Cover crops for early season weed suppression in corn

by

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Abstract

Integrated weed management is becoming more important to prevent herbicide-resistant weeds from reducing corn yield. This study examined the influence various combinations of cover crop species, termination timing, and N rate had on early-season weed suppression and corn yield at Manhattan and Ottawa in 2019 and 2020. Fall cover crops of triticale (x *Triticosecale* Wittm.), pea (*Pisum sativum* L.), and triticale + pea (mixed) were sown in November 2018 and 2019, with the exception of pea sown in spring 2019. Two cover crop termination timings, three weeks before (3WBP) or at corn planting (AP), were subplot factors. The sub-subplot factor was N broadcast applied as urea at rates of 100 or 168 kg N ha^{-1} within two weeks after planting in both years. Cover crops were terminated and no-cover treatments were treated with glyphosate and 2,4-D. Cover crop biomass was collected at termination and weed density was counted regularly from 3WBP through the POST herbicide application of atrazine, glyphosate, and mesotrione at three weeks after planting. Weed density and biomass were collected in August 2020 to quantify control by the POST application. Cover crop biomass production ranged from 2,500 to 7,600 kg ha^{-1} in the mixed and triticale treatments when terminated AP in both years. Weed density was influenced by cover crop species and termination time at Manhattan with reductions of 51 to 59% by using cover crops compared to no cover and 44% when terminated AP compared to 3WBP. There was no reduction in weed density at Ottawa by delay in termination timing, likely due to little cover crop biomass production. Yield was variable between the two locations. Delay in termination timing and the triticale cover crop reduced yield at Manhattan in both years by 14 to 19%. At Ottawa, a 15% increase in yield was observed when termination timing was delayed from 3WBP to AP, and yield increased by 11% with increased fertilizer applied from 100 to 168 kg N ha^{-1}, regardless of cover crop type. Results indicated that cover crops generated varying

results over different regions, soil types, and field management histories, as was exemplified by the locations of this study. Data from this study suggest that using a cover crop species that has high biomass production and corn fertilization with a minimum of 168 kg N ha^{-1} will result in greater weed suppression and less corn yield loss than cover crop treatments fertilized with 100 kg N ha^{-1}.

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Dedication

To my grandparents.

Chapter 1 - Literature Review

Introduction

Highly competitive weeds that respond rapidly to herbicidal selection pressure are troublesome to control in corn. There are currently 512 unique cases of herbicide resistance around the world and weeds have evolved resistance to 23 of the 26 known herbicide sites of action (Heap, 2020). Palmer amaranth (*Amaranthus palmeri* S. Watson) and common waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) are resistant to ALS-, EPSPS-, Photosystem II-, and HPPD-inhibiting herbicides, and to synthetic auxins; Palmer amaranth is also resistant to microtubule inhibitors (Heap, 2020). Managing herbicide-resistant weeds by chemical methods is becoming increasingly challenging because of multiple herbicide resistance in some populations (Patzoldt et al. 2005; Bagavathiannan and Norsworthy, 2016, Legleiter and Bradley, 2008). Herbicide-resistant *Amaranthus* species can be especially troublesome in corn. Weed control in Kansas corn has a significant economic impact on farmers with the potential for up to a 46% yield loss to occur annually in locations that use best management practices but no herbicides (Soltani et al. 2016). Without effective modes of action, Kansas farmers could be left with few options to protect yields from weeds. Thus, the need to create more comprehensive and integrated methods of weed control that promote conservation practices is paramount. One such tool for creating a robust weed management system could be cover cropping.

Cover crops are used for ecosystem services such as erosion reduction, nutrient management, and improvement of soil hydraulic properties (NRCS, 2021). Cover crops are also studied with special interest for their weed management potential. Early research showed weed suppression was possible from a variety of cover crop species and integration within a variety of cropping systems was feasible and could benefit cash crop yields (Teasdale, 1996). Cover crops were also used to increase available N in the soil or protect against N loss through leaching. More recent studies also show improvement in other ecosystem services such as increased total soil microbial biomass relative to non-cover cropped systems, whether tilled or left untilled (Buyer et al. 2010).

Cover Crop Mechanisms for Weed Control

Cover crops can be used during fallow periods or intercropped within a cash crop to control weeds. Mechanisms of weed suppression are similar whether the cover crop is actively growing or is terminated residue. If the cover crop is actively growing, the mechanism of suppression is competition for resources and space, although this may explain only about 20% of the variation in weed suppression (den Hollander et al. 2007; MacLaren et al. 2019). Suppression mechanisms for the terminated residue are similar and greatly depends on amount of biomass produced (MacLaren et al. 2019) to create a physical barrier to weed growth and to heat and light penetration to the soil (Baraibar et al. 2018; Teasdale and Mohler, 1993). Sunlight interception by cover crops is strongly correlated with suppression of weed seedling growth (Kruidhof et al. 2008) and varies by cover crop species. Species that reach their maximum level of ground cover quickly will better suppress weeds because of the critical loss of early light interception by emerging weeds.

Beyond the physical barrier to germinating weeds, weed suppression with cover crops may also include interference by allelopathic chemicals exuded from roots or shoots of the cover crop (Creamer et al. 1996). Some species such as cereal rye (*Secale cereale* L.) and white lupin (*Lupinus albus* L.) release allelochemicals to reduce inter-plant competition during their growth (Barnes and Putnam, 1986; Kruidhof et al. 2008; Reberg-Horton et al. 2005), while others, such as Brassica species, release allelochemicals following hydrolysis during decomposition (Brown and Morra, 1996). Knowing when the cover crop will release chemicals to inhibit weed seed germination is an important factor in the cover crop species selection process to target specific weeds.

Total weed suppression could also be affected by increased soil water storage under the cover crop, potentially increasing weed seed germinability in drier areas (Teasdale and Mohler, 1993). Cover crops can impose a level of unpredictability and caused increases in pigweed biomass and density at some sites when the same management strategy did not increase weed pressure at another site in a study by Hay et al. (2019). This could be of special concern for producers in the Great Plains region who wish to use cover crop residue to conserve soil water but are unsure how the cover crop will influence weed pressure in their fields.

Regardless of region, the most important factor for weed suppression with cover crops is biomass production, because few of the mechanisms for control are possible without considerable biomass. Cover crop biomass is widely reported as being the most important factor for weed suppression (Cornelius and Bradley, 2017; MacLaren et al. 2019; Osipitan et al. 2018; Petrosino et al. 2015; Teasdale and Mohler, 1993; Wiggins et al. 2017). To produce maximum biomass, it is recommended that the cover crop mix be entirely or mostly cereal based (MacLaren et al. 2019). Cereal rye, wheat (*Triticum aestivum* L.), and triticale (x *Triticosecale* Wittm.) consistently produce greater than 2,000 kg ha^{-1} cover crop biomass in temperate regions and greater than 6,000 kg ha^{-1} in more southern regions when grown as winter cover crops (Petrosino et al. 2015; Price et al. 2012; Wiggins et al. 2015, 2017). Wiggins et al. (2017) estimated 1,540 kg ha^{-1} of cereal rye cover crop biomass was required to delay Palmer amaranth emergence and growth to 10 cm of height by approximately 16.5 days. They also reported that Palmer amaranth that emerged in cereal rye took 10 days longer to reach 10 cm than when it emerged in hairy vetch (*Vicia villosa* Roth). Teasdale and Mohler (1993) estimated that residue biomass of two to four times the natural level enhanced the mechanisms required for weed suppression. However, without the use of other weed management techniques, Smith et al. (2011) concluded that cover crop biomass was not sufficient to prevent yield loss from weed competition in an organic soybean system. The difference in these estimates of required cover crop biomass for weed suppression were likely due to different expectations for the length of weed suppression, varying environmental conditions, and target weed species. Biomass accumulation may also differ by emergence timing of the cover crop, which could especially be delayed due to adverse weather (Mirsky et al. 2011), and thus reduce the weed suppression ability of the cover crop.

Cereal rye effectively suppresses weeds partially by its dense residue decreases light interception by the weeds and creates a physical barrier to weed growth. A cereal rye cover crop was reported to limit growth of Palmer amaranth by 67% and of horseweed (*Conyza canadensis* (L.) by more than 94% (Christenson, 2015; DeVore et al. 2012). Austrian winter pea (*Pisum sativum* L.) alone may be capable in some situations of producing greater than 3,000 kg ha^{-1} biomass, but slow early season growth can allow substantial weed establishment, making final biomass a poor indicator of weed suppression ability (Baraibar et al. 2018). However, slow early season growth could be countered by quicker growth of other species in mixes, such as cereal cover crops. Petrosino et al. (2015) reported greater cover crop biomass was produced from an Austrian winter pea and triticale mix than either species produced alone, and the mix suppressed kochia (*Bassia scoparia* (L.) A.J. Scott) biomass by more than 98%. Cereal rye plus hairy vetch also suppressed weeds with nearly equivalent suppression of weed biomass as compared with pure cereal rye (Hayden et al. 2012).

Cover Crop Termination Timing

Delay in cover crop termination timing influences amount of biomass produced because cover crops continue to grow when termination is delayed. When termination was delayed only two weeks, from mid-April to early May, biomass was increased by 39, 41, and 61% for cereal rye, crimson clover (*Trifolium incarnatum* L.), and hairy vetch, respectively (Wagger, 1989). When cover crop termination was delayed up to one month, total biomass varied by regional climate and cover crop species but was reported to increase by 60 to 160% (Clark et al. 1994; Lawson et al. 2015). Great differences in cover crop biomass can be created by just a few weeks delay in termination timing, but consensus on the optimal date varies (Clark et al. 1994; Osipitan et al. 2018; Otte et al. 2019; Rosario-Lebron et al. 2019; Vaughan and Evanylo, 1998). Determining factors for selecting the optimal date for cover crop termination was influenced by weed pressure, N availability, and subsequent crop yield. Osipitan et al. (2018) reported that cover crops effectively suppressed weeds when termination occurred in the early stages of the cash crop with no effect on grain yield. Delayed termination of a winter cover crop of barley (*Hordeum vulgare* L.) also allowed for greater biomass accumulation and thus weed suppression compared to fallow or early termination (Rosario-Lebron et al. 2019).

When considering N availability, the species of cover crop may influence the optimal termination time. Vaughan and Evanylo (1998) recommend late termination, just prior to corn planting, with hairy vetch cover crops to allow for maximum N accumulation. The C:N ratio of hairy vetch allows it to provide N to the crop in the same season it was grown, due to rapid breakdown and release of N. However, with cereal rye cover crops, termination approximately three weeks prior to corn planting was recommended to prevent greater carbon and biomass accumulation that could cause N immobilization in the soil (Vaughan and Evanylo, 1998). Conversely, Otte et al. (2019) reported more efficient N cycling from late-terminated residues and up to three times greater biomass accumulation of late (~7 days prior to corn planting) vs early (~40 days before corn planting) terminated cereal rye. Both Otte et al. (2019) and Vaughan and Evanylo (1998) agree that more cover crop biomass will be produced the longer the cover crop grows but disagree on what happens to N availability with later termination. Lawson et al. (2015) reported up to 60% reduction in cover crop biomass when terminated in late March vs late April in the Pacific Northwest but was not concerned about the change in N dynamics with a delay in cover crop termination because a delay to late April did not decrease residue quality enough to delay N release from the residues.

Cover Crop Termination Methods

Cover crops may also influence cash crop yield by the method in which they are terminated. This is because density of residue at the time of planting can influence crop establishment and herbicides or mechanical methods of termination can influence season-long weed competition or interference of the cover crop with the cash crop.

Cover crop termination via herbicide can kill any weeds that were already emerged and provides an opportunity for inclusion of pre-emergence herbicides to extend weed control. Terminating cover crops with herbicides can benefit post-emergence chemical weed control methods in corn by delaying weed emergence and growth rates to allow more time for effective herbicide applications. Wiggins et al. (2015) found crimson clover and hairy vetch reduced Palmer amaranth density prior to herbicide application and increased growing time for Palmer amaranth to reach 15 cm by 4 and 3 days, respectively, compared to non-treated control plots.

Other methods for termination influence ground coverage by residue, thus influencing the weed population density. Rosario-Lebron et al. (2019) found flail mowing increased the residue coverage on the ground, but herbicide termination left plants standing erect, with less ground coverage. Using a roller-crimper is another termination option that avoids use of chemicals. By roller-crimping, plant stems are broken when the roller goes over the top, but to achieve 100% kill, the plants must be rolled in late vegetative stages and before seed development. Delaying termination of hairy vetch to 20 to 100% flowering improved control of the cover crop as compared to rolling before flowering (Keene et al. 2017).

In drier regions such as western Kansas, water used by the cover crop as it grows in the spring typically is not replenished by rainfall, and drought conditions could be worsened for the following cash crop if cover crops are not managed carefully. This issue can be managed by careful choice of cover crop species, termination timing, and how many successive years it is grown. Unger and Vigil (1998) summarized previous data and reported that in humid to subhumid regions, cover crops should be grown until they provide sufficient ground cover but terminated as early as possible before planting corn to reduce total soil water depletion and allow for rainfall to replenish the water used. In a 13-year study in Iowa, Basche et al. (2016) showed no-till cereal rye improved soil water in a corn-soybean rotation compared to a long term no-till, no-cover treatment. The studies summarized by Unger and Vigil (1998) and reported by Basche et al. (2016) were in various subhumid to humid regions and Iowa, which have starkly different rainfall environments and likely affected water storage under the cover crops and recommendations for termination.

Nutrient Management and Soil Microbiology

Changes in termination timing and cover crop species selection influence nutrient management in the succeeding cash crop as well. Marsh (2014) reported that legumes such as winter field pea can have a positive impact on corn, especially in low N fertilizer input crop production. Field pea was found to contribute an average of 79 kg N ha^{-1}, which can lead to substantial cost savings in years of high fertilizer prices. Corn vigor was improved following crimson clover or hairy vetch cover crops (Wiggins et al. 2015), potentially also due to increased N availability from the breakdown of those legumes.

Cover crops managed for weed control may cause nutrient deficits, requiring greater use of fertilizers or resulting in decreased yield. Nitrogen use by a cereal cover prior to corn is one of the primary concerns of growers wishing to plant a cereal cover crop. Crandall et al. (2005) found N use by cereal cover could be mitigated by terminating the cover crop earlier than one week prior to planting corn and fertilizing the corn prior to V6. With many species, it is possible to accumulate sufficient biomass for weed suppression by this point, unless the corn planting date is very early in the spring.

Cover crops can also have other benefits in addition to weed control and improved N mineralization such as nutrient scavenging and improvements to soil microbiology. In a study by Cooper et al. (2017), a winter oilseed radish (*Raphanus sativus* L.) cover crop reduced soil nitrate concentrations by 75 to 97% over three years. Fall cover cropping following small grains prior to corn was shown to improve total microbial biomass in the soil which was crucial for nutrient breakdown and acquisition and drought tolerance in crops (Lehman et al. 2012; Mbuthia et al. 2015). Cover crops can also provide an off-season influx of lower C:N ratio and thus high-quality substrates to the soil, which improves microbial biomass and soil carbon (Xu et al. 2014). Cover crops used to provide lower C:N ratio residue to a system may also prevent or decrease soil N immobilization by providing an N source to microbes for the breakdown of high C:N crop residues such as corn and wheat stubble.

Challenges to Corn Production

Corn is one of the most important crops in the world and accounts for around 36 million hectares of row crop grown in the U.S. each year, making the U.S. its largest producer globally (USDA - NASS - Statistics by Subject Results, 2020). Volume of commercial fertilizer use in the U.S. is volatile, fluctuating with price and crop demand. In 2015, average commercial fertilizer use in the U.S. was 152 kg ha^{-1} year $^{-1}$ (EPA, 2020). Nitrogen accounted for 59% of total fertilizer applied per hectare and 40% of total commercial fertilizer used in the U.S. was applied to corn (EPA, 2020). While commercial fertilizer use is less today than at its peak in 1981, the proportion of fertilizer applications attributed to corn, specifically of N, continue to make fertilizers an environmental concern due to high risk of leaching and groundwater contamination. Environmental implications can be managed by optimization of timing and rate of N application for corn yield (Abebe and Feysia, 2017), but still more work must be done to reduce the impact of N loss on the environment.

Amaranthus Species in Corn

Palmer amaranth and common waterhemp have become two of the most troublesome weeds in Kansas. Their ability to develop resistance in response to herbicide selection pressure has contributed to their abundance in several cropping systems, including corn.

Dryland and irrigated corn yield can be reduced by more than 50% with four Palmer amaranth plants m^{-1} of row, and significant increases in seed rain have been positively correlated with greater densities of Palmer amaranth (Rule, 2007). Timing of weed emergence was also a critical factor to the competitive ability of Palmer amaranth. Yield loss from Palmer amaranth densities of 0.5 to 8 plants m^{-1} of row in corn ranged from 11 to 91% when plants emerged with the crop versus reductions of 7 to 35% when plants emerged later, and seed production also decreased with delay in emergence timing (Massinga et al. 2001; Keeley et al. 1987).

Palmer amaranth and common waterhemp are summer annuals with a long window of emergence, starting in mid to late spring and lasting through the first frost (Hay and Peterson, 2019), with the bulk of emergence occurring in May and June. These species thrive in warm temperatures and compete fiercely during the hottest parts of the growing season, with growth rates that may exceed one inch per day (Hay and Peterson, 2019). Of the four most prevalent *Amaranthus* species in Kansas, Palmer amaranth and common waterhemp exhibit the greatest plant volumes, often exhibiting leaf area indices and total plant biomass several magnitudes greater than other Amaranthus species such as redroot pigweed (*Amaranthus retroflexus* L.) and tumble pigweed (*Amaranthus albus* L.) (Horak and Loughin, 2000). Common waterhemp was found by to be second in height, branch number, and plant volume only to Palmer amaranth (Horak and Loughin, 2000).

Both Palmer amaranth and common waterhemp have great seed production potential. Massinga et al. (2001) found that Palmer amaranth seed production decreased per plant with greater competition, but seed per unit area increased from 140,000 to 514,000 seeds m^{-2} at densities of 0.5 and 8 plants m^{-1} of row when Palmer amaranth emerged with corn. Seed production by Palmer amaranth was also affected by its emergence timing. Total seed production of 200,000 to 600,000 seeds per plant was observed by Keeley et al. (1987) in March through June plantings, but only 115 to 80,000 seeds per plant was observed when Palmer amaranth was planted in July through September. Palmer amaranth has been reported to produce more seeds than common waterhemp, except at high weed densities when common waterhemp may equal or surpass the production by Palmer amaranth (Bensch et al. 2003). These studies show that for species with a wide range of emergence and great seed rain, increasing crop competition and delaying or reducing weed emergence via cover crops could have a significant impact in reducing annual seed rain and preventing yield reductions.

Herbicide resistance in *Amaranthus* species has increased due to the selection of resistant genotypes through repeated use of either few or the same herbicide modes of action. When herbicide modes of action are used repeatedly over sequential growing seasons and not used in combination with other herbicide families, naturally resistant plants present in the field survive and can transfer their genes to other plants in the field, frequently through pollination (Hay and Peterson, 2019). This is a problem with *Amaranthus* species because of their dioecious nature and ability to share their genes rapidly with a greater portion of the population than those species that are not cross-pollinated. This is a problem because farmers tend to use herbicide programs until they fail completely and it may be difficult to tell initially that resistance is developing (Peterson, 1999). Integrated weed management strategies such as use of cover crops, cultural changes in crop production practices, and diversification of herbicide modes of action are the best ways to slow the development of herbicide resistance in weeds (Norsworthy et al. 2012).

Conclusion

Weed suppression is an important determinant of yield potential in corn. Troublesome *Amaranthus* species can cause significant yield loss in Kansas corn and are rapidly responding to selection pressure from several herbicides. Cover crops, specifically cereal species such as triticale or cereal rye and legumes such as field pea, have potential to lessen herbicide selection pressure on *Amaranthus* and other weed species by providing weed suppression in corn. Cover crop termination timing and N fertilization may influence weed suppression and also may have a direct impact on corn yield. Therefore, the focus of this study was to determine the effects of cover crop, termination timing, and N fertilization on weed suppression and corn yield in eastern Kansas environments.

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Chapter 2 - Cover Crop Effect on Early Season Weed Suppression and Nitrogen Availability in Corn

Abstract

Herbicide-resistant weeds threaten weed management in Kansas corn. This study examined the influence of various combinations of cover crop species, termination timing, and N rate on early-season weed suppression and corn yield at Manhattan and Ottawa in 2019 and 2020. Fall cover crops of triticale (x *Triticosecale* Wittm.), pea (*Pisum sativum* L.), and triticale + pea (mixed) were sown in November 2018 and 2019, with the exception of pea sown in spring 2019. Two cover crop termination timings, three weeks before (3WBP) or at corn planting (AP), were subplot factors. The sub-subplot factor was N broadcast applied as urea at rates of 100 or 168 kg N ha^{-1} at planting in 2019 and within two weeks after planting in 2020. Cover crops were terminated and corresponding no-cover plots were sprayed with glyphosate and 2,4-D at each termination time. Cover crop biomass was collected at cover crop termination and weed density was counted regularly from 3WBP through the POST herbicide application of atrazine, glyphosate, and mesotrione at three weeks after planting. Weed density and biomass were collected in August 2020 to quantify control by the POST application. Cover crop dry biomass production ranged from 2,500 to 7,600 kg ha^{-1} in the mixed and triticale treatments when terminated AP in both years. Weed density was influenced by cover crop species and termination time at Manhattan with reductions of 51 to 59% by using cover crops compared to no cover and 44% when terminated AP compared to 3WBP. There was no reduction in weed density at Ottawa by delay in termination timing, likely due to less cover crop biomass production. Corn yield was variable between the two sites, with reduced yield at Manhattan in both years of 14 to 19% caused by delay in cover crop termination and with the triticale cover crop. At Ottawa, a 15%

increase in yield was observed when termination timing was delayed from 3WBP to AP and an 11% increase in yield with increased fertilizer applied from 100 to 168 kg N ha^{-1}, regardless of cover crop type. Net returns were greatest in no cover treatments that received a burndown AP and were reduced as cover crop species and proportions in mix increased. Results indicated that cover crops generated varying results over different regions, soil types, and field management histories and returns were reduced by the additional costs of cover crop establishment and yield reductions in cover crop treatments. Data from this study suggest that using a cover crop species that produces high biomass and is supplemented with a minimum of 168 kg N ha^{-1} will result in greater weed suppression and less corn yield loss than other treatments evaluated.

Introduction

Corn is grown on more than two million hectares of Kansas land and is worth over $3.3 billion annually (NASS, 2020). All-purpose corn production acreage is the second largest agricultural land use in Kansas, behind wheat. Corn has many options for pre- and post-emergence weed control, but herbicide options are dwindling for the state's most troublesome weeds. Palmer amaranth (*Amaranthus palmeri* S. Watson) has developed resistance to synthetic auxin herbicides and ALS-, EPSPS-, Photosystem II-, HPPD-, and microtubule-inhibiting herbicides (SOA groups 4, 2, 9, 5, 27, and 3) (Heap, 2020). These groups include many important herbicides used in corn production that are no longer options to control this specific weed. Palmer amaranth is just one example of the mounting challenge of herbicide resistance in an already troublesome weed species. The optimal weed control approach in the face of herbicide resistance is integrated weed management. Strategies such as changes to row crop spacing, crop rotation, diversification of herbicide modes of action, and cover crops have been presented as the best approaches to slow the development of herbicide resistance in weeds (Norsworthy et al. 2012).

Cover crops can help manage weeds by competing for resources and space when growing, or through physical interference and alteration of optimal growing conditions for weed seedlings by allelopathy and changes in soil water and temperature (Baraibar et al. 2018; Creamer et al. 1996; den Hollander et al. 2007; Teasdale and Mohler 1993). The most frequently used cover crop species are in the grass and legume families. Cereal cover crops such as rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.) are popular due to their low cost and high biomass production that can be used for weed suppression or for grazing (Magdoff and Van Es, 2009). Cereal cover crops reduce the growth rate of weeds compared to other cover crops that produce less biomass (Wiggins et al. 2017). This feature of cereal cover crops may allow farmers more time to apply a timely POST application while weeds are small enough to be controlled. Legumes are often favored because of their ability to add N to the system through symbiotic N fixation and are frequently the choice for cover crops planted before high N-demand crops, such as corn (Magdoff and Van Es, 2009).

Due to cover crop biomass accumulation and N cycling, termination timing of the cover crop can influence corn yield potential. Delay in termination time can cause an increase in C:N ratios of cereal cover crop residue and an increase in total N removed from the soil, resulting in critical N immobilization for the following cash crop, while legumes fix more N with later termination times and can increase the net return of N to the following crop (Vaughan and Evanylo, 1998). Estimating the optimal time for termination of a cereal or legume species to manage for N availability and weed pressure continues to be a challenge for farmers. This could potentially be mitigated by supplementation of legume species to the cereal cover crop to better meet both goals. When grown alone, winter field pea (*Pisum sativum* subsp *arvense* (L.) Asch) can contribute up to 79 kg N ha^{-1} which could reduce the requirement for additional synthetic fertilizers when cereal cover crops are used for weed management (Marsh, 2014). However, challenges to pea production such as light availability and growing season temperatures and precipitation may influence the amount of N they may supplement when grown in a mixture with other cover crop species.

Managing weeds with cover crops while minimizing the impact of N deficiency also may have a significant influence on farmer profitability. Cover crop management adds to the variable costs a farmer must budget for each year. It is unclear in eastern Kansas environments if this added cost can be a profitable one for corn.

The objectives of this study were to (1) determine the effect of cereal, legume, and cereal + legume mix cover crops when terminated three weeks before and at corn planting and fertilized with low and average rates of N on early-season summer annual weed suppression and corn yield, and (2) determine the effect on farmer profitability of the added variable costs of cover crops in eastern Kansas corn production.

Materials and Methods

The experiment was conducted in 2019 and 2020 near Manhattan, KS (39º 07’ 12” N, 96º 14’ 37” W) and in 2020 near Ottawa, KS (38º 32’ 23” N, 95º 14’ 37” W), both located on Kansas State University - Department of Agronomy Experiment Fields. The soil series at the Manhattan location was a moderately wet Reading silt loam (Fine-silty, mixed, superactive, mesic Pachic Argiudolls) with 1 to 3% slopes. The soil series at the Ottawa location was a Woodson silt loam (Fine, smectic, thermic Abruptic Argiaquolls) with 1 to 3% slopes.

The study was conducted in a randomized complete block design with treatments in a split-split plot arrangement. Whole plots were four cover crop treatments of triticale (x *Triticosecale* Wittm.), pea (*Pisum sativum* L.*)*, triticale + pea (Full mix), and no cover treatments. Subplots were two levels of cover crop termination timing: 3 weeks before corn planting (3WBP) and at corn planting (AP). Sub-subplots were two levels of N fertilization: 100 and 168 kg N ha^{-1} in the form of urea (46-0-0) broadcast by hand at planting in 2019 and no later than two weeks following corn planting in 2020. Sub-subplots were 3 m wide and 10 m long with 3 m borders separating whole plots. Borders were planted to corn, and all corn was managed as recommended by Kansas State Extension specialists other than N application. At each site, P and K were added if required based on soil samples.

Cover crops were drilled with a John Deere 1590 no-till drill into wheat stubble in November 2018 and weedy fallow in November 2019 prior to corn planting the following spring. Triticale was drilled at 100 kg ha^{-1} in early November 2018 and 2019 at each site. On April 12, 2019 spring pea was drilled into standing triticale at 67 kg ha^{-1} to establish the mixed treatment and drilled alone to establish the pea treatment. In November 2019, pea was drilled at a rate of 67 kg ha^{-1} in bulk along with triticale, creating a bulk mix of 167 kg seed ha^{-1} (Table 2.1).

To establish the no-cover treatment, plots were sprayed with glyphosate (Roundup Powermax, 867 g ae ha^{-1}, Monsanto Company, St. Louis, MO) and 2,4-D (Shredder 2,4-D LV4, 216 g ae ha^{-1}, Winfield Solutions, LLC, St. Paul, MN) approximately 10 weeks before corn planting in 2019 and seven weeks before corn planting in 2020 when triticale was tillering but had no elongated stems (Table 2.2) resulting in no measurable residue by the time of corn planting in 2019 or 2020.

To create pea- and triticale-only treatments from the bulk planting in fall 2019, herbicides were applied seven weeks prior to corn planting in 2020. Triticale-only treatments were sprayed with 2,4-D to terminate peas. No injury or stunting of the triticale from 2,4-D exposure not observed at the rates applied. Pea-only plots were sprayed with fluazifop-P-butyl (Fusilade DX, 57 g ai ha^{-1}, Syngenta Crop Protection LLC, Greensboro, NC) to terminate triticale. Graminicides such as fluazifop-P-butyl do not affect dicot species such as pea due to different herbicidal binding site architecture in dicots than in monocots (Herbert et al, 1997). All pre-plant herbicide applications were made at a spray volume of 140 L ha^{-1} using a six-nozzle CO_2 pressurized backpack sprayer with effective spray width of 3 m and walking speed approximately 5 km hr^{-1}. Nozzles used were TeeJet 8002VS (TeeJet Technologies, 2014). Water was conditioned to using spray-grade AMS (2% volume/volume) improve efficacy of glyphosate and crop oil concentrate (1% v/v) was added to increase efficacy of 2,4-D. Cover crops were terminated 3WBP or AP with 867 g ae ha^{-1} glyphosate and 216 g ae ha^{-1} 2,4-D (Table 2.2).

Due to high amounts of precipitation in Manhattan in May 2019, corn planting was delayed beyond the mid-May target planting date and the termination timing treatment for triticale could not be established. Triticale cover crops were reaching the reproductive stage in 2019 resulting in all plots with triticale being terminated 3WBP on May 14, 2019, thus the at planting (AP) termination treatment was dropped from the subsequent analysis. In 2020, the pea-only treatment was not adequately established, resulting in a "partial-mix" treatment composed of approximately 50% of the original stand of peas and 50% of the original bulk planting of triticale. Triticale was not completely terminated by the fluazifop-P-butyl application because of cool temperatures that reduced herbicide efficacy (Syngenta Crop Protection LLC, 2019). Herbicides often do not work as well as expected when plants are not actively and rapidly growing, which occur during cold periods. Additionally, a cold snap in mid-April with low temperatures well below 0 C and high temperatures less than 10 C also reduced the stand of peas after they started growing rapidly with recent exposure to temperatures above 30 C a few days prior.

Aboveground cover crop biomass was harvested at termination from one 0.25 m^2 quadrat from the back of each plot and dried at 60 C to a constant weight, then weighed. Density of all weeds were counted in 0.25 m^2 quadrats when densities were less than 200 plants or in 0.10 m^2 quadrats for all other plots. Weeds were counted bi-weekly in 2019 and weekly in 2020 starting at 3WBP and ending at POST timing, approximately three weeks after corn planting each year. Weed densities were adjusted to plants m^{-2} before analysis.

Corn was planted with a 2018 John Deere 1705 four-row planter on June 5, 2019 and May 20, 2020 in Manhattan and with a White 6100 air planter on May 19, 2020 in Ottawa. Corn seeding rate was 64,000 seeds ha^{-1} of Channel 209-15VT2PRIB in 2019 and DKC 64-25 RIB in 2020. The target planting date for corn was mid-May, which is later than recommended by KSU extension specialists but was chosen to allow more time for cover crop biomass to be produced. However, planting dates were further delayed in 2019 to early June because of high amounts of precipitation in May. Final corn emergence was counted two weeks after corn planting in 2019 and 2020. In 2019 soil plant analysis development (SPAD) readings were taken with a Konica Minolta 502 chlorophyll meter (Konica Minolta Optics, Inc., 2009) at R3 and R5 to estimate chlorophyll content in the corn ear leaf, which is correlated to N level in the plant (Konica Minolta Optics, Inc., 2009). Readings were taken from 20 plants in each plot and averaged to provide one value. In 2020, instead of SPAD readings, 15 top-collared corn leaves were collected six weeks after planting from the center two rows of each plot to make a composite sample and dried at 60 C to constant weight. Leaf tissue N was analyzed via dry combustion to determine plant N status (K-State Soil Testing Lab).

A POST application of a tank mix of (1121 g ai ha^{-1}) atrazine (Aatrex 4L, Syngenta Crop Protection, Greensboro, NC), 1182 g ae ha^{-1} glyphosate, and 105 g ai ha^{-1} mesotrione (Callisto, 105 g ai ha^{-1}, Syngenta Crop Protection, LLC, Greensboro, NC), AMS (2% v/v) (Table 2.2) was made using a CO_2 – powered backpack sprayer in 2019 and a tractor-mounted electric pump-driven sprayer three weeks after planting in 2020. The POST did not achieve complete control in 2020, so weed control ratings were taken three and six weeks after POST application and final weed biomass and density were collected nine weeks after POST application.

Corn grain was harvested from the center two rows of each plot at both site and years with a plot combine and grain yield was adjusted to 15.5% moisture content. Corn seed test weight was recorded during harvest and the seed weight was adjusted to 15.5% moisture.

Data were subjected to analysis of variance (ANOVA) in R (v4.0.2, R Core Team, 2020) using the ‘lmer’ function in the ‘lme4’ package (Bates et al. 2015) at significance level of a = 0.05. Replication was treated as a random effect with the whole plot (cover crop treatment) and subplot (termination time and N rate) factors were nested within replication for error. Location and year were treated as fixed effects and if found significant, data were analyzed separately. If a term was found to be not significant in the model, it was removed and a new model was created, with the error terms adjusted to correctly nest the remaining factors. Data collected prior to N fertilization (cover crop biomass, weed density, corn stand counts) were estimated with only cover crop type and termination time as sources of variation. Post-fertilization data (corn tissue samples, late-season weed densities and biomass, corn yield, corn test weight) were analyzed with cover crop, termination time, and N rate as sources of variation. If an interaction was detected, means were obtained using the ‘emmeans’ function in the ‘emmeans’ package (Lenth, 2020) at significance level of $\alpha = 0.05$ using Tukey’s adjusted p-value.

Results and Discussion

Precipitation for the period of this study in Manhattan in 2019 was greater than in Manhattan and Ottawa in 2020. Temperatures were mostly normal, except for a cold snap in April 2020 that damaged cover crop stands. The data for annual temperatures and precipitation during the study are presented by year and location due to the variability of precipitation at each location.

Total precipitation from cover crop planting in late November of 2018 to corn harvest on October 26, 2019 at Manhattan was 1121 mm (Figure 2.1). The period of December 2018 through May 2019 was a record wet period with total precipitation of 417 mm and with the month of May as the wettest month in 2019 with far above average rainfall of 272 mm. This abundant precipitation delayed corn planting to early June, which may have negatively impacted yield. The 30-year average annual precipitation from 1981 to 2010 for Manhattan was 905 mm, which places 2019 well above average (Global Historical Climate Network Data, 2021). Temperatures were close to average during the growing season with few notable anomalies that could have impacted yield (Figure 2.1).

The 2020 season was characterized by more moderate levels of precipitation that were spread evenly throughout the year compared to 2019. Total precipitation from cover crop planting in November 2019 to harvest in early October 2020 in Manhattan was 914 mm (Figure 2.2). Total precipitation for the same months in Ottawa was 599 mm and well below the annual average of 1024 mm for that area (Global Historical Climate Network Data, 2021) (Figure 2.3). Temperatures were mostly near average in Manhattan and Ottawa in 2020, except for one notable drop to below 0 C in April after a period of warm days (Figure 2.2, Figure 2.3) , which caused visible reduction in the stand of peas in both locations.

Cover Crop Biomass

Cover crop biomass production was different in each site-year so Manhattan 2019, 2020, and Ottawa 2020 site-years were analyzed separately. At Ottawa in 2020, cover crop biomass production was 50 to 75% less than that produced at Manhattan in each year across cover crop treatments. Cover crop biomass production in Manhattan 2019 was influenced by cover crop type and termination timing. Delay in termination timing from 3WBP to AP was a determinant of biomass produced by each cover crop type. Greatest biomass was produced by full mix cover crops terminated AP (6,746 kg ha^{-1}) and least biomass produced by pea-only cover crop when terminated AP (2,347 kg ha^{-1})(Table 2.3). Cover crop biomass production followed a similar trend at Manhattan in 2020 with greatest production in full mix treatments terminated AP (7,962 kg ha^{-1}) and least production in partial mix treatments terminated 3WBP (1,557 kg ha^{-1}) (Figure 2.4).

Cover crop biomass production in Ottawa 2020 was influenced by cover crop type and termination timing, with full mix treatments terminated AP producing the most biomass (3,260 kg ha-1) and partial mix treatments terminated 3WBP producing the least biomass (410 kg ha-1) (Table 2.4). Biomass produced by triticale and full mix treatments were not different, likely due to the stunted peas in full mix treatment in 2020 and because peas struggled to compete with triticale when bulk planted together at the rates used in this study. In the future, to increase biomass of peas in mixture with triticale, the pea seeding rate would need to be greatly increased, the triticale seeding rate decreased, or peas would need to be drilled separately and perpendicular to the triticale to potentially allow them more space in which to grow.

The results of our study agree with that of MacLaren et al. (2019), who reported cover crops containing a high percentage of cereal species produced more biomass than other non-cereal species. Triticale biomass production at Manhattan in 2019 and 2020 was similar to that reported of cereal rye cover crops by Price et al. (2012) in Alabama when sown near the average first frost date. Pea and mixed cover treatments in Manhattan produced similar amounts of biomass as fall-sown cover crops in southwestern Kansas as reported by Petrosino et al. (2015). Cover crops at Ottawa produced similar biomass to that reported by Cornelius and Bradley (2017) in Missouri, which could be due to similar soils or weather between the two studies. Ottawa also may have produced less biomass due to different soil conditions at the time of cover crop planting. The soil structure in the field experiment at Ottawa is characterized by a dense, crusted surface when the soil dries and moderate to severe erosion when it rains, both of which made it difficult to establish and grow cover crops. This problem was likely created from a history of conventional tillage prior to this study that likely destroyed the soil structure and made it more susceptible to compaction. Dense and compacted soils have been shown to adversely affect cover crops with fibrous root systems, such as rye and triticale by preventing them from allocating resources necessary to produce above-ground biomass (Chen and Weil, 2010).

The percent increase in cover crop biomass from 3WBP to AP termination times for triticale, pea, partial mix, and full mix was 57, 99, 69, and 60%, respectively, across the two Manhattan site-years (Table 2.3) (Figure 2.4). In Ottawa in 2020, triticale, partial mix, and full mix increased in biomass between early and late termination by 77, 84, and 82%, respectively (

Table 2.4). The trend of cover crop biomass growth between the two termination times in all site-years were similar to the increases in cover crop biomass observed over a two-week period by Wagger (1989) for rye (39%), crimson clover (41%), or hairy vetch (61%). Peas in our study responded most to the longer growing season, similar to the response of the legumes in the Wagger (1989) study. It is possible that triticale in our study responded better to warmer temperatures and longer days than cereal rye, which could create the greater differences in biomass we observed. The three-week period between termination times in our study likely accounts for the greater increase in cover crop biomass as compared to the shorter two-week window in the study by Wagger (1989).

Weed Density

Weed species community in Manhattan in 2019 and 2020 was approximately 95% Palmer amaranth with the remaining 5% made up of large crabgrass (*Digitaria sanguinalis* (L.) Scop.), carpetweed (*Mollugo verticillate,* L.), velvetleaf (*Abutilon theophrasti* Medik), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), and pitted morningglory (*Ipomoea lacunosa* L.) (data not shown). Large numbers of large crabgrass were only present where Palmer amaranth was not. Palmer amaranth dominated areas without management.

Weed densities one week before planting (1WBP) in Manhattan in 2019 were influenced by cover crop and termination timing (Table 2.3). Weed densities in the no cover treatment that received a burndown 3WBP increased from 19 plants m^{-2} at the time of application to 96 plants m^{-2} at 1WBP, while no weeds were observed 1WBP in the triticale or mixed treatments that were terminated at 3WBP. There was no change in weed density at 1WBP between the two termination timings. Similar amounts of cover crop biomass were present in the triticale and mixed cover crops because they were terminated at the same time, mid-May. The triticale-containing cover crops needed to be terminated by 3WBP because they had already reached reproductive stages. Cool and damp weather may have allowed residual 2,4-D to be present up to the weed count at 1WBP in the 3WBP-terminated cover crops, thus suppressing any new weed seedlings that could have germinated by that point if no herbicide were present. Treatments containing triticale that were terminated 3WBP reduced weeds by 100% at 1WBP compared to no cover treatments that received a burndown at 3WBP and by 92% in those cover crops terminated AP. Weed densities in pea and no cover treatments were similar when both were terminated 3WBP, likely because the peas had little biomass at that time.

Weed densities observed at corn planting in Manhattan 2020 decreased as cover crop biomass increased (Figure 2.4). Cover crop biomass production differed by cover type and termination timing. Greatest weed densities were present in plots with no cover and in plots terminated 3WBP. As cover crop biomass increased, weed density was reduced by more than 51% compared to treatments with no cover crop.

Weed densities three weeks after corn planting at the time of the POST application were not different among cover crop treatments at Manhattan in 2020 but averaged 678 plants m^{-2} (data not shown). Termination timing of cover crops was still an important indicator of weed density, with a 38% reduction in density when cover crops were terminated AP compared to 3WBP. When terminating the cover crop AP, most weeds present were likely also terminated, which reduced the densities observed at the POST application three weeks later. However, herbicides alone likely do not explain reduced densities at the POST application because Palmer amaranth and common waterhemp as well as many other summer annuals continue to emerge during and well beyond that period in the season (Hay and Peterson, 2019).

Weed populations in Ottawa were 95% common waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) with the remaining 5% of species made up of yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), Venice mallow (*Hibiscus trionum* L.), and slender yellow woodsorrel (*Oxalis dillenii* Jacq.). When left unmanaged, common waterhemp frequently became the only species in a plot.

Weed densities in Ottawa at the time of corn planting were influenced by cover crop type and termination timing (Table 2.4). Greatest weed densities were measured in no cover treatment that received a burndown 3WBP and lowest weed densities were measured in treatments with triticale or full mixture of cover crops terminated AP. These results align with our hypotheses that greater amounts of biomass will increase weed suppression when compared to no cover crop. Ottawa did not have a similar response of reduced weed density with increased cover crop biomass as Manhattan 2020, but the general trend was similar. The range of cover crop biomass at Ottawa was less, and thus weed densities in Ottawa were not strongly influenced by differences in cover crop biomass (data not shown).

Weed densities in Ottawa at the time of the POST application were influenced by cover crop and termination timing, likely due to continued weed suppression in treatments with greater cover crop biomass. Greatest weed densities were measured in treatments terminated 3WBP with treatments terminated AP having far fewer weeds (Table 2.5). The 51% reduction in weed densities between partial mix treatments terminated 3WBP and AP indicated that as cover crops increased in biomass, weed suppression increased, even when total cover crop biomass production was low. The relationship was even stronger in treatments with more dense cover crop coverage such as triticale with an 84% reduction in weeds observed between 3WBP and AP termination timings by the POST application.

The weed density suppression due to cover crop biomass measured in both years at Manhattan and at Ottawa in 2020 agrees with other reports of reductions in weed biomass and density with delay of cover crop termination up to planting of the cash crop (Osipitan et al. 2019, Wiggins et al. 2015).

Weed Escapes 2020- Biomass and Density

Continued weed pressure throughout the season due to poor POST weed control in some plots may have had an impact on corn yield in Manhattan in 2020. These escapes were not further controlled and weed control ratings were taken biweekly until a final weed biomass and count was taken 9 weeks after the POST application to determine if cover crop type, termination timing, or N rate influenced the survival and continued growth of the escapes. Biomass of weed escapes did not differ among cover crop treatments terminated AP in Manhattan in 2020 (Table 2.6). All cover crops terminated AP had zero weed biomass 9 weeks after the POST, except for the no cover crop treatment, which received an herbicide application AP and had 38 kg ha^{-1} weed biomass, but was not different than the cover crop treatments terminated AP. All cover crops terminated 3WBP had 300 to nearly 2000 kg ha^{-1} less weed biomass compared to no cover treatments that received a burndown 3WBP and no other herbicide treatment until the POST application. These results imply that delayed cover crop termination can limit weed density and size, making POST herbicide applications more effective. This observation agrees with findings by Saini et al. (2006) that greater cover crop biomass reduced early season weed interference and allowed more flexibility of POST application. Delayed termination of cover crops allowed more biomass to accumulate and can behave like a PRE would if it were applied with the burndown at 3WBP to the no cover treatments. Without a cover crop, delay of burndown herbicide application until corn planting was more effective than applying a burndown 3WBP in limiting the size and density of weeds up to the POST application.

At Ottawa 2020, biomass of weed escapes was influenced by termination timing and N rate, with greatest weed biomass observed in cover crops terminated 3WBP and fertilized with 100 kg N ha^{-1} (Table 2.7). Late season weed density at Ottawa was influenced only by termination timing, with average weed densities of 28 plants m^{-2} in treatments terminated 3WBP compared to 7 plants m^{-2} in treatments terminated AP.

The results indicated that when high biomass cover crops were present, a POST herbicide application of atrazine, glyphosate, and mesotrione three weeks after planting was effective in 100% reduction in late-season weed biomass. These data agree with Yenish et al. (1996) who reported 96% reduction of late-season weed biomass in cover crops that received a POST application 50 to 60 days after corn planting, which was around the same calendar date as our POST applications. Yenish et al. (1996) also reported cover treatments with a PRE + POST application had similar weed biomass to those receiving only a POST. This corroborates our observation that high biomass cover crops may be nearly as good as pre-emergence residual herbicides at limiting early-season weed density and reducing pressure on POST herbicide chemistry and timing.

Corn Plant Population

Delay in termination timing from 3WBP to AP reduced average corn plant population by 20% in 2019 at Manhattan (Table 2.8). This reduction was likely because the corn was planted in the same direction as the cover crops, causing some rows to directly overlap. Corn seed in these overlapping rows of cover crop had poor seed placement and germination. Some treatments such as peas terminated AP also had drier and harder soil due to lack of ground coverage. While cover crop type was not significant in plant population differences, lower populations were recorded in treatments with less ground coverage.

In 2020, corn plant population in Manhattan was affected by an interaction between cover crop and termination timing with greatest populations measured in partial mix treatment terminated 3WBP (60,690 plants ha^{-1}) and lowest populations measured in full mix treatment terminated AP (54,670 plants ha^{-1}). All other cover crop and no cover treatments terminated 3WBP or AP were not different from either the partial mix treatment terminated 3WBP or from full mix treatment terminated AP (Table 2.8). There were no differences in corn plant populations in Ottawa in 2020, likely due to less cover crop biomass production and difference between cover crop treatments. Our results are similar to those of Kessavalou and Walters (1997) who found corn plant populations were reduced by rye residue in one year of their study, potentially due to allelopathy from the rye. The winter of 2018-2019 was a cold winter that could have delayed triticale development and increased allelopathic potential (Kessavalou and Walters, 1997) but cover crop residues were not tested for allelopathic chemicals in our study. The difference in corn plant populations in each location in 2020 was likely due variability in cover crop biomass and site characteristics.

Corn Nitrogen Status

In 2019, SPAD measurements were taken at R3 and R5 to estimate differences in corn ear leaf chlorophyll content. Significant main effects that influenced chlorophyll content of the ear leaf at R3 at Manhattan in 2019 were cover crop type, termination timing, and N rate. Corn chlorophyll content was greatest in pea and no cover crop treatments at 57.1 and 56.9 μmol chlorophyll m-2, respectively (Table 2.9). Chlorophyll content trends were similar at the R5 measurements, but all treatments had less chlorophyll as plants physiologically matured (Table 2.9).

In 2020, corn leaf tissue samples were taken when corn plants were between V8 and V13 growth stage. An interaction of termination timing and N rate influenced plant N percentage at Manhattan and Ottawa. At Manhattan, the greatest corn tissue N content (3.88%) was measured in cover crops terminated 3WBP with 168 kg N ha-1 applied. There was no difference in corn tissue N content between termination timings that received 168 kg N ha-1 or cover crops terminated AP that received 100 kg N ha-1 (Table 2.10). The only difference in corn tissue N content was between cover crops terminated 3WBP with 100 kg N ha-1 and 3WBP with 168 kg N ha-1 added. At Ottawa, the greatest corn tissue N content was in treatments with cover crops terminated AP with 168 kg N ha-1 applied. The lowest N content was in treatments with cover crops terminated 3WBP and 100 kg N ha-1 added (Table 2.11). It is unclear if 100 kg N ha-1 was insufficient for corn production at each site or if less cover crop biomass in treatments terminated 3WBP contributed to less contribution of N from the cover crop and thus less N available for uptake.

Corn Grain Yield

Corn grain yield in 2019 at Manhattan was affected by main effects of cover crop and termination timing. Presence of mixed cover crop reduced corn yield by 24% compared to no cover and by 21% compared to a pea cover crop (Table 2.12). In 2019, cover crop termination AP reduced corn yield by nearly 14% compared to termination at 3WBP and could be caused by delayed corn planting, high amounts of precipitation in May, or N immobilization by low quality cover crop residue. Greatest corn test weights in 2019 were in treatments terminated 3WBP with average test weight of 68.1 kg hl^{-1} compared to treatments terminated AP (67.7 kg hl^{-1}) but were not different among cover crop or nitrogen rate treatments (Table 2.12).

In 2020, corn yield at Manhattan was affected by an interaction between cover crop and termination timing, and by a main effect of N rate. The greatest yield observed was 10,960 kg ha^{-1} in no cover treatment that received a burndown AP (Table 2.13). Termination AP of partial and full mix cover crops decreased yield compared to no cover treatment that received a burndown AP. Corn yield in triticale-only treatment terminated AP was 15% less than no cover treatment with a burndown application AP. Corn yield was not different among cover crops terminated AP, likely due to the high proportion of triticale and potential N immobilization caused by that species.

Greater N rates positively influenced corn yield relative to low N rates at Manhattan in 2020 and there were no differences among any cover crop treatment and no cover treatments when all were fertilized with 168 kg N ha^{-1}. Increased N rate from 100 to 168 kg N ha^{-1} increased yield by 10 to 16% within cover crop treatments, with the greatest increase in treatments containing triticale.

Corn test weights at Manhattan in 2020 were greater than in 2019 and were influenced by an interaction between cover crop type and termination timing. No cover treatment that received an herbicide application AP had the greatest test weight at 77.9 kg hl^{-1} (Table 2.13) but was not different from corn harvested from any treatments terminated 3WBP. The AP terminated cover crops had lower test weights than no cover treatment receiving a herbicide application AP. This reduction in test weights could have been the main contributor to the 15% decrease in yield observed between triticale and no cover treatments that were terminated AP.

In 2020, corn yield in Ottawa was affected by main effects of cover crop termination timing and N rate but not cover crop type (Table 2.14). Corn grain yield was 16% greater when cover crops were terminated AP as compared to 3WBP. Similar to Manhattan, increased N rate from 100 to 168 kg N ha^{-1} resulted in an 11% increase in yield, indicating that the low N rate did not provide sufficient N. Termination AP increased corn yield at Ottawa while it decreased corn yield at Manhattan, likely due to differences in total cover crop biomass produced and overall level of weed densities at each location. Test weights of treatments at Ottawa were not different. Another factor in Ottawa 2020 yield was likely a dry period in June when less than 75 mm of precipitation was recorded for the month (Figure 2.3) and stunting and wilting of the corn was visually evident. The month of June was a critical period in corn development when the plant determines the number of kernel rows and the number of potential kernels per row and when four consecutive days of visible wilting can reduce yield potential 5 to 10% (Thelen, 2007).

These data indicate that presence of a triticale cover crop may require increased N fertilization; triticale was more responsive to increased N rates than the other cover crops. The lack of differences in corn yields among cover crop types fertilized with the same N rate implies that cover crop species may not be the only factor influencing soil N availability. This could be because the C:N ratio of the residue in this study was not high enough to cause immobilization of available N in the soil. These results are different than those of Dapaah and Vyn (2008), who reported diverse monocultures of annual ryegrass, red clover (*Trifolium pratense* L.), and oilseed radish (*Raphanus sativus* L.) depressed corn growth and yield and that yield was more responsive to cover crop species than N rate.

Another potential reason there was no difference in corn yield among cover crop treatments fertilized with the same level of N could be that the cover crops were terminated early enough in 2020 to prevent excess N uptake by the cereal cover crop that occurs during the reproductive phase. This theory is supported by Vaughan and Evanylo (1998), who reported that termination of cereal cover crops 3WBP allowed for reductions in N-immobilization as residues decomposed. However, the timing for cereal cover crop termination reported by them was at an earlier calendar date than termination of cover crops in this study, thus it is likely other factors influenced N availability in this study, such as weed pressure and timing of N application.

Precipitation and soil temperatures prior to corn planting can influence the amount of cover crop residue accumulated by the time for termination and likely also influences N availability for corn uptake later in its development. For the mid-May corn planting date in 2020, there was no difference in corn yield when triticale was terminated AP vs. no cover treatment receiving burndown AP at Manhattan, and delayed termination timing increased yields in Ottawa. The conservation of soil moisture by the residue or reduced weed density could benefit yields, but the influence on N availability was not clear. During 2019, urea was applied AP, on June 5, 2019. During 2020, urea was applied two weeks after corn planting. In 2019, the corn was not at a growth stage to use readily available N, making it more susceptible to loss. During 2020, the delayed N fertilization may have not resulted in loss, which could have resulted in lesser yield reductions observed in 2020. Conversely, Crandall et al (2005) observed relative corn N deficiencies and grain yield reductions did not occur in corn following cereal rye unless termination timing was delayed until corn planting and all N was applied at V6. While our N was applied slightly before V6, delay in N application to after cover crop termination AP and after corn emergence may have contributed to yield reductions in Manhattan in 2020 despite less opportunity for N loss than 2019 (Table 2.12, Table 2.14). Unlike Manhattan corn grain yield in 2019 and 2020, less total cover crop biomass, timing of N placement, and low June precipitation may explain the increase in yield in cover crops terminated AP and fertilized with 168 kg N ha^{-1} observed at Ottawa in 2020 (Table 2.14).

Corn yield may have also been affected by season-long weed pressure at Manhattan and Ottawa in 2020. Page et al. (2012) reported the onset of the critical period for weed control (CPWC) in corn was between the three and five- leaf tip stages when weeds emerged near the time of crop emergence. In our study, weeds emerged near or before crop emergence and were not sprayed until around the time of the six-leaf tip stage, which allowed weed pressure beyond the onset of CPWC. Weed densities in the early season were not correlated with corn yield in Manhattan in 2020, but biomass and density of weed escapes surviving to nine weeks after the

POST were correlated with corn grain yield. Weed biomass at Manhattan in 2020 nine weeks after POST was correlated with reductions in corn yield (*r* = -0.415), as was weed density (*r* = -0.431). Biomass of weed escapes was correlated with yield (*r* = -0.483) at Ottawa, as was density (*r* = -0.383), suggesting greater weed biomass and density also decreased corn yield at that site. The fewest weed escapes and least effect on grain yield were observed in those treatments that combined triticale or mixed cover crops with an AP herbicide application at Manhattan and Ottawa (Table 2.6,Table 2.7). However, N rate had a significant influence on weed biomass and corn grain yield at Ottawa, unlike at Manhattan. This could be in part due to low precipitation totals during June that could have reduced the competitive ability of the corn relative to the weeds when fertilized with 100 kg N ha^{-1}. While season-long weed pressure likely affected corn grain yield in 2020, the moderate correlations indicate other factors likely also impacted corn grain yield.

Net Return on Variable Costs

When changes in any crop management system are considered, an important factor for acceptable change is return on expense of the new management strategy. If the new strategy does not return more profit than the operation did before it was implemented, it is often not a sound financial decision (Myers et al. 2019). There are situations where this is not true, and one of them is when the strategy is a long-term change that may take years to realize a profit, such as cover cropping. Cover crops alter a cropping system in many ways. Some changes are reduced soil erosion and water pollution or changes in weed populations, soil organic matter and structure, or insect and disease pressure. These changes are difficult to quantify into dollars saved or profit because they are realized over a longer term than a single production cycle. However, one can quantify the costs and returns directly associated with the management change to compute whether increases in yield can cover those new costs. This is called a partial budget analysis because it assesses only the effects a change in production practices will have on profit (NDSU, 2021). The management variables in the budget corresponded with the treatment variables in the study and were as follows: cover crop type, termination timing, and N rate. Other factors such as corn seed, custom costs for fertilizer application, corn planting, chemical application, and taxes and insurance were considered constants that would not change among management strategies and were not included in this partial budget. Herbicides were also constants that would not change in this budget because it is assumed a farmer would still apply herbicides prior to crop emergence to terminate weeds in the absence of a cover crop; the application pass to terminate cover crops is not a change to the current management system. Total cost and quantity of herbicides could change in the absence of cover crops if weeds are more difficult to control, but that was not a factor examined in this study so it will not be considered in this analysis. Variable costs compared among management strategies included in this budget were total expense for N application (100 and 168 kg N ha^{-1}), cost of cover crop seed, and custom cost to drill cover crops. Effect of termination timing on profit is considered in total yield return but is not reflected by any input costs. Variable costs used to calculate receipts and expenses were from 2019 and 2020 market data with the exception of urea which was sourced from the most recent survey on national cost data conducted in 2014 (USDA-ERS, 2019)(Table 2.15).

Cover crop and termination timing interacted to influence profitability of each management combination in our study, but N rate did not influence profitability. This may be because cover crop and termination timing had a greater influence on weed density and thus yield than N rate did at Manhattan in 2020 (Table 2.13). Therefore, when considering only changes in cover crop type and their termination timing, the most profitable strategy indicated by our study was no cover crop with a burndown AP. Although corn yields were not different between no cover with burndown AP and triticale terminated AP, the 15% decrease in yield observed in triticale terminated AP (while not statistically significant) and the added cost of triticale seed and drilling made that strategy less profitable in a single season. The least profitable management strategy indicated by our study was the full mix terminated AP, where net return was around 50% of the most profitable management strategy of no cover with a burndown AP. The full mix decreased yield by more than 2,700 kg ha^{-1} compared to no cover with a burndown AP and variable costs were greater than triticale alone or no cover to implement. Although costs for full mix cover crop management strategy were not different than the partial mix established in Manhattan in 2020, the detriment to yield was greater.

The results of this study, both in terms of yield and net return indicate there was no short-term benefit to having a two-way species mix rather than a monoculture of triticale in 2020 or pea in 2019 (Table 2.12,Table 2.13,Table 2.14). The loss in revenue due to use of cover crops prior to corn was also reported in results from a survey of Iowa farmers by Plastina et al. (2018). Their reported loss was credited to yield reduction and farmers not using cover crops for grazing or forage and was despite participation in cost-share programs. While our analysis did not include cost-share programs or potential profit from using cover crops for other purposes such as for livestock, it is important to notice that single-year loss in revenue when implementing cover crops may be a substantial barrier to farmer adoption of cover crops for long-term use.

Conclusion

This research contributes to the existing body of evidence indicating high biomass cover crops such as triticale and high-proportion triticale mixes are important and effective tools for weed suppression. However, there remain challenges in managing cereal cover crops for weed suppression prior to corn, namely in N management. Our study included only two N levels, which was not enough to indicate an optimal level of N fertilization with cover crops for corn yield. Nitrogen proved to have a greater influence on corn yield than the cover crop species but cover crop presence did influence corn yield in two of three site-years. The single-season benefits of cover crops at these levels of fertilization were not sufficient to overcome or prevent yield losses in corn, and thus were not economically feasible. However, benefits of long-term use of cover crops could change single-season profitability over time. Delayed cover crop termination or burndown of the no cover treatment was most effective in suppressing weeds and limiting potential for weedy escapes from the POST application. Despite benefits in weed control, delayed termination likely influenced corn yield by contributing to poor seed placement in 2019 and N-immobilization by cover crop residues. Based on our data, a monoculture cover crop of triticale terminated AP and fertilized with at least 168 kg N ha^{-1} was the most profitable combination for using cover crops prior to corn, compared to the other cover crop species and N rates. However, the level of yield loss measured in our study may be beyond the acceptable threshold for many farms. Overall, the management of cover crops prior to corn is a complex system that will require more detailed research into N dynamics and residue effects on corn growth to determine the optimal system for cover crop use prior to corn. There may still be opportunity to incorporate legumes in a more functional ratio than conditions allowed in our study that could change N-availability and system profitability in Kansas corn. This research indicates the margin between profitability and loss with cover crops in corn is narrow enough to allow future development of a system that will increase farmer profitability and reduce selection pressure on weeds.

Figures

Figure 2.1. Daily precipitation (solid line) and daily maximum (dashed line) and minimum (dotted line) temperatures in C in Manhattan, KS November 1, 2018 through corn harvest October 26, 2019 with dates of pea establishment, two termination timings (three weeks before planting (3WBP) and at corn planting (AP)) and time of POST.

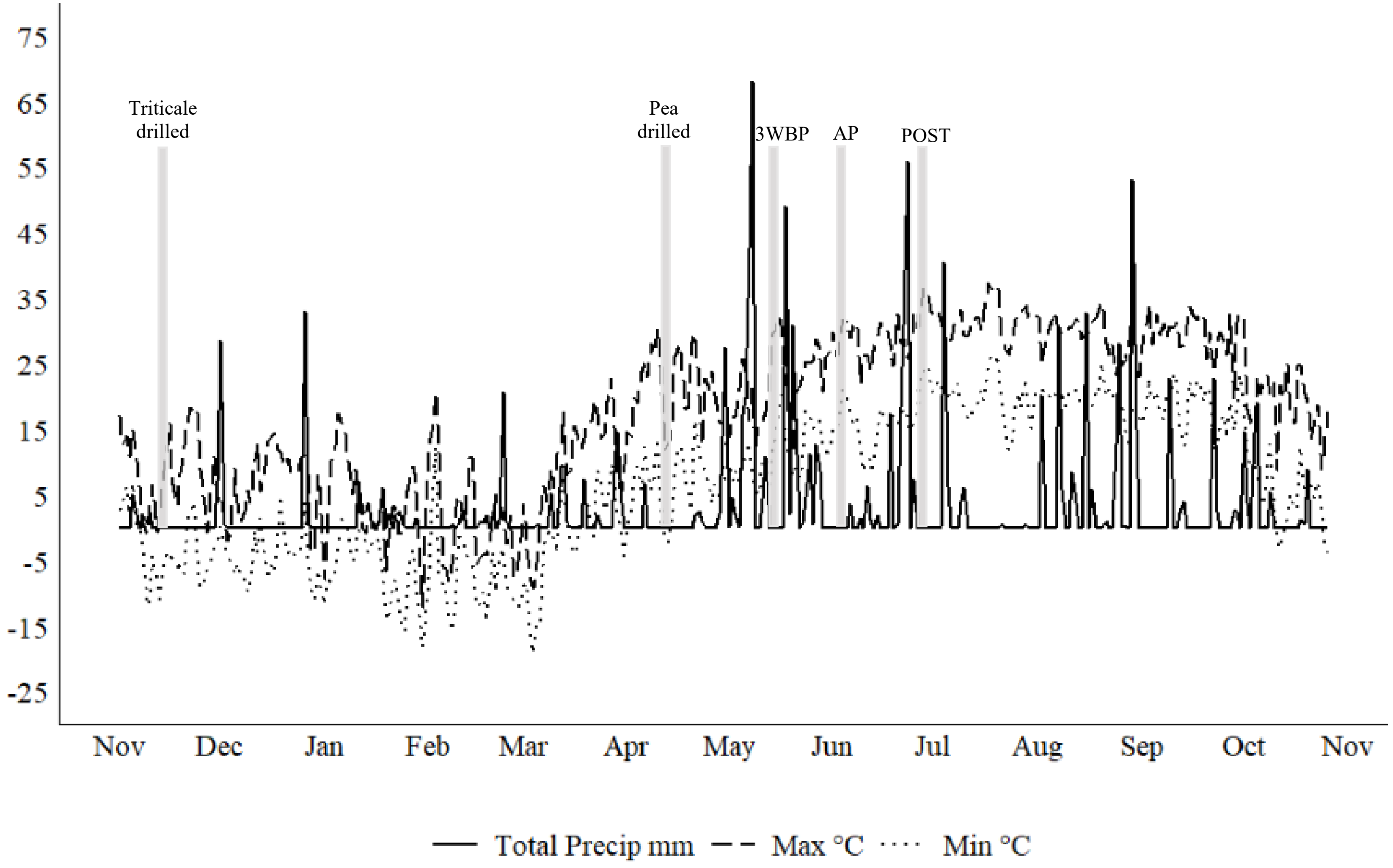


Figure 2.2.Daily precipitation (solid line) and daily maximum (dashed line) and minimum (dotted line) temperatures in C in Manhattan, KS from November 1, 2019 through corn harvest October 1, 2020 with dates of two termination timings (three weeks before planting (3WBP) and at corn planting (AP)), and time of POST.

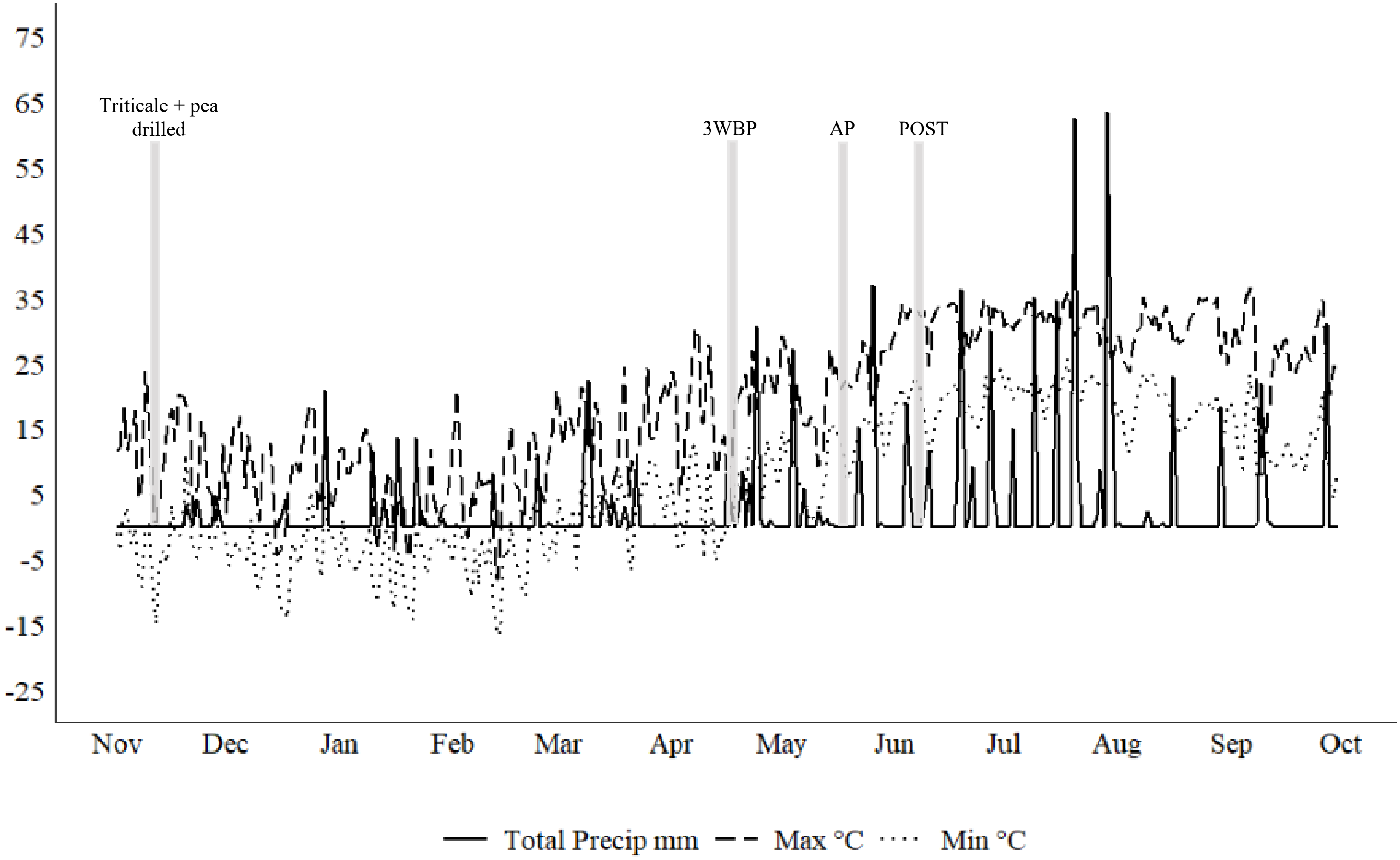


Figure 2.3. Daily precipitation (solid line) and daily maximum (dashed line) and minimum (dotted line) temperatures in °C in Ottawa, KS from November 1, 2019 through corn harvest October 1, 2020 with dates of two termination timings (three weeks before planting (3WBP) and at corn planting (AP)), and time of POST.

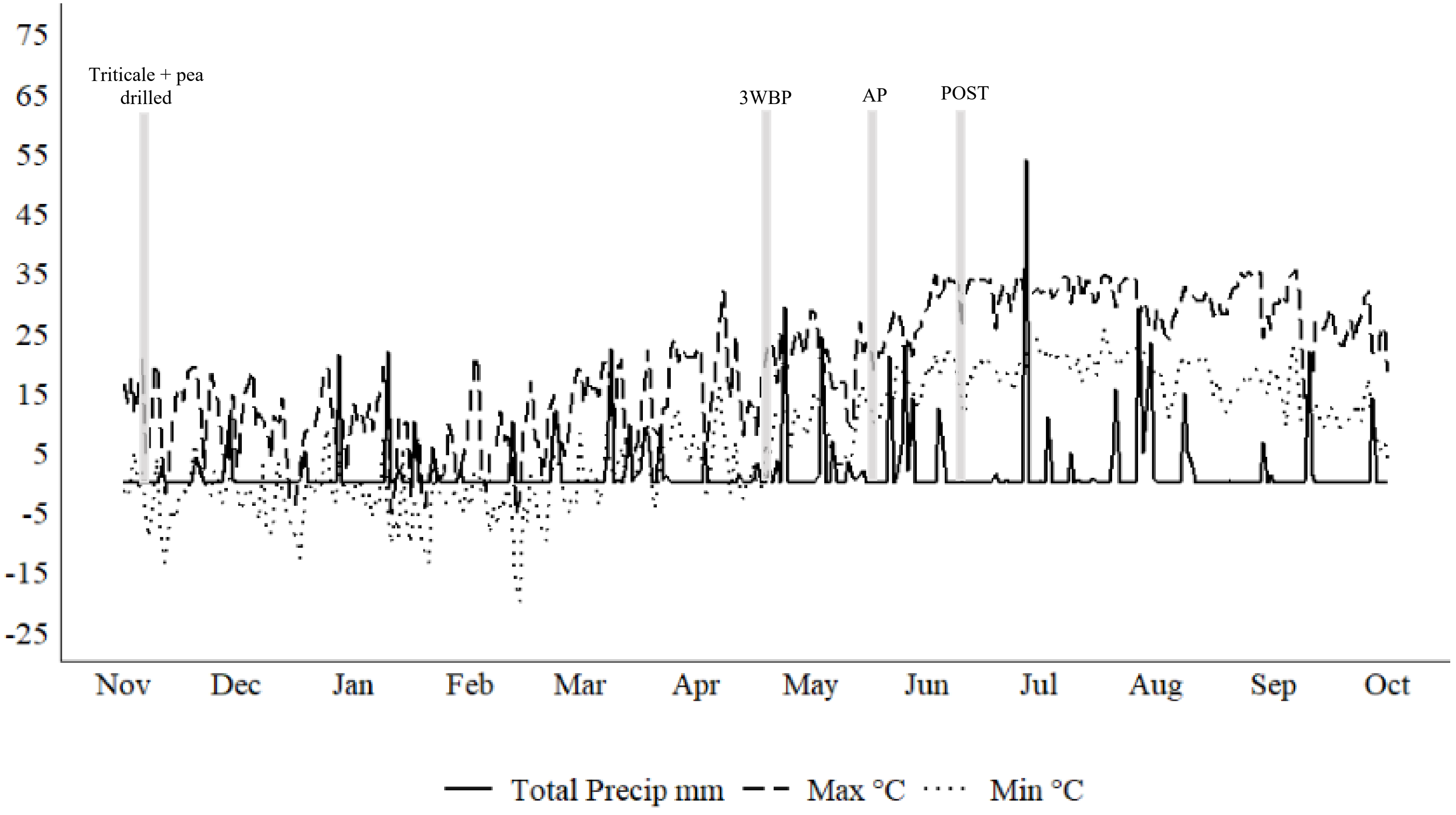
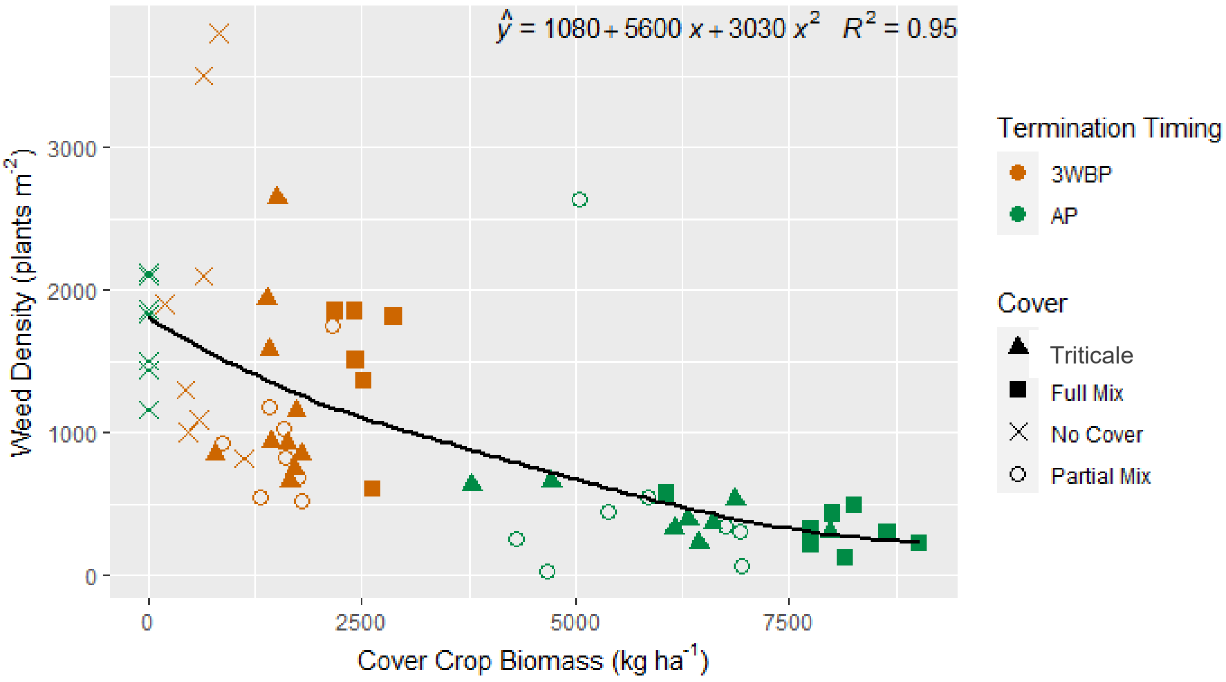


Figure 2.4. Weed density at corn planting as influenced by cover crop biomass across termination timings and cover crop species in Manhattan, 2020. Fitted polynomial regression model to the data.



Tables

Table 2.1. Cover crop and corn planting dates, corn hybrid, soil properties, total season rainfall in experiments in 2019 and 2020.

Site-Year	Cover crop planting date	Cover crop species	Cover crop termination date	Corn planting date	Corn hybrid [c]	Soil series	Total precipitation [d] mm
Manhattan 2019	11/2018 04/2019	triticale [a] spring pea [b]	05/14/2019 06/05/2019	06/05/2019	Channel 209-15VT2PRIB	Reading silt loam	672
Manhattan 2020	11/2019	triticale [a] winter pea [b]	04/21/2020 05/20/2020	05/20/2020	Dekalb DKC64-25RIB	Reading silt loam	430
Ottawa 2020	11/2019	triticale [a] winter pea [b]	04/20/2020 05/19/2020	05/19/2020	Dekalb DKC64-25RIB	Woodson silt loam	599

[a] Drilled at 100 kg ha^{-1}

[b] Drilled at 67 kg ha^{-1}

[c] Planted at 64,000 seeds ha^{-1}, 2” depth

[d] Precipitation from planting of cover crop in November preceding the crop year to corn harvest in October of each year.

Table 2.2 Herbicide application timing, product, and rates used at all locations in 2019 and 2020.

Application Timing	Product [d]	Rate
no cover treatment burndown	glyphosate + 2,4-D AMS + COC	867 g ae ha^{-1} + 216 g ae ha^{-1} 2% v/v + 1% v/v
3WBP[a] cover crop termination		
AP[b] cover crop termination		
POST[c]	glyphosate + atrazine + mesotrione + AMS	1182 g ae ha^{-1} + 2242 g ai ha^{-1} + 105 g ai ha^{-1} + 2% v/v
pea-only establishment (2020)	fluazifop-P-butyl + COC	57 g ai ha^{-1} + 0.5% v/v
triticale-only establishment (2020)	2,4-D + COC	216 g ae ha^{-1} + 1% v/v

[a] 3 weeks before corn planting, Manhattan: May 14, 2019; May 1, 2020; Ottawa: April 30, 2020

[b] At corn planting, Manhattan: June 5, 2020; May 20, 2020; Ottawa: May 19, 2020

[c] Post-emergent herbicide application

[d] Roundup PowerMax (Monsanto Company, St. Louis, MO); Shredder, LV 4 (Winfield Solutions, LLC, St. Paul, MN); Ammonium sulfate; Crop Oil Concentrate; Aatrex 4L (Syngenta Crop Protection, Greensboro, NC); Callisto (Syngenta Crop Protection, Greensboro, NC); Fusilade DX (Syngenta Crop Protection, Greensboro, NC)

Table 2.3 Mean (SE) cover crop biomass measured at time of termination and mean (SE) weed density on May 30, 2019 one week before corn planting as influenced by cover crop treatment and two termination timings (3 weeks before planting (3WBP)) and at corn planting (AP)) at Manhattan in 2019.

Cover crop	Termination timing	Cover crop biomass	Weed density*
		kg ha^{-1}	plants m^{-2}
No cover	3WBP	0 e	19 (8) C
Pea	3WBP	380 (35) de	39 (12) BC
Triticale	3WBP	5,520 (737) ab	0 C
Full mix	3WBP	3,737 (667) bc	0 C
No cover	AP	0 e	98 (15) A
Pea	AP	2,347 (246) cd	72 (12) AB
Triticale	AP	no data	no data
Full mix	AP	6,746 (204) a	8 (7) C

Mean cover crop biomass and weed density values for each observation followed by same letter in the same column are not different at $\alpha = 0.05$.

* Cover crops in treatments to be terminated AP were live at the time of this count.

Table 2.4 Mean (SE) cover crop biomass measured at time of termination and mean (SE) weed density counted at corn planting as influenced by cover crop species and two termination timings (3 weeks before planting (3WBP) and at corn planting (AP)) at Ottawa in 2020.

Cover crop	Termination timing	Cover crop biomass	Weed density
		kg ha^{-1}	plants m^{-2}
No cover	3WBP	151* (19) cd	185 (87) ab
Partial mix	3WBP	410 (100) cd	66 (28) ab
Triticale	3WBP	636 (86) c	148 (34) ab
Full mix	3WBP	600 (60) c	135 (53) ab
No cover	AP	0 d	426 (153) a
Partial mix	AP	2580 (194) b	75 (22) ab
Triticale	AP	2814 (118) ab	59 (17) ab
Full mix	AP	3264 (246) a	188 (65) ab

Mean cover crop biomass values for each observation followed by same letter are not different at $\alpha = 0.05$ level.

Mean weed density values for each observation followed by the same letter are not different at $\alpha = 0.10$.

*Represents remaining cover crop residue from termination of cover crop bulk planting 7 weeks prior to corn planting

Table 2.5 Mean (SE) weed density at POST application (3 weeks after corn planting) as influenced by cover crop and two termination timings (three weeks before planting (3WBP) and at corn planting (AP)) at Ottawa in 2020.

	Weed density	
Cover crop	3WBP	AP
	plants m^{-2}	
No cover	354 (109) abcd	274 (127) abcd
Partial mix	146 (37) abcd	71 (32) abcd
Triticale	489 (157) bcd	80 (32) abc
Full mix	429 (116) cd	75 (36) ab

Weed density means followed by the same letter are not different at α = 0.05 level.

Table 2.6. Mean (SE) biomass and density of weed escapes nine weeks after the POST application in Manhattan 2020 as influenced by cover crop type and termination timings (three weeks before planting (3WBP) and at planting (AP)) and averaged across the levels of N rate.

Cover crop	Termination timing	Weed biomass	Weed density
		kg ha^{-1}	plants m^{-2}
No cover	3WBP	1586 (235) a	196 (38) a
Partial mix	3WBP	350 (232) b	52 (35) b
Full mix	3WBP	545 (145) b	44 (6) b
Triticale	3WBP	680 (312) b	48 (22) b
No cover	AP	38 (35) b	4 (3) b
Partial mix	AP	0 b	0 b
Full mix	AP	0 b	0 b
Triticale	AP	0 b	0 b

Mean values for each observation followed by same letter in the same category are not different at α =0.05.

Table 2.7. Mean (SE) biomass and density of weed escapes nine weeks after POST application in Ottawa 2020, as influenced by termination timings (three weeks before planting (3WBP) and at corn planting (AP)) and two N rates. Weed biomass averaged across cover crop type and weed density averaged across cover crop type and N rate.

Termination timing	N rate	Weed biomass	Weed density
	kg N ha^{-1}	kg ha^{-1}	plants m^{-2}
3WBP	100	1029 (249) a	28 (6) A
	168	616 (203) b	
AP	100	70 (65) b	7 (3) B
	168	130 (106) b	

Mean cover crop biomass and weed density values for each observation followed by same letter in the same case are not different at $\alpha = 0.05$.

Table 2.8 Mean (SE) corn plant populations recorded two weeks after corn planting as influenced by main effect termination timings of three weeks before planting (3WBP) and at corn planting (AP) or by interaction of cover crop and termination timing for three locations over 2019 and 2020.

	Main effects		Corn plant population
	Cover crop	Termination timing	plants ha^{-1}
Manhattan 2019			
	--	3WBP	60,350 (1791) a
	--	AP [*]	48,130 (2577) b
Manhattan 2020	No cover	3WBP	57,300 (1146) abc
		AP	59,610 (1146) abc
	Partial mix	3WBP	60,690 (1146) a
		AP	55,910 (1146) bc
	Triticale	3WBP	60,110 (1251) abc
		AP	58,940 (1173) abc
	Full mix	3WBP	59,460 (1146) ab
		AP	54,670 (1146) c
Ottawa 2020	--	--	62,510 (NS)

Means followed by the same letter within the same location are not different at α = 0.05.

[*] Triticale terminated AP was not present in 2019 and thus is not included in the calculation for AP mean or means separation in that year.

Table 2.9. SPAD chlorophyll content of corn ear leaf at R3 and R5 as influenced by cover crop, two termination timings (three weeks before planting (3WBP) and at corn planting (AP)), or N rate in Manhattan in 2019. **Calculations for SE and mean separation do not include triticale treatments because the AP triticale treatment was not present in 2019.

Main effect treatment	Treatment levels	Chlorophyll	
		R3	R5
		μmol m^{-2}	
Cover crop	No cover	56.9 a	53.4 a
	Pea	57.1 a	53.8 a
	Mixed	51.1 b	46.4 b
	Triticale**	49.0	44.3
Termination timing	3WBP	52.8	48.6
	AP	56.1	52.3
N rate	100 kg N ha^{-1}	55.0	49.0
	168 kg N ha^{-1}	53.0	51.1

Means followed by the same letter in the same category are not different at the level of $\alpha = 0.05$.

Table 2.10. Mid-vegetative stage corn leaf tissue N content (%) as influenced by two termination timings (three weeks before planting (3WBP) and at corn planting (AP)) and two N rates, averaged over four cover crop types for Manhattan in 2020.

Termination timing	N rate	Tissue N
	kg N ha^{-1}	%
3WBP	100	3.71 b
3WBP	168	3.88 a
AP	100	3.79 ab
AP	168	3.80 ab

Mean tissue N % values for each observation followed by same letters are not different at $\alpha = 0.05$ level.

Table 2.11. Mid-vegetative stage corn leaf tissue N content (%) as influenced by cover crop termination timing or N rate, averaged over four cover crop types for Ottawa in 2020.

Main effect treatments	Treatment levels	Tissue N
		%
Termination Timing	3WBP	3.52 B
	AP	3.89 A
N Rate	100 kg N ha^{-1}	3.56 b
	168 kg N ha^{-1}	3.85 a

Mean tissue N% values for each observation followed by same letter and case are not different at $\alpha = 0.05$ level.

Table 2.12. Mean (SE) corn grain yield, and net returns as influenced by main effect of cover crop type and by main effect of termination timing (3 weeks before planting (3WBP) and at corn planting (AP)) and mean (SE) corn grain test weight as influenced by main effect of termination timing, and net returns as influenced by main effect of N rate in Manhattan, 2019. Main effect means averaged over levels of the other treatment factors.

Main effect treatments	Treatment levels	Test weight	Yield	Net return
			kg ha^{-1}	\$ ha^{-1}
Cover crop **	No cover	--	8880 (250) a	1147 (44) a
	Pea	--	8520 (400) a	869 (63) b
	Triticale	--	7210 (220) *	781 (36) *
	Full mix	--	6770 (280) b	529 (44) c
Termination timing	3WBP	68.1 (0.23) a	8640 (200) a	897 (1285) a
	AP	67.7 (0.23) b	7470 (270) b	760 (55) b
N rate **	100 kg N ha^{-1}	--	8110 (NS)	911 (57)
	168 kg N ha^{-1}	--	7760 (NS)	766 (55)

Corn yield means and net returns followed by the same letter in the same column are not different at α = 0.05.

* Calculations for SE and mean separation do not include triticale treatments because the triticale terminated AP treatment was not present in 2019.

** Cover crop type was not a significant factor in test weight and N rate was not a significant factor in corn grain test weight or yield. Yield means for N rate are displayed for comparison purposes only.

Table 2.13. Mean (SE) corn grain test weight, yield, and net returns as influenced by interaction between cover crop type and two termination timings (three weeks before planting (3WBP) and at corn planting (AP)) and main effect of N rate in Manhattan, 2020. Interaction means averaged over two N rates and main effect of N averaged over cover crop type and two termination timings. Net returns calculated with P_Y = \$0.14 kg^{-1} and variable costs provided in

Cover crop	Termination timing	Test weight	Yield	Net return
		kg hl^{-1}	kg ha^{-1}	\$ ha^{-1}
No cover	3WBP	74.6 (0.16) bcde	8,170 (340) b	959 (40) bc
Partial mix	3WBP	74.7 (0.18) ab d	9,230 (370) b	806 (46) bcd
Full mix	3WBP	74.7 (0.15) abc	8,790 (290) b	744 (33) cd
Triticale	3WBP	74.7 (0.22) abcde	8,702 (480) b	917 (56) bc
No cover	AP	75.5 (0.09) a	10,960 (220) a	1350 (21) a
Partial mix	AP	73.8 (0.26) c e	8,830 (330) b	750 (37) cd
Full mix	AP	73.8 (0.15) de	8,220 (240) b	665 (26) d
Triticale	AP	74.0 (0.24) bcde	9,280 (340) ab	998 (37) b
Nitrogen rate (kg ha^{-1})	100	74.3 (0.10) b	8,470 (167) b	868 (23.3) b
	168	74.7 (0.10) a	9,570 (167) a	930 (23.3) a

Table 2.15. Test weight and yield were adjusted to 15.5% moisture.

Test weight, corn yield, and net return means followed by the same letter within same interaction or main effect column are not different at α = 0.05.

Table 2.14. Mean (SE) corn yield and net return on variable costs as influenced by two termination timings (three weeks before planting (3WBP) and at corn planting (AP)) and two N rates at Ottawa in 2020. Termination timing means are averaged over the levels of cover crop type and N rate and N rate means are averaged over the levels of cover crop type and termination timing.

Main effect treatments	Treatment levels	Yield	Net return
		kg ha^{-1}	\$ ha^{-1}
Termination Timing	3WBP	7,250 (260) b	650 (117) B
	AP	8,550 (260) a	832 (41) A
N Rate	100 kg N ha^{-1}	7,460 (270) b	726 A*
	168 kg N ha^{-1}	8,340 (280) a	757 A*

Corn yield means and net returns followed by the same letter are not different at $\alpha = 0.05$.

*N rate was not significant for net return, shown for reference only.

Table 2.15. Variable costs used to calculate net returns for various management scenarios. Fertility costs calculated from average U.S. farm price of 44-46% urea in 2014 (USDA-ERS, 2019). Cover crop costs based on market data, fall 2019 (Star Seed, 2019) and custom rates in NE Kansas (KSU Dept Ag Econ, 2020).

Input/Return	Price	Quantity	Total cost
Fertility	$ kg^{-1}	kg N ha^{-1}	$ ha^{-1}
Urea 46-0-0	0.63	100	138
	0.63	168	230
Cover Crops		kg seed ha^{-1}	
Triticale seed	0.77	100	77
Austrian winter pea seed	2.76	67	185
Drilling cover crop	-	-	40
Corn Price			
Oct 2019	0.15	-	-
Oct 2020	0.14	-	-

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Appendix- Additional Tables and Raw Data

Table A. 1 Analysis of significance of fixed effects and interactions for cover crop biomass production, weed density one week before planting (1WBP), corn emergence, SPAD chlorophyll content estimation, corn grain yield, and corn grain test weights for Manhattan 2019.

Fixed effects	Cover crop biomass	Corn emergence	Weed density 1WBP	SPAD chl content R3	SPAD chl content R5	Corn grain yield	Corn grain test weight
	----------	----------	----------	P-value	----------	----------	----------
Cover crop	<0.0001	0.6688	<0.0001	0.0038	<0.0001	<0.0001	0.2348
Termination timing	<0.0001	<0.0001	<0.0001	0.0033	0.0083	0.0003	0.0426
N rate	--	--	--	0.0026	0.0130	0.2133	0.5647
Cover crop by termination timing	0.0035	0.2838	0.0018	0.2955	0.1982	0.4470	0.2781
Cover crop by N rate	--	--	--	0.3104	0.2450	0.6574	.0484
Termination timing by N rate	--	--	--	0.3188	0.9339	0.4452	0.0880
Cover crop by termination timing by N rate	--	--	--	0.9975	0.7905	0.8294	0.8416

-- signify where term was not included in the model

Table A. 2 Analysis of significance of fixed effects and interactions for cover crop biomass production, weed density at corn planting (AP), corn emergence, corn tissue N %, late-season weed biomass and density, corn grain yield, and corn grain test weights for Manhattan 2020.

Fixed effects	Cover crop biomass	Corn emergence	Weed density AP	Corn Tissue N %	Late season weed biomass	Late season weed density	Corn grain yield	Corn grain test weight
	---------- P-value ----------							
Cover crop	<0.0001	0.3657	0.0045	0.9985	0.0003	0.0098	0.1674	0.0191
Termination timing	<0.0001	0.0044	0.0001	0.9938	<0.0001	<0.0001	0.0017	0.0010
N rate	--	--	--	0.0235	0.9128	0.1035	<0.0001	0.0041
Cover crop by termination timing	<0.0001	0.0019	0.0973	0.7152	0.0006	.0009	<0.0001	<0.0001
Cover crop by N rate	--	--	--	0.6284	0.7234	0.6182	0.2773	0.9354
Termination timing by N rate	--	--	--	0.0465	0.9668	0.1346	0.5295	0.6294
Cover crop by termination timing by N rate	--	--	--	0.9970	0.6882	0.7048	0.7594	0.5188

-- signify where term was not included in the model

Table A. 3 Analysis of significance of fixed effects and interactions for cover crop biomass production, weed density at corn planting (AP), corn emergence, corn tissue N %, late-season weed biomass and density, corn grain yield, and corn grain test weights for Ottawa 2020.

Fixed effects	Cover crop biomass	Corn emergence	Weed density AP	Corn Tissue N %	Late season weed biomass	Late season weed density	Corn grain yield	Corn grain test weight
		--- P-value						---
Cover crop	<0.0001	0.5362	0.2098	0.0508	0.4055	0.5281	0.3983	0.6524
Termination timing	<0.0001	<0.0001	0.1740	<0.0001	0.0032	0.0021	0.0039	0.3235
N rate	--	--	--	<0.0001	0.1000	0.2204	0.0072	0.4223
Cover crop by termination timing	<0.0001	0.3112	0.0395	0.3756	0.2558	0.1008	0.5232	0.5406
Cover crop by N rate	--	--	--	0.3755	0.1906	0.7011	0.7113	0.5410
Termination timing by N rate	--	--	--	0.5028	0.0302	0.4107	0.0841	0.2444
Cover crop by termination timing by N rate	--	--	--	0.5567	0.2650	0.6651	0.1086	0.3294

-- signify where term was not included in the model