley ($P < 0.001$), and the parameter estimate for rate (b) was also significant at both sites ($P < 0.001$).

It is well established that at lower populations, soybean can maintain yield per unit area through increased partitioning of dry matter to branches, a greater number of seeds per plant, and

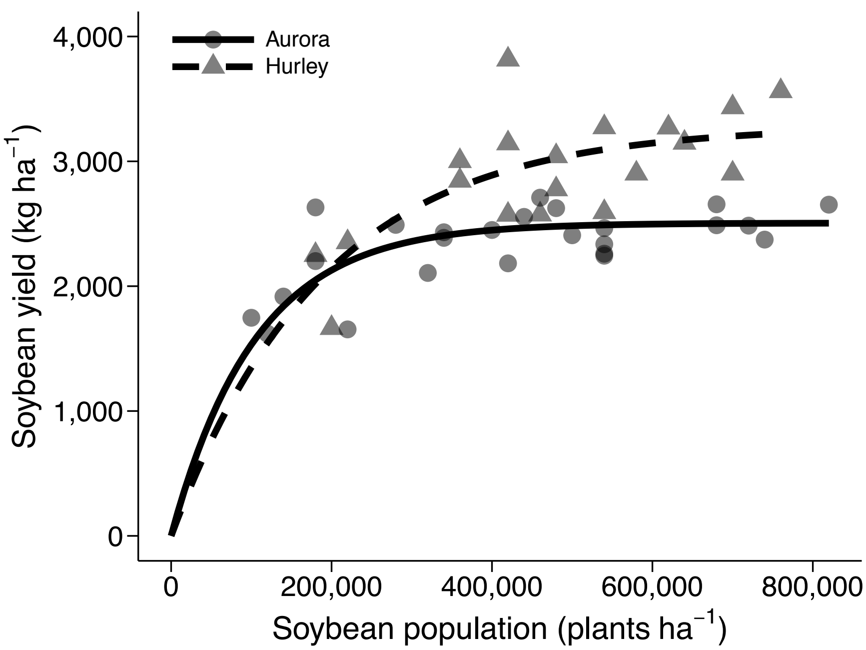

Figure 2.4. Relationship between soybean population (plants ha^{-1}) and yield (kg ha^{-1}). An asymptotic model constrained to pass through the origin (Equation 3) was used with block as a random effect. In Aurora, the horizontal asymptote (a) was predicted at 2,506 kg ha^{-1}, and the natural logarithm of the rate constant (b) was -11.6 ($P < 0.001$). In Hurley, a = 3,282 kg ha^{-1} and b = -12.1. Both parameter estimates at each site were significant ($P < 0.001$).

other forms of compensatory growth (Board 2000; Carpenter and Board 1997; Lueschen and Hicks 1977; Pedersen and Lauer 2002; Weber et al. 1966; Wells 1991). Consequently, yield gains from higher planting rates have been inconsistent, which corresponds to the variability introduced through interactions among cultivar genetics, environmental conditions, and management practices (Salado-Navarro et al. 1986). Numerous researchers have reported that yield initially increases in response to increasing plant populations, but then it will remain static or decline above a certain population level (Ball et al. 2000a, 2000b; Duncan 1986; Egil 1988; Norsworthy and Oliver 2001; Weber et al. 1966; Wiggans 1939). In our experiment, soybean yield increased nonlinearly as population increased, eventually plateauing at higher plant densities. This asymptotic relationship between increasing plant population and yield has been attributed to reduced radiation use efficiency (Purcell et al. 2002), as well as more intense intraspecific competition (Egli 1988) resulting in diminishing yield gains (Edwards and Purcell 2005) or "Phase III" constant yield (Duncan 1986).

Higher populations also tend to result in taller plants (Hicks et al. 1969; Johnson and Harris 1967; Wilcox 1974), which can contribute to an increased incidence of lodging (Cooper 1971b; Costa et al. 1980; Weber et al. 1966). When lodging is not severe, soybean yield is often the same across a range of populations (Cooper 1971b), or optimum populations can be higher (Probst 1945). Above optimum populations, an increase in lodging—especially when it occurs during early pod fill (Cooper 1971a)—can result in lower yields (Weber et al. 1966). Despite populations exceeding 700,000 plants ha^{-1}, minimal lodging was observed in our experiment, neither slowing harvest nor reducing yield. Based on feedback from organic farmers in New York, the cover crop-based organic rotational no-till system can hasten soybean harvest and help farmers avoid damaging their combine head on protruding rocks that are common in soybean fields where inter-row cultivation is used (K. Martens, personal communication, 2015), which is a major concern for many soybean farmers on shallow, rocky soils (T. Oechsner, personal communication, 2015).

Partial Profitability

In Aurora, the quadratic model predicted a maximum partial return of \$2,356 ha^{-1} at a planting rate of 650,000 seeds ha^{-1}, whereas in Hurley, the predicted maximum was \$3,033 ha^{-1} at a rate of 720,000 seeds ha^{-1} (Figure 2.5). These two predicted economically optimal planting

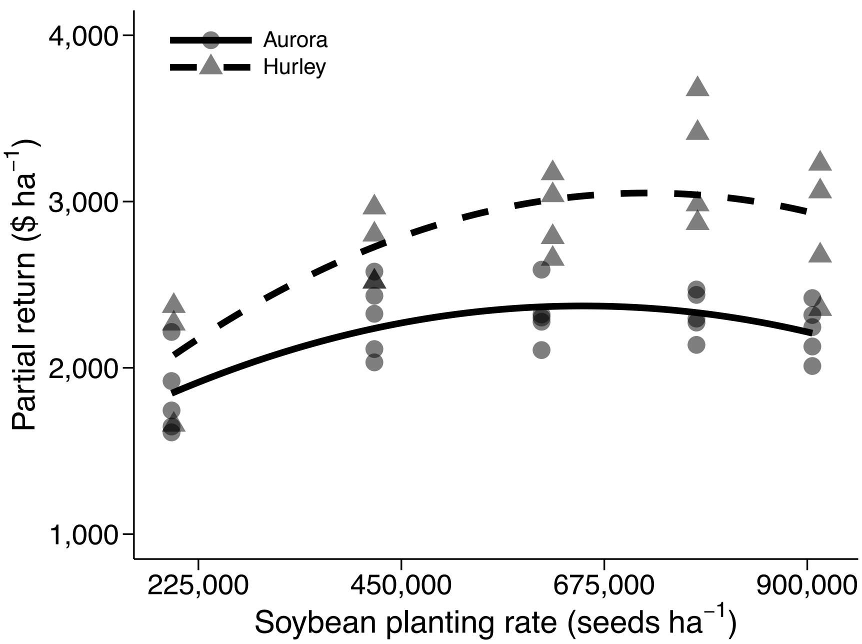

Figure 2.5. Partial return (\$ ha^{-1}, y) as a function of soybean planting rate (seeds ha^{-1}, x). As described in Equation 4, this response is augmented by soybean seed cost (\$0.0004 seed^{-1}) and the mean market price for organic food-grade soybean in 2014 (\$1.04 kg^{-1}). A quadratic model with block as a random effect represents this relationship at both sites. In Aurora, the equation is y = -2.53×10$^{-9}x^2$ + 0.00327x + 1300.57 (R_m^2= 0.48, R_c^2 = 0.78; first-degree term, P < 0.001; second-degree term, P < 0.001), and in Hurley, y = -3.54×10$^{-9}x^2$ + 0.00509x + 1202.92 (R_m^2= 0.50, R_c^2 = 0.69; first-degree term, P = 0.01; second-degree term, P = 0.04).

rates correspond to average emerged soybean populations of 466,000 and 539,000 plants ha^{-1} in Aurora and Hurley, respectively (Figure 2.1). At planting rates above the predicted optimums, partial returns began to decline as the increase in seed cost was not offset by a significant increase in yield (Figure 2.4). Using an average planting rate (685,000 seeds ha^{-1}) based on the economically optimal rates from both sites, the estimated changes in partial return were positive across all seed cost and market price combinations (Table 2.2) due to the substantial predicted yield advantage (416 kg ha^{-1}) obtained when planting at 685,000 seeds ha^{-1} instead of 321,000 seeds ha^{-1}.

Although high planting rates have been associated with enhanced weed suppression and greater yields in some instances, higher rates do not consistently improve profitability due to the

Table 2.2. The estimated change in partial return ($ ha^{-1}) across a range of market prices and seed costs for planting at 685,000 seeds ha^{-1} (the average economically optimal rate based on both sites), rather than planting at the recommended conventional soybean planting rate of 321,000 seeds ha^{-1} for 76-cm row spacing. Estimated change in partial return was calculated by multiplying the yield advantage (416 kg ha^{-1}) by the market price ($ kg^{-1}), and then subtracting the product of the seed cost ($ seed^{-1}) and the additional seed (364,000 seeds ha^{-1}) required for the higher planting rate of 685,000 seeds ha^{-1}.

	Estimated change in partial return				
	Market price				
	$ kg^{-1}				
Seed cost[a]	0.74	0.84	0.94	1.04	1.14
$ seed^{-1}	$ ha^{-1}				
0.00029	203.12	241.30	283.30	325.30	367.30
0.00035	183.47	221.65	263.65	305.65	347.64
0.00040	163.81	201.99	243.99	285.99	327.99
0.00045	144.16	182.34	224.34	266.33	308.33
0.00051	124.50	162.68	204.68	246.68	288.68

[a] Based on 4,630 seeds kg^{-1}, these seed costs correspond to $1.35, $1.60, $1.85, $2.10, and $2.35 kg^{-1}.

concomitant increase in seed costs. In an experiment conducted by Harder et al. (2007), increasing the population from approximately 300,000 to 445,000 plants ha^{-1} did not significantly increase soybean yield, resulting in lower profit due to the increased seed cost. As another example, Norsworthy and Oliver (2001) found that higher soybean planting rates sometimes required only one application of glyphosate, whereas lower rates of 185,000 and 247,000 seeds ha^{-1} required three glyphosate applications to maintain 90% control of weed species. However, the reduced costs associated with fewer herbicide applications at high planting rates were negated by technology fees and the high cost of herbicide-resistant soybean seed; as a result, maximum gross profit margin was achieved at the lowest planting rate. In our analysis, the substantial partial returns at the high planting rates of 650,000 and 720,000 seeds ha^{-1} depend on correspondingly high yields and the considerable price premium obtained for organic food-grade soybean. It is important to acknowledge that organic feed-grade soybean market prices are lower than organic food-grade prices, but they are still often double the price of conventional feed-grade prices (USDA-AMS 2016; USDA-NASS 2016). Although organic feed-grade soybean command a lower price, yields are typically greater than food-grade soybean cultivars.

The economic advantage of planting soybean at 685,000 seeds ha^{-1} decreases as seed cost increases or market price decreases, but farmers would still realize an increase in partial returns of \$124.50 ha^{-1} (before hauling costs) at the highest seed cost and lowest market price in Table 2.2. Notably, the average food-grade price for organic soybean was \$0.92 kg^{-1} between 2008 and 2014 (USDA-AMS 2016). As a relatively high price of \$0.0004 $seed^{-1}$ (\$1.85 kg^{-1}; 4,630 seeds kg^{-1}) was used for the partial return calculations in Figure 2.5, farmers that save their own seed or source less-expensive seed would realize even greater returns (as supported by the complementary analysis in Table 2.2). The two highest seed costs of \$0.00045 and \$0.00051 seed^{-1} were included in the analysis so that we could estimate partial returns at highly unfavorable seed cost-market price combinations. If lodging does not result in yield losses at harvest or economic losses due to slower harvesting, our results indicate that a high planting rate of between 650,000 and 720,000 seeds ha^{-1} optimizes profitability in cover crop-based organic rotational no-till soybean production.

Management Considerations

As previously discussed, narrower row spacing can improve ground cover and increase shading by attaining canopy closure earlier than wider row spacing. However, grain drills tend to result in less uniform seed depth and more variable within-row distance between seeds compared with row crop planters (Bertram and Pedersen 2004), which can negatively affect emergence and reduce final stand uniformity (Cox and Cherney 2011). Unless cover crop biomass levels are relatively low, planters are recommended in organic no-till planted soybean production to achieve better seed placement through the thick layer of mulch (Mirsky et al. 2013). We planted soybean on 76-cm row spacing primarily because it facilitates inter-row high-residue cultivation if weed suppression from the cover crop is insufficient. A high-residue cultivator can be a very effective tool for managing weeds that have broken through the mulch between the rows (Nord et al. 2012). Furthermore, soybean in wider row spacing have been shown to perform better than narrow row soybean when soil moisture is limited (Alessi and Power 1982; Devlin et al. 1995), and lodging tends to be reduced compared with narrower spacing when the planting rate is elevated (Cooper 1971b).

As a compromise between narrow drilled spacing (e.g., 19 cm) and wide planted rows (≥76 cm), a split-row planter for 38-cm rows would provide the improved seed placement and stand uniformity of a row crop planter, as well as earlier canopy closure, enhanced shading, and potentially higher yields compared with wide row spacing (Bertram and Pedersen 2004; Costa et al. 1980; De Bruin and Pedersen 2008a). Although high-residue cultivation would not be possible at this row spacing, greater shading from the narrower soybean rows might help reduce the need for this practice.

At both sites, increasing the soybean planting rate resulted in lower weed biomass and higher soybean yields. Our results suggest that the greatest partial returns are attained at planting rates nearly double the recommended rates used by most conventional and tillage-based organic soybean producers. When high planting rates do not reduce yield via lodging or other deleterious effects, such rates can provide some "insurance" against poor seed germination (Duncan 1986). Given the high price premium for organic soybean, high planting rates are relatively cheap insurance when the benefits of improved weed suppression and higher yields are also included during planting rate decision-making for cover crop-based organic rotational no-till soybean management. Additional research should be conducted to assess the consistency of these results under different environmental conditions, and to develop planting rate recommendations specifically for organic no-till planted soybean production.

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