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Spring-planted cover crops for weed control in soybean

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Abstract

Replacing tillage with cover crops (CC) for weed management in corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] systems with mechanical weed control has many soil health benefits but in the western Corn Belt, CC establishment after harvest is hampered by cold temperatures, limited labor and few compatible CC species. Spring-planted CC may be an alternative, but information is lacking on suitable CC species. Our objective was to evaluate four spring-planted CC with respect to biomass production and weed suppression, concurrent with CC growth and post-termination. Cover crop species tested were oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), brown mustard [*Brassica juncea* (L.) Czern.] and yellow mustard (*Brassica hirta* Moench). They were compared to no-CC treatments that were either tilled pre- and post-planting of soybean (no-CC tilled) or not tilled at all (no-CC weedy). CC were planted in late March to early April, terminated 52–59 days later using an undercutter, and soybean was planted within a week. The experiment had a randomized complete block design with four replications and was repeated for 3 years. Mustards and small grains produced similar amounts of biomass (1.54 Mg ha^{-1}) but mustard biomass production was more consistent (0.85–2.72 Mg ha^{-1}) than that of the small grains (0.35–3.81 Mg ha^{-1}). Relative to the no-CC weedy treatment, mustards suppressed concurrent weed biomass in two out of 3 years, by 31–97%, and small grains suppressed concurrent weed biomass in only 1 year, by 98%.

Six weeks after soybean planting, small grains suppressed weed biomass in one out of 3 years, by 79% relative to the no-CC weedy treatment, but mustards did not provide significant weed suppression. The no-CC tilled treatment suppressed weeds each year relative to the no-CC weedy treatment, on average 87%. The ineffective weed control by CC reduced soybean biomass by about 50% six weeks after planting. While spring-planted CC have the potential for pre-plant weed control, they do not provide adequate early season weed suppression for soybean.

Introduction

Weeds are the major cause for yield reductions in organic soybean systems that rely on mechanical weed management (Cavigelli *et al.*, 2008). Weed control in these systems includes tillage prior to planting soybean, and during early soybean growth until canopy closure. Reducing the amount of tillage can have many benefits, including improved soil structure, reduced erosion, retention of organic matter and nutrients and cost savings, as tillage is an energy and labor-intensive process. Cover crops (CC) are often used to improve soil structure and soil organic matter (Blanco-Canqui *et al.*, 2015), but they are increasingly recognized as a tool for sustainable weed management. CC can reduce weed density and biomass during early season crop growth, a period when weed control is critical (Osipitan *et al.*, 2018). CC suppress weeds by competition (Sturm *et al.*, 2018) and by creating a physical barrier in the form of their residue (Teasdale, 1996). CC residue modifies the quantity and quality of solar radiation, in particular altering the ratio of red:far-red light that reaches the surface, decreasing weed seed germination (Teasdale and Mohler, 1993).

The amount of CC biomass is generally proportional to its ability to provide weed control (Finney *et al.*, 2016). In addition, some CC release allelopathic compounds that contribute to weed suppression by inhibiting germination and early growth (Kunz *et al.*, 2016; Rehman *et al.*, 2019). The CC termination method also impacts its ability to suppress weeds during early-season crop growth. In systems with mechanical CC termination, undercutting the CC resulted in lower grassy weeds and greater soil moisture than disking the CC (Wortman *et al.*, 2012a, 2013).

In corn (*Zea mays* L.)-soybean systems, CC are usually established in the fall after corn harvest and terminated prior to soybean planting. However, labor and equipment constraints challenge CC establishment after corn harvest in the western Corn Belt (Oliveira *et al.*, 2019).

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Another window for establishing CC is early spring before soybean planting. The short growing season in early spring limits CC to those that grow rapidly in cool weather and provide weed suppression while alive and as mulch once terminated. Organic farmers in this region often delay soybean planting until the end of May when warmer soil temperatures prevail (Delate, 2003; Moncada and Sheaffer, 2010), which could benefit CC biomass production. In contrast to fall-planting, spring-planted species do not have to be winter-hardy which allows for greater diversity of CC species than fall-planting. Suitable species include mustards (*Brassica spp.*) and spring small grains as they have fast emergence, germinate at cold temperatures, produce high amounts of above-ground biomass necessary to compete with weeds for light, and high below-ground biomass to compete for water and nutrients (Wortman *et al.*, 2012b; Brust *et al.*, 2014). In addition, small grains and mustards have allelopathic effects on a number of weed species (Schulz *et al.*, 2013; Rehman *et al.*, 2019).

In the Western Corn Belt, spring-planted mustard and small grain CC are much less common than fall-planted CC. Two previous studies (Krishnan *et al.*, 1998; Wortman *et al.*, 2012a) investigated weed suppression by mustard CC in the western Corn Belt but to our knowledge, no studies compared mustard and small grain CC to mechanical weed control practices.

With our research, we (1) quantified the biomass production of spring-planted mustard and small grain CC, (2) assessed the weed suppression of spring-planted CC pre- and post-planting of soybean compared to tillage-based, no-CC methods and (3) determined spring-planted CC effects on subsequent soybean growth. Our hypotheses were that mustard CC would produce more above-ground biomass than small grain CC. We hypothesized CC would have greater weed suppression both pre- and post-planting of soybean compared to the no-CC weedy treatment but would have lower weed suppression than the no-CC tilled treatment. We expected that CC would not affect soybean growth.

Materials and methods

Site

The experiments were carried out in 2017, 2018 and 2019 at the Agroforestry Farm of the Eastern Nebraska Research and Extension Center near Mead, Nebraska (41°29′N; 96°30′W; 354 m above mean sea level; sub-humid; zone 5b; 768 mm annual precipitation). Soils at the site are mapped as Yutan silty clay loam (fine-silty, mixed, superactive, mesic Mollic Hapludalf) and Tomek silt loam (fine, smectic, mesic Pachic Argiudoll) with a slope of <5% and organic matter content of 3.5%. All fields were organically managed according to National Organic Program standards between 2005 and 2017 and were in a soybean-winter wheat-corn rotation, with cattle manure applications of 56 Mg ha^{-1} (wet weight) after winter wheat harvest. High weed pressure led to the decision to end organic management and switch to conventional management with a corn–soybean rotation starting in 2018.

Experimental design

There were four CC treatments: spring barley (*Hordeum vulgare* L. 'Robust'), spring oats (*Avena sativa* L. 'Jerry'), yellow mustard (*Brassica hirta* Moench 'Ida Gold') and brown mustard [*Brassica juncea* (L.) Czern. 'Kodiac']. There were two treatments without CC: a no-CC treatment that was tilled for weed control and a no-CC 'weedy' treatment where no tillage was carried out. Plots measured 6 m × 12 m and were arranged randomly, in complete blocks with four replications.

Table 1. Field and plot management activities in each year of the experiment (2017, 2018, 2019)

Activities	2017	2018	2019
Pre-CC tillage[a]	mid-March	Late March	Apr. 4, Apr. 8
Cover crop planting	Mar. 21	Apr. 2	Apr. 9
Cover crop biomass sampling	May 18	May 23	May 31
Weed biomass May sampling	May 18	May 23	May 31
Pre-soybean tillage[b]	May 7, May 25	May	May
Cover crop termination/ undercutting[c]	May 30	May 23	Jun. 2
Soybean planting	May 31	May 24	Jun. 8
Early season inter-row cultivation[d]	–	weekly	weekly
Weed biomass July sampling	Jul. 14	Jul. 10	Jul. 23
Soybean biomass sampling	–	Jul. 10	Jul. 23

[a]Pre-CC tillage was done in all plots, including no-CC plots, prior to the date when CC were planted. It consisted of disking.
[b]Pre-soybean tillage was only carried out in no-cover crop (no-CC), weed-free plots prior to the undercutting application. It consisted of rotavating. In 2018 and 2019, plots were tilled on two days, but exact dates were not available.
[c]Cover crops were terminated using an undercutter. No-cover crop plots were undercut at the same time.
[d]Early season inter-row cultivation was only carried out in no-CC, tilled plots. It consisted of rototilling plots once per week between the time of soybean emergence and July weed biomass sampling.

Plot management

All plots, including the two no-CC treatments, were disked (Kewanee 1010 disk, Kewanee, IL) at a depth of 0.2 m prior to CC planting. CC were drill planted in late March to early April (Table 1) with a Land Pride APS1586 solid stand seeder (Salina, KS) in rows 0.18 m apart. Barley and oats were drilled at 135 kg ha^{-1} and the mustards were drilled at 16 kg ha^{-1}. Prior to planting of soybean, the no-CC tilled treatments were tilled twice with a Long 1537 rotavator (Tarboro, NC) (Table 1), whereas the no-CC weedy treatments were not tilled. CC were terminated by undercutting with a Richardson stubble mulch sweep-plow (Springfield, IL) set to a depth of 0.1 m. With this method, CC residue remained on the soil surface as a mulch. Both tilled and weedy no-CC plots were also undercut. The target soybean planting was late May, with CC termination a day before soybean planting. However, in 2019, 75 mm of rain fell between May 26 and 28 and 64 mm between June 3 and 4, delaying CC termination and soybean planting (Table 1). Soybeans were planted with a no-till planter (Case IH 900, Racine, WI) at a row spacing of 0.76 m. In 2017, the soybean seed was organically certified (variety unknown), planted at 457,000 live seeds ha^{-1}. Non-organic glyphosate [*N*-(phosphonomethyl)glycine]-resistant cultivars Pioneer 31T11 (relative maturity 3.1) and Pioneer 25A29X (relative maturity 2.5) were planted in 2018 and 2019, respectively, at 390,000 live seeds ha^{-1}. After soybean planting,

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Table 2. Source of variation, degrees of freedom (d.f.), and significance values for cover crops (CC) biomass (sampled in May at termination), weed biomass (sampled in May at CC termination and in July in early-season soybean) and soybean biomass (sampled in July)

	CC biomass[a]		Weed biomass[b]				Soybean[c]	
Source of variation	d.f.	May	d.f.	May	d.f.	July	d.f.	July
Treatment	3	0.868	5	<0.001	5	<0.001	5	<0.001
Year	2	<0.001	2	<0.001	2	0.119	1	0.033
Treatment × Year	6	0.011	10	<0.001	9	0.011	5	0.498

Degrees of freedom vary, because not all treatments and/or years were included in each analysis of variance.
[a]Includes the four CC treatments (brown mustard, yellow mustard, barley, oats) and all years (2017, 2018, 2019).
[b]Includes all treatments (brown mustard, yellow mustard, barley, oats, no-CC tilled and no-CC weedy treatments) and all years, except no-CC tilled treatment in July 2017.
[c]Includes all treatments, and 2 years (2018, 2019).

the no-CC tilled treatments were inter-row cultivated weekly with a walk-behind Troybilt rototiller (Valley City, OH) until six weeks after planting (WAP). In 2017, no-CC tilled plots were not inter-row cultivated. No weed control was carried out in the CC treatments and the no-CC weedy treatment until mid-July (Table 1).

In 2017 and 2018, the experiment was carried out in fields with large soil seed banks. Organic management on the Agroforestry Farm organically certified acres ceased in 2018 because of the problematic weed pressure. In 2018 and 2019, after soybean and weed biomass sampling were completed, soybean was sprayed with glyphosate. Soybean yield data is not included here because of the confounding effects of the glyphosate application but is available in the Supplementary files.

Sampling

Cover crop and weed biomass was assessed in late May of each year (Table 1). To sample, we placed two 0.3 m × 1.5 m frames randomly in the plots, clipped all biomass, and sorted it into CC and weeds. Weeds were not separated by species as weed biomass was below 0.1 Mg ha^{-1} in most samples. Weed species present were field pennycress (*Thlaspi arvense* L.), pigweeds (*Amaranthus* spp.), common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.) and foxtails (*Setoria* spp.).

To assess early season weed control provided by CC (Osipitan *et al.*, 2018), we sampled weed biomass six WAP soybean, by clipping all biomass within two randomly placed 0.3 m × 1.5 m frames. At that sampling time, weed biomass were separated into the four weeds present: pigweeds, common lambsquarters, velvetleaf and foxtails. In 2017, inter-row cultivation was not carried out in the no-CC tilled plots and subsequently, weed biomass data was not collected in these plots. In 2018 and 2019, we also collected soybean biomass at the same time using the same frame as an indicator of soybean performance.

All biomass samples were dried in a forced air oven at 60°C for one week and were then weighed to obtain dry matter. Weed biomass sampled six WAP was weighed separately by species in 2017 and 2019. The proportion that each weed species contributed to the total amount of weed biomass was calculated. In 2018, only total weed biomass was determined.

In 2019, CC biomass was analyzed for total C and N by combustion analysis at Ward Laboratories (Kearney, NE).

Weather data

The daily soil temperature at a depth of 0.1 m, daily air temperature and precipitation reported were from a weather station about 1 km away from the trial site (Automated Weather Data, High Plains Regional Climate Center, 2020). Long-term normal temperature and precipitation, beginning in 1981 and ending in 2020, were obtained from the same station. Cover crop growing degree day (GDD) from the date of CC planting to the date of CC termination was calculated using daily high and low temperature with a base temperature of 0°C (Robertson *et al.*, 2002; Björkman *et al.*, 2015).

Statistical analysis

Data were analyzed with the GLIMMIX procedure in SAS 9.4 (SAS) using analysis of variance (ANOVA). Fixed factors were treatment, year and their interaction. The block by year interaction was a random factor. The LSMEANS statement was used to determine statistically significant differences between treatment means at a significance level of $\alpha = 0.05$. Not all treatments and years were included in each ANOVA. For CC biomass, the predictor variables were the four CC species and three years. For May weed biomass, the predictor variables were the six treatments (four CC species and two no-CC treatments) and three years. For July weed biomass, predictor variables were the six treatments and three years. Predictor variables for weed biomass proportions were the six treatments and two years. Weed control as the percentage of weed biomass reduction in reference to the no-CC weedy treatment (Osipitan *et al.*, 2018) was calculated for treatments that significantly reduced weed biomass and was given in the text. For soybean biomass, the predictor variables were the six treatments, but only two years because soybean biomass was not sampled in the first year.

After comparing individual species, we carried out a second ANOVA where we combined CC species data into families (small grains and mustards) and contrasted them to the no-CC treatments. Fixed factors were family, year and their interaction, and the random factor was block. Where differences existed, means and *P* values were given in the text. The source of variation table including treatment means for this comparison can be found in the Supplementary files.

Results and discussion

Cover crop biomass

Cover crop biomass production was influenced by the CC species by year interaction (Table 2). The interaction resulted from the biomass differences among CC species in 2017 (Fig. 1). CC were most productive in 2017 (Fig. 1) with biomass yields of 3.81 Mg ha^{-1} for oat, 3.48 Mg ha^{-1} for barley, 2.72 Mg ha^{-1} for

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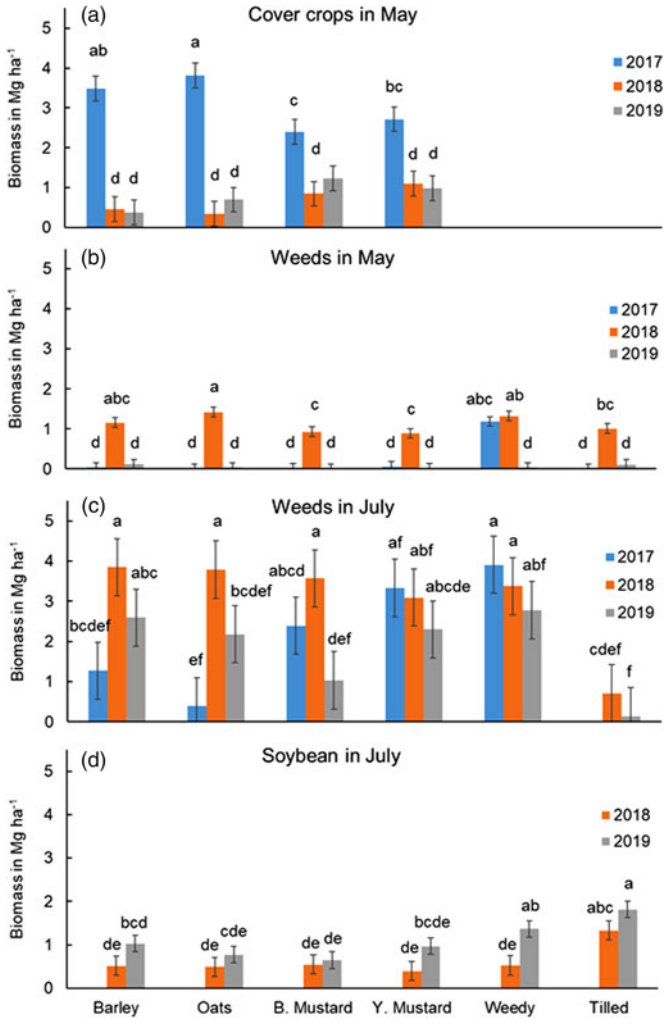


Fig. 1. Biomass of cover crops (CC) at termination (a), weeds at CC termination (b), weed biomass in soybean six weeks after planting (c) and soybean biomass six weeks after planting (d). Treatments were barley CC (Barley), oats CC (Oats), brown mustard CC (B. mustard), yellow mustard CC (Y. mustard), no-CC plots that were not tilled (Weedy) and no-CC plots that were tilled for weed control (Tilled). The study years were 2017 (blue bars), 2018 (red bars), and 2019 (grey bars). Soybean biomass was not available in 2017. Lines above bars indicate standard errors. Bars with the same letters indicate means that are not significantly different from each other at $\alpha = 0.05$.

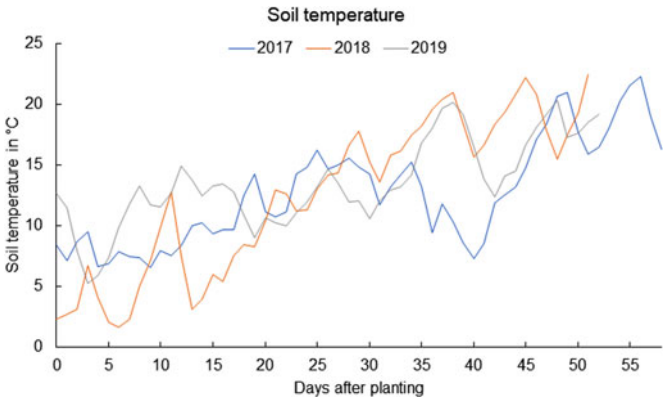


Fig. 2. Soil temperature from the day of CC planting to the day of CC termination for each year of the study.

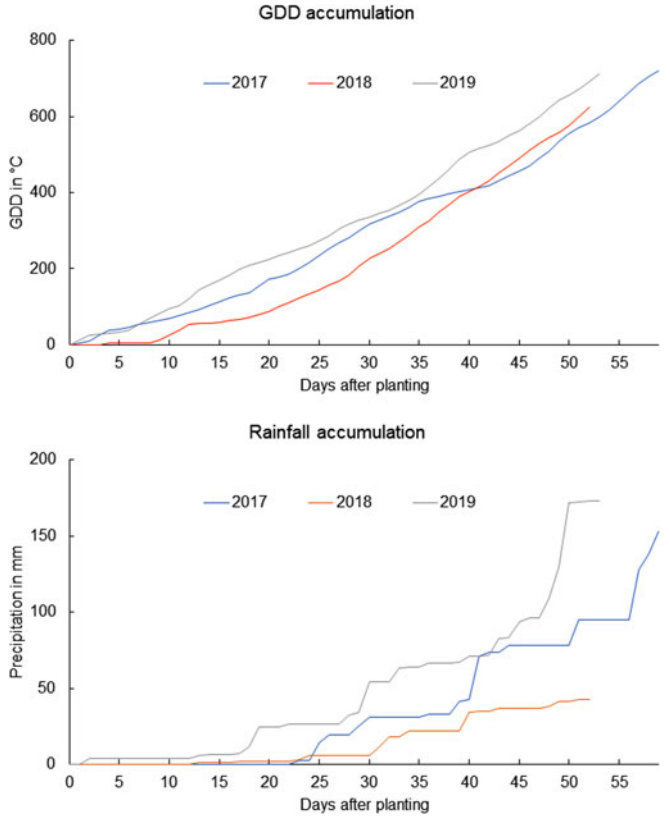


Fig. 3. Growing degree day (GDD) accumulation (top) and rainfall accumulation (bottom) from the day of CC planting to the day of CC termination for each year of the study.

yellow mustard and 2.40 Mg ha^{-1} for brown mustard. In the other two years, biomass production was not different among CC species and was 0.69 Mg ha^{-1} in 2018 and 0.82 Mg ha^{-1} in 2019.

We combined CC species into families to better contrast productivity differences between small grains and mustards (data not shown). In 2017, small grains produced 1.08 Mg ha^{-1} more biomass than the mustards ($P < 0.001$). In 2018, mustards produced 0.98 Mg ha^{-1} biomass, 0.57 Mg ha^{-1} more than the small grains ($P = 0.057$) and in 2019, mustards produced 1.11 Mg ha^{-1}, 0.57 Mg ha^{-1} more than the small grains ($P = 0.058$). Averaged across years, mustards and small grains had the same amount of biomass (1.55 and 1.53 Mg ha^{-1}, respectively, $P = 0.906$), however, mustards were more reliable producers, with a narrower range of biomass production (Fig. 1).

More favorable weather conditions in 2017 were likely the major contributor to high CC biomass (Figs 2 and 3). Mustards, oats and barley germinate at low soil temperatures, and have greater than 90% emergence at soil temperatures of 6°C (Dubetz *et al.*, 1962). In 2017 and 2019, from the time of CC planting, daily soil temperatures at a depth of 0.1 m were always above 6°C (Fig. 2). In 2018, for the first eight days after planting, soil temperatures were below 6°C. The required 120–130 GDD for emergence of brassicas and small grains (Miller *et al.*, 2001; Robertson *et al.*, 2002) were accumulated by April 4 in 2017, April 24 in 2018 and April 20 in 2019 (Fig. 3). Late April temperatures in 2017 were lower than in 2018, 2019 and the long-term average, which may have extended the vegetative growth period of the

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CC because it took longer to reach the 500 GDD necessary to begin flowering in mustards. Oats and barley did not flower, because the 750 GDD for flowering were not accrued in any year (Miller *et al.*, 2001). CC accumulated 719 GDD in 2017, 56 GDD more than the long-term average. In 2018, temperatures were below freezing for most of the first two WAP, delaying CC emergence. CC had effectively only one month of growing time, and accumulated 625 GDD, whereas the normal accumulation for this period is 676 GDD. In 2019, although there were only 52 days between planting and termination, 713 GDD were accumulated, similar to 2017. GDD accumulation was faster, and the reproductive stage was reached 40 days after planting, likely reducing additional biomass accrual as mustards began flowering.

Rainfall accumulation in 2017 was 153 mm, the same as the long-term average, although there was little precipitation for the first 25 days (Fig. 3). The spring of 2018 was very dry with only 43 mm of rainfall. In 2019, rainfall was highest at 173 mm and was more evenly distributed.

Other studies in eastern Nebraska have reported similar ranges in biomass values for mustards. In a study where mustards were planted in late March to early April and terminated 46–56 days later, brown mustard produced 0.77–1.09 Mg ha^{-1}, yellow mustard 'Martigena' 0.5–0.62 Mg ha^{-1} and yellow mustard 'Salvo' 1.34–1.39 Mg ha^{-1} (Krishnan *et al.*, 1998). A trial at the same site as ours reported that the mean biomass of four brassica species, including mustards, was 2.78 Mg ha^{-1} in 2010 and 2.1 Mg ha^{-1} in 2011 (Wortman *et al.*, 2012b). A study that measured biomass production of spring-planted oats for forage in eastern Nebraska reported that by early June, oat biomass was 4.5–8.5 Mg ha^{-1} (Pflueger *et al.*, 2020). In a cover crop study in Illinois, oat was the most consistent biomass producer with 2.05–3.95 Mg ha^{-1}. Brown mustard 'Kodiak' produced high amounts of biomass in some years (3.27–4.48 Mg ha^{-1}) but very low biomass in some years due to insect damage (Holmes *et al.*, 2017). In western Canada, oats and barley planted in mid-April and terminated in late May produced 0.42 and 0.46 Mg ha^{-1} of biomass (Blackshaw, 2008).

In our study, the greatest biomass production occurred in the year with the earliest planting date. However, a study comparing mustard CC production for different spring-planting dates with sites in Illinois, Michigan and New York, found a correlation of planting date and mustard biomass only in Illinois, but not in the other states. Mustards received between 400 and 900 GDD and produced between 0.5 and 4 Mg ha^{-1}. There was no correlation with GDD and mustard biomass production. The authors concluded that factors other than GDD, such as precipitation, were limiting mustard growth in the spring (Björkman *et al.*, 2015). Our experiment was located in a subhumid climate, with dry and cold winters that typically do not have the high amounts of spring soil moisture that the previous study reported. Earlier planting may be more effective in drier climates for several reasons. Soil moisture may be greater earlier in the spring, benefitting germination, and there is more time to accumulate GDD and precipitation. The combination of these factors likely boosted biomass productivity in 2017.

Soil fertility, especially N availability, may also have influenced CC biomass production but was not measured in our study. Residual soil N may have been low after the corn crop that preceded soybean in our fields, however, we did not observe signs of N deficiency in CC in any year. Continuous N mineralization from the legacy of manure applications at this site could have supplied enough N for the CC. In a previous study under organic management in these fields, fields following corn had on average 11 mg NO_{-3} kg^{-1} at a depth of 0–0.2 m at the time of soybean planting (Koehler-Cole, 2015).

Weed biomass in May

Weed biomass at the time of CC termination depended on the main effects of CC treatment, year and their interaction (Table 2). In 2017, weed biomass in the CC and the no-CC tilled plots ranged from 0.01 to 0.06 Mg ha^{-1} and did not differ by treatment. In contrast, the no-CC weedy treatment had 1.82 Mg ha^{-1} of weed biomass (Fig. 1). Compared to the no-CC weedy treatment, small grains reduced weed biomass by 98% and mustards reduced weed biomass by 97%. In 2018, all treatments had much higher weed biomass than in 2017. Weed biomass in yellow and brown mustard treatments was similar at 0.91 Mg ha^{-1} which is 0.41 Mg ha^{-1} lower than the no-CC weedy treatment and equivalent to 31% weed control. Oat and barley biomass did not differ and was 1.29 Mg ha^{-1}. Small grains did not reduce weed biomass compared to the no-CC weedy treatment. In 2019, weed biomass was the same in all treatments, including the no-CC weedy treatment, and averaged 0.06 Mg ha^{-1} (Fig. 1). Except for the no-CC weedy treatment, all treatments in 2019 had similar weed biomass to the treatments in 2017.

We did not quantify the fraction of biomass by weed species but observed that field pennycress was the dominant weed. Common lambsquarter, velvetleaf, pigweeds and foxtails were present in each year at CC termination but were small.

The greatest weed biomass reduction occurred in 2017, the year with the earliest CC planting and highest CC productivity which may have led to a competitive advantage for CC. In turn, all CC suppressed weeds as well as the tilled treatment in this year. Although the spring of 2017 was wetter and warmer than 2018, weeds in plots without tillage or CC produced comparable biomass in 2017 and 2018. Despite favorable growing conditions, in 2019, weed biomass was low in all treatments. Late pre-CC tillage which was carried out in all plots (Table 1) may have delayed weed emergence and subsequent growth, compared to the previous years when pre-CC tillage occurred earlier.

Results from our study suggest that weed suppression by CC varies considerably from year to year and between species. Previous studies also found highly variable weed suppression in mustards with early plantings tending to control weeds better (Björkman *et al.*, 2015). In Illinois, out of six spring-planted CC species tested, mustard had greatest weed suppression, followed by oats. Weed and CC biomass were negatively correlated (Holmes *et al.*, 2017). In our study, CC may have impacted weeds not only by competition but also by allelopathy although we did not directly measure allelopathic effects. Small grains synthesize benzoxazinones (Schulz *et al.*, 2013) and mustards glucosinolates (Rehman *et al.*, 2019), which inhibit weed seed germination and early growth (Schulz *et al.*, 2013; Rehman *et al.*, 2019). Allelopathic effects caused up to 28% of weed suppression by CC (Sturm *et al.*, 2018), however, allelochemicals tend to degrade quickly and effects are unlikely to persist beyond two weeks (Rice *et al.*, 2012).

Weed biomass in July

The main effect of treatment and the interaction of treatment and year influenced weed biomass in early-season soybean six WAP (Table 2). In 2017, oat and barley treatments reduced weed

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Table 3. The effect of year, treatment and their interaction on the proportion of biomass contributed by different weeds and cover crop (CC) regrowth at the July sampling

	Weed and CC regrowth contribution to weed biomass				
Source of variation	Pigweed	CHEAL	ABUTH	Foxtail	CC regrowth
Year	Proportion in %				
2017	9b	38a	25a	28a	0b
2019	67a	5b	7b	3b	19a
P value	<0.001	<0.001	0.005	0.001	<0.001
Treatment					
Barley	47a	26	17	8	2b
Oats	33a	10	24	9	25a
Brown	12b	20	18	21	29a
Yellow	39a	25	8	28	0b
Weedy	42a	31	14	12	–
Tilled[a]	98	1	0	2	–
P value	<0.001	0.444	0.522	0.340	<0.001
Treatment × Year					
2017					
Barley	10c	50	24	16	0b
Oats	26bc	11	46	17	0b
Brown	2c	35	21	41	0b
Yellow	2c	43	14	42	0b
Weedy	3c	56	19	22	–
Tilled	na[b]	na	na	na	–
2019					
Barley	84a	1	11	0	4b
Oats	39b	9	2	1	49a
Brown	22bc	5	14	1	58a
Yellow	76a	8	2	14	0b
Weedy	81a	7	9	3	–
Tilled	98a	1	0	2	–
P value	0.001	0.180	0.219	0.710	<0.001

Treatments were the four CC (brown mustard, yellow mustard, barley, oats) and the no-CC tilled and no-CC weedy treatments. Weeds present were pigweed (*Amaranthus* ssp.), CHEAL (*Chenopodium album* L.), ABUTH (*Abutilon theoprasti* Medik.) and foxtail (*Setaria* ssp.). Cover crop regrowth is given because incomplete CC termination in 2019 resulted in CC biomass in some treatments. No data was available for 2018 and for the no-CC tilled treatment in 2017. Within a column, numbers followed by the same letter are not significantly different from each other at $\alpha = 0.05$.

[a]Only 2019 data available.

[b]na = data not available.

biomass relative to the no-CC weedy treatment (3.91 Mg ha^{-1}), by 68 and 90%, respectively. Yellow and brown mustard did not have lower weed biomass than the no-CC weedy treatment (Fig. 1). Weed biomass was not measured for the no-CC tilled treatment in that year. In 2018, only the no-CC tilled treatment (0.71 Mg ha^{-1}) reduced weed biomass, by 2.66 Mg ha^{-1} compared to the no-CC weedy treatment. In 2019, the no-CC tilled treatment decreased weed biomass by 2.64 Mg ha^{-1} and the brown mustard by 2.3 Mg ha^{-1} or 83%. The other treatments had on average 2.53 Mg ha^{-1} weed biomass. In that year, oats and brown mustard regrew after undercutting and contributed 49 and 58% of biomass to the total weed biomass (Table 3), which was 2.18 Mg ha^{-1} in oat plots and 1.03 Mg ha^{-1} in brown mustard plots.

The no-CC tilled treatment which was inter-row cultivated weekly after soybean planting (Table 1) was the only treatment with consistently low early season weed biomass, on average 0.42 Mg ha^{-1}. Compared to the no-CC weedy treatment, the no-CC tilled treatments reduced weed biomass by 79% in 2018 and 95% in 2019. Across years, weed biomass in the no-CC tilled treatment was always lower than weed biomass in the small grains ($P < 0.01$) or mustards ($P < 0.05$). Small grains and mustards had similar levels of weed biomass (2.35 and 2.62 Mg ha^{-1}, $P = 0.415$,

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data not shown) but only small grains decreased weed biomass relative to the no-CC weedy treatment, by an average of 30% across years. Looking at CC species individually, oat and brown mustard CC reduced weed biomass, by an average of 37 and 31%, respectively, but the other CC did not.

We measured the effect of CC on the proportion of biomass contributed by different weeds in 2017 and 2019 (Table 3). For each weed, there was a strong effect of year on their respective proportion of biomass, but the treatments and their interactions only impacted the proportion of pigweed. In 2017, pigweed made up 9% of the weed biomass, whereas velvetleaf, foxtails and lambsquarters each contributed between 25 and 38% of the biomass. In 2019, pigweed comprised about 67% of weed biomass across all treatments. Both no-CC treatments and the CC treatments without CC regrowth had greater proportions of pigweed than the treatments with high CC regrowth. Overall, brown mustard had the smallest proportion of pigweed in both years. Brown mustard may impact pigweed (Table 3), the predominant weed in 2019 which may explain brown mustard's low weed biomass in this year.

Cover crop biomass quantity and quality, such as the C:N ratio, impact early season weed control after CC termination (Finney *et al.*, 2016; Osipitan *et al.*, 2018). In our study, biomass C:N ratio was between 12:1 and 17:1 (tested in 2019, data not shown) likely resulting in fast break-down, whereas extended weed suppression is more likely with residue C:N ratios of around 25:1 and greater (Finney *et al.*, 2016). Cover crop biomass in our study was much lower than the 4 to 8 Mg ha^{-1} that have been identified as a threshold residue amount for lasting weed suppression (Mirsky *et al.*, 2013; Finney *et al.*, 2016). In 2017, the year with the highest CC productivity in our study, small grains suppressed weeds whereas mustards did not (Fig. 1). In a previous study in Nebraska, where mustard biomass was only 1 Mg ha^{-1}, total weed biomass was 40–49% lower seven weeks after CC termination at one site, probably due to allelopathy (Krishnan *et al.*, 1998). Mustards in our study were flowering at the time of termination, which decreases the concentration of allelochemicals in mustard tissue, possibly making them less effective at weed suppression (Krishnan *et al.*, 1998).

While CC in our study provided some weed biomass reduction, the level of reduction varied greatly between years. CC are not a reliable method of weed control and should be used along with other weed management tools such as inter-row cultivation. Yellow mustard had the highest mean weed biomass with the least annual variability and may not be a good choice for weed control in soybean. High CC biomass is key in improving weed suppression with CC and the most important management options to improve CC biomass production are earlier planting dates, delayed termination dates, improved establishment and soil fertility (Mirsky *et al.*, 2013; Ruis *et al.*, 2019). For maximum CC biomass, fall-planting may be a better option than spring-planting. In eastern Nebraska, fall-planted cereal rye (*Secale cereale* L.) produced between 0.57 and 2.22 Mg ha^{-1} by early May when it was terminated (Koehler-Cole *et al.*, 2020a). If allowed to grow as long as spring-planted CC in our study, cereal rye would likely produce greater quantities of biomass, with improved weed suppression potential, than spring-planted oats, barley, and mustards.

Soybean biomass in July

The main effects of CC treatment and year impacted soybean biomass six WAP, but their interaction did not (Table 2). Soybean biomass was 0.64 Mg ha^{-1} in 2018 and 1.10 Mg ha^{-1} in 2019. Across years, soybean biomass was 1.57 Mg ha^{-1} in the no-CC tilled treatment, twice the amount of the other treatments (Fig. 1). Cover crop treatments and the no-CC weedy treatment had similar soybean biomass with a mean of 0.76 Mg ha^{-1} (Fig. 1), although in 2019, oats and brown mustard treatments had lower soybean biomass than the no-CC weedy treatment ($P = 0.025$ and $P = 0.008$, respectively).

Weed removal is most critical to soybean growth and productivity between V2 and R3 (Van Acker *et al.*, 1993; Knezevic *et al.*, 2003). In our experiment, soybean was in the V4 to V6 stages at the July sampling, and the high weed pressure in the CC treatments and no-CC weedy treatments likely reduced soybean growth. Similar findings were reported by Krishnan *et al.* (1998) in mustard CC plots that did not receive additional weed control. In our study, there may also have been a CC specific effect on soybean biomass. In 2017, a year with high CC productivity, we observed that in barley and oat plots, soybean population was lower and soybean plants were smaller than in the other plots, despite low weed pressure in oat and barley plots compared to the other plots. Soybeans were planted with a no-till planter which achieved good seed–soil contact. However, low soil moisture due to water uptake by the CC may have limited soybean emergence. In addition, precipitation between soybean planting and biomass sampling was 37 mm below the long-term average (data not shown) and could have further restricted soybean growth. Precipitation during the same period in 2018 was 74 mm above the long-term average and was the same as the long-term average in 2019. In 2019, low soybean biomass after brown mustard and oat may have been due to competition or allelopathic effects from the surviving CC (see above). Germination and/or early growth of corn were impacted by allelochemical extracts of grass CC (Burgos and Talbert, 2000) and mustard CC (Chovancová *et al.*, 2015) in laboratory studies. Causal relationships of allelopathic CC on soybean growth have not been reported in the literature but their potential impact cannot be excluded because allelopathic effects of CC on row crops in the field are rarely measured (Koehler-Cole *et al.*, 2020b).

Conclusion

Spring-planted mustard CC were more consistent biomass producers over three years than spring-planted small grains. Mustard CC provided more consistent weed suppression than small grain CC, although both reduced weed biomass by 98% in one of three years. Weed suppression pre-soybean planting may be as effective as tillage if CC are established early and can produce high amounts of biomass. After their termination, oats and brown mustard CC provided some early-season weed control for soybean, but not comparable to the control achieved with weekly inter-row cultivation. CC did not produce biomass in large enough quantities or with high enough C:N ratio to adequately suppress weeds during early soybean growth. In CC plots, high weed pressure and in one year CC regrowth reduced soybean growth compared to plots that received weekly inter-row cultivation post-planting of soybean.

While spring-planted CC have the potential to replace tillage pre-plant soybean, our results indicate that they should be used in combination with other management practices to control weeds post-plant soybean. CC provide many other benefits to cropping systems, such as preventing nutrient loss, increasing nutrient

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cycling and providing food for pollinators, and these benefits should be part of the decision-making process. Identifying fast-growing, highly productive spring CC species or species mixes, in combination with optimum CC planting, termination and soybean planting dates may improve CC weed suppressive abilities. Further research should focus on finding strategies that optimize weed control pre- and post-soybean planting using a combination of CC and mechanical weed management.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170521000107.

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