ABSTRACT

Title of Thesis: ***GETTING LEGUME COVER CROPS TO WORK IN MID-ATLANTIC CROP ROTATIONS***

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In the mid-Atlantic United States, legume cover crop adoption is limited by the shortened establishment window after double-crop soybean (*Glycine max* (L.) Merr.) harvest. Interseeding legume cover crops into wide-row (76 cm) double-crop soybean presents an opportunity to supplement inorganic nitrogen (N) fertilizer in the subsequent corn (*Zea mays* L.) crop. We conducted field trials in Maryland and Delaware in which mixtures of cereal rye (*Secale cereale* L.) + hairy vetch (*Vicia villosa* Roth), crimson clover (*Trifolium incarnatum* L.), red clover (*Trifolium pratense* L.), or winter pea (*Pisum sativum var. arvense* (L.) Poir) were interseeded into double-crop soybean. We then examined the N contributions of the cover crop mixtures in combination with sidedress applications of inorganic N fertilizer on corn yields in Maryland in 2018 and 2019. This research demonstrated that interseeding cover crops into double-crop soybean is a potential strategy for increasing regional adoption of legume cover crops.

GETTING LEGUME COVER CROPS TO WORK IN MID-ATLANTIC CROP ROTATIONS

by

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Dedication

Dedicated to my grandparents,

Carolyn and Chuck Peterson

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Chapter 1: Getting legume cover crops to work in mid-Atlantic cropping systems: the effects of interseeding on double-crop soybean yields and cover crop performance

Introduction

Cover crop usage has expanded in the mid-Atlantic region of the US in response to concerns regarding water quality and soil health, and federal and state-based incentives (CTIC et al., 2016; Bryant, 2019). Maryland and Delaware farmers lead the country in cover crop adoption, with use at 29% and 20% of arable acreage, respectively, compared to the national average of 3.9% (Zulauf and Brown, 2019). Cereal cover crops, such as cereal rye, wheat (*Triticum aestivum* L.), and triticale *(x Triticosecale* Wittmack) are the primary species grown in the mid-Atlantic US due to the regional emphasis on improving water quality. Grasses are excellent nitrogen (N) scavengers that also require fewer fall heat units than legumes for successful establishment (Clark, 2013; Duiker, 2014). Legume cover crops fill an important gap in cropping systems because they release N more slowly than mineral fertilizers and also prevent the N immobilization sometimes caused by cereal cover crops by balancing out the C:N of cover crop biomass (Snapp et al., 2005; Tonitto et al., 2006; Poffenbarger et al., 2015). Therefore, in order to improve the efficiency of N cycling in crop rotations, there is a need to better integrate legume cover crops into regional crop rotations.

In the mid-Atlantic region, the typical cash crop rotation consists of corn (*Zea mays* L.)-winter wheat/double-crop soybean or corn-soybean-wheat/double-crop soybean. Within the two-year rotation, the only open period for planting cover crops is between double-crop soybean harvest in the fall and corn planting in the spring.

Double-crop soybean is typically harvested in mid- to late- November, which is too late in the season for a post-harvest planting of a legume cover crop given the need for early fall planting to ensure establishment and winter survival (Mirsky et al., 2011; Clark, 2013). The three-year rotation incurs the same problem; however, cereal cover crops are typically planted after the corn crop to take up any remaining N because no N application is recommended for the following full-season soybean.

To better integrate cover crops into these regional crop rotations, farmers and researchers have explored a suite of interseeding techniques. In corn and soybean, there has been considerable work testing broadcast and drill technology. For example, cover crop seed can be broadcast into fields with mature cash crops via small fixed-wing aircraft, or by modifying high-boy herbicide sprayers or spinner-spreaders typically used for applying dry amendments (Shipman, 2010; Zinkland, 2010). Most of these approaches are fast, inexpensive, and permit greater flexibility in timing of planting; however, establishment of cover crops is highly variable due to low seed-to-soil contact and the need for continuous surface soil moisture (Baker and Griffis, 2009; Fisher et al., 2011; Wilson et al., 2013). Broadcast seed on the soil surface is vulnerable to being washed away by strong rains or seed predation by birds, rodents, beetles, and slugs (Wilson et al., 2013; Curran et al., 2018). Consistent cover crop stands can also be difficult to establish with aerial broadcasting due to pilot operator error, wind blowing the seeds off target, and seeds catching in standing crop plants (Belfry and Van Eerd, 2016). Considering these drawbacks, broadcasting cover crop seeds is not an ideal planting method for intercropping into double-crop soybean.

Drilling cover crops may address the downsides of broadcast seeding: seed is placed at a uniform depth to maximize seed-to-soil contact, seed is buried to reduce predation and seedling establishment is improved. Modified drills, like the InterSeeder cover crop drill (Interseeder Technologies, LLC, Woodward, PA), have been developed to drill between the rows of an established grain crop planted in rows at least 76 cm wide (Noland et al., 2018). The InterSeeder has been tested in full-season soybean and corn crops, with mixed results (Curran et al., 2018; Noland et al., 2018; Caswell et al., 2019). Previous field trials of interseeding cover crops into full-season soybean have demonstrated an inverse relationship between cover crop and soybean performance; in fields with optimal vegetative growth of full-season soybean, the cover crops were unable to survive under the dense soybean canopy through the summer and fall (Caswell et al., 2019). Canopy closure is particularly problematic in warmer climates where the crop canopy closes quickly and there are often dry conditions during maturation (Moore et al., unpublished data). However, double crop soybean presents a unique opportunity since interseeding can take place later in the summer (late August to early September) than with full-season soybean. This timing benefits both the cover crop (which must survive under the soybean canopy for a shorter length of time) and the cash crop (since large amounts of biomass from an early-established cover crop can impede soybean harvest) (Hively and Cox, 2001). The shorter season of double-crop soybean and a later interseeding date should allow cover crops to establish, but not produce enough biomass to hamper soybean harvest.

One potential downside to interseeding cover crops into double-crop soybean involves row spacing. In order for the interseeding planter to pass through the field without damaging the soybean, the crop must be planted on 76 cm wide rows. Typically, farmers in the mid-Atlantic region plant soybean in 19- to 38-cm rows to maximize light capture and therefore yield potential. The benefit of narrow soybean row spacing to maximize light capture is less robust for late-planted (mid-June through July) soybean, where there is often no yield penalty for wider soybean row spacing (Alessi and Power, 1982; Hodges et al., 1984; Weaver et al., 1990; Board and Harville, 1994; Pedersen and Lauer, 2003). Additionally, 76-cm is the standard corn row width spacing, allowing farmers to use the same equipment for sowing soybean and avoid new equipment purchases.

Given the benefits for including a legume cover crop between double-crop soybean and corn in mid-Atlantic cropping systems, this research was developed to evaluate the efficacy of interseeding cover crops into established double-crop soybean. Since interseeding must be conducted in 76-cm rows, we also evaluated the impact of wide-row spacing on double-crop soybean yield. Our research objectives were to evaluate (1) the yield difference between double-crop soybean planted in 38- and 76-cm rows; (2) the yield difference between double-crop soybean planted in 76-cm spaced rows with and without cereal rye + legume cover crop mixtures; and (3) interseeded cover crop biomass and N content prior to termination.

Methods

Study sites

Field experiments were conducted at the Beltsville Agricultural Research Center (BARC; 39.03 ˚N, 76.93 ˚W) near Beltsville, MD; the University of Maryland Central Maryland Research and Education Center (CMREC; 39.01˚ N, 76.83 ˚W) near Glenn Dale, MD; and the University of Delaware Carvel Research Farm (UD; 38.64 ˚N, 75.46 ˚W) near Georgetown, DE. We established two experimental sites 2017, three sites in 2018, and four sites in 2019. The two 2017 sites were both established at BARC, one on a loamy sand (MD-1) and the other on a silt loam (MD-2). The three 2018 sites were established at three different locations: one at CMREC on a sandy loam (MD-3), one at BARC on a sandy loam-silt loam complex (MD-4), and one at UD on a loamy sand (DE-5). Finally, the four 2019 sites were all planted at BARC on a sandy loam (MD-6, MD-7, MD-8, and MD-9; USDA - NRCS, 2020; Table 1.1).

All field experiments were initiated in the double-crop soybean phase of a two-year rotation of wheat/double-crop soybean-corn. All five sites established in 2017 and 2018 were interseeded with cover crop treatments. Cover crop establishment was successful at three sites, which were maintained through the winter and concluded in the spring at cover crop termination (Sites MD-1, MD-3 and MD-4). Two sites were discontinued after soybean harvest due to insufficient measurable cover crop biomass growth (Sites MD-2 and DE-5). All four of the sites established in 2019 concluded at soybean harvest in November 2019; they were not interseeded (Sites MD-6, MD-7, MD-8, and MD-9; Fig. 1.1).

Average monthly temperatures were several ˚C higher overall than the 1981-2010 means but otherwise followed typical seasonal variation (Fig. 1.2; NOAA NCDC, 2020). Precipitation, however, was highly variable between the three experimental field seasons. This was especially true in the September of each year, a crucial month for both the cover crop and double-crop soybean growing seasons. In 2017, the sites received 47 mm of rain in September, below the 104 mm 30-yr mean. The fall of 2018 was characterized by heavy rainfall; the Maryland and Delaware sites received 307 and 167 mm of rain in September, respectively. The next year, 2019, September was notably dry, with only 2.3 mm of rainfall in September, 2% of the 30-yr average (104 mm; Fig. 1.2).

Experimental design

The row spacing and cover crop treatments were established in a randomized complete block design with at least four replicates per field. Each replicate block consisted of two soybean row spacing treatments (38- and 76-cm) without cover crops (no cover crop control), along with five cover crop treatments interseeded into double-crop soybean on a 76-cm row spacing for a total of seven treatments (Fig. 1.3). Each plot was at least 6 m wide and 61 m long. Postemergence herbicides with no residual control was applied to eliminate weed competition and not interfere with cover crop establishment.

Field operations

Double-crop soybean was planted in either 38-cm or 76-cm row spacing at 72,720 seeds ha^{-1} following winter wheat harvest in June or early July. Cover crop interseeding occurred at soybean growth stage R5 (late August - early September) in

most of the fields, except for MD-4, which took place at R7 (October) due to wet field conditions. The cover crop mixtures were planted into the double-crop soybean plots at the rates described in Table 1.2 using a no-till drill InterSeeder. This planting equipment sows three rows of cover crop seeds between established cash crop rows using the same technology as cash crop no-till grain drills. Cover crop mixtures included: (1) cereal rye; (2) cereal rye + hairy vetch; (3) cereal rye + crimson clover; (4) cereal rye + red clover; and (5) cereal rye + winter pea. These species were selected because they are the most common cover crops grown in the mid-Atlantic region; the legumes reflect a gradient of shade and cold tolerance.

The following spring, the entire experimental site was treated with herbicide to terminate cover crops and control weeds. At MD-1, an herbicide combination of glyphosate (0.63 kg a.e. ha^{-1}), dimethylamine salt of dicamba (0.56 kg a.e. ha^{-1}), and 2,4-D (0.53 kg a.e. ha^{-1}) was applied on 9 May 2018. The field site at MD-3 was sprayed on 16 May 2019 with glyphosate (1.68 kg a.e. ha^{-1}), mesotrione (0.18 kg ae ha^{-1}), metolachlor (1.45 kg a.e. ha^{-1}), and atrazine (0.78 kg a.e. ha^{-1}). MD-4 was sprayed on 9 May 2019 with metolachlor (1.46 kg a.e. ha^{-1}), atrazine (1.46 kg a.e. ha^{-1}), mesotrione (0.19 kg a.e. ha^{-1}), 2,4-D (0.80 kg a.e. ha^{-1}), and glyphosate (1.54 kg a.e. ha^{-1}). Sites MD-2 and DE-5 were not treated with herbicide because there was insufficient cover crop biomass at these sites to terminate for continuation of the experiment.

Data collection

Soybean stand counts (emerged seedlings per 6.1 linear meters of row) were recorded three weeks after emergence at three random locations in each replicate in

2017 and 2018. In the 2019 fields only testing yield of narrow- vs. wide-row spacing at BARC, soybean stand counts were collected in two random locations within each plot six weeks after soybean emergence. Light transmission through the soybean canopy was measured using a point sensor and light bar sensor (LI-COR BioSciences, Lincoln, NE) within one day of interseeding.

Soybean were harvested in November all three years, except at site MD-4 in 2018, which was harvested in December due to poor field conditions. Yields were collected either by a specialized plot combine with integrated weight scale or by a combine and weigh wagon. Harvest moisture levels were measured on sub-samples of each plot harvest in a harvest moisture meter (Churchill Industries, Minneapolis, MN) and then adjusted to 13% moisture.

Just prior to cover crop termination in the spring, aboveground biomass was collected in each plot within 1 m^2 quadrats by cutting plants at ground level; mixtures were separated into component species. This biomass was dried at 60 °C for a minimum of seven days, weighed, and then analyzed for total C and N using dry combustion [2018 samples - LECO CN Analyzer (LECO Corporation, St. Joseph, MI); 2019 samples - Perkin Elmer 2400 Series II Elemental CHN Analyzer (PerkinElmer Corporation, Waltham, MA)].

Statistical approach

In order to test the effect of row spacing on soybean yield across all sites, a linear mixed effects (LME) model was used with row spacing as the main effect and site as the random effect. Then, soybean yields by row spacing were analyzed by individual sites using an LME model with row spacing as the main effect and block

as the random effect. To test the effect of cover crop mixtures on soybean yield, an LME model was used with cover crop treatments (e.g., no cover crop, cereal rye, cereal rye + crimson clover, etc.) as the main effect and block as the random effect. Additional LME models were used to test the effect of cover crop mixture on overall cover crop biomass production and cover crop N concentration with cover crop mixture as the main effect and block as the random effect. The tests for cover crop biomass and N concentration included data from the three sites where the cover crops grew sufficiently to measure these parameters (Table 1.3). All LME models were run using the *lmer* function in the *nlme* package in R (Bates et al., 2015; Pinheiro et al., 2020). No transformations were necessary to improve the normality of the soybean yield or cover crop biomass data sets. Analyses were conducted in the R environment for Macintosh (R Core Team, 2018).

Results

Light transmittance through soybean canopy

At the time of interseeding in 2017, the average recorded light transmission through the soybean plant canopy was 15% at MD-1 and 6% at MD-2. In 2018, the average light transmission was 40% at both MD-3 and MD-4, and 4% at DE-5 (Table 1.3).

Soybean yields

When sites were analyzed together; there was no difference detected in double-crop soybean yield between the 76-cm (wide) and 38-cm (narrow) row spacings; nor were differences detected at six of the eight field sites when tested by individual site (Fig. 1.4; p = n.s.). In these six fields, the average double-crop soybean

yield by field for the non-interseeded plots ranged from 2.1 to 3.8 Mg ha^{-1}. At the two field sites where a significant difference was found between row-spacing treatments, double-crop soybean yields were higher in the narrow-row spacing plots than the wide-row plots (MD-8: $p = 0.011$; MD-9: $p = 0.03$). The mean yield of the narrow-row double-crop soybean plots was 3.2 ha^{-1} in MD-8 and 3.0 Mg ha^{-1} in MD-9 compared to 2.8 and 2.7 Mg ha^{-1}, respectively, in the 76 cm wide rows at these sites (Fig. 1.4). The narrow-row spaced double-crop soybean at the MD-4 field site failed, so no double-crop soybean yield data was collected for row spacing comparison.

There was no effect of cover crop species on double-crop soybean yields at the MD-1 or MD-2 field sites in 2017, nor at the MD-4 field site in 2018 (Fig. 1.5). However, at MD-3 in 2018, the double-crop soybean yields in the no cover crop treatment were higher than in most of the interseeded treatments: cereal rye only ($p = 0.0093$), cereal rye + hairy vetch ($p = 0.0013$), cereal rye + crimson clover ($p = 0.0032$), and cereal rye + winter pea treatments ($p = 0.014$; Fig 1.5c). However, there was no significant difference in soybean yield between the no cover crop plots and the cereal rye + red clover (p = n.s.; Fig. 1.5c). At DE-5 in 2018, no differences were detected in double-crop soybean yields among the cover crop treatments except yields were significantly lower in cereal rye + hairy vetch ($p = 0.0094$; Fig. 1.5e).

Cover crop biomass

The interseeded cover crop treatments emerged but failed to survive at the MD-2 and DE-5 sites; however, they established successfully at the MD-1, MD-3, and MD-4 sites (Table 1.3). At MD-1, cereal rye + hairy vetch and cereal rye + crimson clover produced significantly more biomass than cereal rye alone (p = 0.020

and $p = 0.0053$, respectively; Fig. 1.6a), but no significant differences were detected among the other cereal rye + legume mixtures. At MD-3, cereal rye + crimson clover produced significantly more biomass than all other treatments (cereal rye + hairy vetch:$p = 0.00033$, other cover crop treatments: $p < 0.0001$; Fig. 1.6b). At MD-4, cereal rye + winter pea had significantly less biomass than cereal rye alone ($p = 0.0020$; Fig. 1.6c), but there were no other differences detected in cover crop biomass among any of the cover crop mixture combinations.

At MD-1, the cereal rye + legume mixtures had significantly higher biomass N than cereal rye alone ($p < 0.0001$; Fig 1.7a), but there were no differences detected among the cereal rye + legume mixtures. At MD-3, biomass N was significantly higher in cereal rye + crimson clover than any of the other treatments ($p < 0.0001$; Fig. 1.7b). At MD-4, cereal rye + crimson clover and cereal rye + winter pea had significantly higher biomass N than cereal rye alone (cereal rye + crimson clover: $p = 0.0061$, cereal rye + winter pea: $p = 0.0003$; Fig. 1.7c).

Discussion

After three years of field trials, we found that widening row spacing to 76 cm to accommodate interseeding cover crop mixtures has little to no impact on double-crop soybean yield potential.

Cover crops successfully established at three of the five interseeded sites, where light transmission through the soybean canopy was highest. The interseeded cereal rye + legume cover crop mixtures had higher spring biomass and N content than the cereal rye treatment alone.

Row spacing did not affect soybean yields.

Any significant reductions in crop yield will inhibit adoption of an agricultural practice. Therefore, the first goal of our work was to test the impact of widening row spacing on soybean yields. These field trials show that widening row spacing to accommodate interseeding in the mid-Atlantic US has little to no impact on double-crop soybean yield potential. Even in 2019, when two field sites showed lower yields in wide-row soybean than narrow-row soybean, the differences were minimal and the yields in the wide-row soybean (2.8 and 2.9 Mg ha^{-1}; Fig. 1.4) were still higher than mean soybean yields in Maryland from 2013-2017 (2.4 Mg ha^{-1}; 44 bu $acre^{-1}$; USDA NASS, 2017). Therefore, the data suggest that adjusting row spacing to accommodate interseeding should not pose a risk to double-crop soybean yields.

In addition, at the two field sites where row spacing did impact double-crop soybean yield, the benefits of widening the crop rows to accommodate interseeding could compensate for the loss in soybean revenue. The 0.25 to 0.42 Mg ha^{-1} yield discrepancy between the narrow- and wide-row soybean at sites MD-8 and MD-9 in 2019 represents a \$17-\$28 ha^{-1} (\$7-\$11 per acre) revenue loss in soybean sales (USDA NASS, 2020a). At the same time, integrating cover crops, especially legumes, into this cropping rotation could reduce N fertilizer requirements and costs the following spring (Marcillo and Miquez, 2017). By participating in cover crop planting incentive programs, such as the Natural Resources Conservation Service Environmental Quality Incentives Program (NRCS EQIP) and Maryland Department of Agriculture Cover Crop Program, farmers could receive subsidies of \$111-222 ha^{-1} (\$45-90 $acre^{-1}$), further compensating for lost revenue from soybean yields (Myers et al., 2019; MDA, 2020). Thus, although overall there was no effect of widening row

spacing on soybean yields, if this practice did negatively impact yields, it is likely that the economic benefits of integrating legume cover crops would offset the difference.

Cover crops did not affect soybean yield.

Across the five interseeded field sites, there was no evidence of mechanical damage from the interseeding operation or competition from cover crops that would impart yield reductions. Interseeding and cover crop growth took place well after the critical soybean growth period, which ends at V3, when the yield could have been impacted the most (Soltani et al., 2019). At two of the 2018 field sites (MD-3 and DE-5), soybean yields in some cover crop treatments were lower than the no cover control, but there was no clear pattern to these differences, and there was little variability in mean yields (MD-3: 1.6-2.2 Mg ha $^{-1}$; DE-5: 3.0-3.6 Mg ha $^{-1}$; Fig. 1.5). At DE-5 in 2018, only the double-crop soybean in the cereal rye + hairy vetch treatments yielded lower than the non-interseeded soybean but none of the interseeded cover crops survived at that field site so the yield penalty could not be explained by any competition between the cover crops and double-crop soybean.

Light transmission determined cover crop establishment.

Cover crop failure in MD-2 in 2017 and DE-5 in 2018 was likely due to poor light transmission through the double-crop soybean canopy at the time of interseeding (Table 1.3). At the three sites where the interseeded cover crops survived (MD-1 in 2017; MD-3 and MD-4 in 2018), light transmission readings indicated 15-40% of ambient sunlight reached the soil through the soybean canopy (Table 1.3). Only 4-6% of ambient sunlight level was recorded underneath the soybean canopy at MD-2 and DE-5, where the cover crops failed to establish. Light transmission data were

collected only at the time of interseeding to define environmental conditions. However, future trials could use light transmission as a treatment factor to determine the lowest light transmittance at which the interseeded cover crops are still likely to successfully establish.

Legumes produced less biomass but more nitrogen than cereal rye in mixtures.

In the mid-Atlantic US, cover crops are typically terminated between early March and late April (Clark, 2012). Thus, biomass levels can vary greatly among fields [3.6 - 5.6 Mg ha^{-1} (Clark, 2007; Thapa et al., 2018a)], as can the level of the corresponding agroecosystems services provided (Blanco-Canqui et al., 2015). For instance, it has been shown that nitrate-N leaching is minimized at cover crop biomass levels between 4 and 8 Mg ha^{-1} (Thapa et al., 2018b). In our study, cover crop biomass levels were below this threshold at two of our research sites, and only at MD-1 in 2017 did total biomass levels of cover crop mixtures surpass 4 Mg ha^{-1} (Fig. 1.6a). Cover crop growth was most likely lower in the 2018-2019 growing season due to high rainfall in the fall and winter. Furthermore, legume establishment was poor at MD-4 in 2018 since interseeding was delayed until 10 October due to heavy rains in September. Nevertheless, the drill interseeded cover crops at MD-3 and MD-4 produced equivalent or larger amounts of spring biomass than past studies on drill interseeding or broadcasting cover crop seeds into full-season soybean [100-800 kg ha^{-1} (Hively and Cox, 2001); 692 - 2701 kg ha^{-1} (Norris, 2014); 50-875 kg ha^{-1} (Caswell et al., 2019)].

Even when the legume components of cover crop mixtures performed poorly, the legumes contributed proportionately higher N levels than the larger cereal rye

biomass. At both MD-1 in 2017 and MD-3 in 2018, the cover crop treatments with the highest biomass also had the highest N content (Fig. 1.6, 1.7). At MD-4 in 2018, the field-site with the lowest legume cover crop biomass accumulation, what legume biomass was present increased the N content of the mixtures above the cereal rye alone (Fig. 1.6c, 1.7c). At MD-1 in 2017, where total cover crop biomass ranged from 2.8-7.2 Mg ha^{-1}, the N content of all four of the cereal rye + legume mixtures fell within the documented range (78-225 N kg ha^{-1}) for cover crops planted into fields post-harvest (Decker et al., 1994; Dou et al., 1994; Duiker et al., 2010; Clark, 2013). At MD-3 and MD-4 in 2018, where cover crops established but did not accumulate as much biomass as MD-1, the N content ranged from 24-89 kg ha^{-1}, similar to documented N content for cover crops interseeded into full-season soybean in earlier trials [31-69 kg ha^{-1} (Norris, 2014; Caswell et al., 2019)]. Thus, interseeding cover crops into double-crop soybean in late summer enabled sufficient legume cover crop establishment to accumulate more N in the cover crop biomass than when only a grass cover crop is planted after soybean harvest.

Conclusion

We found that double-crop soybean yields were not impacted overall by modifying row spacing or by interseeding cover crops with a seed drill in late summer. Interseeded cover crops successfully established in double-crop soybean fields at three out of five field sites where there was sufficient light transmission through the soybean canopy. At these three field sites, the accumulated cover crop biomass was equal to or greater than cover crop biomass levels in broadcast studies or

previous interseeding studies into corn. The presence of a legume species in the cover crop mixtures increased biomass N levels compared to cereal rye alone, providing a potential source of N to the successive cash crop. Thus, we demonstrate that legume cover crops can be viably interseeded with a modified drill into double-crop soybean before soybean canopy closure and that this method can benefit N management in mid-Atlantic cropping systems.

Table 1.1. Soil properties and study years of double-crop soybean-cover crop trials in the mid-Atlantic US.

Year	Field site	Field location	Location coordinates	Soil type†	Soil organic matter (%)†	Bulk density, g cm^{-3}†
2017 - 2018	MD-1	BARC North Farm Beltsville, MD	39.03˚N, 76.93˚W	Hammonton loamy sand (coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults)	1.60	1.42
	MD-2	BARC South Farm Beltsville MD	39.03˚N, 76.94˚W	Codorus and Hatboro silt loam (fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts)	2.12	1.34
2018 - 2019	MD-3	Central Maryland Research and Education Center Glenn Dale, MD	39.01˚N, 76.83 ˚W	Downer-Hammonton complex: Downer loamy sand (coarse-loamy, siliceous, semiactive, mesic Typic Hapludults); Hammonton loamy sand (coarse-loamy, siliceaous, semiactive, mesic Aquic Hapludults); and Russett-Christiana complex: Russett sandy loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludults); Christiana silt loam (fine, kaolinitic, mesic Aquic Hapludults)	2.19	1.52
	MD-4	BARC East Farm Beltsville, MD	39.03˚N, 76.89˚W	Russett-Christiana complex: Russett sandy loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludults); Christiana silt loam (fine, kaolinitic, mesic Aquic Hapludults)	2.9	1.5

	DE-5	University of Delaware Carvel Farm	38.64˚N, 75.46 ˚W	Pepperbox loamy sand (loamy, mixed, semiactive, mesic Aquic Arenice Paleudults) and Rosedale loamy sand (Loamy, siliceous, semiactive, mesic Arenic Hapludults)	1.09	1.64
2019	MD-6, MD-7, MD-8, MD 9	BARC East Farm Beltsville, MD	39.03˚N, 76.90˚W	Russett-Christiana complex: Russett sandy loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludults); Christiana silt loam (fine, kaolinitic, mesic Aquic Hapludults)	2.68	1.47

† Published in USDA NRCS, 2019.

Table 1.2. Cover crop planting species and seeding rates for a double-crop soybean interseeding experiment in the mid-Atlantic US.

Double-crop row spacing (cm)	Cover crop treatment	Seeding rates
38	None	N/A
76	None	N/A
76	Cereal rye	Cereal rye (126 kg ha^{-1})
76	Cereal rye + hairy vetch	Cereal rye (34 kg ha^{-1}); hairy vetch (22 kg ha^{-1})
76	Cereal rye + crimson clover	Cereal rye (34 kg ha^{-1}); crimson clover (22 kg ha^{-1})
76	Cereal rye + red clover	Cereal rye (34 kg ha^{-1}); red clover (11 kg ha^{-1})
76	Cereal rye + winter peas	Cereal rye (34 kg ha^{-1}); winter pea (78 kg ha^{-1})

Table 1.3. Cover crop planting dates, growth conditions, and termination dates.

Year	Field	Cover crop survival	Light transmission through soybean canopy	Date interseeded	Fall GDD	Date terminated	Spring GDD
2017	**MD-1**	Yes	15%	5 Sept 2017	950	9 May 2018	537
	MD-2	No	6%	5 Sept 2017	933	n/a	n/a
2018	**MD-3**	Yes	40%	27 & 28 Aug 2018	1146	8 May 2019	608
	MD-4	Yes	40%	10 Oct 2018	310	9 May 2019	589
	DE-5	No	4%	23 Aug 2018	11672	n/a	n/a

Table 1.4. Double-crop soybean planting dates, growth conditions, and termination dates.

Year	Field	Date Planted	Soybean variety	Maturity group	Date Interseeded with Cover Crops	Date Harvested
2017	**MD-1**	7 July 2017	Pioneer 93Y84	3.8	5 Sept 2017	18, 20 Nov 2017
	MD-2	16 July 2017	Pioneer 93Y84	3.8	5 Sept 2017	17 Nov 2017
2018	**MD-3**	10 July 2018	TA Seeds TS3959R2S	3.9	27 & 28 Aug 2018	23 Nov 2018
	MD-4	18 July 2018	Hubner H32-13R2	3.2	10 Oct 2018	13 Dec 2018
	DE-5	2 July 2018	Dynagrow S42LL63	4.2	23 Aug 2018	20 Nov 2018
2019	**MD-6, MD-7, MD-8, MD-9**	24, 28 June 2019	Channel 3707R2/SR/ STS	3.7	N/A	5 Nov 2019

Figure 1.1. Experimental timeline: Double-crop soybean interseeded with cover crop mixtures. Light green boxes represent double-crop soybean growing season. Black vertical dashes represent interseeded cover crops duration of growth

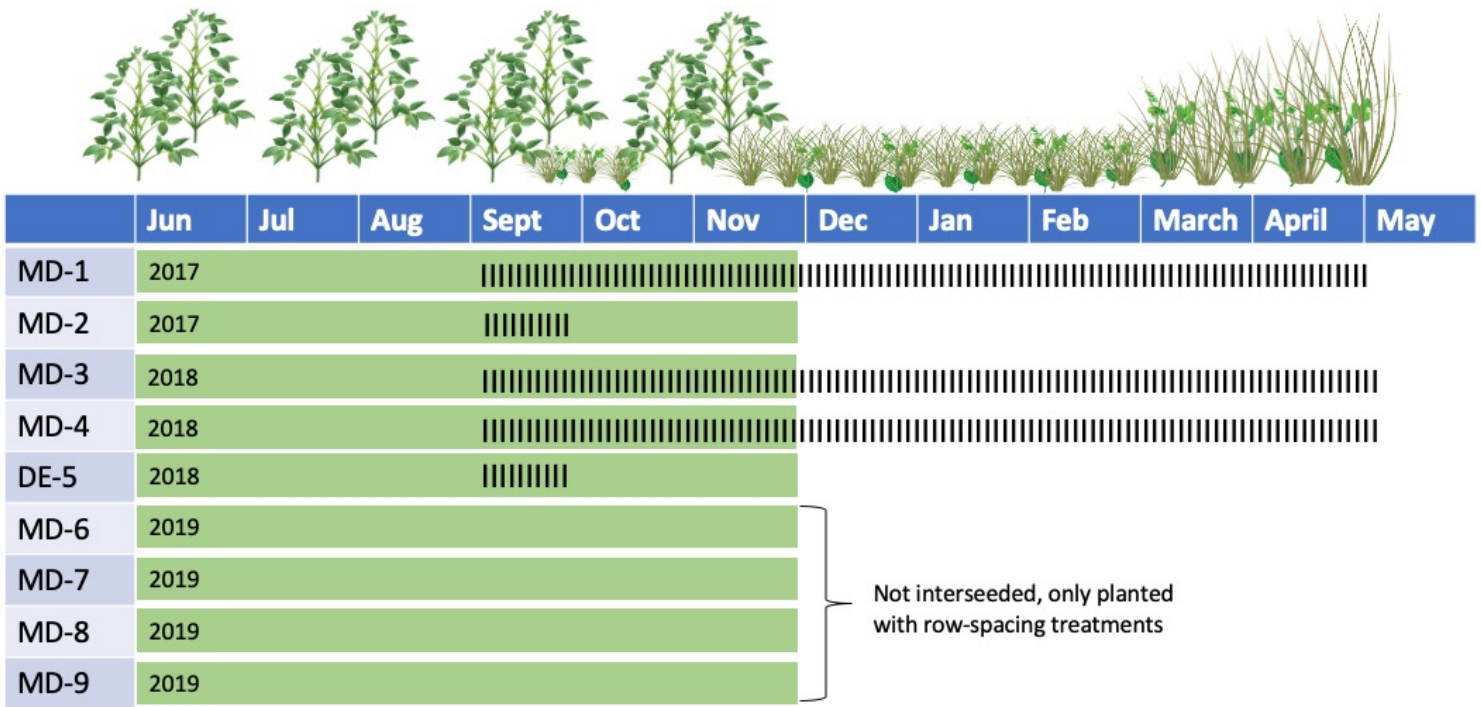


Figure 1.2. Mean recorded monthly air temperature (solid line) and cumulative precipitation (dark grey bars) during the 2018-2019 growing seasons and 30-yr mean monthly air temperature (dotted line) and cumulative precipitation (light grey bars).

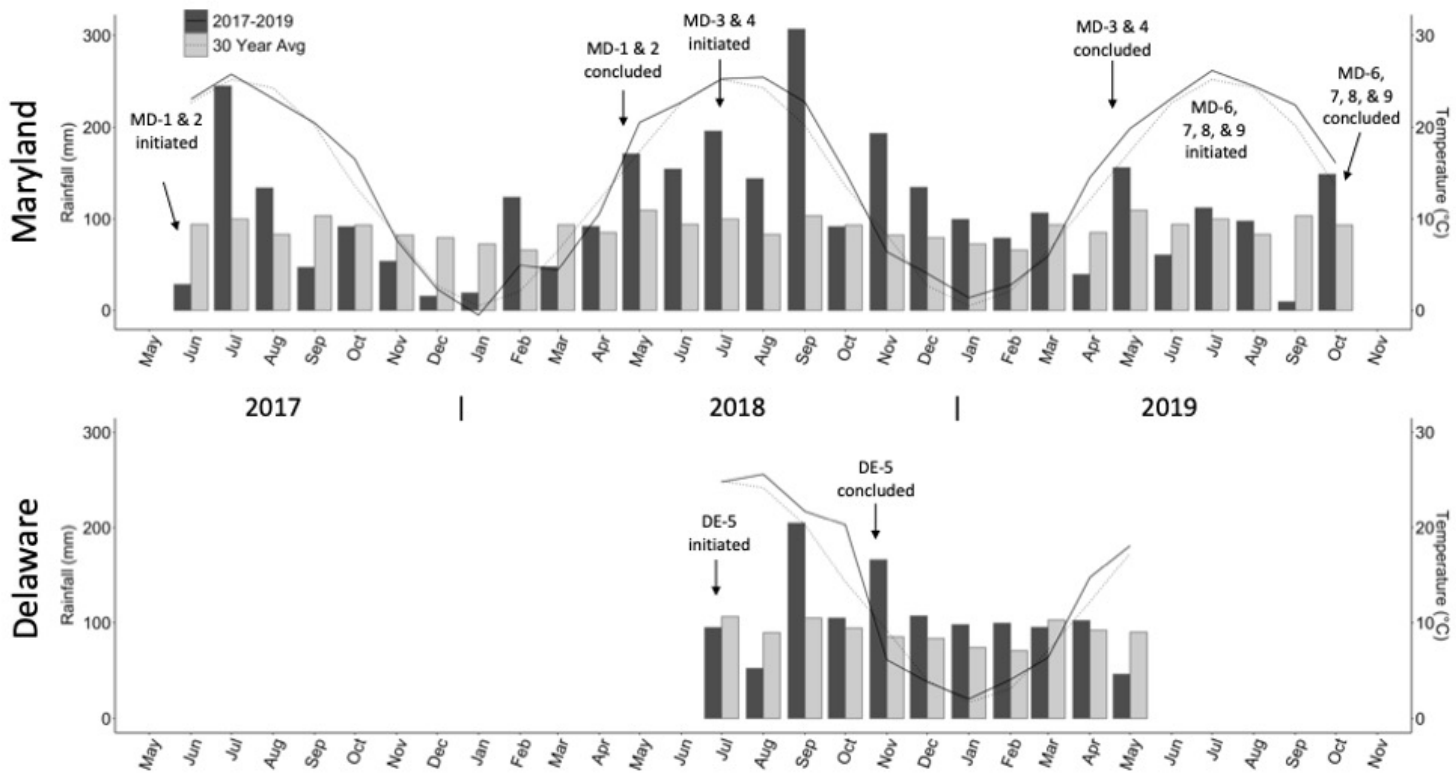


Figure 1.3. Depiction of experimental soybean row spacing and interseeded cover crop placement. Note, the same number of soybean were planted in the narrow- and wide-row plots (indicated by green squares).

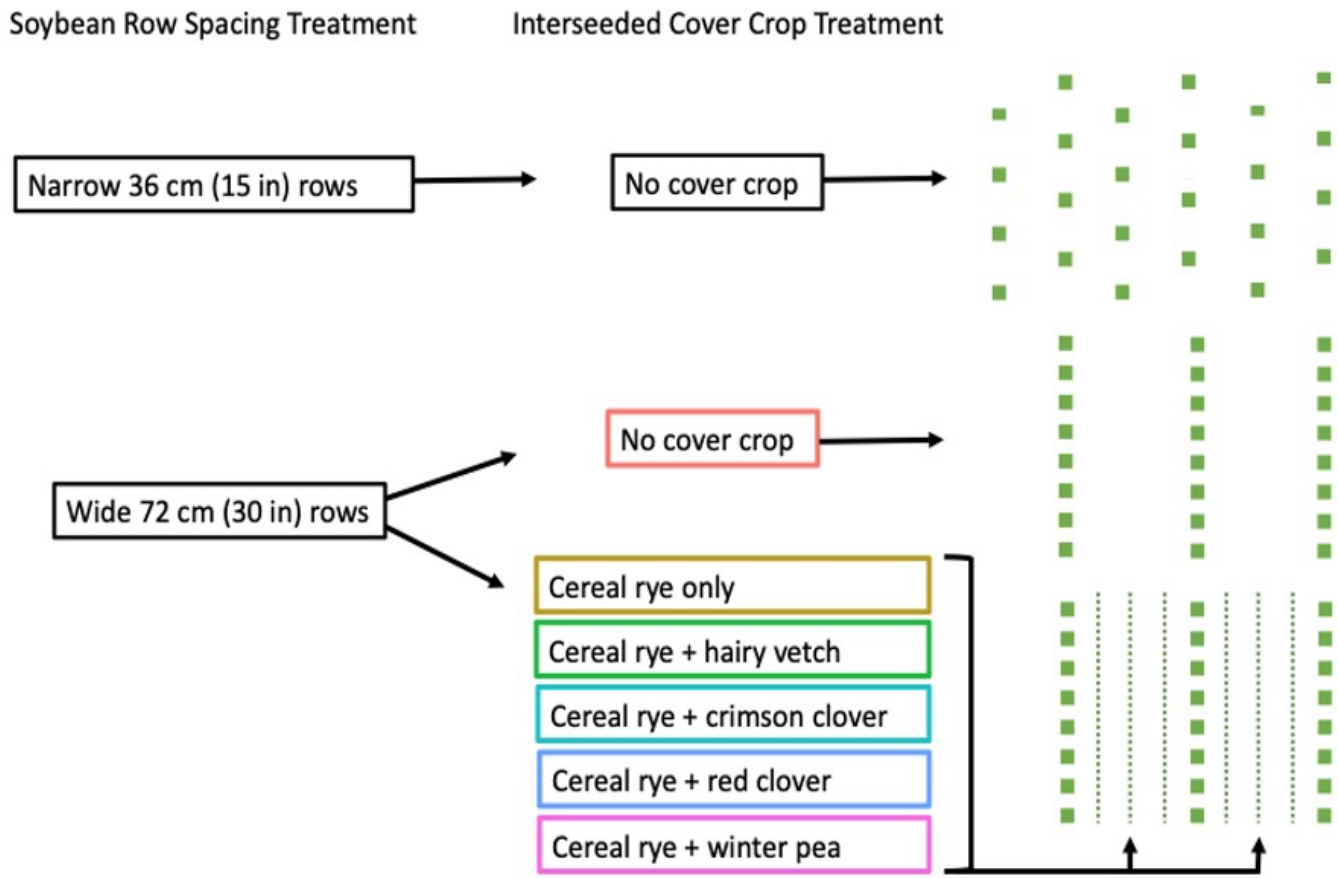


Figure 1.4. Double-crop soybean yields comparing narrow (36 cm) and wide (72 cm) row spacing across six site years (2017-2019). Bars represent the standard error of the mean.

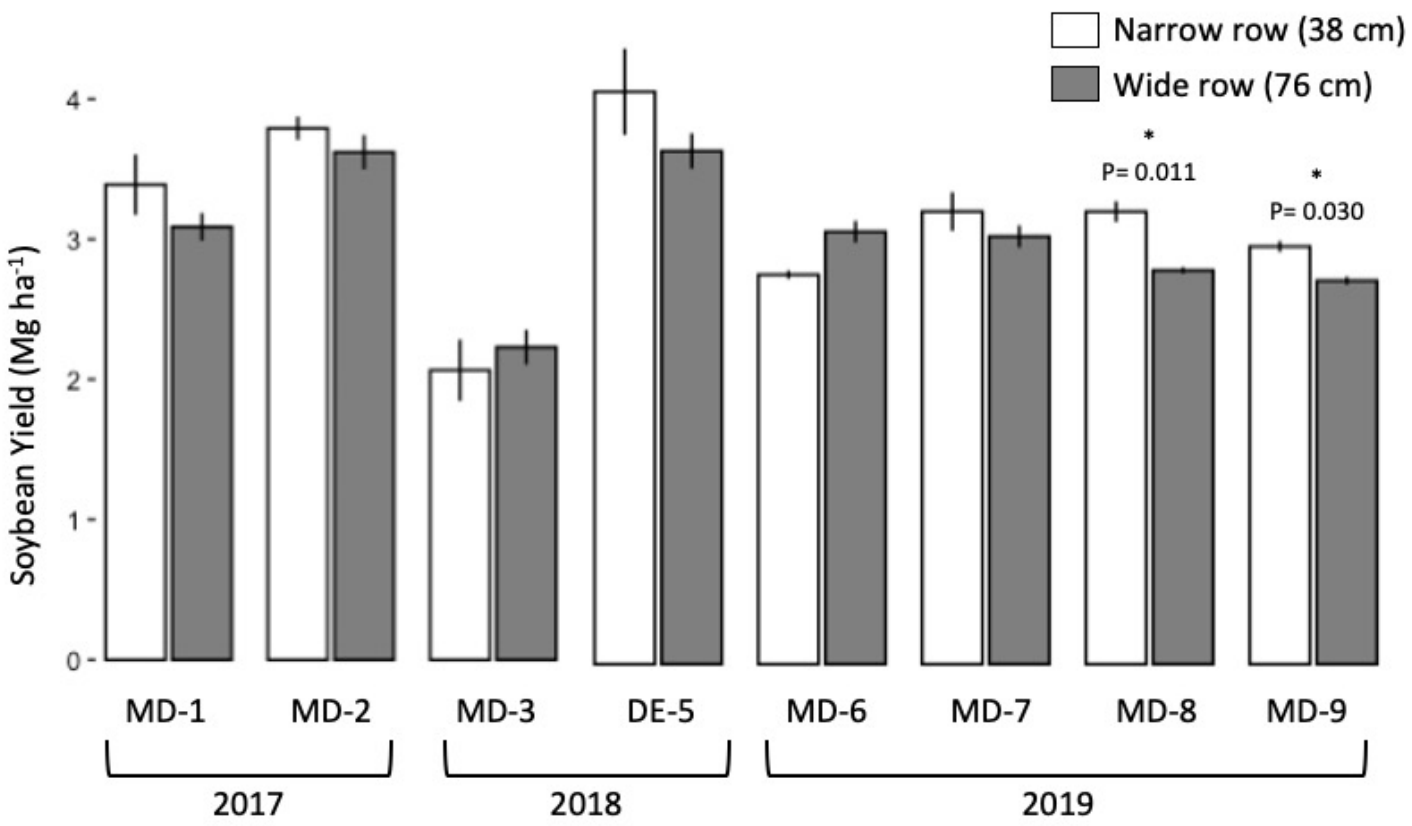


Figure 1.5. Double-crop soybean yields across interseeded cover crop treatments. Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site. Error bars represent the standard error of the mean. ❖ indicates field site where cover crops failed to establish.

Figure 1.6. Interseeded cover crop biomass by cover crop treatment. The plain color bars represent the cereal rye component of the biomass, the white lined bars represent the legume component of the biomass, and the outer outline represents the total cover crop biomass. Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site.

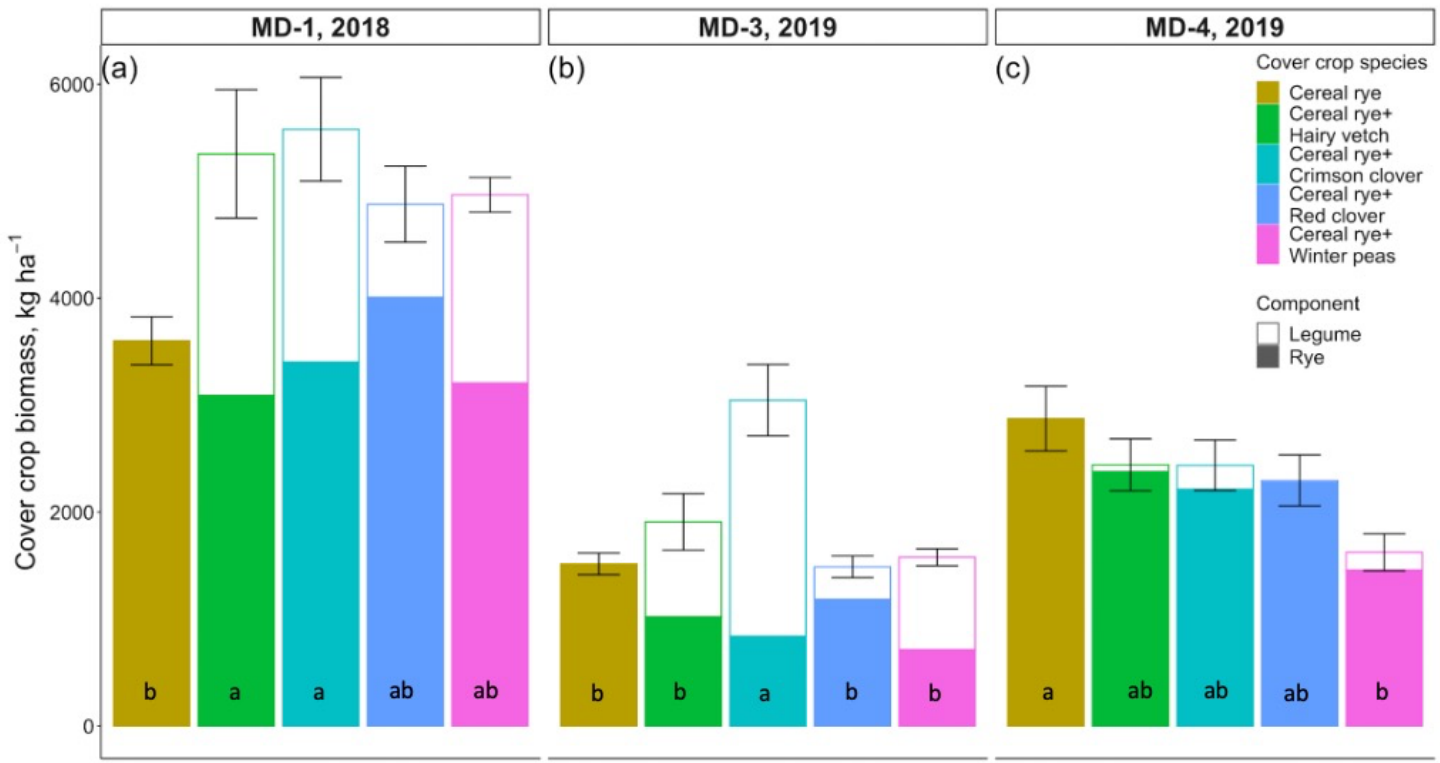
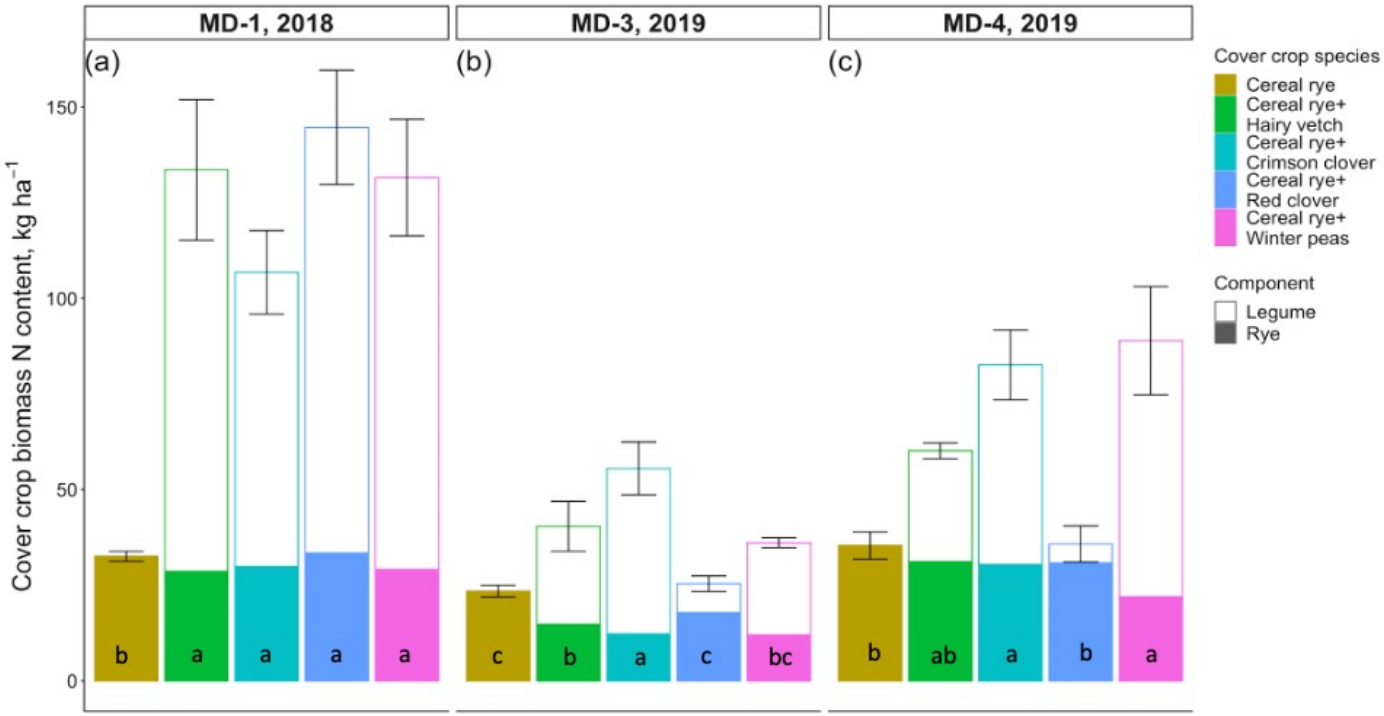


Figure 1.7. Nitrogen (N) content of cover crop biomass by cover crop treatment. The plain color bars represent the cereal rye component of the biomass, the white lined bars represent the legume component of the biomass, and the outer outline represents the total cover crop biomass. Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site.



Chapter 2. Evaluation of a corn crop following interseeded legume cover crop mixtures

Introduction

Corn (*Zea mays* L.) is the most widely planted cash crop in the US at 37 million ha; it is also one of the most heavily fertilized, with farmers applying an average of 167 kg nitrogen (N) ha^{-1} (USDA NASS, 2020b; USDA ERS, 2019). Nitrogen fertilizer is thus typically the largest single input cost for corn producers and the most annually-variable cost given its inextricable link to the prices of oil and gas (USDA ERS, 2020; Chen, et al., 2010). Further, only 40-55% of N fertilizer is recovered by the corn crop during the growing season (Cassman et al., 2002; Galloway and Cowling, 2002). The residual N is vulnerable to leaching into ground and surface waters, negatively impacting both freshwater and marine ecosystems (Howarth and Marino, 2006; Baron et al., 2013). Cover crops can be planted outside of the cash crop growing season to recover excess N left unused by the previous crop (typically grass species) (Meisinger et al., 1991; Shipley et al., 1992; Staver and Brinsfield, 1998); and provide organic N to the subsequent cash crop (typically legume species)(legume species) (Holderbaum et al., 1990; Decker et al., 1994; Tonitto et al., 2006). In rotation with corn, the capacity of cover crops to both scavenge residual N and fix new N can decrease dependence on inorganic fertilizers.

Previous evaluations of corn following winter cover crops have demonstrated that legume cover crops boosts corn performance compared to no cover crop and compared to planting grass cover crops alone (Marcillo and Miguez, 2017; Abdalla et al., 2019). Grass cover crops primarily are used to scavenge excess N in the soil

(Meisinger et al., 1991; Shipley et al., 1992; Abdalla et al., 2019) and only tend to increase crop yields when they increase water infiltration and storage or suppress weeds (Dabney et al., 2001; Blanco-Canqui et al., 2015; Kay and Quemada; 2017). Legume cover crops provide new N to the agroecosystem through N fixation (Holderbaum et al., 1990; Decker et al., 1994; Snapp et al., 2005); a comprehensive meta-analysis found a 30% corn yield advantage following either legumes or grass-legume cover crop mixtures (Marcillo and Miguez, 2017). The biomass of spring-terminated legume cover crops contains enough N to offset inorganic fertilizer applications, if not meet all of corn N demands (Decker et al., 1994; Sullivan and Andrews, 2012; Clark, 2013). Fitting legume cover crops into the rotation and maximizing their performance have been two major factors limiting greater adoption.

In the mid-Atlantic region of the United States, the only opportunity to establish cover crops within the typical two-year crop rotation of corn - winter wheat (*Triticum aestivum* L.) - double-crop soybean (*Glycine max* (L.) Merr.) is in the fall/early winter between double-crop soybean and corn. However, double-crop soybean is not typically harvested until mid-November, roughly 8 to 10 weeks after the optimal planting time for legume cover crops (Mirsky et al., 2011; Clark, 2013). Interseeding cover crops provides an opportunity to establish legumes in this cash crop rotation. Aerial seeding and air-seeders have been used to seed cover crops into soybean prior to harvest, but these methods do not provide for reliable stand establishment. To improve cover crop stand establishment during the late vegetative stage of soybean, a modified seed drill has been developed to interseed cover crops into standing cash crops on 76 cm row spacing (Interseeder Technologies, LLC,

Woodward, PA). This technology holds promise to increase legume cover crop performance and therefore adoption.

In addition to including legumes in the system, grasses are often planted with legumes in mixture because of the benefits of targeting multiple objectives. Interseeding grass + legume mixtures and their resulting performance is not well documented, but we predict that these will influence the benefits to corn. Therefore, we sought to link previous interseeding field trials with the subsequent performance of a corn crop. We previously found that cereal rye + legume cover crop mixtures can be interseeded directly between 76 cm wide rows of double-crop soybean with little to no impact on soybean yields (Peterson et al., *in prep*). To fully investigate how this interseeding strategy might affect the standard mid-Atlantic crop rotation of corn - winter wheat - double-crop soybean, we planted corn after termination of the interseeded cover crop. Our objective was to measure the impact of a previously interseeded cover crop on the corn cash crop at three points: (1) sixth leaf vegetative stage V6; (2) kernel blister stage R2; and (3) corn yield at harvest. Quantifying the impact of fall-interseeded cover crops on corn performance at these critical growth periods will contribute to refining cover crop and N management strategies in mid-Atlantic cropping systems.

Methods

Study sites

Field experiments were established at the USDA Beltsville Agricultural Research Center in Beltsville, MD in 2018 (39.03˚ N, 76.93 ˚W) (BARC) and at the

University of Maryland Central Maryland Research and Education Center in Glenn Dale, MD in 2019 (39.01˚ N, 76.83 ˚W) (Table 2.1) (CMREC), both on Aquic Hapludult soils. The BARC site was established in 2017 on a Hammonton loamy sand with 1.6% organic matter and bulk density of 1.42 g cm^{-3} (USDA - NRCS, 2020). The CMREC site was established in 2018 on a mixture of both a Downer-Hammonton loamy sand complex and Russett sandy loam and Christiana silt loam complex, with 2.19% organic matter and bulk density of 1.52 g cm^{-3} (USDA - NRCS, 2020). Both field experiments were initiated by interseeding cover crops directly into the double-crop soybean phase of a two-year rotation of corn - winter wheat - double-crop soybean. The sites were maintained through the winter and concluded the following fall at corn harvest.

From August 2017 to November 2019, mean monthly temperature was 1-3˚C higher than the 1981-2010 averages but followed typical seasonal patterns (Fig. 2.2). Monthly precipitation varied widely between years and diverged from 30-yr monthly averages, especially in September of each year. During cover crop establishment in September 2017, BARC received only 47 mm of precipitation compared to the 30-yr average of 104 mm. The following September, during the corn season at BARC and cover crop establishment at CMREC, Maryland received 307 mm of precipitation, three times the 30-yr monthly rainfall average (Fig. 2.2). Fall 2019, during the corn season CMREC, was notably dry, with only 2.3 mm of rainfall in September, 2% of the 30-yr average (Fig. 2.2).

Experimental design

The cover crop treatments were established in a randomized complete block design with six replicates in each field. The six cover crop treatments included: (1) cereal rye alone; (2) cereal rye + hairy vetch (*Vicia villosa* Roth); (3) cereal rye + crimson clover (*Trifolium incarnatum* L.); (4) cereal rye + red clover (*Trifolium pratense* L.); (5) cereal rye + winter pea (*Pisum sativum var. arvense* (L.) Poir); and (6) no cover crop. These species were selected because they are the prominent cover crops used in the mid-Atlantic US and reflect a gradient of shade and cold tolerance (Clark, 2013). Each cover crop plot was at least 6 m wide and 61 m long. During the following corn season, each of the cover crop plots was divided into six subplots of 3 m wide and 9 m long (BARC, 2017-2018) or 18 m long (CMREC, 2018-2019). These subplots were treated with six different N sidedress fertilizer rates at corn growth stage V6 (0, 34, 67, 100, 135, and 190 kg N ha $^{-1}$). Placement of fertilizer subplots was randomized in each larger cover crop plot.

Field operations

Double-crop soybean was planted at 72,720 seeds ha^{-1} in 76 cm wide rows, regardless of cover crop treatment, following winter wheat harvest in June or early July 2017 and 2018. The soybean varieties planted were 'Pioneer 93Y84' maturity group 3.8 in 2017 and T.A. Seeds 'TS3959R2S' maturity group 3.9 in 2018. Cover crops were planted into the double-crop soybean on 5 Sept in 2017, and 27, 28 August in 2018 at the rates described in Table 2.2 using a no-till drill InterSeeder (InterSeeder Technologies, LLC, Woodward, PA). The following spring, the entire experimental site was treated with herbicides to terminate cover crops and control weeds. In 2018, an herbicide combination of glyphosate (0.63 kg a.e. ha^{-1}),

dimethylamine salt of dicamba (0.56 kg a.e. ha^{-1}), and 2,4-D (0.53 kg a.e. ha^{-1}) was applied on 9 May, 17 days before corn planting. In 2019, the corn was planted directly into the live cover crop biomass in the field on 10 May 2019. The entire site was then sprayed on 16 May 2019 with glyphosate (1.68 kg a.e. ha^{-1}), mesotrione (0.18 kg ae ha^{-1}), metolachlor (1.45 kg a.e. ha^{-1}), and atrazine (0.78 kg a.e. ha^{-1}). Corn ('Pioneer 0506AM') was planted at 74,000 seeds ha^{-1} into the terminated cover crop plots on 26 May 2018 and 9 May 2019 with 34 kg N ha^{-1} of starter fertilizer applied as urea ammonium nitrate solution (30% N; UAN). The six different rates of N fertilizer (0, 34, 67, 100, 135, and 190 kg N ha^{-1}) were applied to the corn subplots by dribbling UAN solution between corn rows on 2 July 2018 and 26 June 2019 at corn stage V6.

Data collection

A suite of corn growth and biomass measurements were collected at growth stage V6 (N sidedress), stage R2, and harvest.

At V6 (prior to sidedress N rate applications), six representative corn plants per plot were removed by clipping at the soil level to evaluate biomass accumulation, leaf area index (LAI), and N content. After collection, the corn plants were immediately weighed in the field to record fresh biomass weight. Nitrogen content was evaluated by measuring leaf chlorophyll concentration on six corn plants per cover crop treatment plot using a SPAD meter (SPAD 502 Chlorophyll Meter; Spectrum Technologies, Inc., Aurora, Il). We collected three chlorophyll content measurements on the highest collared leaf of six different corn plants and then calculated the mean of all 18 measurements. In 2018, corn leaf chlorophyll

measurements were performed in the laboratory within two days of removal from the field; in 2019, the V6 leaf chlorophyll measurements were taken on corn plants still growing in the field.

After chlorophyll content measurements were taken, all green leaves were removed from the corn stalk at the collar to measure leaf area index (LICOR 3100C; LI-COR Biosciences, Lincoln, NE). Corn leaves without a developed collar were removed at the point of emergence from the whorl. The corn plant samples were dried at 60 °C for 7-10 days until constant mass was achieved, weighed, and ground to pass through a 1-mm mesh sieve. Sub-samples of ground corn plant tissue were measured for N and carbon (C) content using dry combustion [2018 samples - LECO CN Analyzer (LECO Corporation, St. Joseph, MI); 2019 samples - Perkin Elmer 2400 Series II Elemental CHN Analyzer (PerkinElmer Corporation, Waltham, MA)].

At growth stage R2 (following N sidedress applications), corn height, fresh biomass, dry biomass, and leaf chlorophyll content were also recorded for six representative plants in each sidedress N subplot to determine the combined effect of the cover crop and N rate on corn growth. Corn height and chlorophyll content were measured on growing corn plants in the field. Chlorophyll content was measured three times from each of the six corn plants from the leaf immediately above the corn ear. We then calculated the mean chlorophyll content in each subplot (n=18 per subplot). Separately, six corn plants from each sidedress N subplot were removed from the field by clipping the plant at the soil level and the total fresh biomass weight was immediately recorded in the field. The corn plant samples were clipped to fit

inside sample bags, dried at 60 °C for 7-10 days, and weighed to record the dry biomass.

At harvest, the center two rows of corn from each sidedress treatment subplot were harvested with an Almaco SPC-40 Specialized Plot Combine (Almaco, Nevada, IA). Corn grain moisture was measured by the integrated combine moisture meter for each N rate plot in 2018 and as a whole plot area mean in 2019, and then grain weight was adjusted to 15.5% moisture content.

Statistical approach

Three separate linear mixed effects (LME) models were used to analyze the effect of previous cover crops treatment on corn leaf chlorophyll content, LAI, and N content of the whole corn plant at stage V6. The cover crop treatment (e.g., no cover crop, cereal rye, cereal rye + legume) was used as the main effect and block as the random effect for each model.

To analyze corn yield and corn height, dry biomass, and chlorophyll content at growth stage R2, we fit an ensemble of models with cover crop treatment, N rate, and their interaction as fixed effects, with block as the random effect. As both whole plots (cover crop species) and subplots (N rate) were completely randomized, we could analyze effects without nesting.

We assessed fits of plateau, linear, quadratic, linear plateau, and quadratic plateau mixed effects models (Eqs. 1-5) of corn response to N rate by cover crop species. Model selection was conducted using likelihood ratio tests on hierarchically nested pairs of models (e.g., adding or removing a single coefficient at a time). All LME models were run using the *lme* function in the {nlme} package in R with the

maximum likelihood method (Pinheiro et al., 2020). For each corn performance metric, the following models were fit; each coefficient was estimated for each cover crop treatment:

Plateau: $Y = X$ (1)

Linear: $Y = \boldsymbol{\beta}_1 \cdot X + \boldsymbol{\beta}_0 + \mathbf{B}_{Block} + \boldsymbol{\varepsilon}$ (2)

Quadratic: $Y = \boldsymbol{\beta}_2 \cdot X^2 + \boldsymbol{\beta}_1 \cdot X + \boldsymbol{\beta}_0 + \mathbf{B}_{Block} + \boldsymbol{\varepsilon}$ (3)

Linear plateau: $Y = \boldsymbol{\beta}_1 \cdot X + \boldsymbol{\beta}_0 + \mathbf{B}_{Block} + \boldsymbol{\varepsilon}$ if $X < X_P$ (4)

$Y = P$ if $X \geq X_P$

Quadratic plateau: $Y = \boldsymbol{\beta}_2 \cdot X^2 + \boldsymbol{\beta}_1 \cdot X + \boldsymbol{\beta}_0 + \mathbf{B}_{Block} + \boldsymbol{\varepsilon}$ if $X < X_p$ (5)

$Y = P$ if $X \geq X_P$.

where *Y* is the dependent variable [plant height (cm), dry biomass (Mg ha^{-1}), chlorophyll content (SPAD index unit), or corn grain yield (Mg ha^{-1})]; and *X* is the N rate (kg ha^{-1}). P is the plateau Y value and X_P is the value for X at which the linear or quadratic response meets the plateau. After selecting the model according to the likelihood ratio tests, coefficient contrasts were conducted with the {emmeans} (Lenth, 2019) and {multcomp} (Hothorn et al., 2008) packages. Goodness-of-fit for each model was reporting using an R2 analog that is derived from the likelihood ratio test (Magee, 1990; Kramer, 2005):

$$R^2 = 1\text{-}\exp(-\ (2/n)(\log L_m - \log L_o)) \quad (6)$$

where $\log L_M$ is the log-likelihood of the model of interest, $\log L_O$ is log-likelihood of the intercept only model, and n is the number of observations. No data transformations were necessary to improve the normality of the corn performance

measurements or corn yield. Analyses were conducted in the R environment for Macintosh (R Core Team, 2019).

Results

Corn growth stage V6 (pre-sidedress): Corn leaf area index, N content, and chlorophyll content.

Leaf area index (LAI), N content, and chlorophyll content data were collected at corn stage V6 in each cover crop treatment before sidedress N rates were applied. In 2018, mean corn plant leaf area index (LAI, leaf m^{-2} by ground m^{-2}) did not differ by cover crop treatment (Fig. 2.3a). In 2019, mean corn LAI in the cereal rye + winter pea cover crop treatment was significantly higher (1.85 m^2 m^{-2}) than in the no cover crop treatment (1.19 m^2 m^{-2}; $p = 0.0018$; Fig. 2.3b). LAI varied by year, with mean LAI in 2018 (0.30 m^2 m^{-2}) only reaching 20% of the mean LAI of the corn in 2019 (1.55 m^2 m^{-2}; Fig. 2.3).

The N content of the dried corn plant biomass (N kg ha^{-1}) was similar across all cover crop treatments in 2018 (Fig. 2.4a). In 2019, the corn plants in the cereal rye + winter pea cover crop treatment plots had higher biomass N content than corn in any of the other cover crop plots except for cereal rye + hairy vetch ($p = 0.032$; Fig. 2.4b).

No differences were detected in corn leaf chlorophyll content (SPAD index units) among the six cover crop treatments at either site (Fig. 2.5).

Corn growth stage R2: Corn plant height, biomass, and chlorophyll content

At corn growth stage R2, corn plant height, biomass, and chlorophyll content were collected in each of the six sidedress N subplots within each cover crop plot.

The patterns in corn plant height were best described by linear models in both years (2018 $R^{lrt} = 0.57$; 2019 $R^{lrt} = 0.22$). Both years, corn plants were significantly taller in all five of the interseeded cover crop treatments (2018: 115.0 cm; 2019: 180.5 cm) than corn plants in the no cover crop treatment (2018: 83.5 cm; 2019: 165.4 cm; $p < 0.0001$ both years; Fig. 2.6). In 2018, a significant N rate response was observed across all cover crop treatments; mean corn plant height increased from 100.6 cm in the 33.6 kg N ha^{-1} plots to 110.5 cm in the 224 kg N ha^{-1} ($p = 0.013$, Fig. 2.6a). No N rate response was observed in 2019 corn plant height.

Corn plant biomass was also best fit with linear models in both years (2018 $R^{lrt} = 0.64$; 2019 $R^{lrt} = 0.10$; Fig. 2.7). In 2018, corn biomass varied by cover crop treatment. The mean corn plant biomass in three of the cereal rye + legume mixtures (cereal rye + hairy vetch: 2.26 Mg ha^{-1}; cereal rye + crimson clover: 2.26 Mg ha^{-1}; and cereal rye + winter pea: 2.61 Mg ha^{-1}) was larger than in the no cover crop (1.13 Mg ha^{-1}, $p < 0.0001$) and cereal rye only plots (1.70 Mg ha^{-1}; $p = 0.0002$; Fig. 2.7a). A significant response to N rate was also detected in all cover crop treatments in 2018, with mean plant biomass increasing from 1.74 Mg ha^{-1} in 33.6 kg N ha^{-1} to 2.17 Mg ha^{-1} in 224 kg N ha^{-1} ($p < 0.0001$, Fig. 2.7a). At the 2019 site, no significant effect of cover crop treatment was observed for corn plant biomass (Fig. 2.7b). Nitrogen rate response was significant ($p = 0.034$) but varied by cover crop treatment; corn biomass in cereal rye + red clover plots responded positively to increased N application but corn biomass in cereal rye + winter pea plots decreased with higher N rates ($p = 0.016$, Fig. 2.7b).

The chlorophyll content in 2018 was the only data found to be best modeled by a linear plateau ($R^{lrt} = 0.84$), with all six cover crop treatments plateauing at a similar SPAD index unit (60.4; Fig. 2.8a). Before reaching the model plateau, the mean chlorophyll content increased significantly with increasing N rate in all of the cover crop treatments ($p < 0.0001$), however, the mean SPAD index in the cereal rye + hairy vetch treatment were 13.3% higher (56.6) than cereal rye only plots (49.9, $p = 0.031$; Fig. 2.8). The following year, 2019, no differences in corn chlorophyll content were detected among cover crop treatments. However, we observed a significant (60%) linear increase in the corn chlorophyll content as N rate increased from 33.6 to 224 N kg ha^{-1} in all of the cover crop treatments ($R^{lrt} = 0.37$, $p < 0.0001$, Fig. 2.8).

Corn yield at harvest

The corn yield response in 2018 to N rate and cover crop treatment was best fit with a quadratic response model ($R^{lrt} = 0.64$; Fig. 2.9). Corn yield was higher in the cereal rye + crimson clover (6.68 Mg ha^{-1}) than the no cover crop (5.56 Mg ha^{-1}; $p=0.049$) but corn yield in the cereal rye + hairy vetch (7.58 Mg ha^{-1}) was higher than in both the no cover crop (5.56 Mg ha^{-1}; $p < 0.0001$) and the cereal rye only plots (5.71 Mg ha^{-1}, $p = 0.0002$; Fig. 2.9a). A significant N rate response was observed in all cover crop treatments. Corn yield in 2018 increased from a mean of 4.27 Mg ha^{-1} in the 33.6 N kg ha^{-1} plots to 7.75 Mg ha^{-1} in the 224 N kg ha^{-1} plots ($p < 0.0001$, Fig. 2.9a).

In 2019, the corn yield was best fit with a linear model ($R^{lrt} = 0.36$), however, there was no difference in overall mean corn yield between any of the cover crop treatments (11.1 Mg ha^{-1}; Fig. 2.9b). Corn yield in 2019 increased significantly with

N rate in all cover crop treatments, from a mean of 8.09 Mg ha^{-1} in the 33.6 N kg ha^{-1} plots to 13.7 Mg ha^{-1} in the 224 N kg ha^{-1} plots, a 70% increase across all cover crop treatments ($p < 0.0001$, Fig. 2.9b).

Discussion

The high rainfall during the 2018 field season led to smaller corn plants and lower corn grain yield compared to 2019. However, we found that corn performance in 2018 was stronger in plots with a previously interseeded cereal rye + legume cover crop treatment compared to no cover crop and cereal rye only. In 2019, cover crop biomass was too small to positively or negatively impact corn performance. As climate change is predicted to increase the frequency and intensity of rainfall events in the mid-Atlantic US region, interseeded cereal rye + legume cover crop mixtures may confer agroecosystem resilience in the face of a changing climate.

Differences in corn performance between years was likely due to precipitation.

Corn yield, as well as mid-season plant LAI and height in 2018, were much lower than in 2019 (at times 20-50% the value of the same metrics), which was likely the result of excessive precipitation during the 2018 corn growing season (Fig. 2.2). After 60-100% higher than average rainfall every month from May to August 2018, precipitation peaked with a monthly rainfall total of 305 mm in September 2018, three times the monthly 30-year mean in Maryland (NOAA NCDC, 2020). By the end of the year, 2018 was the rainiest year recorded in Maryland since 1889 (NOAA NWS, 2019). In contrast, monthly precipitation in 2019 was average or drier than average compared to 30-year means (Fig. 2.2). The difference in corn performance between these two years was reflected statewide. The 2018 state mean corn yield in

Maryland (9.16 Mg ha^{-1}, 146 bu $acre^{-1}$) was the lowest recorded since 2012 (USDA NASS, 2017). The statewide mean corn yield rose back to 10.10 Mg ha^{-1} (161 bu $acre^{-1}$) in 2019, when weather returned to a more typical precipitation pattern (USDA NASS, 2020c). The excessive precipitation in 2018 no doubt contributed to the poor corn performance we observed in 2018 compared to 2019.

The excessively wet and waterlogged field conditions damaged corn performance in 2018 through two key mechanisms: stunted corn growth, and delayed planting and harvesting operations. The heavy precipitation throughout the 2018 growing season resulted in several instances of prolonged saturated field conditions. The detrimental effects of waterlogged field conditions on corn crops is well documented; previous research has estimated a 40% reduction in yield for waterlogging events longer than three days (Li et al., 2011) or a corn yield loss of 0.42-0.72 Mg ha^{-1} per each day of waterlogging (Kaur et al., 2017). Prolonged soil saturation interferes with corn root development (Parent et al., 2008) and gas exchange in the root zone (Geigenberger, 2003). Past field experiments found that waterlogging events at V3 and V6 reduced corn plant height by 4-14% and lowered LAI compared to the control (Ren et al., 2014). Later in the season, this leads to smaller corn ear volume and diminished grain development because the corn plant has less N source material to redistribute into reproductive growth (Gallais et al., 2006; Ren et al., 2014; Nasielski et al., 2019). In a meta-analysis of corn yield loss caused by extreme weather, excessive precipitation in June had the most severe negative impact on corn yield than any other month in the growing season (defined as May-August; Li et al., 2019), which was clearly reflected in our study.

The high levels of rainfall in 2018 also delayed corn planting and harvesting dates, causing further reductions in yield. Wet field conditions in the spring of 2018 pushed corn planting back until 26 May, nearly one week after the end of the typical corn planting period in MD (30 April-20 May; USDA NASS, 2010). In 2019, corn was planted on 10 May, well within the expected planting period for the region, and the benefit to corn yield was reflected at harvest. That year, the mean corn yield (11.1 Mg ha^{-1}) was higher than the state average (10.1 Mg ha^{-1}; USDA NASS, 2020c). Negative corn yield response to delayed planting is well documented (Imholte and Carter, 1987; Bundy and Widen, 1991; Nafziger et al., 1994); Maryland extension sources estimate that planting corn 10 days past May 15th in Maryland reduces corn yield by 10-17% (Kratochvil, 2018). Corn harvest in 2018 was also postponed due to delayed corn grain drydown and continually wet conditions prohibiting equipment entry into the field. The typical corn harvest window in Maryland is 22 September-22 October, however, in 2018, the corn was not harvested until 1 November. The lower corn yields in 2018 caused by late planting and frequently waterlogged growing conditions at critical growth stages were further reduced by a postponed harvest date.

Early season corn growth was not affected by cover crop treatment.

Our goal for collecting pre-sidedress corn measurements at growth stage V6 was to directly compare corn growth among cover crop treatments before sidedress N rates were introduced; however, few differences were detected. Regardless of cover crop biomass and N accumulation in the spring, the corn LAI, N content, and chlorophyll content were similar across cover crop treatments in both 2018 and 2019. Corn in the cereal rye + winter rye plots did have higher mean corn plant LAI and N

content than corn in the no cover crop control plots in 2019, yet no other differences were detected. These stage V6 corn measurements were collected at 6-8 weeks after cover crop termination, at which point cover crop decomposition should have been underway and differences in plant available N between cover crop treatments could be expected to emerge (Ranells and Wagger, 1996; Sullivan and Andrews, 2012). However, none of the differences in cover crop biomass or N content were reflected in the V6 corn growth analysis. Since the majority of corn N uptake begins at growth stage V6 and continues until stage VT (Cornell University Cooperative Extension, 2017), it is likely that differences in cover crop treatment did not emerge because the 34 kg ha^{-1} starter N applied to all plots at planting was sufficient for the first weeks of corn plant development before growth stage V6.

Despite extreme weather damaging the corn crop in 2018, corn performance was boosted by cereal rye + legume cover crop treatments.

Across all three R2 data measurements and yield analyses in 2018, corn in one or more of the cereal rye + legume cover crop treatments (most consistently cereal rye + hairy vetch) outperformed corn in the no cover crop or cereal rye only treatment. With increased chlorophyll content, biomass, and height at corn growth stage R2, clearly there was greater available N in the grass-legume cover crops than in the no cover crop control. Cereal rye + legume cover crop mixtures, especially cereal rye + hairy vetch, have been found to release N more synchronously with corn N uptake demands than monocultures of cereal rye or legumes alone, in addition to reducing N leaching losses (Parr et al., 2014; Poffenbarger et al., 2015; Thapa et al., 2018b). With climate scientists predicting an increase in frequency and intensity of rainfall events, both globally (Trenberth et al., 2011; IPCC 2013) and specifically in the mid-Atlantic

region (Spierre and Wake, 2010; Lu et al. 2015; Skeeter et al., 2018), farmers can bolster the resiliency of mid-Atlantic cropping systems by incorporating cereal rye + legume cover crop mixtures.

Among the four cereal rye + legume cover crop treatments tested, corn in the cereal rye + hairy vetch cover crop treatments outperformed the corn in cereal rye and no cover crop plots in more metrics than any of the other cereal rye + legume cover crops. There is substantial evidence of higher corn grain yields following a hairy vetch or cereal rye + hairy vetch cover crop compared to a no cover crop control or a grass species monoculture (Lictenberg et al., 1994; Clark et al., 1995; Sainju and Singh, 2001; Clark et al., 2007). However, there are no studies that directly compare hairy vetch N release with the other legume species in our study in mixture with cereal rye. Furthermore, results vary when N release rates and N flux in topsoil under a hairy vetch monoculture are compared with other legume species (Parr et al. 2014; Yang et al., 2020). There were no observed differences in our study to explain why corn planted into a cereal rye + hairy vetch cover crop residue outperformed the other cereal rye + legume treatments. The cereal rye + hairy vetch spring cover crop in 2018 had similar biomass, N content, and C:N to the other three cereal rye + legume treatments that year, all of which were optimal for providing an N benefit to the corn crop. Therefore, the corn in the cereal rye + hairy vetch cover crop plots could have benefitted from more optimal N dynamics than in the other treatments later in the growing season that was not captured by our measurements.

Corn production was unaffected by low spring cover crop biomass in 2019.

Among all of the corn performance metrics measured at growth stage R2 and yield, the only difference detected in 2019 between cover crop treatments was in plant height. The lack of a cover crop treatment response in 2019 was likely due to the lower spring cover crop biomass (mean 1.9 Mg ha^{-1}) compared to 2018 (4.9 Mg ha^{-1}). Corresponding to the biomass, the N content of the cereal rye + legume cover crop mixtures was also dramatically lower in 2019 (mean 35.1 kg ha^{-1}) compared to 2018 (mean 131.9 kg ha^{-1}). Previous interseeding field trials in Maryland observed similar results: significant differences in corn biomass and grain yield emerged following cover crop biomass accumulation of 700-800 kg ha^{-1}, but not after cover crop biomass of only 100-200 kg ha^{-1} (Hively and Cox, 2001). Cover crop N content of cereal rye + legume mixtures is tightly linked to biomass accumulation (Thapa et al., 2018a), so we could have expected more differences in 2019 corn performance to emerge if spring cover crop biomass levels were comparable to biomass accumulation in spring 2018.

Conclusion

In these field trials, we observed that interseeded cereal rye + legume cover crop mixtures can boost corn yields in extreme weather years, increasing agroecosystem resilience to climate change. Since 2018 was the wettest field season in recorded history in Maryland, corn yields were dramatically reduced by delayed planting and harvesting, as well as by waterlogged field conditions throughout the growing season. However, in this wet year, we observed benefits to corn height,

biomass, chlorophyll content, and yield in the cereal rye + legume cover crop plots, compared to no cover crop and cereal rye only plots. Although precipitation patterns in 2019 were more typical of the season, spring cover crop biomass levels were too low for us to determine a positive or negative effect on corn performance. With increasingly frequent and intense rainfall events predicted for the mid-Atlantic US region, interseeded cereal rye + legume cover crop mixtures can increase agroecosystem resilience in the face of climate change.

Table 2.1. Study site locations and soil characteristics.

Field site	Field location	Location coordinates	Soil type†	Soil organic matter (%)†	Bulk density, g cm^{-3} †
2017 - 2018	BARC North Farm Beltsville, MD	39.03˚N, 76.93˚W	Hammonton loamy sand (coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults)	1.6	1.42
2018 - 2019	Central Maryland Research and Education Center Glenn Dale, MD	39.01˚N, 76.83 ˚W	Downer-Hammonton complex: Downer loamy sand (coarse-loamy, siliceous, semiactive, mesic Typic Hapludults); Hammonton loamy sand (coarse-loamy, siliceaous, semiactive, mesic Aquic Hapludults); and Russett-Christiana complex: Russett sandy loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludults); Christiana silt loam (fine, kaolinitic, mesic Aquic Hapludults)	2.19	1.52

† Published in USDA NRCS, 2019.

Table 2.2. Cover crop planting species and seeding rates for a double-crop soybean interseeding experiment in the mid-Atlantic US.

Double-crop row spacing (cm)	Cover crop treatment	Seeding rates
38	None	N/A
76	None	N/A
76	Cereal rye	Cereal rye (126 kg ha^{-1})
76	Cereal rye + hairy vetch	Cereal rye (34 kg ha^{-1}); hairy vetch (22 kg ha^{-1})
76	Cereal rye + crimson clover	Cereal rye (34 kg ha^{-1}); crimson clover (22 kg ha^{-1})
76	Cereal rye + red clover	Cereal rye (34 kg ha^{-1}); red clover (11 kg ha^{-1})
76	Cereal rye + winter peas	Cereal rye (34 kg ha^{-1}); winter pea (78 kg ha^{-1})

Table 2.3. Dates of field operations and sampling activities.

	Double-crop soybean planted	Cover crop interseeded	Double-crop soybean harvested	Cover crop terminated	Corn planted	Corn V6 data collected	Sidedress N rate applied	R2 data collected	Corn grain harvested
2017-2018	7 July 2017	5 Sept 2017	18, 20 Nov 2017	9 May 2018	26 May 2018	3 July 2018	2 July 2018	8 August 2018	1 Nov. 2018
2018-2019	10 July 2018	27, 28 Aug 2018	23 Nov 2018	16 May 2019	10 May 2019	23 June 2019	26 June 2019	31 July 2019	25 & 26 Sept. 2019

Figure 2.1. Experimental timeline: Double-crop soybean interseeded with cover crop mixtures. Light green bars represent double-crop soybean growing season. Black vertical dashes represent interseeded cover crops duration of growth. Yellow bars represent corn growing season.

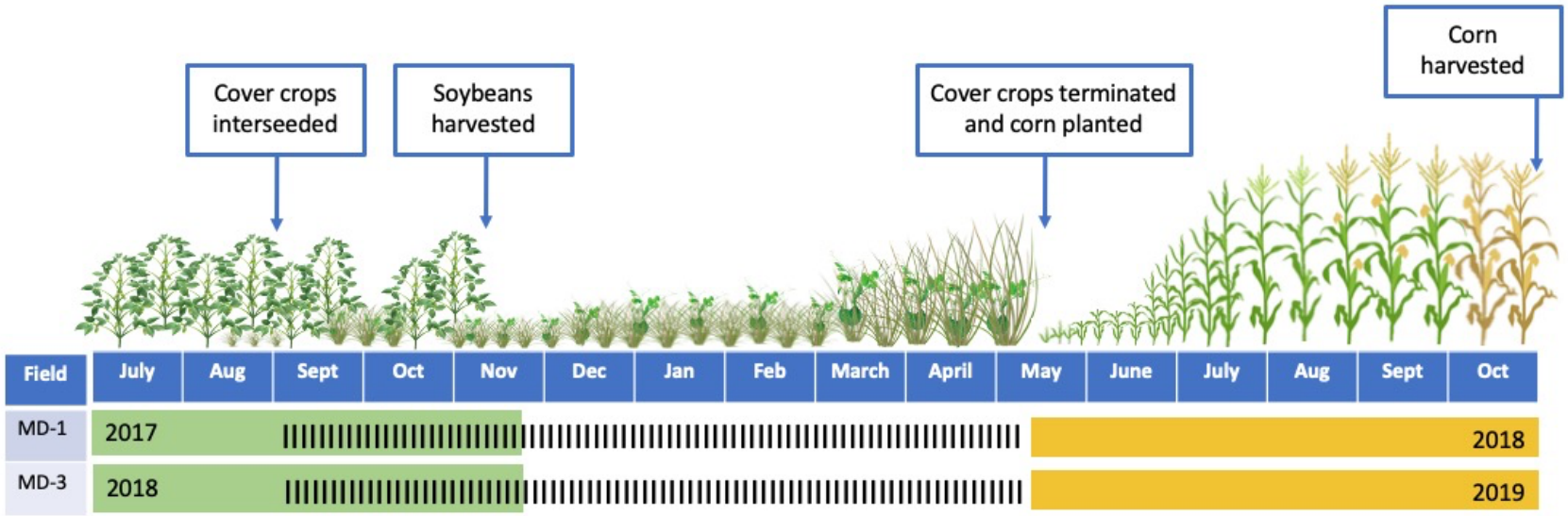


Figure 2.2. Mean recorded monthly air temperature (solid line) and cumulative precipitation (dark grey bars) during the 2018-2019 growing seasons and 30-yr mean monthly air temperature (dotted line) and cumulative precipitation (light grey bars).

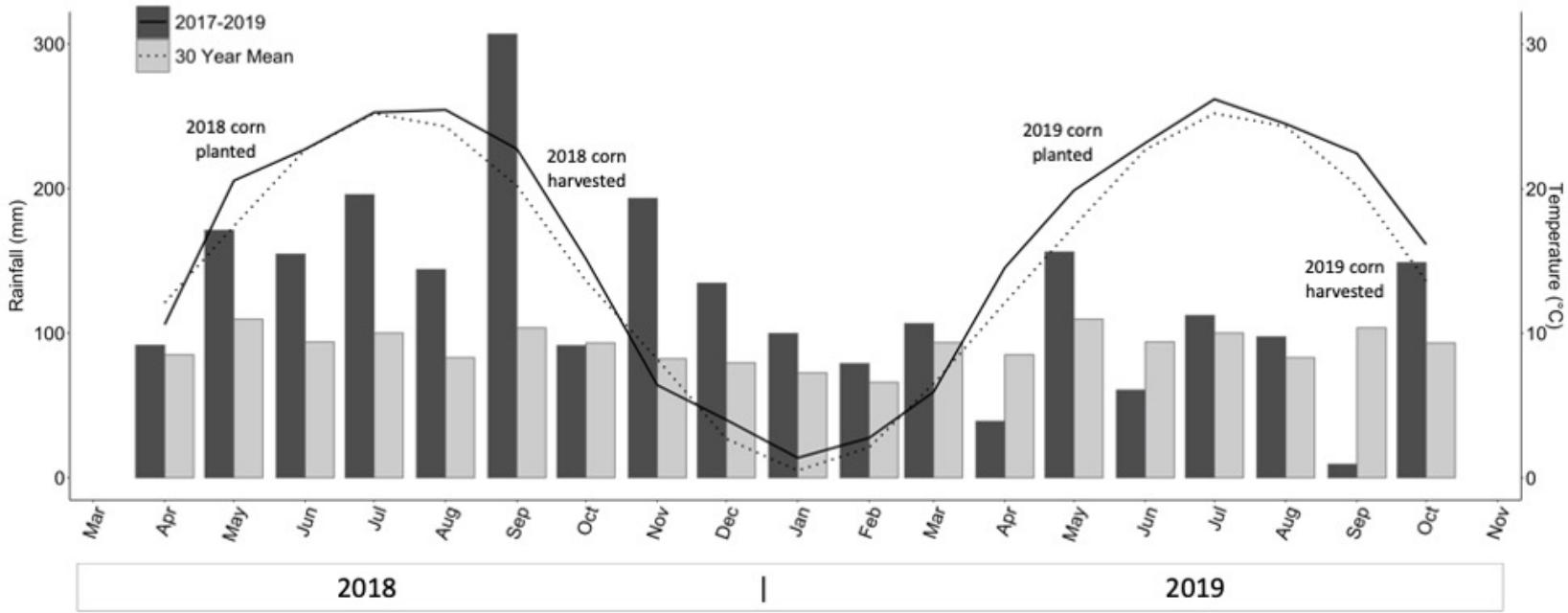


Figure 2.3. Mean leaf area index (leaf m^{-2} by ground m^{-2}) of corn plants by cover crop treatment at sidedress (growth stage V5-V6). Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site. Error bars represent the standard error of the mean.

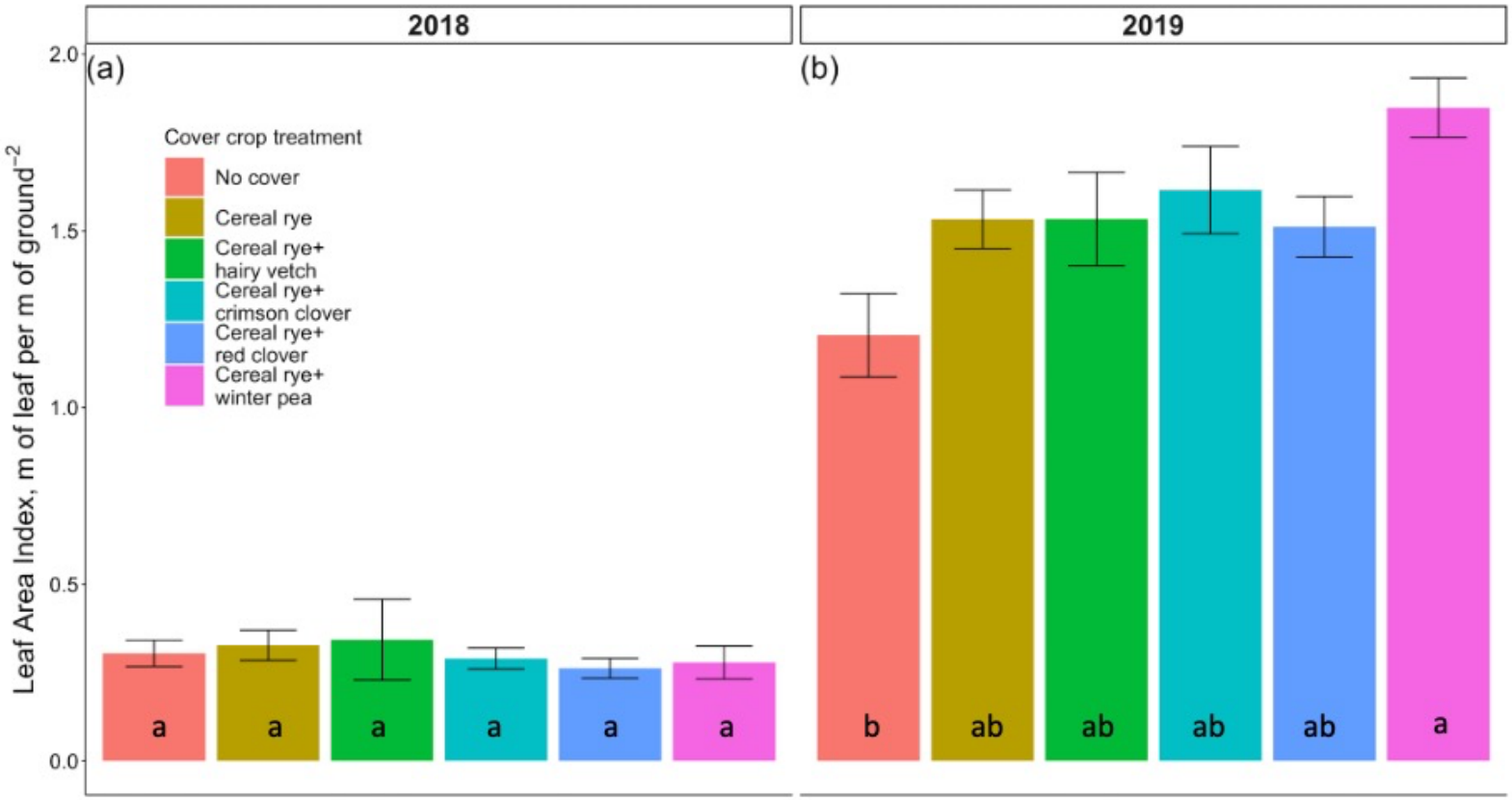


Figure 2.4. Nitrogen (N) kg ha[1] in corn biomass at sidedress (growth stage V5-V6). Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site. Error bars represent the standard error of the mean.

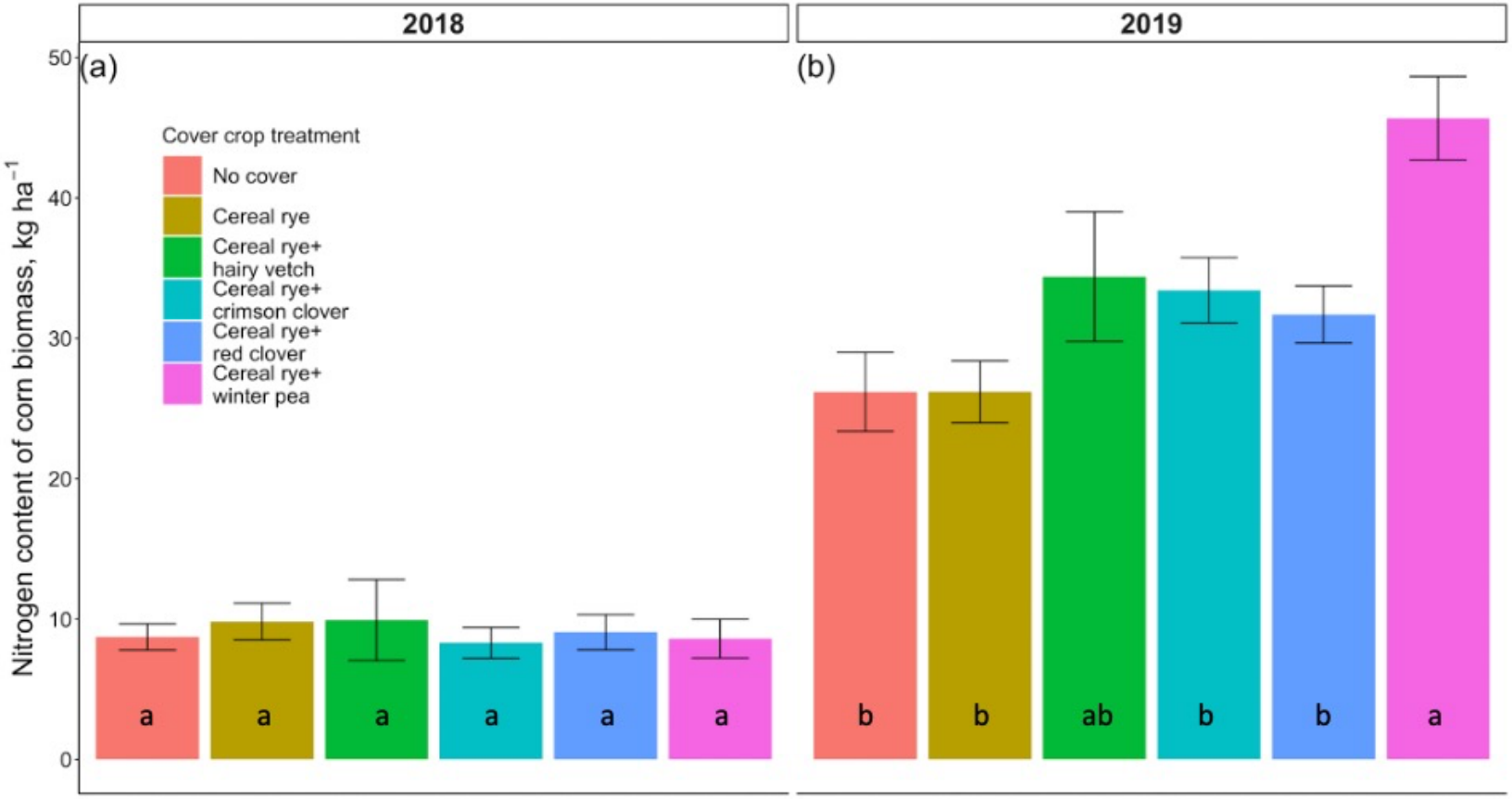


Figure 2.5. Mean chlorophyll content measurement of corn by cover crop treatment at sidedress (growth stage V5-V6). Letters inside each bar represent significance of *post-hoc* Tukey contrasts ($p < 0.05$) among cover crop treatments within field site. Error bars represent the standard error of the mean.

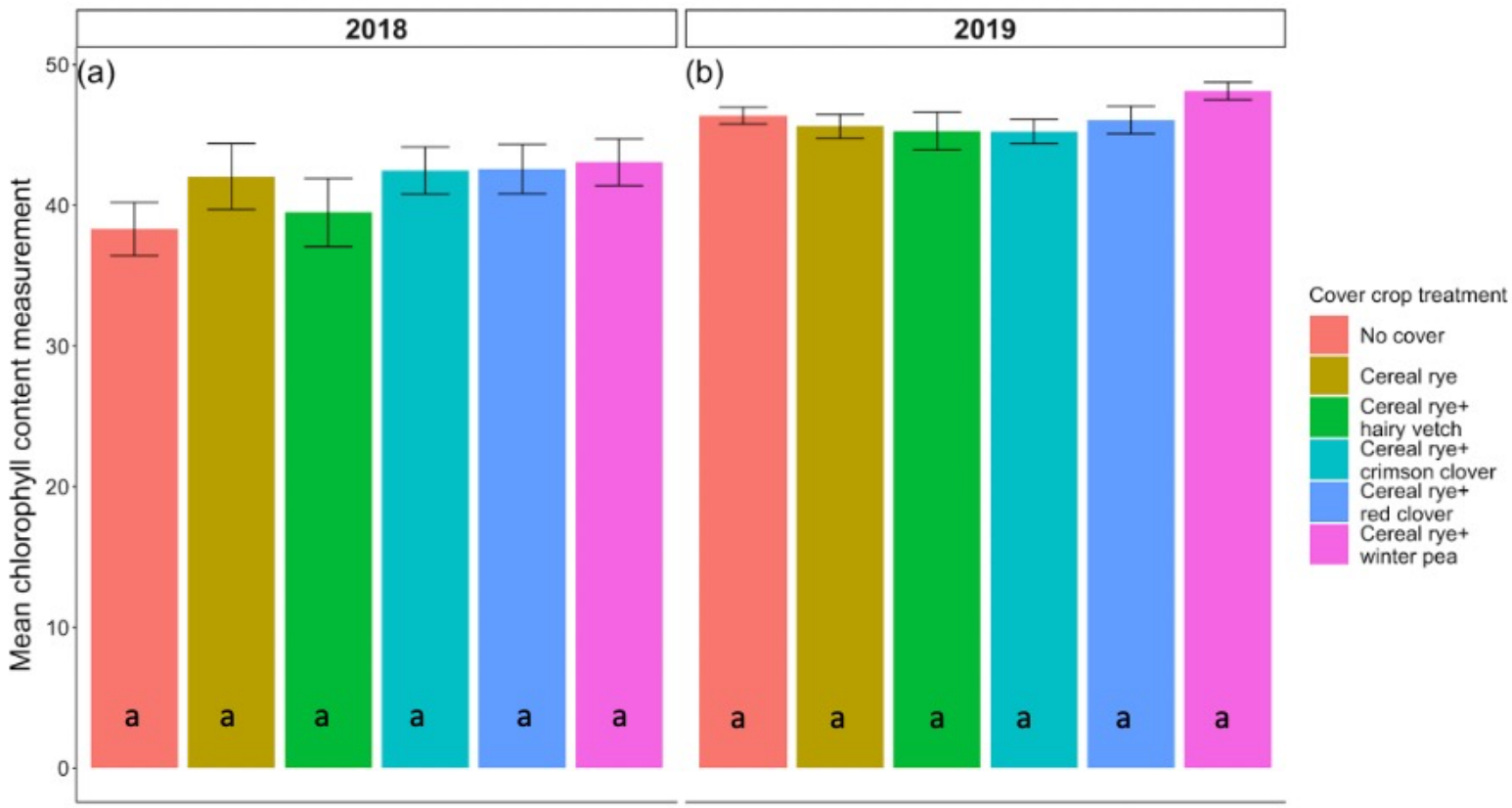


Figure 2.6. Corn plant height by cover crop treatment at corn growth stage R2. The patterns in corn plant height were best described by linear models in both years (2018 $R^{lrt} = 0.57$; 2019 $R^{lrt} = 0.22$). Lines represent the modeled values for each cover crop treatment. Points represent the mean observed values at each total N rate and error bars represent the standard error of the mean.

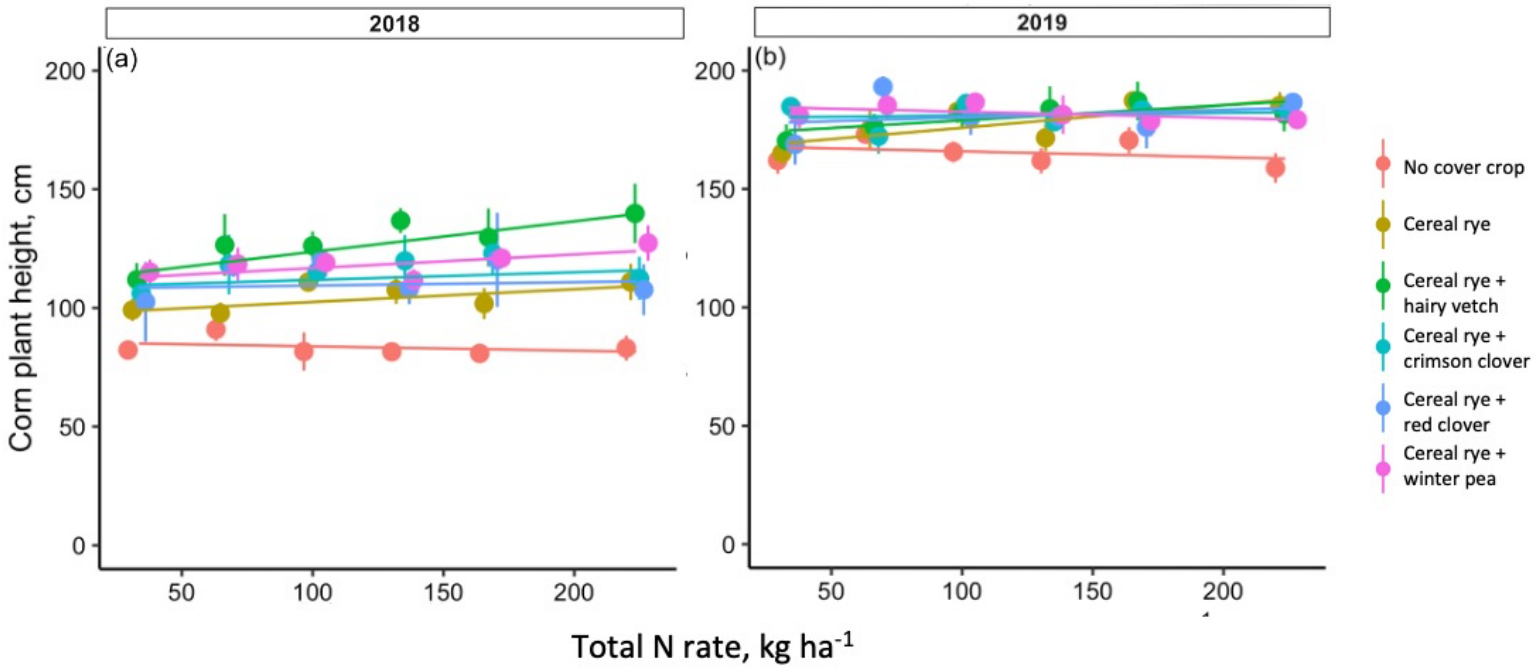


Figure. 2.7. Corn plant biomass of corn by cover crop treatment at corn growth stage R2. The patterns in corn plant biomass were best fit with linear models in both years (2018 R^{lrt} = 0.64; 2019 R^{lrt} = 0.10). Lines represent the modeled values for each cover crop treatment. Points represent the mean observed values at each total N rate and error bars represent the standard error of the mean.

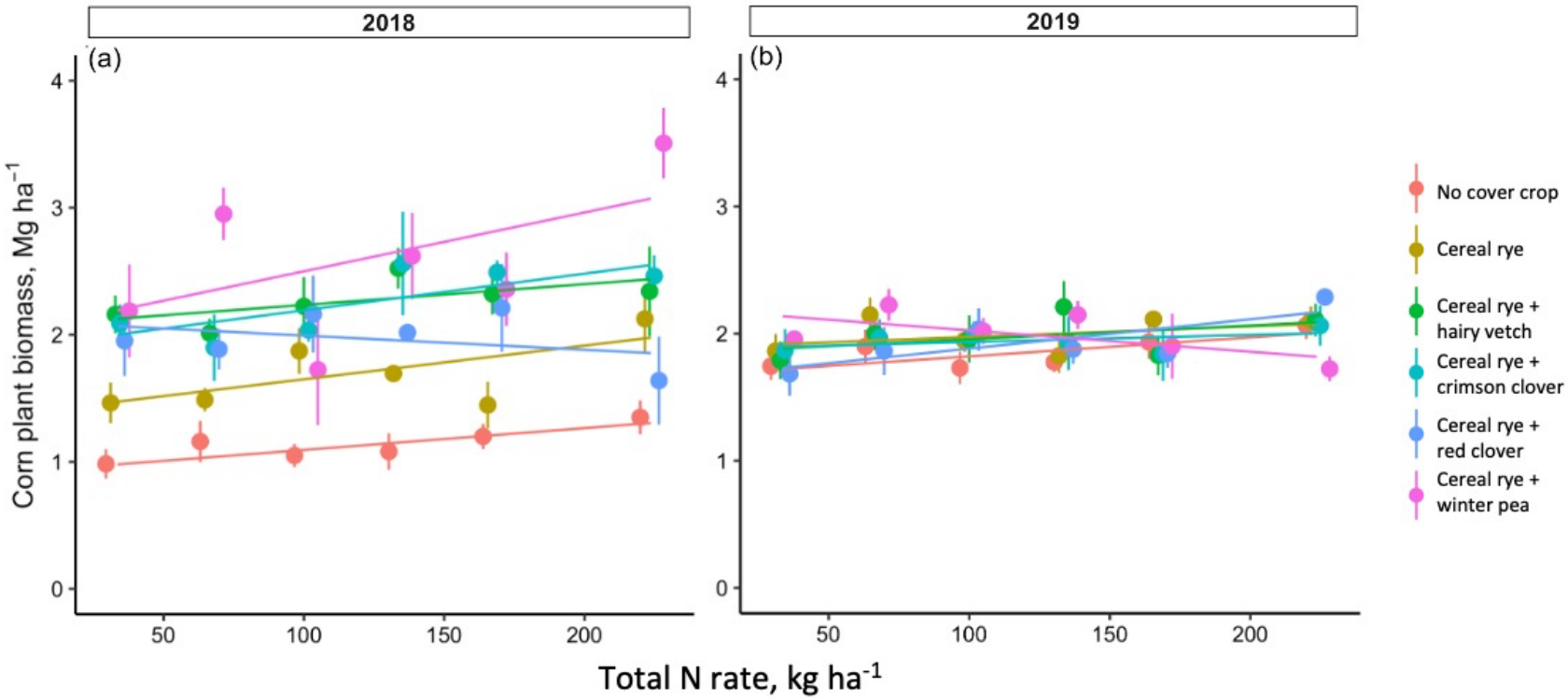


Figure 2.8. Corn chlorophyll content at corn growth stage R2. The chlorophyll content was best modeled by a linear plateau model in 2018 (R^{lrt} = 0.84) and a linear model in 2019 (R^{lrt} = 0.37). Lines represent the modeled values for each cover crop treatment. Points represent the mean observed values at each total N rate and error bars represent the standard error of the mean.

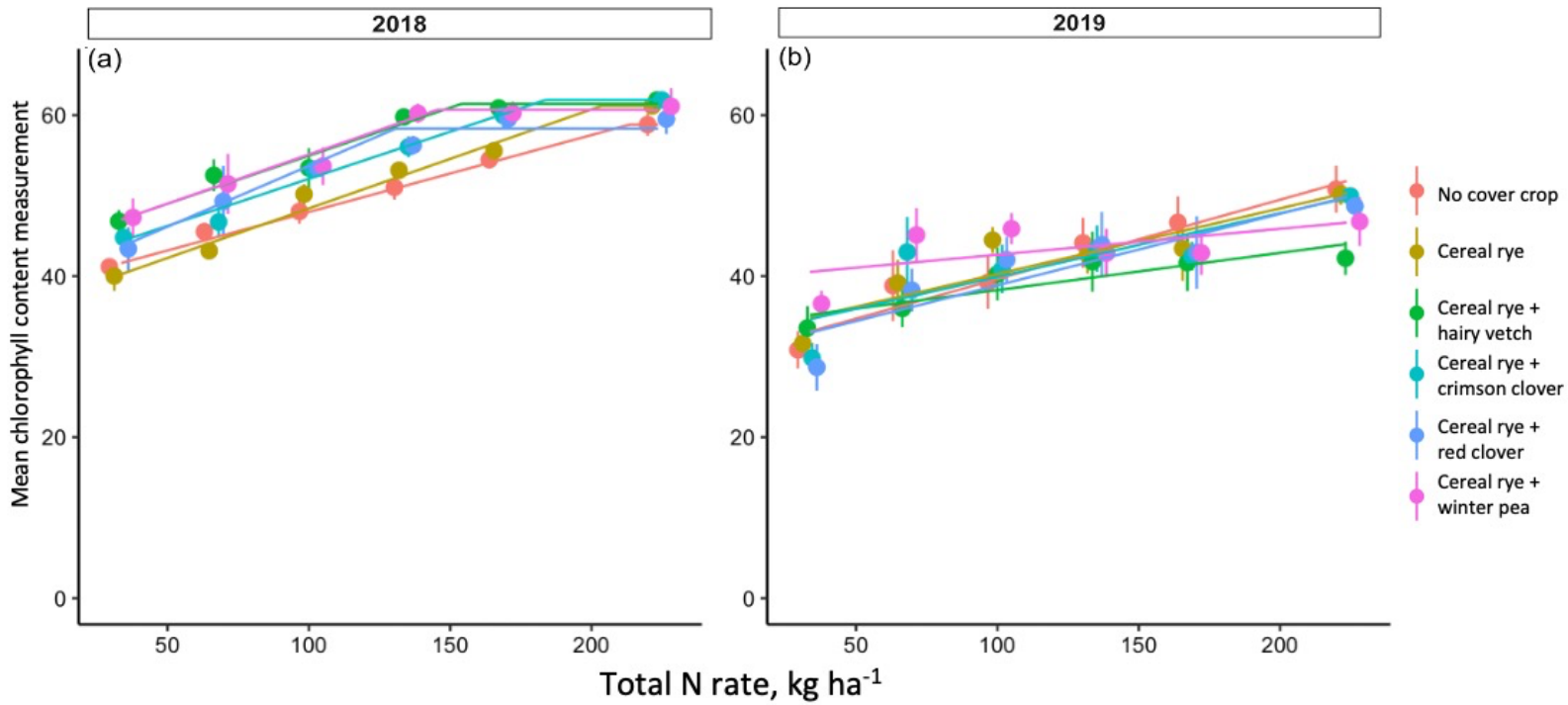
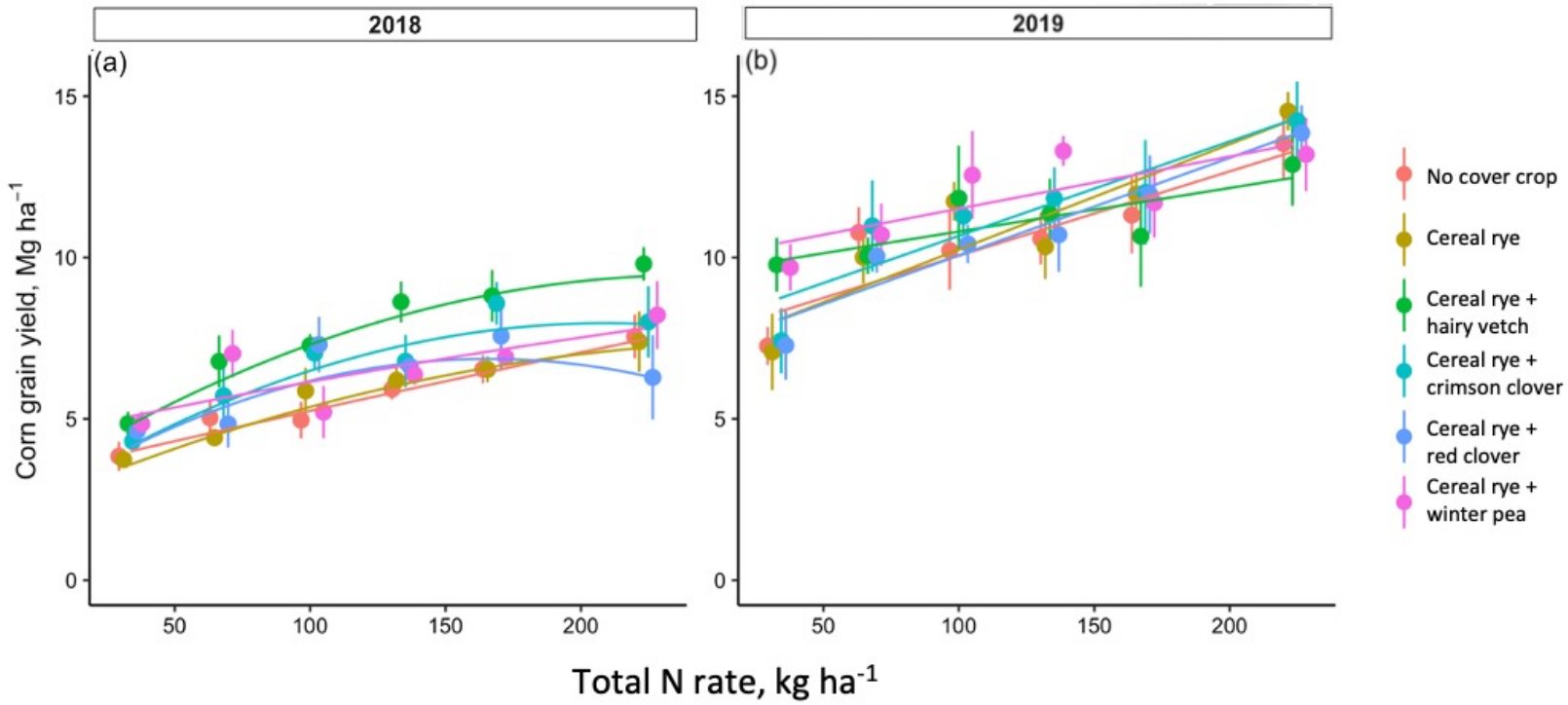


Figure 2.9. Corn grain yield by cover crop treatment. The corn yield was best fit with a quadratic model in 2018 ($R^{lrt} = 0.64$) and a linear model in 2019 ($R^{lrt} = 0.36$). Lines represent the modeled values for each cover crop treatment. Points represent the mean observed values at each total N rate and error bars represent the standard error of the mean.



Supplemental Table 2.1. Model estimates on corn height at growth stage R2 as a function of cover crop treatment and N rate. Estimates are accompanied by standard error in parentheses.

Corn 2018 R2 Height **Best Fit: Linear, R^{lrt} = 0.57**			
Cover crop	Slope	Intercept	Asymptote
No cover	-0.02 (0.04)	85.6 (5.4) d	--
Cereal Rye	0.05 (0.04)	97.1 (7.2) c	--
Cereal rye + hairy vetch	0.13 (0.05)	110.8 (7.8) a	--
Cereal rye + crimson clover	0.03 (0.04)	108.6 (7.8) bc	--
Cereal rye + red clover	0.01 (0.05)	108.1 (8.2) bc	--
Cereal rye + winter pea	0.05 (0.05)	111.0 (8.2) ab	--

Corn 2019 R2 Height **Best Fit: Linear, R^{lrt} = 0.22**			
Cover crop	Slope	Intercept	Asymptote
No cover	-0.03 (0.03)	168.4(5.37) b	--
Cereal Rye	0.10 (0.05)	166.3 (6.51) a	--
Cereal rye + hairy vetch	0.06 (0.05)	172.5 (6.51) a	--
Cereal rye + crimson clover	0.01 (0.05)	179.9 (6.51) a	--
Cereal rye + red clover	0.03 (0.05)	177.0 (6.51) a	--
Cereal rye + winter pea	-0.03 (0.05)	185.2 (6.51) a	--

Supplemental Table 2.2. Model estimates on corn biomass at growth stage R2 as a function of cover crop treatment and N rate. Estimates are accompanied by standard error in parentheses.

Corn 2018 R2 Plant Biomass **Best fit: Linear, R^{lrt} = 0.64**			
Cover crop	Slope	Intercept	Asymptote
No cover	0.002 (0.001)	0.92 (0.17) d	--
Cereal Rye	0.003 (0.002)	1.38 (0.23) c	--
Cereal rye + hairy vetch	0.002 (0.002)	2.07 (0.25) ab	--
Cereal rye + crimson clover	0.003 (0.002)	1.90 (0.25) ab	--
Cereal rye + red clover	-0.001 0.002)	2.10 (0.26) bc	--
Cereal rye + winter pea	0.005 0.002)	2.04 (0.27) a	--

Corn 2019 R2 Plant Biomass **Best fit: Linear, R^{lrt} = 0.10**			
Cover crop	Slope	Intercept	Asymptote
No cover	0.0015 (0.00) AB	1.67 (0.12)	--
Cereal Rye	0.0008 (0.0012) AB	1.89 (0.17)	--
Cereal rye + hairy vetch	0.0011 (0.0013) AB	1.85 (0.18)	--
Cereal rye + crimson clover	0.0006 (0.0012) AB	1.88 (0.17)	--
Cereal rye + red clover	0.0023 (0.0012) B	1.65(0.17)	--
Cereal rye + winter pea	-0.0017 (0.0012) A	2.19 (0.17)	--

Supplemental Table 2.3. Model estimates on corn chlorophyll content at growth stage R2 as a function of cover crop treatment and N rate. Estimates are accompanied by standard error in parentheses.

Corn 2018 R2 Chlorophyll Content **Best fit: Linear Plateau, R^{lrt} = 0.84**				
Cover crop	Slope	Intercept	Asymptote	N kg ha value at plateau
No cover	0.10 (0.01)	38.4 (1.3) ab	58.8 (1.4)	204.0 (225-186.3)
Cereal Rye	0.12 (0.02)	36.1 (2.0) b	61.2 (1.9)	209.0 (252-178.6)
Cereal rye + hairy vetch	0.12 (0.02)	43.0 (2.3) a	61.4 (1.8)	153.3 (189-149.2)
Cereal rye + crimson clover	0.12 (0.02)	40.4 (2.1) ab	61.9 (2.0)	179.2 (216-152.9)
Cereal rye + red clover	0.15 (0.04)	38.6 (3.1) ab	58.4 (1.6)	132.0 (193-96.3)
Cereal rye + winter pea	0.12 (0.03)	42.9 (2.5) ab	60.7 (1.8)	148.3 (205.6-114)

Corn 2019 R2 Chlorophyll Content **Best fit: Linear, R^{lrt} = 0.37**			
Cover crop	Slope	Intercept	Asymptote
No cover	0.10 (0.02)	29.8 (2.6)	--
Cereal Rye	0.08 (0.02)	32.1 (3.4)	--
Cereal rye + hairy vetch	0.05 (0.02)	33.6 (3.4)	--
Cereal rye + crimson clover	0.08 (0.02)	32.0 (3.4)	--
Cereal rye + red clover	0.09 (0.02)	30.0 (3.4)	--
Cereal rye + winter pea	0.03 (0.02)	39.4 (3.4)	--

Supplemental Table 2.4. Model estimates on corn grain yield at growth stage R2 as a function of cover crop treatment and N rate. Estimates are accompanied by standard error in parentheses.

Corn 2018 Grain Yield **Best fit: Quadratic, R^{lrt} = 0.64**			
Cover crop	Slope	Intercept	N^2
No cover	0.02 (0.01)	3.35 (0.77) c	-4.0×10^{-6} (0.00)
Cereal Rye	0.04 (0.02)	2.46 (1.09) bc	-6.3×10^{-5} (7.37×10^{-5})
Cereal rye + hairy vetch	0.05 (0.02)	3.20 (1.17) a	-1.0×10^{-4} (8.06×10^{-5})
Cereal rye + crimson clover	0.05 (0.02)	2.56 (1.18) ab	-1.2×10^{-4} 8.10×10^{-5})
Cereal rye + red clover	0.05 (0.02)	2.55 (1.25) abc	-1.5×10^{-4} (8.33×10^{-5})
Cereal rye + winter pea	0.02 (0.02)	4.49 (1.27) abc	-1.4×10^{-5} 8.73×10^{-5})

Corn 2019 Grain Yield **Best fit: Linear, Rlrt = 0.36**			
Cover crop	Slope	Intercept	Asymptote
No cover	0.03 (0.01)	7.44 (0.93)	--
Cereal Rye	0.03 (0.09)	6.98 (1.16)	--
Cereal rye + hairy vetch	0.01(0.09)	9.46(1.16)	--
Cereal rye + crimson clover	0.03 (0.09)	7.75 (1.16)	--
Cereal rye + red clover	0.03 (0.09)	7.04 (1.16)	--
Cereal rye + winter pea	0.02 (0.09)	9.90 (1.16)	--

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