ADVANCED AGRONOMIC MANAGEMENT PRACTICES FOR SOYBEAN PRODUCTION SYSTEMS IN OKLAHOMA

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ADVANCED AGRONOMIC MANAGEMENT PRACTICES FOR SOYBEAN PRODUCTION SYSTEMS IN OKLAHOMA

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Abstract: Advanced agronomic management strategies for soybean (*Glycine max*) systems are gaining interest throughout the soybean growing regions of Oklahoma. With current increases in input prices and the emphasis on agricultural sustainability, careful considerations of existing approaches are needed to both maximize profit and ensure lasting viability of production systems. In response to this need, two studies were developed and conducted in Bixby and Perkins, Oklahoma throughout 2019, 2020, and 2021. The first study aimed to determine the effects of fallow season cover crops on overall soybean production, fallow season and in-season weed management, and soil health indicators within the system. Treatments included 4 fall-planted cover crops, 2 spring-planted cover crops, and a fallow treatment. Results of this study showed that the greatest and most consistent effect of cover crops on a soybean rotation system was improved weed management during the fallow season. Cover crops planted in the fall consistently produced greater biomass than those planted in the spring. The higher cover crop biomass led to reductions in weed biomass present at cover crop termination when compared to both the fallow treatment and the spring planted cover crops which could potentially lead to fewer needed herbicide applications. Inconsistent and non-significant results were generally observed across yield and soil health data suggesting that 3 years of fallow season cover crops would not provide benefits in those areas. The objective of the second study was to determine the impacts of a late season insecticide application, a desiccation application, and delayed harvest timings on soybean yield and seed quality. The results of this trial showed that harvest delays resulted in significant yield loss due to significant pre-harvest shatter. It was also found that an additional late season insecticide application generally resulted in higher yields than a mid-season application alone. The desiccation treatment had little effect on overall soybean yield. Prioritizing and ensuring a timely soybean harvest is vital to maintaining yield.

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CHAPTER I

INTRODUCTION

Soybean (*Glycine max*) is a major legume oilseed crop grown throughout the world and used for its oil, seed, and meal. Global soybean production has steadily increased for over 50 years. In 2019, 120,000,000 hectares (ha) of soybean were grown producing nearly 335,000,000 tons worldwide (FAO STAT, 2021). According to the United States Department of Agriculture (USDA), the United States and Brazil together lead in world soybean production accounting for 66.5% of total production in 2018 and 66.2% in 2019 (USDA FAS, 2020). Within the United States, Illinois, Iowa, Minnesota, Indiana, and Nebraska consistently produce the most soybean (USDA NASS, 2021).

Oklahoma is not among the top soybean producing states in the country, nor is soybean the most abundantly grown crop within the state; however, with high commodity prices, Oklahoma producers have been increasingly incorporating soybean systems into their operations. The 2020 Oklahoma soybean crop was valued at around $163,620,000 ranking fourth in crop commodity values for the state in front of grain sorghum (*Sorghum bicolor*), canola (*Brassica napus*), and peanuts (*Arachis hypogaea*) (USDA NASS, 2021). Soybean production in the state is centered in the north-central and northeast regions with Kay, Garfield, Grant, and Wagoner counties historically planting and producing the most soybean within the state

(USDA NASS, 2021). Advanced agronomic management strategies for soybean systems are gaining interest throughout the soybean production regions of Oklahoma. While planting date, seeding rates, and fertilizer management are important to the success of soybean production systems, several other management options can impact yield and seed quality, but are often overlooked. The utilization of cover crops before planting soybeans is one such management opportunity that is not commonly adopted but is increasingly encouraged by entities promoting both soil conservation and the improvement of soil health. It is thought that cover crops not only benefit the system through soil improvements, but also aid in successive crop production and in-season weed management. Another topic of interest is the late-season management of soybeans. Several variables such as insect pressure, temperature, precipitation, and humidity can affect soybean yield as well as seed quality well after seed fill and even harvest maturity stages. There are options for managing these stressors, however, they are not regularly considered.

Research has been conducted to address the growing interest in the advanced management of soybean. The objectives of the trials discussed later are: 1) to determine the effects of cover crops on soil health, soybean yield, and weed management and 2) to quantify the impact of late-season insecticide treatments, desiccation applications, and harvest delays on soybean yield and seed quality.

CHAPTER II

REVIEW OF LITERATURE

COVER CROPS

The Natural Resources Conservation Service (NRCS) defines cover crops as "grasses, legumes, and forbs planted for seasonal vegetative cover" (USDA NRCS, 2014). The United States Department of Agriculture (USDA) recognizes the implementation of cover crops as an agronomically sound practice for soil conservation and improvement (USDA RMA, 2018). Cover crops have been utilized by agriculturalists for centuries to improve the production of their food crops by diversifying their systems (Groff, 2015). There are no specific species that qualify plants as 'cover crops'; instead, it is the purpose of the crop that determines the classification. Cover crops are not grown for cash revenue, but for non-monetary benefits. Benefits associated with growing cover crops include, but are not limited to:

- reduction of soil erosion (Langdale et al., 1991)
- reduction in soil compaction (Williams and Weil, 2004)
- improvement of soil structure (Hermawan and Bomke, 1997)
- improvement of water quality (Blanco-Canqui, 2018)
- increase in water infiltration (Folorunso et al., 1992)
- increase in soil organic matter (Ding et al., 2006)

- enhancement of soil health (Ghimire et al., 2019)
- management of weed pests (Fisk et al., 2001)

To achieve the intended benefit of cover crops in any given system, certain families and species are often used due to their specific growth patterns and traits.

Soil Conservation

In the 1930s, the USDA created a new agency called the Soil Conservation Service (SCS) in response to the Dust Bowl that was occurring during that time (Helms, 1992). This agency was later renamed to be the NRCS. The Dust Bowl caused great concern for the conservation of United States topsoil as extreme amounts were translocated across the country. The loss of topsoil is severely detrimental to crop production as it contains both essential nutrients and organic matter (Fageria, Baligar, and Bailey, 2007). This concern brought about changes in management practices to crop production areas in the country. Cover cropping is one among numerous strategies used to mitigate both wind and water erosion. Cover crops not only provide above-ground cover to reduce erosion caused by wind and water, but also provide below-ground stability through root structures leading to soil strength and aggregation (Kelly et al., 2012).

Cash Crop Production

Cover crops grown in fallow periods between cash crop seasons have potential to influence the cropping system, thereby directly or indirectly affecting cash crop production. Research on the effects of cover crops on the yield of subsequent cash crops has been inconsistent. Regardless of the benefits provided by cover crops to the cropping system, if the cash crop yields are negatively affected by the cover crops, producers are unlikely to continue the practice. Cover crops must remain economically viable for continued implementation to be a reasonable agricultural practice. Therefore, is it vital to understand the potential impacts of cover crops on cash crop yields.

Numerous studies have found that in certain situations and with proper management, cover crops can result in increased cash crop yields. Chu et al. (2017) completed a study to determine the effects of single species cover crop treatments, two-species cover crop treatments, a multi-species cover crop treatment, and a cover-crop free (fallow) treatment on subsequent soybean crop yield and different soil properties. They observed that in the fourth year of the trial, the multi-species cover crop mix resulted in a 15% yield increase compared to all other treatments in the study (Chu et al., 2017). It was found that in both the multi-species and the two species mix, there were increased levels of inorganic N as well as increased soil moisture when compared to the fallow and single species treatments which could have led to the increased yields. In a different study conducted by Andraski and Bundi (2005), corn yields were higher following single species winter cover crop treatments of oat (*Avena sativa*), rye (*Secale cereale*), and triticale when compared to the fallow treatment. This increase was statistically significant in the latter two years of the three-year experiment except for the triticale treatment, which was only significantly higher in the third year. The authors contribute this increase to adding diversity to the system through further crop rotation. In a third study, DeLaune et al. (2020) evaluated cotton yield under four different tillage systems, strip-till, conventional till, no-till, and no-till with the addition of a wheat cover crop and three different levels of irrigation, low, medium, and high in cotton. They found that regardless of irrigation treatment, the no-till plus cover crop treatment produced significantly higher lint yields than both the conventional and strip-till treatments and although the difference was not significant, also produced greater lint yields than the no-till treatment (DeLaune et al., 2020). The authors indicated that the increased yield with the no-till plus cover crop treatment can be attributed to reduced water evaporation as well as increased water infiltration.

In contrast to the previously discussed studies, other studies have noted a significant yield reduction when cover crops were incorporated into the system. Acharya et al. (2020) evaluated how the utilization of winter rye and camelina (*Camelina sativa*) affected the growth, disease management, and yield of both soybean and corn. They observed that corn following winter rye generally yielded significantly less than corn following a camelina cover crop or a fallow treatment. They found that one year out of the three-year study, the decrease in corn yield following a rye cover crop could be attributed to a significant reduction in the number of ears ha^{-1} and conjectured that for the other two years the yield loss was due to reduction in seed weight (Acharya et al., 2020). They state that these issues could have been caused by reduced N availability after the rye cover crop as well as increased root diseases in corn seedlings. In the same study, soybean yield was not affected by either winter rye or camelina cover crops. Nielson et al. (2016) found in a study aimed to determine the effect of different spring cover crop mixes on subsequent winter wheat yield that in dry environmental conditions winter wheat yields significantly suffered after cover crops when compared to after a fallow season. However, when soil moisture was adequately replenished prior to wheat planting and throughout the growing season, the yield of wheat behind cover crops was not significantly different from the fallow treatment although numerically it was slightly lower. They did not find any significant differences in wheat yield between single species cover crop treatments and multi-species cover crop treatments. Krueger et al. (2011) conducted a field experiment with three cover crop treatments: a rye cover crop terminated around 4 weeks before corn was seeded, a rye cover crop harvested for grain 2 days before corn was seeded, and corn seeded into a fallow treatment (no cover crop). They found that the corn silage yield was significantly reduced if it followed the harvested rye cover crop when compared to the fallow treatment, but there was not a yield decline observed if corn was seeded 4 weeks after the rye cover corp was terminated compared to the fallow treatment. This difference in silage yield response between rye cover crop treatments can be attributed to a significant reduction in soil moisture following the harvested rye when compared to the terminated rye (Krueger et al., 2011).

Weed Management

Cover crops can provide weed management and suppression benefits to cropping systems through their integration during the fallow seasons (Osipitan et al., 2019). Living cover crops and cover crop residues have been shown to suppress weed emergence and growth through both physical (Creamer et al., 1996; Lawley, Teasdale, and Weil, 2012; Finney, White, and Kaye, 2016) and chemical (Weston 1996; Dhima et al., 2006) mechanisms. Through a meta-analysis of research investigating the potential of cover crops to aid in weed management, Osipitan et al. (2019) found that weed suppression using cover crops was certainly possible but often depended on the management practices associated with both the cover crop and cash crop production.

Type of cover crop, seeding rate, planting timing, termination timing, amount of time in between cover crop termination and cash crop planting, additional weed management practices in the cash crop season, and the tillage system were all major determining factors in the success of weed management by cover crops (Osipitan et al., 2019).

When considering the use of cover crops for weed suppression, it is vital to select the best species or mix of species to plant is vital to ensure success. Years of research have been done that compare weed suppression effectiveness between multi-species cover crop mixes versus single species mixes. Florence et al. (2019) conducted an 11-site year study testing 18 different species and several mixes containing various combinations of those species on their effectiveness at suppressing weed presence during the cover crop season. Their results showed that the main factor in weed suppression was the total amount of cover crop biomass present. More specifically, an increase in cover crop biomass resulted in increased weed suppression. When comparing total biomass between single species treatments and multi-species mixes, the authors found no differences between biomass produced by single species mixes compare to the highest producing multi-species mix (Florence et al., 2019). They discussed that the utilization of a multi-species mix does not inherently result in higher cover crop biomass or increased weed suppression and that the use of a high biomass producing single species cover crop can be just as beneficial. Similarly, MacLaren et al. (2019) performed a study to determine the importance of species diversification on weed suppression and observed that total cover crop biomass had more influence on weed suppression than species diversification. Their research showed that cereal and brassica cover crops resulted in greater weed suppression than legume crops. However, they stated that when grown prior to cereal or brassica cash crops, the cover crops could act as a harbor for pests and diseases (MacLaren et al., 2019). Buckwheat was used as a cover crop by Bjorkman and Shail (2013) to reduce weed pressure in a pea crop. They found that with adequate temperatures, buckwheat accumulated enough biomass to significantly reduce weed pests.

Due to the noted importance of high cover crop biomass for weed suppression, seeding rate, planting date, and termination date are vital production decisions to make. A study done by Ryan et al. (2011) investigated the effects of increasing seeding rates of cover crops and applying poultry litter on weed suppression. The results showed that increasing the seeding rate of a cereal rye cover crop did result in increased weed suppression, but this was not due to increased biomass production. Adding poultry litter did increase cover crop biomass production, but unlike previously discussed studies, this did not result in decreased weed pressure. The authors note that this finding could be attributed to the fact that high cover crop biomass often results in reduced N availability to the weed pests, but when fertilizer was applied, the nutrient was still readily available for the weeds to succeed (Ryan et al., 2011). Mirsky et al. (2011) conducted a study to determine the effects of cover crop type, planting date, and termination date on weed suppression. They found that all three of the tested treatments played a significant role in weed suppression due to their influence on total cover crop biomass. The cover crop that resulted in the best weed suppression was a high biomass producing rye variety, which performed better than a rye variety with noted high allelopathic activity (Mirsky et al., 2011). According to their findings, cover crops planted early in the fall produced higher biomass, leading to a reduction in weed pressure when compared to later planted cover crops. In accordance, they observed that later termination of the cover crops allowed for further biomass production, also resulting in greater weed suppression (Mirsky et al., 2011). However, research has shown that delaying the termination of a cover crop could further deplete the soil of necessary moisture before cash crop planting (Krueger et al., 2011). Because cover crops are typically grown for several different purposes, determining a compromise between management practices may be necessary for successful cash crop production.

Not only can cover crops aid in weed suppression through physical means, but certain cover crops produce allelochemicals that reduce weed emergence and growth. Dhima et al. (2006) established that residues of certain winter cereal cover crops, particularly a specific barley cultivar, which contained chemical compounds that, when incorporated as a mulch, suppressed the emergence of barnyardgrass (*Echinochloa crus-galli*) and bristly foxtail (*Setaria verticillata*) weeds, but did not affect corn emergence. Hoffman et al. (1996) were able to distinguish weed suppressing allelopathic activity in rye and the effects of competition. They found that allelochemicals extracted from rye cover crops significantly reduced the number of leaves in barnyardgrass leading to lower total weed biomass. Between physical competition and allelochemical interactions, a mix of species planted as a cover crop can achieve both mechanisms allowing for greater weed control (Hoffman et al., 1996). Although research has been conducted to better understand allelopathic control of weed species, there is still a lot of uncertainty in terms of the extent and mechanisms of this control tactic.

Soil Health

Soil health, as defined by the USDA NRCS, is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (USDA NRCS, 2021). Several properties of the soil's physical, chemical, and biological components can act as indicators for the overall health of a soil system. Doran and Zeiss (2000) provide five criteria that a soil property should meet to qualify as a soil health indicator: they should be sensitive to changes in management practices, highly related to beneficial functions of the soil, helpful in explaining beneficial soil functions, understandable to producers, and efficiently tested both financially and temporally. Important soil health indicators and the impact that cover crop integration has on them will be discussed.

Soil Organic Matter

Soil organic matter (SOM) is an important characteristic of soil and can be indicative of its potential productivity. Dalal et al. (2011) credits soil organic matter as the key indicator of soil health. Soil organic matter is responds to management practices and can be significantly reduced if the soil is not managed conservatively (Janzen et al., 1997). It is highly influential in soil processes such as nutrient cycling, temperature regulation, water infiltration, cation exchange, and chemical adsorption (Nelson and Sommers, 1996). Globally, soil contains the greatest amount of organic carbon which occurs in the organic matter component of the soil (Lehmen and Kleber, 2015). Interest in sequestering atmospheric carbon to mitigate global climate change is increasing, and is considered a promising carbon sink. Organic C in the atmosphere is taken in by plants as CO_2 during photosynthesis and portions are then released into the soil through various biological processes including incorporation of dead plant materials. The carbon is then stored in short-term pools, that are readily decomposed, and long-term pools that are protected in aggregates (Janzen, 2006). Carbon sequestration is best achieved when carbon is stored in the long-term pool and protected from decomposition. However, in terms of agricultural production systems, the benefit of SOM comes when it is decomposed through its release of nutrients (Janzen, 2006). Janzen (2006) suggests that a potential resolution to this conundrum is three-fold; increase the amount of C going into the soil, manage the soil to manipulate the timing of SOM decay, and increase focus on the movement of C throughout the soil itself as opposed to strictly the accumulation.

Soil organic matter content of a soil is inherently limited based on the type of soil; however, because SOM decreases with high intensity management such as long-term cultivation and tillage (Liu et al., 2006), most agricultural soils have lost SOM throughout the past several decades and have room for accumulation. Because agriculturally cultivated soils are considered depleted of SOM, a major priority of the soil health movement is to increase SOM. A practice that holds promise to increase SOM in agricultural systems is the incorporation of cover crops into crop rotations.

Bulk Density

Bulk density (ρ_b) is an important soil physical property that impacts soil water infiltration and retention, soil thermal conductivity, soil hydraulic conductivity, soil strength, plant root growth and more (Zhang, 2000; Arias et al., 2005; Ochsner, 2021). It is the mass of oven-dried soil per unit volume of soil and is commonly reported in the units g cm^{-3}. Generally, the ρ_b of mineral soils ranges from 0.8 to 2.0 g cm^{-3} (Ochsner, 2021). As soil becomes compacted, its ρ_b increases and pore volume decreases (USDA NRCS, 1996). Crop root growth may become restricted in soils with high ρ_b leading to reduced production. The ρ_b values at which root restriction typically occurs vary based on the texture of the soil. The minimum ρ_b at which root growth becomes constricted is 1.55 g cm^{-3} for a silt, silt loam soil (USDA NRCS, 1996). Due to its characteristics and impact on crop production, ρ_b is often used as an indicator of soil quality and soil health (Allen, Singh, and Dalal, 2011; Haruna et al., 2020). Practices such as no-till, conservation tillage, and implementing cover crops have been suggested to decrease ρ_b and improve soil health.

Several studies have been conducted to determine the impact of utilizing cover crops to decrease ρ_b. Chalise et al. (2018) found that returning residue to the soil and growing cover crops decreased ρ_b when compared to no residue returned and no cover crops planted respectively. They discuss that the reduction in ρ_b is likely due to the increase in SOC, reduction in compaction, and the influence of the cover crop root structures (Chalise et al., 2018). An increase in SOC or SOM aids in providing structure to the soil, which results in a lower $\rho_{b.}$ Similarly, Villamil et al. (2006) found that the use of winter cover crops in a corn/soybean rotation system resulted in significantly lower bulk densities from 0 to 5 cm compared to when the field was left fallow. They did note that the ρ_b increased at lower depths of 15 to 30 cm, likely to the reduction in soil water when cover crops were terminated later in the spring (Villamil et al., 2006). Blanco-Canqui et al. (2011) planted hairy vetch and later in the 15-year study, sunn hemp (*Crotalaria juncea*), to serve as cover crops in a wheat/grain sorghum rotation to determine the impacts on soil physical properties. They observed that ρ_b was reduced through the inclusion of cover crops due to the increase in SOC contents to the soil. These studies suggest that both an increase of SOM to the system as well as the root growth activity associated with cover crops can lead to an improvement in ρ_b.

Infiltration Rates

The infiltration rate of a given soil is a valuable soil health indicator as it responds to management practices and affects plant grwth. Infiltration rates are highly influenced by the development of macropores and soil aggregate stability (Arias et al., 2005). High infiltration rates can lead to greater soil moisture storage and less runoff. In certain situations, tillage can aid in breaking up compaction temporarily leading to increased infiltration rates. However, repetitive can disrupt soil aggregation and structure resulting in an increase of compaction, reduction in macropores, and a reduction in overall infiltration rates (Arias et al., 2005). No-till has been recommended as a means to promote soil structure and porosity which can lead to increased infiltration rates. Another recommended practice for improving infiltration is the incorporation of cover crops. Cover crops can be very beneficial to increasing soil infiltration rates as they add SOM to the soil, build and maintain soil structure and aggregation, reduce surface compaction, and create macropores through the root channels (Dunn and Phillips, 1991; Dabney, 1998; Unger and Vigil, 1998).

As discussed earlier, reduced soil moisture that can occur as a result of cover crop growth can lead to diminished early season cash crop growth. However, when managed to increase soil infiltration rates, cover crops can result in a positive effect for the following cash crop in terms of soil moisture (Unger and Vigil, 1998). Through a field trial aimed to determine the impact cover crops have on soil infiltration rates, Folorunso et al. (1992) found that the use of cover crops increased infiltration by up to 41% compared to no cover crops. Mitchell et al. (2017) also found that implementing cover crops into a tomato-cotton rotation resulted in increased rates of water infiltration. The cover crop mix of triticale, rye, vetch, pea (*Pisum sativum* L.), faba bean (*Vicia faba* l.), radish (*Raphanus sativus*), and Phacelia (*Phacelia tanacetifoli*) increased infiltration rates 2.8 times above treatments without cover crops. The increase in infiltration rates was likely due to the formation of macropores by the cover crop roots (Mitchell et al., 2017). Ghahremani et al. (2021) found that cover crop mixes reduced the time for water to infiltrate the soil by half when compared to soil without cover crops. They also note that cover crop mixes had a greater impact on soil infiltration rates than single species cover crop mixes.

Aggregate Stability

Aggregate stability is the ability of soil aggregates to withstand dispersion (Shah et al., 2017). Soil aggregate stability is a valuable soil health indicator as the presence of stable aggregates are necessary for good soil structure (Amezketa, 2008). Aggregate stability influences soil water movement, soil water holding capacity, microbial populations, and consequently, crop growth (Castiglioni and Kraemer, 2019). Reductions in soil aggregate stability are one form of soil degradation caused by intensive management practices and frequent tillage events (Liu, Ma, and Bomke, 2005). Although cover crops have been promoted as a means to manage the continuation of soil aggregate stability degradation, according to a meta-analysis conducted by Blanco-Canqui and Ruis (2020), their effects on aggregate stability are variable.

The meta-analysis by Blanco-Canqui and Ruis (2020) found that wet aggregate stability was increased by an average of 16% (range of 0%-95%) with the addition of cover crops but dry aggregate stability was not consistently affected. Dry aggregate stability is an indicator of soils' susceptibility to wind erosion and is an important indicator of changes in soil structure while wet aggregate stability reflects the soils' susceptibility to water erosion (Blanco-Canqui and Ruis, 2020).

Hermawan and Bomke (1997) found that winter cover crops resulted in greater soil aggregate stability when compared to soil left fallow. The increase in aggregate stability was attributed to the increase in soil organic carbon (Hermawan and Bromke, 1997). Similarly, in a study to determine the effects of various cover crops on soil aggregate stability and corn yield, Dapaah and Vyn (2008) observed greater aggregate stability when cover crops were grown compared to when they were not. They found that annual ryegrass (*Lolium multiflorum* L.) resulted in the greatest and most persistent effect on aggregate stability and they suggest that it be used in cases of severe soil deterioration (Dapaah and Vyn, 2008). However, Acuna and Villamil (2014) conducted a one-year study on the short-term effects of cover crops on soil properties and found that after one year, there were not significant differences in aggregate stability.

Soil Microbes and Nutrient Cycling Assessments

Soil microbes are a vital component of soil as they are instrumental in nutrient cycling and availability, sequestering carbon, increasing aggregate stability, and remediating soil contaminates (Fierer, Wood, and de Mesquita, 2021). Due to the role of microbes in these vital soil processes, the soil health concept has placed a great emphasis on promoting microbial growth and diversity. Several assessments are available in order to better understand how different management practices influence soil microbes and their functions. Although there are concerns with some of the current methods and the usefulness of their interpretations, improvements have been made in both the accessibility and affordability of such tests (Fierer, Wood, and de Mesquita, 2021).

There are several different approaches to estimating microbial populations, their diversity, and their activity. One method to determining the abundance and diversity of soil microbial communities is to profile the fatty acid methyl esters (FAME) within a sample of soil to determine the types of microbes present in the soil based on their FAME signatures (Li et al., 2020). Two main tests are used for this method, ester-linked fatty acid methyl ester (EL-FAME) and phospholipid fatty acid (PLFA) (Li, et al., 2020). A study done by Li et al. (2020) found that both tests were comparable in their results, but the ease and efficiency of the tests themselves differed. They determined that EL-FAME was a simpler, more affordable, and time efficient method when compared to PLFA, but PLFA showed greater reactiveness to differences in soil properties. Miura et al. (2017) also observed that with EL-FAME and PLFA were similar in their bacterial assessment, but PLFA performed better in fungi assessment.

Quantifying soil respiration is an approach used to determine microbial activity within the soil (McGowen et al., 2018). Measuring CO_2 respiration from the soil gives an indication of the presence and ability of soil microbes to decompose organic matter and contribute to the availability of nutrients in the soil (Solvita, 2022). Haney, Britton, and Evans (2008) compared the Solvita 24-hr CO_2 burst test, a titration method, and an infrared gas analysis on soil respiration. They found that all three methods were correlated with each other, but that the Solvita CO_2 burst test was simple and quick. They suggest that the ability to rapidly measure soil microbial activity can aid in determining effects of different management practices within a system (Haney, Britton, and Evans, 2008).

Permanganate oxidizable carbon (POXC) is a measurement of the labile C pool within the soil (Culman et al., 2012). This pool is made of C that is readily available to soil microorganisms and is vital to nutrient cycling and other microbial processes (Weil et al., 2003). Weil et al. (2003) developed an updated method to determine the active C of a soil in a more efficient manner. They found that the active C determined by their test was more related to soil respiration, aggregated stability, and total microbial biomass than measuring total organic carbon (Weil et al., 2003). They also observed that their test results were more sensitive to changes in management practices (Weil et al., 2003). However, Duval et al. (2018) conducted a study to determine the effects of different management practices on soil organic C fractions. They found that out of soil organic C, particulate organic C, water and acid extractable C, POXC, as determined by the method Weil et al. (2003) created, showed the least amount of sensitivity to the different management styles (Duval et al., 2018). They did acknowledge, that due to its simple methodology, the test can still be useful for soil health diagnostics.

Cover crops have been suggested as a means to improve soil microbial populations and their activity. Rankoth et al. (2019) found that the use of cover crops during a fallow period overall resulted in higher microbial biomass in soils compared to those without cover crops. Through PLFA analysis, the results showed that the increase in microbial abundance was not from a single microbial group, but increases over several groups (Rankoth et al., 2019). In agreeance, Muhammad et al. (2020) through a meta-analysis of the effects of cover crops on microbial populations found that overall the implementation of cover crops increase microbial abundance within the soil. This was observed through substantial increases in microbial biomass C, microbial biomass N, and

PLFA measurements (Muhammad et al., 2020). In addition, Wood and Bowman (2021) conducted a large-scale experiment on several farms throughout a number of states and determined that the use of cover crops increase microbial activity when compared to no-cover crops. They also found that these values increased over years of cover crop implementation (Wood and Bowman, 2021).

Commercial soil health tests are conducted at different laboratories. An example of a commercially available soil health test is the Haney Soil Health Test that aims to determine the amounts of N, P, and K that are available to plants as well as evaluate the nutrient cycling capability of the soil (Haney et al., 2018). The approach of the Haney Soil Health Test attempts to mimic the soil environment to portray more reasonable measurements of plant available nutrients for fertilizer recommendations (Haney et al., 2018). A major difference between nutrient analysis from the Haney Soil Health Test and other nutrient tests such as Mehlich 3 and Olsen, is the type of extractants used (Haney et al., 2018). The Haney test uses water and an extractant called H3A which consists of weak organic acids that represent root exudates (Haney et al., 2010). Chu et al. (2019) found that the P and K extracting efficiency of the H3A extractant was less than both Mehlich 1 and Mehlich 3 tests, but that it still was highly correlated to the other extractants. In addition to soil chemical indicators, the Haney Soil Health Test includes biological indicator testing as well through the Solvita 24-hr CO_2 Burst Test.

LATE SEASON MANAGEMENT

Delayed Harvest

Limited workforce and untimely weather events delay soybean harvest past the ideal plant and seed harvest maturity (Philbrook and Oplinger, 1989). Harvest delays inevitably subject the mature soybeans to environmental conditions that can lead to overall deterioration of their pods and seeds (Tekrony, Egli, and Phillips, 1980). The effects of delayed harvest on soybean yield and seed quality are not extensively reported on throughout literature. However, the available data suggests that pod shatter is the main contributing factor to yield loss as harvest is delayed.

Pod shatter can occur during the period between plant maturity and harvest as well as during the harvest process (Burnside et al., 1969; Lamp et al., 1962). Pod dehiscence is a natural process in soybeans for the purpose of dispersing their seeds (Bhor, Chimote, and Deshmukh, 2014). However, when the trait is not controlled in cultivated soybeans, it acts as a major detriment to overall yield. This trait in soybeans and other crops has been well researched in order to advance breeding of cultivated soybean varieties to limit the trait within production systems (Romkaew and Umezaki, 2006). Hot and dry environmental conditions promote pod shatter in mature soybean crops (Bara, Khare, and Shrivastava, 2013). Argawal et al. (2002) also found that shattering is associated with large fluctuations in moisture and temperature. Pod shattering that occurs before harvest is largely due to movement within the canopy leading to pods hitting other pods or stems (Bhor, Chimote, and Deshmukh, 2014).

Pod shatter accounts for the majority of significant yield loss found when harvest is delayed. Lee et al. (2020) observed >40% shatter when harvest was delayed 40 days with no rainfall during that period. They determined that pod shatter was the main factor influencing the yield loss of up to 3.4 kg ha^{-1} day^{-1} that was observed throughout their study. Similarly, Tukamuhabwa et al. (2002) observed yield losses ranging from 0 – 186 kg ha^{-1} in shatter susceptible varieties due to shatter loss. The shatter resistant varieties tested in the same trial did not shatter even when harvest was delayed by 21 days. Tiwari and Bhatnagar (1991) observed yield losses from 34-99% due to pod shatter based mainly on soybean variety, weather after maturity, and delays in harvest. Philbrook and Oplinger (1989) observed a daily yield loss of 11 kg ha^{-1} throughout a 42-day delay in harvest and found that harvesting more than 14 days after soybeans reach harvest maturity would lead to yield reductions.

Delayed harvest decreases seed quality. Delouche (2021), indicated that soybean quality is highly dependent on the climatic conditions from the time they reach physiological maturity to the harvest period. Wetting and drying of seed pods in conjunction with high heat is detrimental to seed quality during the delayed harvest periods (Delouche, 2021). Hepperly and Sinclair (1978) discuss that seed deterioration or ‘weathering’ often occurs in warm/moist conditions. They also acknowledge that most symptoms associated with seeds described as ‘weathered’ can be attributed to the fungi, *Diaporthe phaseolorum*. The most common issue with soybean seed quality is reduced germination and vigor (Delouche, 2021). Late season infection of *Phomopsis* can lead to major reductions in germination to as low as 12% (Hepperly and Sinclair, 1978). Lee et al. (2020) found that when harvest was delayed by 40 days with no rainfall, seed germination was reduced by nearly 25%.

Insect Control

Insect control in soybeans is vital to maintaining both seed yield and quality. In the United States, major outbreaks of pod and foliage feeders that commonly occur during soybean production can result in economic losses throughout soybean growing regions (Turnipseed, 1967). Examples of detrimental insects common in Oklahoma soybean production systems are: threecornered alfalfa hoppers (*Spissistilus festinus*), bean leaf beetles (*Cerotoma trifurcata*), soybean loopers (*Psuedoplusia includens*), grasshoppers (Orthopetera: Acrididae), and stinkbugs (Family: Pentatomidae) (Royer et al., 2016; Royer, 2021). These insects feed on all different parts of the plant, seedlings, stems, pods, and leaves (Royer et al., 2016; Royer, 2021).

Threecornered alfalfa hopper are stem feeders that form girdles around the stem restricting sugar transport through the phloem (Beyer et al., 2017). Bean leaf beetles cause defoliation in early season soybeans that can lead to a reduction in light interception, plant height and yield (Hunt, Higley, and Witkowski, 1994). Soybean loopers are defoliating caterpillars that feed on the lower portions of plants that can lead to reduced leaf area (Herzog, 1980). Grasshoppers can feed on leaves and pods of soybean plants and are often found following drought conditions (Funderburk, McPherson, and Buntin, 1998). Stinkbugs are among a group of insects that use their piercing, sucking mouth parts to inject certain enzymes into soybean seeds to disintegrate the seed which allows the stinkbugs to retrieve nutrients (Depieri and Panizzi, 2010).

Stinkbugs are one of most detrimental insect pests to soybean crops across the world (Kogan and Turnipseed, 1987). Several different species have proven to problematic to soybean crops, the Southern green stinkbug (*Nezara viridula* (L.)), the red-banded stinkbug (*Piezodorus guildinii* (Westwood)), and the Neotropical brown stinkbug (*Euschistus heros* (F.)) (Depieri and Panizzi, 2010). The Southern green stinkbug is considered the most detrimental stinkbug species to soybean production; therefore, it is also likely the most studied (Depieri and Panizzi, 2010).

Todd and Turnipseed (1974) investigated the influence of different amounts of Southern green stinkbug feeding on soybean yield and seed quality. They found that seed germination, emergence, and seedling growth were significantly reduced by as little as 1 stinkbug per 0.3 m. Oil content was also reduced while protein content increased as amount of stinkbug damage increased (Todd and Turnipseed, 1974). Varying thresholds for insecticide applications are recommended for Southern green stinkbugs depending on soybean growth stage. According to Musser et al. (2010) the Southern green stinkbug reaches its highest density around the R6-R7 soybean growth stage. They evaluated the significance of stinkbug pressure during the R7 growth stage and determined that although not significant, yield loss did occur. In addition, seed weight and overall seed damage also increased (Musser et al., 2010). They determined that with the non-significant yield loss in conjunction with the seed quality loss, an insecticide application made during the R7 growth stage would be economically justified.

Desiccation Application

Producers use chemical desiccants, or harvest aids, to accelerate crop maturation and terminate any remaining weed pests. These late season herbicide applications allow for an earlier, more efficient soybean harvest. They also can result in a purer seed collection with less foreign material (Griffin, Boudreaux, and Miller, 2010). Harvest aids are a commonly used practice in many cropping systems including grain sorghum, canola, cotton, and others. The effects of the use of a desiccant have been explored in soybean crops as well, especially with the increase in green plant material retention seen in more recent years.

Boudreaux and Griffin (2011), assessed yield effects from chemical desiccants applied to soybeans at various seed moistures. They found that applying a desiccant at 60% seed moisture resulted in yield loss and seed reduction, but when applied at 40% moisture, soybean yield or seed weight was not affected. It was determined that when paraquat was applied at the ideal soybean moisture and in compliance with the 15-day pre-harvest interval, the early harvest benefit of applying a desiccant was lost. When paraquat was applied after seed physiological maturity, Griffin, Boudreaux, and Miller (2010) found that the number of green pods, leaves, and stems were reduced compared to the non-treated soybeans. They also were able to harvest the desiccated soybeans up to 10 days earlier when compared to the non-desiccated plots. Whigham and Stoller (1979) found that the application of paraquat as a desiccant for soybeans did not reduce seed germination or seedling vigor.

CHAPTER III

THE EFFECTS OF COVER CROP MIXES ON PLANT PHYSIOLOGY AND SEED PRODUCTION OF SOYBEAN SYSTEMS

ABSTRACT

The implementation of cover crops into a crop rotation has been suggested to promote soil conservation, improve soil health, and reduce weed pressure. As cover crops are not harvested and sold, they do not directly provide monetary gain to producers. Therefore, it is imperative that planting cover crops do not negatively affect the subsequent cash crop. However, there is not an overall consensus in literature regarding the effects of cover crops on cash crop yield. Numerous examples of cover crops having a negative, positive, or neutral effects on cash crop yield are presented throughout literature. To better understand the effects of cover crops on soybean growth and yield in Oklahoma soybean systems, trials were conducted in Bixby, OK in 2019 and Perkins, OK in 2019, 2020, and 2020. The objectives of these trials were to 1) determine how different cover crop mixes affect soybean physiological growth parameters and 2) determine if cover crops significantly influence soybean seed yield when managed in accordance with common Oklahoma soybean production practices. Treatments within the trials included four fall-planted cover crop mixes, two spring-planted cover crops, and a fallow treatment. Soybeans were planted after termination of cover crops and yield data as well as growth parameter data were collected at harvest. No significant differences or consistent trends were found in yield between different treatments at either location in any year. Significant differences were observed in some growth parameters; however, those were not consistent across site years and did not translate into significant yield differences. Based on our data, cover crops would not benefit the overall cash crop production in the continuous cover crop soybean system in Oklahoma. However, the fact that cover crops did not consistently or significantly reduce soybean yield allows for growers to explore other benefits such as weed management or soil health improvement.

INTRODUCTION

Cover crops have historically been used as a conservation tool during fallow seasons to provide ground cover and underground root biomass. More recently, cover crops have been integrated into cropping systems at higher rates as a means to improve soil health. From a soil health perspective, single species or mixes of different species are planted to add diverse benefits to the system such as deep roots, high above-ground biomass, nitrogen fixation, among other aspects. However, if the addition of cover crops reduces growers' profitability, the continuation of the practice is not viewed as a sustainable to operation, regardless of soil health benefits. Due to this, the importance of maintaining cash crop yield is imperative to the success of cover cropping. The effects of cover crops on cash crop growth and yield have been inconsistent throughout the literature. Several studies have found that the use of cover crops had no effect on soybean yield (De Bruin, Porter, and Jordan, 2005; Nascente and Crusciol, 2012; Hunter, Kemanian, and Mortenson, 2021). However, some negative effects associated with cash crop production following cover crops such as excess residue biomass at planting causing stand issues and a lack of soil moisture from cover crop growth affecting germination. Certain studies have observed significant decreases in yield with the introduction of cover crops to the system (Reddy, 2001; Reddy, 2003; Kelly, 2015). In contrast, Unger and Vigil (1998) found that when implemented and managed properly for the promotion of greater water infiltration and reduction of evaporation, subsequent crop yields can be improved. Due to the inconsistent findings throughout literature and the importance of cover crop management practices on the cash crop yield, further research would be beneficial to this region. To better understand the effects of cover crops on soybean growth and yield in Oklahoma soybean systems, trials were established to 1) determine how different cover crop mixes affect soybean physiological growth parameters and 2) determine if cover crops significantly influence soybean seed yield when managed in accordance with common Oklahoma soybean production practices.

MATERIALS AND METHODS

Oklahoma Field Trial

Field experiments were established at the Cimarron Valley Research Station in Perkins Oklahoma in from 2018-2021 and the Mingo Valley Research Station in Bixby Oklahoma in 2018. Table 1 includes the dominant soil series and their descriptions as well as the geographic coordinates for each location of the study. Climatic conditions for each site year are given in Figures 1-4.

Table 1. Locations, soil series, and soil descriptions for Oklahoma trials.

Location	Latitude and Longitude	Soil Series	Description
Perkins, OK	35°59'08.9"N 97°02'50.3"W	Teller	Fine-loamy, mixed, active, thermic udic argiustolls
Bixby, OK	35°57'49.8"N 95°51'42.0"W	Wynona	Fine-silty, mixed, active, thermic cumulic epiaquolls

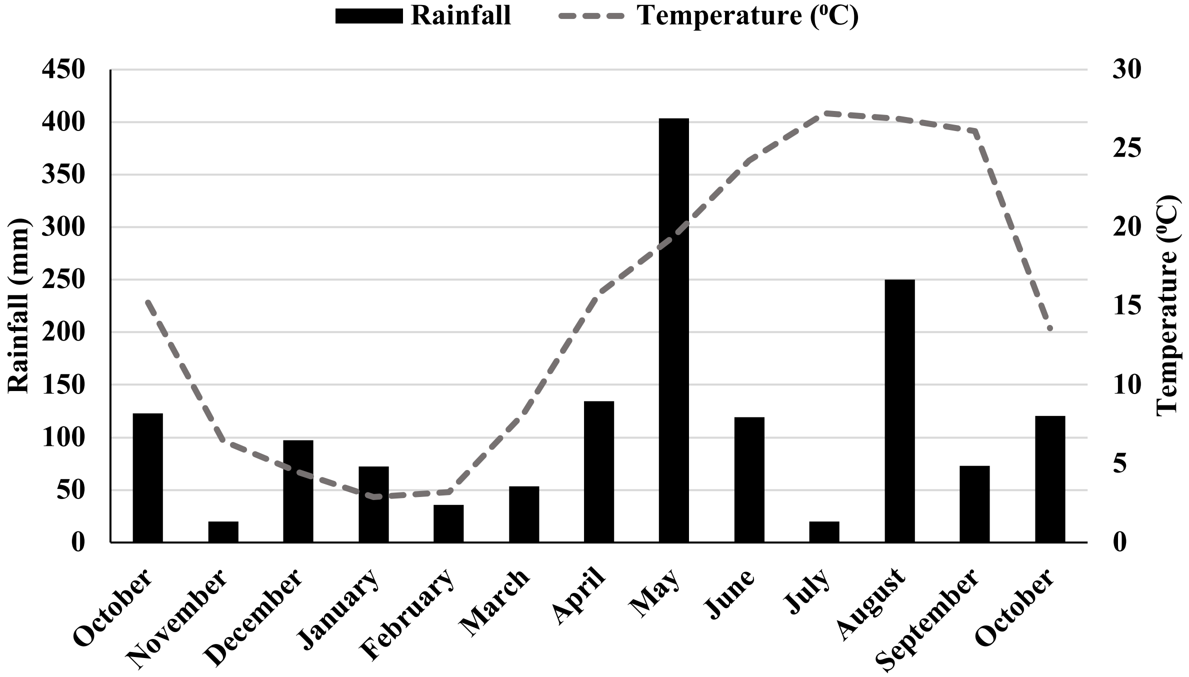

Figure 1. Total rainfall and average daily temperature for each month of the 2018-2019 cover crop and soybean season in Perkins, Oklahoma.

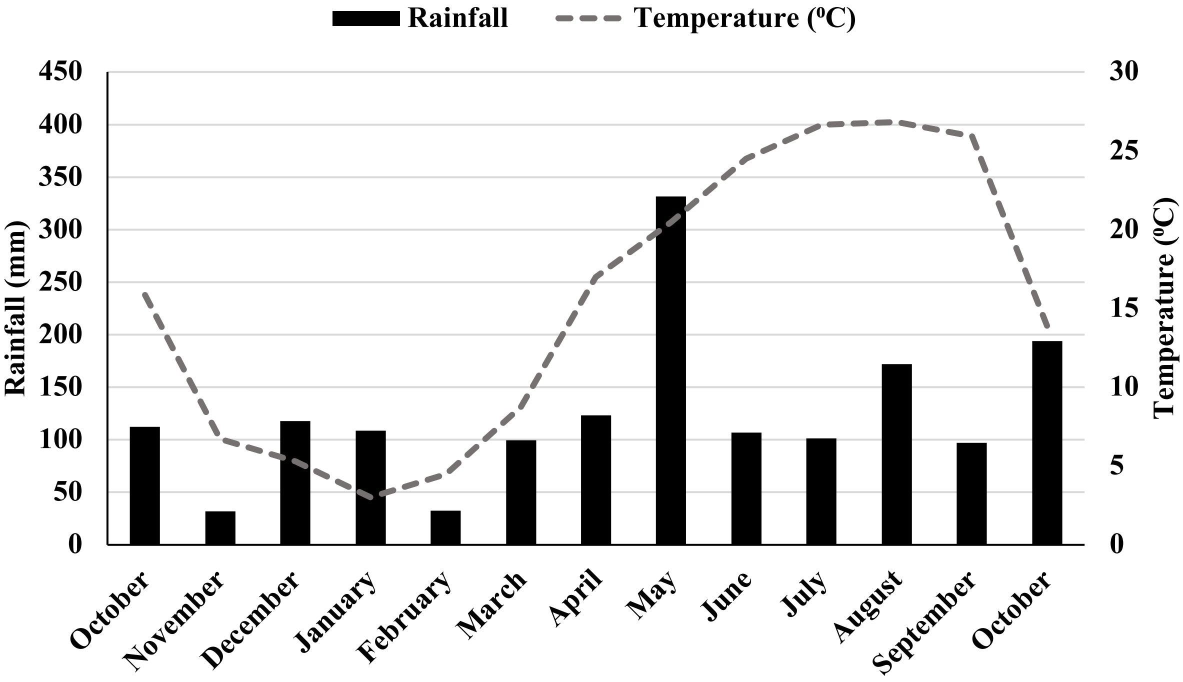

Figure 2. Total rainfall and average daily temperature for each month of the 2018-2019 cover crop and soybean season in Bixby, OK.

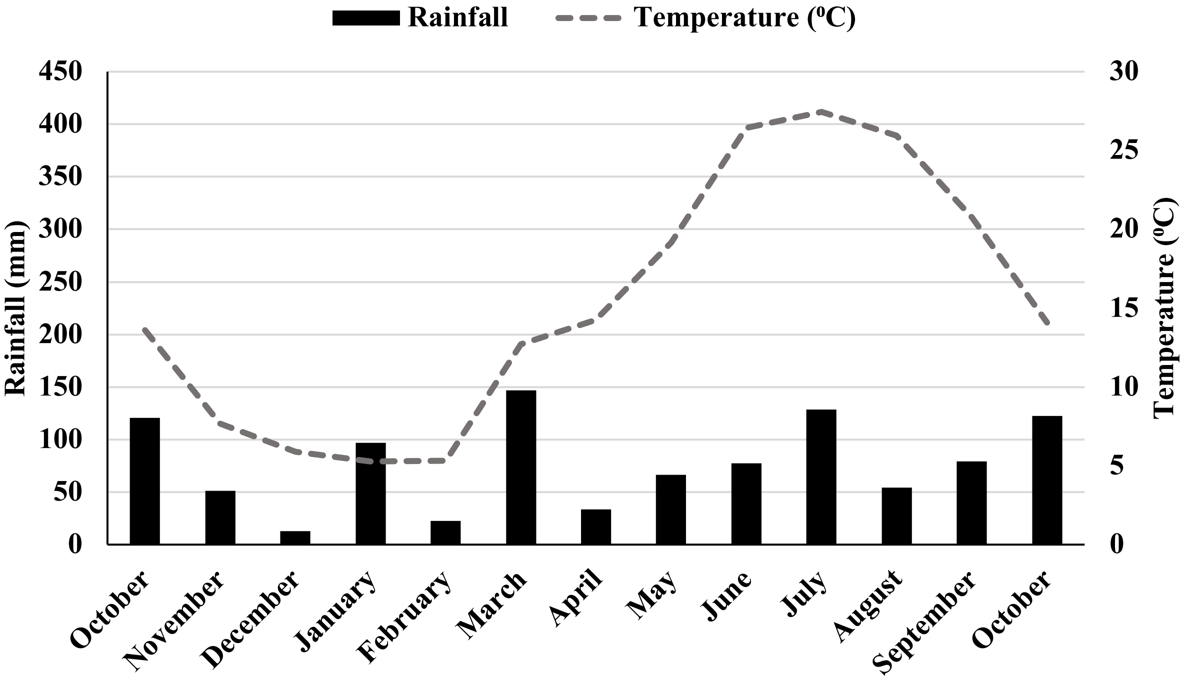

Figure 3. Total rainfall and average daily temperature for each month of the 2019-2020 cover crop and soybean season in Perkins, OK.

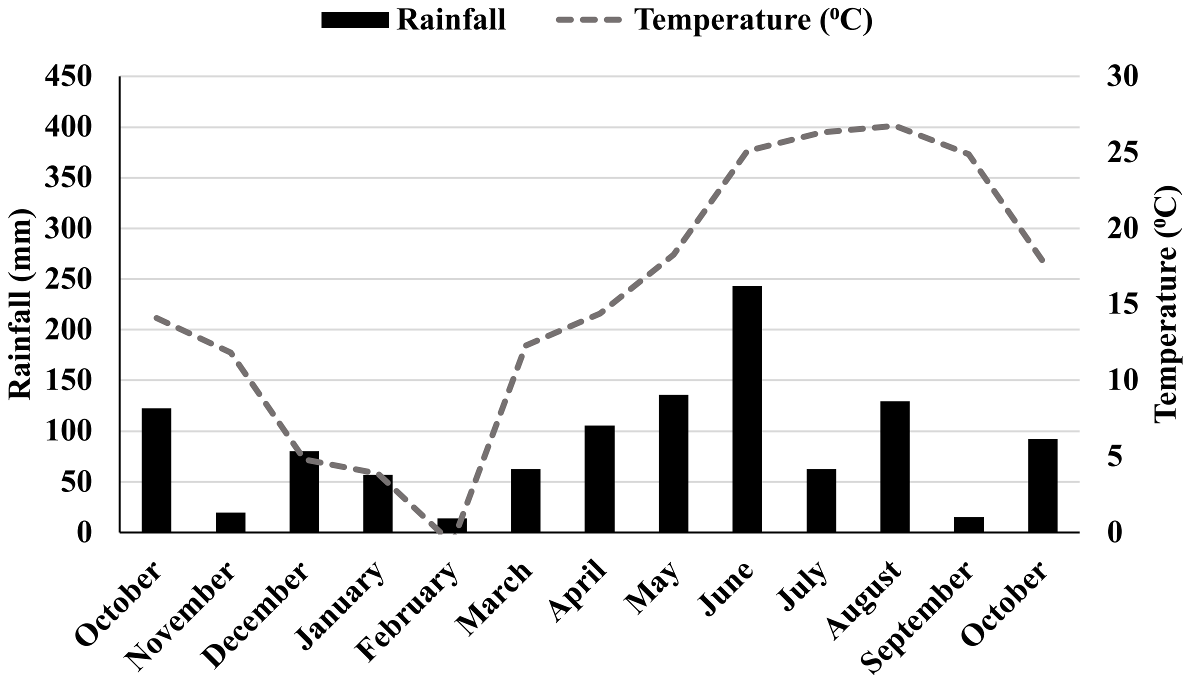

Figure 4. Total rainfall and average daily temperature foreach month of the 2020-2021 cover crop and soybean season in Perkins, OK.

The trials were arranged in a randomized complete block design with a one-way factorial treatment structure plus a control. The seven treatment levels consisted of six different cover crop mixes and a control that was left fallow, but was managed similarly to the cover crop treatments. Each treatment was replicated four times. Trials at the Perkins location were in the same location within the field each year. Due to flooding, the second replication at Bixby was removed from harvest and in-season data analysis because soybean stands were inconsistent throughout the block. Similarly, for each year of the trial, the first replication at the Perkins location had consistently higher weed pressure and lower stands for both cover crops and cash crop that were absent throughout the remaining three replications. Therefore, all in-season and harvest data was removed from analysis for this replication. Wheat served as a base for all cover crop mixes due to rye, a commonly planted cover crop in other regions, is major weed pest within Oklahoma wheat systems. The treatments consisted of both fall and spring cover crop mixes with four treatments planted in the fall and two treatments planted in the spring. The sunn hemp and chicory mixes were planted in the spring as neither species is suitable for winter growth. The cover crop treatments, mix ratios, and planting rates are presented in Table 2.

Table 2. Cover crop treatment mixes, mix ratios, and seeding rates for 2018-19, 2019-20, and 2020-21 trials in Oklahoma.

Treatment Mixes	**Mix Ratios**	**Seeding Rate (kg ha^{-1})**	**Planting Season**
Fallow	-	-	-
Wheat-Rye-Oats (Rye-Oats)	1:1:1	63.7	Fall
Wheat-Canola (Canola)	6:1	41.4	Fall
Wheat-Buckwheat (Buckwheat)	6:1	41.4	Fall
Wheat-Sunn hemp (Sunn Hemp)	3:1	41.4	Spring
Wheat-Rye-Oats-Chicory (Chicory)	2:2:2:1	63.7	Spring
Kitchen Sink	Wheat- 5: Rye- 5: Oats- 5: Canola- 1: Buckwheat- 1: Sunn hemp- 2.5: Chicory- 1	63.7	Fall

Cover Crop Management

Soils were cultivated before the first year of cover crops were planted. Cover crops were using a 1.52 m Truax Drill (Truax Company; New Hope, Minnesota, USA) pulled by a T5040 New Holland Tractor (New Holland Agriculture; New Holland, Pennsylvania, USA). The drill was set on 0.19 m rows. Each plot was 6.10 m long and 3.05 m wide. The cover crops did not receive any inputs before establishment or throughout the season such as fertilizer, insecticide, herbicide, and irrigation. Termination of cover crops was achieved by spraying 1,728 g a.e. ha^{-1} of glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri) mixed with 39.5 oz ha^{-1} of dicamba (XTENDIMAX; Bayer; St. Louis, Missouri). Dates of all activities for each trial are given in Tables 3-6.

Soybean Management

After termination of the cover crops, soybean were planted into the standing residue. The Asgrow variety AG48X7 was planted in 2019 and 2020 and due to inability to source the same soybean variety, LGS 4808XF was used in 2021. Each year and location seed was planted using a four row Monosem vacuum planter (Monosem Inc., Edwardsville, Kansas) set on 76.2 cm spacing at a rate of 258,362 seeds ha^{-1}. Soybean plot sizes were identical to cover crop plots at 6.10 m long and 3.05 m wide. In-season weed and insect pest management was conducted in accordance to the Oklahoma Cooperative Extension Service’s best management practices. Varying rates of glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri) and dicamba (XTENDIMAX; Bayer; St. Louis, Missouri) were applied when needed based on label suggestions and size of targeted weeds. At physiological maturity, soybeans were desiccated using 24.7 oz ha^{-1} of paraquat (Solera; Yuma, Arizona). Two weeks later the middle two rows of each plot of soybeans were mechanically harvested using a Wintersteiger plot combine (Wintersteiger; Ried im Innkreis, Austria). Plot weights were used to estimate yield on a per hectare basis.

Table 3. Dates of field activities during the 2018-2019 trial in Perkins, OK.

Date	Activity
10/30/2018	Planted fall cover crops
11/27/2018	Collected soil samples
3/19/2019	Planted spring cover crops
5/13/2019	Terminated cover crops and collected biomass
5/17/2019	Planted soybeans
7/22/2019	Conducted weed ratings
8/19/2019	Sprayed herbicide
9/18/2019	Sprayed insecticide
9/30/2019	Desiccated soybeans
10/7/2019	Collected soybean plant samples, harvested soybean, and collected seed subsamples

Table 4. Dates of field activities during the 2018-2019 trial in Bixby, OK.

Date	Activity
10/29/2018	Planted fall cover crops
11/26/2018	Collected soil samples
3/19/2019	Planted spring cover crops
5/16/2019	Terminated cover crops and collected biomass
5/21/2019	Planted soybeans
8/7/2019	Conducted weed ratings and sprayed herbicide
10/4/2019	Desiccated soybeans
10/23/2019	Collected soybean plant samples, harvested soybean, and collected seed subsamples

Table 5. Dates of field activities during the 2019-2020 trial in Perkins, OK.

Date	Activity
10/14/2019	Planted fall cover crops
12/3/2019	Collected soil samples
2/17/2020	Collected bulk density cores (0 cm to 5.08 cm)
2/19/2020	Planted spring cover crops
4/24/2020	Collected biomass and took weed ratings
4/27/2020	Terminated cover crops
5/18/2020	Planted soybeans
6/4/2020	Conducted weed ratings and sprayed herbicide
7/1/2020	Conducted weed ratings and sprayed herbicide
7/22/2020	Sprayed insecticide
8/31/2020	Sprayed insecticide
9/30/2020	Desiccated soybeans
10/16/2020	Collected soybean plant samples, harvested soybean, and collected seed subsamples

Table 6. Dates of field activities during the 2020-2021 trial in Perkins, OK.

Date	Activity
10/22/2020	Planted fall cover crops
11/19/2020	Collected soil samples
3/4/2021	Planted spring cover crops
4/8/2021	Collected biomass and took weed ratings
4/9/2021	Terminated cover crops
5/3/2021	Collected bulk density cores
5/3/2021	Planted soybeans
6/4/2021	Conducted weed ratings and sprayed herbicide
7/23/21	Conducted weed ratings and sprayed herbicide
9/17/2021	Desiccated soybeans
9/29/2021	Collected soybean plant samples, harvested soybean, and collected seed subsamples
11/19/2021	Collected final soil samples

Data Collected

Soybean Yield and Physiological Parameters

To understand the effects of the different cover crop treatments on soybean production and quality, several data were collected on growth parameters, seed size, and quality, as well as yield. Soybean plant populations were estimated by counting each plant within 1 m of row from two rows in each plot. The counts were averaged between the two rows and then averaged over like treatments to attain one average plant population value for each treatment. This value was used for comparison between different treatments.

After desiccation of the soybeans, physiological measurements including plant height, height to first harvestable node (HFN), number of nodes per plant, number of nodes per mainstem, total number of pods per plant, and number of 0, 1, 2, 3, and 4 bean pods per plant were taken from each plot. The number of 0, 1, 2, 3, and 4 bean pods per plant are presented as percent of total pods for each bean number category and will be referred to as detailed harvest pod counts. Plant height measurements were taken from the soil surface to the top node of five random plants per plot. On those same five plants, HFN was recorded as the measurement from the soil surface to the lowest seeded pod. Additional physiological measurements were taken on five plant subsamples that were randomly collected from each plot before soybean harvest. The height and HFN measurements were not necessarily taken from the same plants that were collected for plant samples. Once the plant samples were collected nodes were counted on the mainstem as well as the entire plant. After counting nodes, all pods were removed from the plant, separated into 0, 1, 2, 3, and 4 bean groups, and counted.

Soybean seed yield was collected at harvest along with a subsample of seed from each plot. The seed collected was then used to attain 100 seed weight, quality ratings, oil content, and protein content. The 100 seed weight value was determined by randomly counting 100 seeds from each subsample and weighing them. Using the same 100 seeds, a visual quality rating was taken for each plot. These visual ratings were taken on a 0-10 scale with 0 represented seed samples that had nearly 0% abnormal seeds while 10 represented samples with 100% abnormal seeds. Abnormal seeds refer to seeds that were shriveled or shrunk, were green, had purple seed stain, were covered in white powdery mold, or if the seed coat was cracking. These abnormalities are symptoms of damage caused by insects or diseases. Oil and protein contents were determined using a Perten Model DA7250 At-Line Near-Infrared (NIR) instrument (PerkinElmer, Inc.; Waltham, Massachusetts).

Louisiana Field Trial

A mirrored study was conducted at the Louisiana State University AgCenter's Northeast Research Station in St. Joseph, Louisiana from 2018 to 2021. Table 7 includes the geographic coordinates for the site, the dominant soil series and their descriptions.

Table 7. Location, soil series, and soil description for the Louisiana trial.

St. Joseph, LA	Commerce	Fine-silty, mixed, superactive, nonacid, thermic fluvaquentic endoaquepts

Plots were arranged in a randomized complete block design with a one-way factorial treatment structure plus a control. Just like the Oklahoma trial, there were six cover crop mixes and a control treatment that was left fallow to make up the seven treatments. Each treatment was replicated four times. Due to having a different climate then Oklahoma, all cover crop treatments were established in the fall as would be common agronomic practice in the state. The cover crop treatments, mix ratios, and planting rates are given in Table 8. For the Louisiana trial, radishes were used in mix with wheat as opposed to buckwheat and chicory was a single species cover crop. These differences were due to different agronomic practices common to the state and greater climate suitability.

Table 8. Cover crop treatment mixes, mix ratios, and seeding rates for 2018-19, 2019-20, and 2020-21 trials in Louisiana.

Treatment Mixes	Mix Ratios	Seeding Rate (kg ha^{-1})
Fallow	-	-
Wheat-Rye-Oats (Rye-Oats)	1:1:1	94.1
Wheat-Canola (Canola)	8.2:1	51.1
Wheat-Radish (Radish)	10:1	49.7
Wheat-Sunn hemp (Sunn Hemp)	2.5:1	68.1
Chicory (Chicory)	1	9
Kitchen Sink	Wheat- 7: Rye- 7: Oats- 7: Canola- 1: Radish- 2.3: Sunn hemp- 5: Chicory- 2.3	67.2

Data Analysis

All data was analyzed using SAS v. 9.4 (SAS Institute Inc., Cary, NC) to determine significant impacts of cover crop treatments on fallow season cover crop and weed biomass and in-season percent weed coverage. Cover crop treatments were considered fixed effects and replication and its interactions were considered random. Year and location both significantly affected results, therefore all years and locations were tested independently. Analysis of variance was conducted using Procedure Mixed (PROC MIXED). Post-hoc analysis was done with a Tukey adjustment to determine differences between individual mean values. An $\alpha = 0.05$ was used for all analysis.

RESULTS

Oklahoma Seed Yield

Regardless of year or location, there were no significant differences in soybean yield between the various cover crop treatments. Average soybean yields ranged from 5341 kg ha^{-1} to 6504 kg ha^{-1} at the Bixby location in 2019 (Figure 5). The fallow treatment had the highest overall yield average while the canola mix had the lowest. For the Perkins 2019 location, the highest average yield was 2668 kg ha^{-1} from the kitchen sink cover crop treatment, while the lowest yield was 2171 kg ha^{-1} from the canola mix (Figure 6). Differing results again were found at the Perkins 2020 location. At this site, the canola mix resulted in the highest average yield of 2908 kg ha^{-1} while the kitchen sink mix resulted in the lowest average yield of 1891 kg ha^{-1} (Figure 7). At Perkins in 2020, the chicory mix resulted in the highest average soybean yield at a value of 1778 kg ha^{-1} (Figure 8). The lowest yield observed at this location was found in the fallow treatment at 1441 kg ha^{-1}.

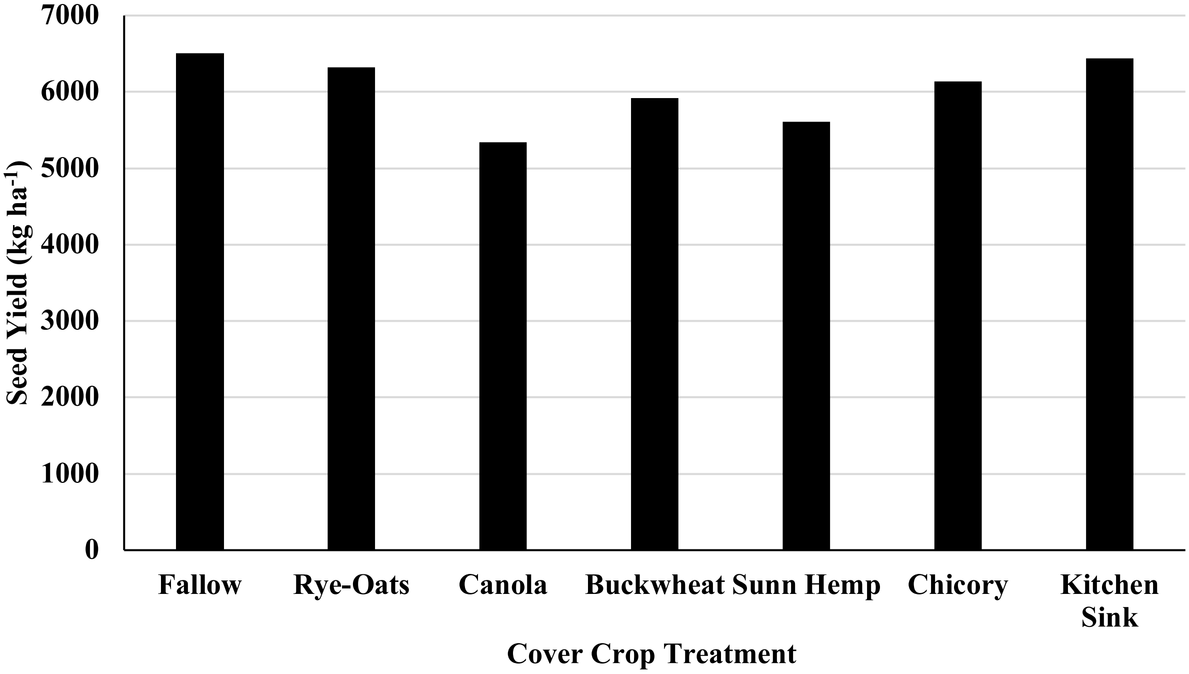

Figure 5. Soybean seed yield (kg ha^{-1}) for the Bixby location in 2019.

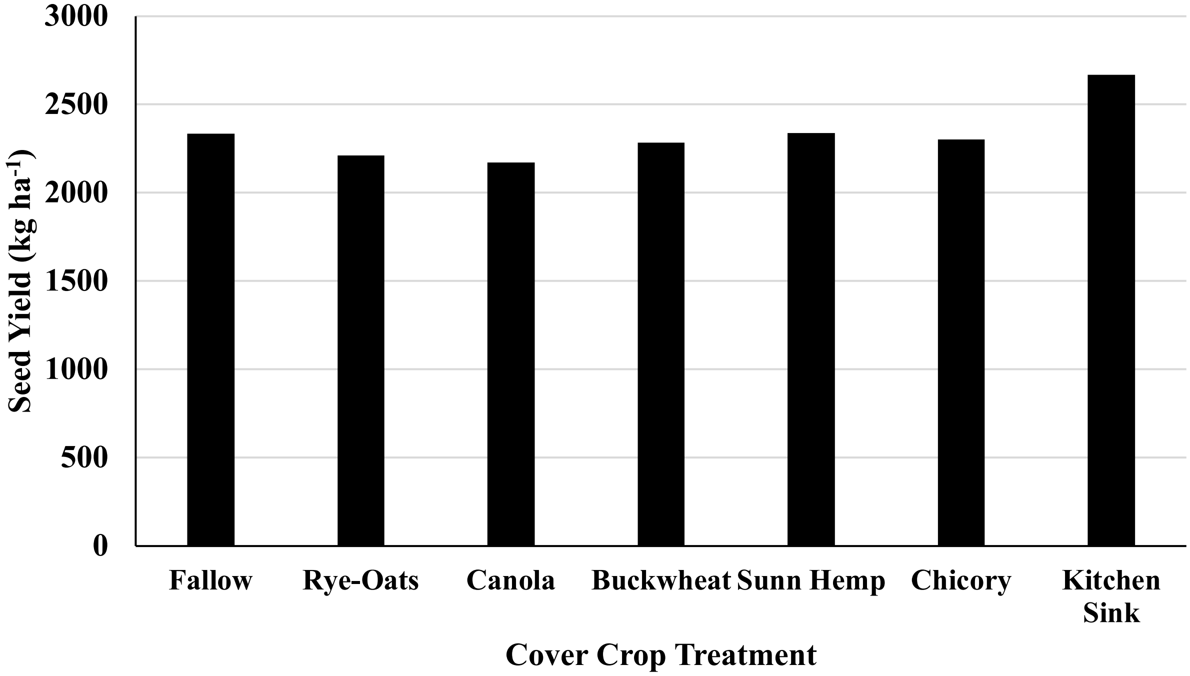

Figure 6. Soybean seed yield (kg ha^{-1}) for the Perkins location in 2019.

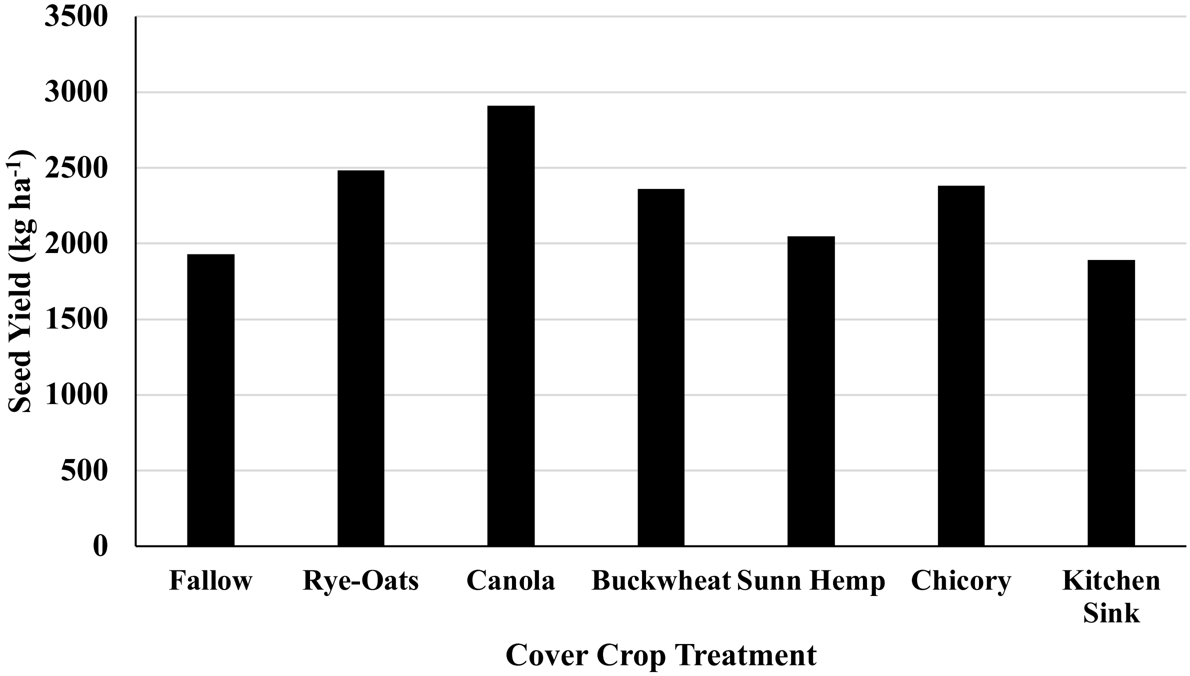

Figure 7. Soybean seed yield (kg ha^{-1}) for the Perkins location in 2020.

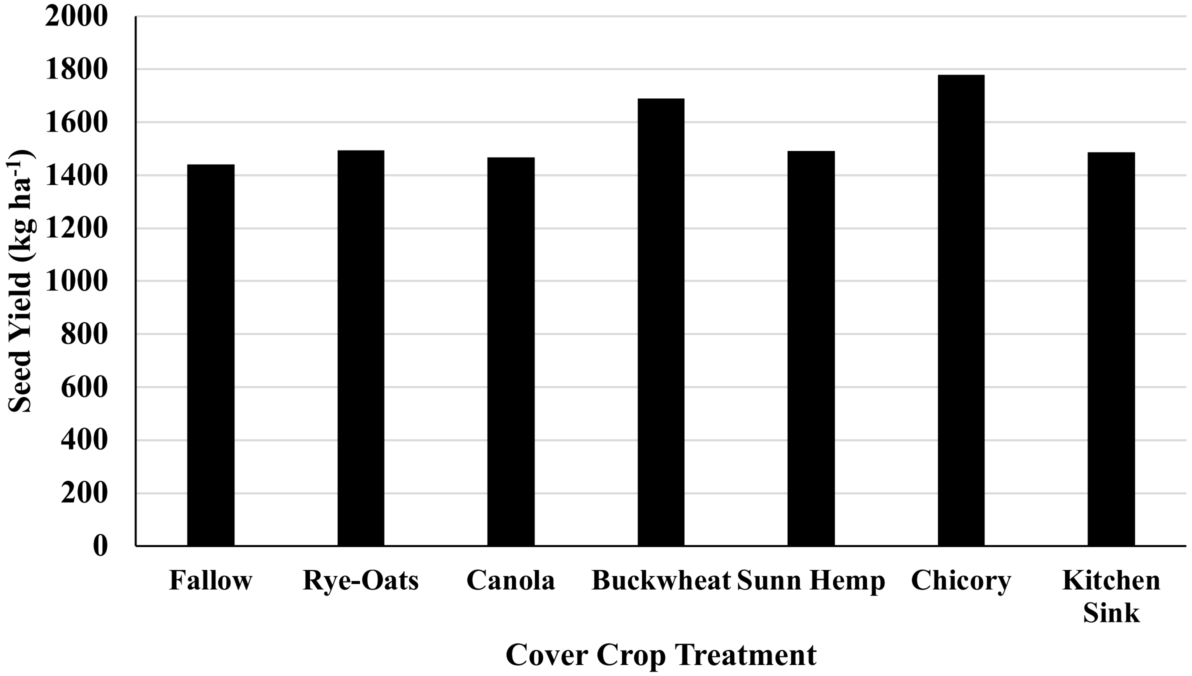

Figure 8. Soybean seed yield (kg ha^{-1}) for the Perkins location in 2021.

Louisiana Seed Yield

Much like in Oklahoma, the trials conducted at St. Joseph in Louisiana did not result in significant yield differences. For the trial harvested in 2019, the rye-oats cover crop treatment produced the highest average soybean yield at 3070 kg ha^{-1} while the kitchen sink mix resulted in the lowest at 1950 kg ha^{-1} (Figure 9). For the 2020 trial, the chicory treatment yielded the highest at 3352 kg ha^{-1} with the rye-oats mix averaging the lowest yield of 2875 kg ha^{-1} (Figure 10). And finally, in 2021, the highest yielding cover crop treatment was the chicory treatment at an average yield of 3855 kg ha^{-1} while the lowest treatment was the rye-oats treatment at 3205 kg ha^{-1} (Figure 11).

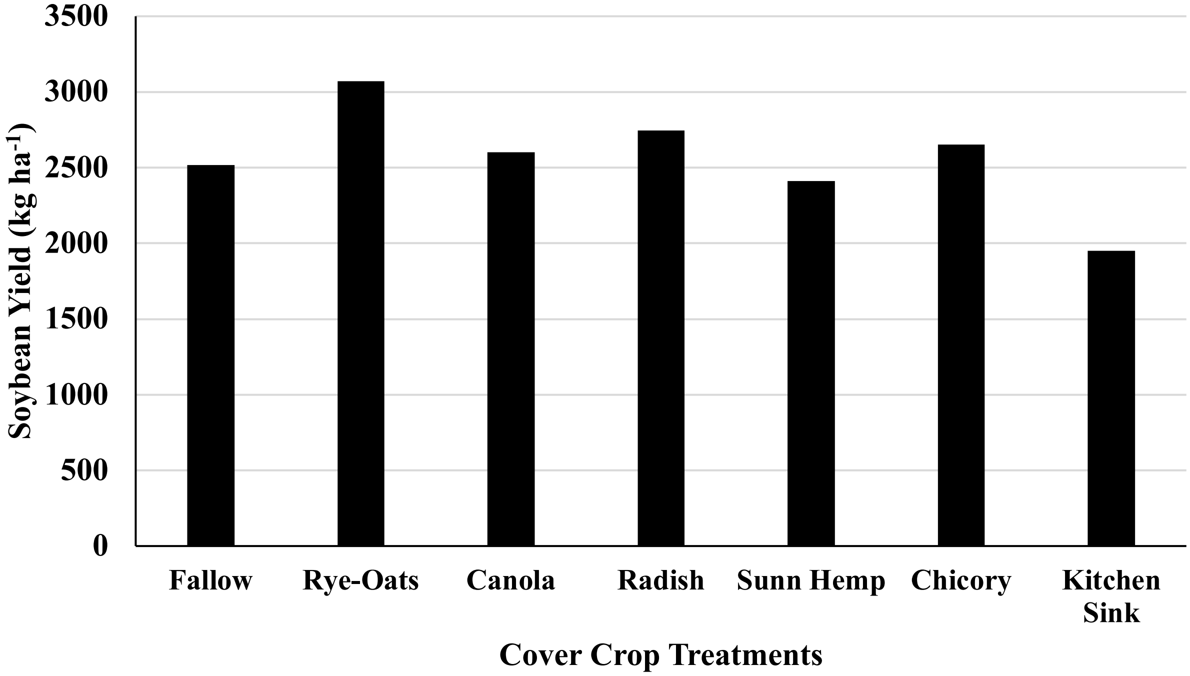

Figure 9. Soybean seed yield (kg ha^{-1}) for the St. Joseph, LA location in 2019.

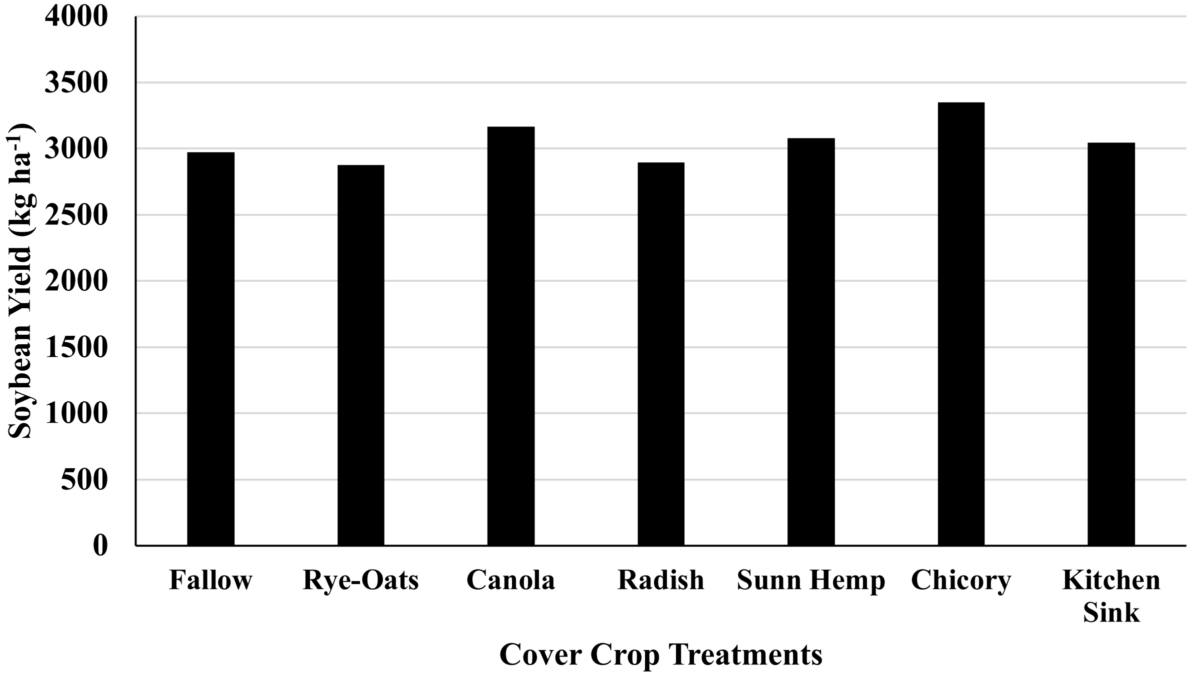

Figure 10. Soybean seed yield (kg ha^{-1}) for the St. Joseph, LA location in 2020.

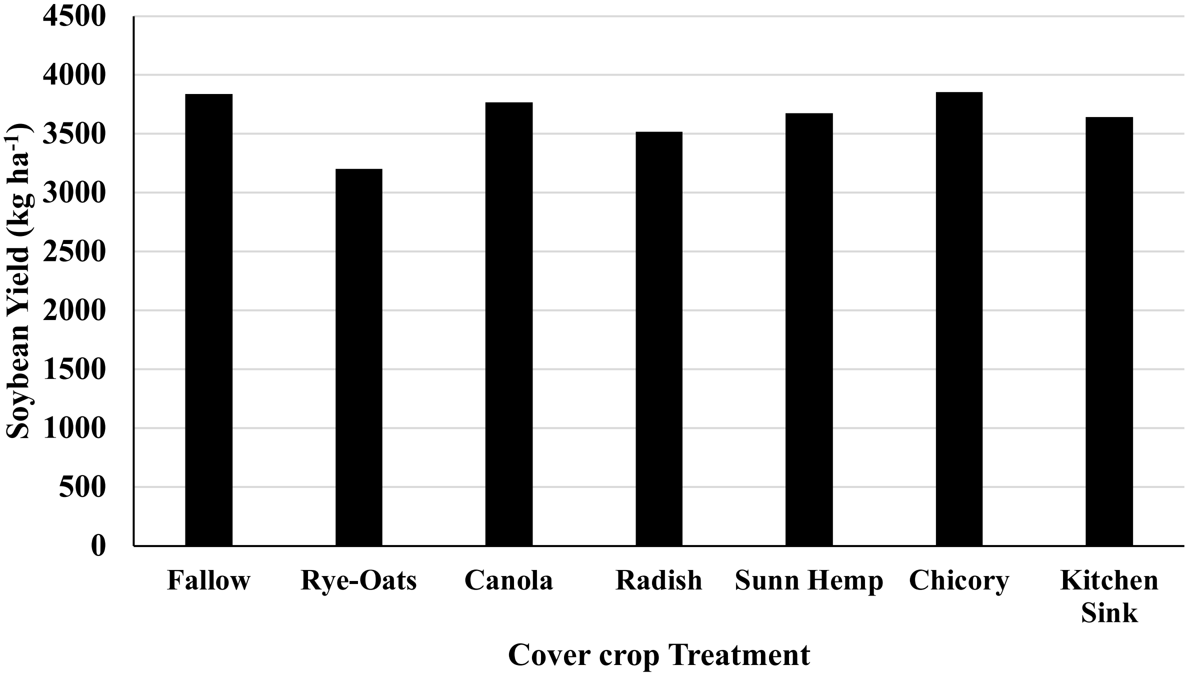

Figure 11. Soybean seed yield (kg ha^{-1}) for the St. Joseph, LA location in 2021.

Harvest Plant Measurements

There were no significant differences in plant heights, HFN, or estimated 100-seed weights between any cover crop treatment at either location in any year (Table 9). However, numeric differences were present between treatments at each site year. At the Bixby location in 2019, the average plant height ranged from 71.9 cm to 80.2 cm resulting from the chicory mix and the fallow treatment respectively. The HFN was highest in the canola mix at 16.0 cm and the lowest from the buckwheat mix at 13.3 cm. Estimated 100-seed weight values ranged from an average of 15.0 g in the chicory mix to 16.3 g in the rye-oats mix. For the Perkins location in 2019, the average plant height was highest in the kitchen sink mix at 67.0 cm and was lowest in the chicory mix at 60.8 cm. The average HFN ranged from 10.1 cm to 11.2 cm from the rye-oats and both chicory kitchen sink mixes respectively. Average estimated 100-seed weights were greatest in the fallow treatment at a total of 16.2 g and lowest in the buckwheat mix at 14.7 g. Differing from both previous site years, the greatest average plant height found in the Perkins 2020 trial was in the rye-oats mix at 93.3 cm and lowest in the canola mix at 83.0 cm. The fallow treatment and the kitchen sink mix resulted in the same average HFN of 12.0 cm, higher than the other treatments. The lowest HFN was found in the canola mix at 9.7 cm. The average estimated 100-seed weights ranged from 12.3 g in the rye-oats mix to 14.4 g in the chicory mix. Lastly, for the Perkins 2021 site year, the average plant heights ranged from 61.5 cm to 66.0 cm in the canola and chicory mixes respectively. The highest average HFN was found in the kitchen sink mix and fallow treatment at 6.1 cm and the lowest was found in the chicory mix at 5.3 cm. The kitchen sink mix had the highest average estimated 100-seed weight at 8.9 g and the chicory mix resulted in the lowest at 6.8 g.

Table 9. Stand counts and estimated plant height, height to first node (HFN), and 100-seed weight for each treatment in every site year.

Site Year	Parameter	Cover Crop Treatment						
		Fallow	Rye-Oats	Canola	Buckwheat	Sunn Hemp	Chicory	Kitchen Sink
Bixby 2019	Stand Count (plant m^{-1} row)	7.7	6.5	10.5	8.8	10.8	9.0	12.2
	Plant Height (cm)	80.2	75.6	76.6	76.2	72.0	71.9	74.0
	HFN (cm)	14.4	13.4	16.0	13.3	14.1	13.7	14.4
	100-Seed Weight (g)	15.3	16.3	16.2	16.2	15.3	15.0	16.1
Perkins 2019	Stand Count (plant m^{-1} row)	12.2	10.7	10.7	15.8	12.5	13.3	11.0
	Plant Height (cm)	65.3	65.5	64.8	62.5	62.5	60.8	67.0
	HFN (cm)	11.1	10.1	10.6	10.5	10.9	11.2	11.2
	100-Seed Weight (g)	16.2	15.6	15.4	14.7	15.1	15.6	15.7
Perkins 2020	Stand Count (plant m^{-1} row)	6.9	6.9	6.4	6.1	6.3	7.0	6.1
	Plant Height (cm)	84.9	93.3	83.0	89.5	85.6	86.3	86.7
	HFN (cm)	12.0	11.2	9.7	11.2	10.3	10.7	12.0
	100-Seed Weight (g)	13.3	12.3	13.3	14.2	13.3	14.4	13.9
Perkins 2021	Stand Count (plant m^{-1} row)	18.9	18.0	17.9	17.9	16.9	17.3	17.4
	Plant Height (cm)	65.6	65.9	61.5	62.0	64.9	66.0	65.4
	HFN (cm)	6.1	5.9	5.9	5.9	5.8	5.3	6.1
	100-Seed Weight (g)	7.6	7.2	8.4	8.4	8.2	6.8	8.9

Detailed Harvest Pod and Node Counts

Differences in detailed harvest pod and node counts between various cover crop mixes were entirely non-significant except for the percent 3 bean pods at the Perkins 2020 and 2021 site years (Tables 10-13). The significant exceptions in 2020 and 2021 were a result of the main effect of cover crop treatments. In 2020, the buckwheat mix had the highest percentage of 3 bean pods at 40.1%. This value was significantly higher than the fallow treatment, canola mix, and chicory mix. In 2021, the canola treatment had the highest percentage of 3 bean pods at 63.5%; however, the buckwheat mix was only slightly lower with a percent of 3 bean pods of 63.4%. These treatments had significantly higher percent of 3 bean pods values than the fallow treatment and kitchen sink mix.

Numerical differences between treatments did exist in each data variable in all site years. At Bixby in 2019, the average total pods per plant ranged from 91.9 pods in the canola mix to 123.3 pods in the kitchen sink mix. For the Perkins 2019 site the highest average total pods per plant were also found in the kitchen sink mix at 72.7 pods; however, the lowest amount of average total pods was found in the chicory mix at an average of 46.5 total pods. At the Perkins location in 2020, the highest average total pod number was found after the canola mix at 135.9 pods while the lowest came from the sun hemp treatment at 98.9 pods. Lastly, for the Perkins trial in 2021 the highest average total pods were found in the sunn hemp treatment at 29.8 pods and the lowest total pods were from the chicory treatment at an average of 19.3 pods.

Table 10. Average percent of total pods and average number of total pods, mainstem nodes, and total nodes of cover crop treatments for the Bixby 2019 location.

	Percent of Total Pods (%)							
	0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
Fallow	1.3	7.4	36.0	52.9	2.5	102.1	19.7	46.3
Rye-Oats	2.0	10.7	39.1	47.3	0.9	96.6	19.3	46.2
Canola	1.6	9.1	39.1	48.6	1.6	91.9	18.3	46.3
Buckwheat	3.4	9.1	37.6	48.3	1.7	104.0	19.9	50.4
Sunn Hemp	2.6	11.3	38.2	46.8	1.2	93.0	16.2	48.0
Chicory	1.1	7.0	36.7	53.7	1.5	96.7	20.3	49.8
Kitchen Sink	1.8	15.3	36.2	45.2	1.5	123.3	21.5	53.3

Table 11. Average percent of total pods and average number of total pods, mainstem nodes, and total nodes of cover crop treatments for the Perkins 2019 location.

	Percent of Total Pods (%)							
Treatment	0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
Fallow	1.8	16.1	43.1	38.8	0.2	57.7	17.9	44.3
Rye-Oats	2.1	12.9	42.5	42.1	0.4	70.5	20.2	52.0
Canola	4.0	15.3	37.2	42.7	0.8	70.1	19.8	49.3
Buckwheat	2.5	14.8	42.3	40.4	0.1	53.5	16.9	41.8
Sunn Hemp	1.8	17.2	39.4	41.4	0.3	54.0	20.5	48.7
Chicory	2.0	13.4	44.2	40.2	0.1	46.5	17.1	38.1
Kitchen Sink	1.2	14.0	39.6	44.2	0.9	72.7	19.6	51.8

Table 12. Average percent of total pods and average number of total pods, mainstem nodes, and total nodes of cover crop treatments for the Perkins 2020 location.

	Percent of Total Pods (%)							
Treatment	0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
Fallow	14.3	16.4	35.9	32.1 BC*	1.3	133.2	26.1	52.5
Rye-Oats	9.7	15.1	37.4	35.9 AB	1.9	106.3	25.4	57.3
Canola	8.9	18.9	38.9	32.4 BC	0.9	135.9	23.0	56.1
Buckwheat	8.5	12.8	38.2	40.1 A	0.5	120.9	25.1	64.0
Sunn Hemp	7.0	16.1	38.6	37.3 AB	1.0	98.9	24.1	54.9
Chicory	11.7	21.4	38.1	28.2 C	0.6	124.1	25.3	59.7
Kitchen Sink	8.2	13.8	41.8	35.5 AB	0.6	104.0	23.7	57.2

*Differing letters denote significant differences between cover crop treatments.

Table 13. Average percent of total pods and average number of total pods, mainstem nodes, and total nodes of cover crop treatments for the Perkins 2021 location.

	Percent of Total Pods (%)							
Treatment	0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
Fallow	18.4	8.9	33.8	33.9 C*	5.0	22.8	12.9	21.1
Rye-Oats	9.2	5.1	28.4	56.5 AB	0.8	27.7	13.5	24.7
Canola	3.3	2.4	30.7	63.5 A	0.2	24.9	12.2	19.9
Buckwheat	3.2	5.0	28.4	63.4 A	0.0	29.4	11.7	23.6
Sunn Hemp	3.1	9.5	38.5	47.9 ABC	1.0	29.8	14.7	24.5
Chicory	9.5	10.9	32.3	47.2 ABC	0.0	19.3	12.9	19.6
Kitchen Sink	6.2	13.6	36.3	41.9 BC	2.1	20.9	13.1	20.1

*Differing letters denote significant differences between cover crop treatments.

DISCUSSION

Agricultural production operations, like any business, are only sustainable if their overall net income is positive. This happens when an operation’s total revenue exceeds its total expenses. The incorporation of cover crops into the fallow period of a crop rotation inherently adds certain expenses to the overall system including seed costs, planting costs, and termination costs. Although planting cash crops include these similar or additional expense, the difference between the two lies in the fact that cash crops produce revenue, while cover crops do not. Because cover crops are not harvested and sold, they must provide benefits worth their expense, such as increased cash crop yield or reduction in fertilizer or herbicide applications to cash crops. However, the literature suggests that effects of cover crops on cash crop yields are inconsistent with several studies finding reductions in cash crop yields following cover crops. If this occurs, not only are producers adding expenses to their operation, but also reducing the total revenue from their cash crop. In this circumstance, cover crops are often considered to be uneconomical (Reddy, 2001).

The results of this 3-year study did not show significant declines in soybean yield following any of the cover crop mixes. In fact, the cover crops did not significantly influence cash crop yield in any way. These results are not surprising as similar studies found that cover crops did not affect cash crop yield. Hunter et al. (2019) evaluated the effects of multi-species mixes on soybean, corn silage, and wheat yields and found that implementing cover crops into rotation did not significantly affect yield of the cash crops. They acknowledge that the lack of yield response in cash crops to multi-species mixes can allow for greater ecological and agronomical benefits to the system without posing as a detriment. Moore, Gillespie, and Swanton. (1994) found that different treatments of cover crop mulches did not affect the yield of subsequently grown soybean when weeds were not present but noted once exceptions at a location with a high weed presence, showed a yield increase associated with cover crops due to a diminished weed pressure in those plots (Moore, Gillespie, and Swanton., 1994). Williams II, Mortensen, and Doran (2000) found that when soybean stands are not reduced by the implementation of cover crops, the soybean yield is not diminished.

Soybean yield is influenced by several growth traits including, but not limited to, plant stand, mass of seed, node number, and plant height (Assefa et al., 2019; Williams II, Mortensen, and Doran, 2000). Within this study, stand counts, plant height, and height to first node showed no significant differences among treatments. The lack of differences observed in these plant growth parameters help to corroborate the lack of differences in yield results that were observed. According to Williams II, Mortensen, and Doran (2000) a significant yield reduction would not be expected in the absence of a significant preceding stand loss. Supporting this notion, Reddy et al. (2003) observed significant yield loss due to cover crops and attributed the loss to a significant reduction in stand loss. Alternatively, Moore, Gillespie, and Swanton (1994) observed significant stand reductions due to emergence issues caused by the cover crop mulch, though this did not result in significant yield loss. The lack of significant difference in yield for the treatments that had lower stand counts could potentially be attributed to yield recovery through significantly increased soybean leaf area, number of branches per plant, and number of nodules per plant (Moore, Gillespie, and Swanton, 1994). Although the growth parameters collected within this study are different than those mentioned above, the results do not suggest that any treatments were compensating to recover yield. In a different study, both no-till and conventionally tilled treatments without cover crops yielded higher than seven cover crop treatments (Reddy, 2001). The yield decline was partly attributed to reduced soybean stands and plant heights resulting from the cover crop biomass and possible chemicals released from the residues (Reddy, 2001).

Total node number, pod number, and seed number are often considered the overall determining factor of soybean yield (Bianchi et al., 2019; Egli, 2013;). Kokubun and Watanabe (1984) found that during flowering and early seed development, the ability of leaves to photosynthate and act as a source primarily determines soybean yield potential, but that it eventually shifts to the sink capacity (number of pods or seeds) throughout seed development. Research done by Board (1987) showed high correlation between total number of seed, number of pods, and number of nodes. Similarly, Egli (2013) determined that node numbers below a certain threshold can result in reduced seed yield; however, above that threshold, the number of pods are determined by the ability of the canopy to undergo photosynthesis and increase seed fill. In addition to total number of seeds, the mass of the established seeds directly effects overall soybean yield. Roekel, Purcell, and Salmeron (2015) suggest that planting the soybean crop early allows for longer seed filling periods leading to greater seed weights and increase yields. The only significant differences in any plant growth parameters within this study were seen in the percent of 3-bean pods in two site years; however, this did not result in a significant difference in total number of seeds or pods. Once again, as there were not differences in total node number, mainstem node number, pod number, seed number, or 100-seed weight throughout this study, it justifies the lack of differences in yield between cover crops treatments.

While not statistically significant, there were numerical differences in yield between cover crops. All cover crop treatments at the Bixby location in 2019 and nearly all at the Perkins location in 2019 resulted in less yield than what was obtained from the fallow treatment (Table 14). These differences however were nearly reversed in the later two years at Perkins. When yield loss does occur, significant or not, overall net revenue is decreased resulting in lower net income. This study did not provide evidence to suggest that planting cover crops results in consistent yield loss as this was not the case every year and neither yield nor growth parameters were significantly different. Regardless of net revenue made from the different treatments, the cost of seed should be considered before choosing a cover crop mix. Table 15 gives the price per hectare (\$ ha^{-1}) of seed planted for each cover crop mix. In future chapters, additional benefits will be discussed and can be used to provide context for financial impacts of cover crops.

Table 14. Numerical comparisons of soybean yield and gross revenue between fallow treatment and cover crop mixes. Simulated price of soybeans used was \$0.44 kg^{-1}.

	Difference in Yield from Fallow Treatment ($kg\ ha^{-1}$)				
	Bixby 2019	**Perkins 2019**	**Perkins 2020**	**Perkins 2021**	**Cumulative***
Fallow	0	0	0	0	0
Rye-Oats	-184	-125	556	54	484
Canola	-1163	-164	980	28	843
Buckwheat	-582	-50	431	248	628
Sunn Hemp	-896	2	121	51	173
Chicory	-368	-33	452	337	757
Kitchen Sink	-62	332	-37	45	340
	Difference in Net Revenue from Fallow Treatment (\$ ha^{-1})				**Cumulative**
Fallow	0	0	0	0	0
Rye-Oats	-\$128.98	-\$103.16	\$197.13	-\$24.25	\$132.46
Canola	-\$577.02	-\$136.61	\$367.85	-\$51.91	-\$141.05
Buckwheat	-\$296.17	-\$61.62	\$150.47	\$70.05	\$20.26
Sunn Hemp	-\$465.07	-\$69.12	-\$16.57	-\$47.38	-\$318.77
Chicory	-\$323.79	-\$176.03	\$37.85	-\$13.05	\$171.72
Kitchen Sink	-\$167.65	\$5.94	-\$156.86	-\$120.38	\$122.61

*Cumulative values are across years at the Perkins location and does not include the Bixby location.

Table 15. Cost of seed for each cover crop treatment.

Cover Crop Mix	Cost (\$ ha^{-1})	Cost (\$ ac^{-1})
Rye-Oats	47.93	19.41
Canola	64.16	25.97
Buckwheat	39.38	15.94
Sunn Hemp	69.84	28.27
Chicory	161.68	65.46
Kitchen Sink	140.39	56.84

CONCLUSION

Cover crops have been shown to benefit cropping systems through soil conservation, soil health improvement, and weed management. However, the impacts of cover crops on subsequent cash crop yields have been inconsistent throughout literature. As cover crops do not provide financial revenue for producers, it is imperative that they do not reduce the yield of revenue-producing. This study was conducted to determine if the implementation of cover crops into a continuous cover crop/soybean rotation affected soybean growth and yield. The results of this study did not show a significant effect of cover crops on soybean growth parameters and yield. While cover crops did significantly increase percent of 3 bean pods, these differences did not translate into yield differences. The average yields of the different cover crop treatments were inconsistent throughout each year and major trends were not present. The addition of cover crops did not result in higher yields compared to the fallow treatment. Throughout all four site years, the fallow treatment yielded the least out of all cover crop treatment only once. This can be a valuable finding for producers that are considering implementing cover crops into their system. Although yield differences were not significant, the effects on revenue could be real and greatly impact the overall operation. Based on the data from this cover crops would not benefit the overall cash crop production in the continuous cover crop soybean system in Oklahoma. However, the fact that cover crops did not consistently or significantly reduce soybean yield allows for the growers to consider other benefits of cover crops such as weed management or soil health improvement.

CHAPTER IV

THE EFFECTS OF COVER CROP MIXES ON WEED MANAGEMENT OF A SOYBEAN SYSTEM

ABSTRACT

Cover crops have been documented to reduce weed pressure during the fallow season and early in the cash crop season. Due to recent disruptions in herbicide production and transport, producers have been challenged by lower herbicide availability and increased prices. These challenges in conjunction with the constant potential for herbicide resistance in problematic weed species are forcing producers to consider alternative weed control methods. The implementation of cover crops could potentially reduce the number of herbicide applications required throughout the fallow period, particularly in no-till systems, as well as in the early stages of the cash crop. To better understand the effects of cover crops on soybean growth and yield in Oklahoma soybean systems, trials were conducted in Bixby, OK in 2019 and Perkins, OK in 2019, 2020, and 2020. Treatments within the trials included four fall-planted cover crop mixes, two spring-planted cover crops, and a fallow treatment. The objectives of this portion of the study were to determine 1) if various cover crop mixes have different effects on weed

pest abundance throughout the cover crop season and 2) if the planting of cover crop mixes reduce weed presence within the cash crop season. At cover crop termination, biomass was collected in a 1 m^2 area and separated into cover crops and weeds. Weed ratings were taken throughout the cash crop season prior to herbicide applications. Throughout this study, significant differences were observed in both cover crop biomass and weed biomass between different cover crop treatments. Fall-planted cover crops consistently produced significantly higher biomass than the spring planted cover crops. The high biomass produced by the fall-planted cover crops generally resulted in significantly less weed biomass compared to both the spring planted cover crops and the fallow treatment. Although significant differences were observed in in-season weed ratings, those differences were not consistent. In future studies, emphasis should be placed on the first few weeks of the cash crop season for in-season weed ratings. Overall this study showed that planting high biomass producing cover crops in the fall can significantly suppress fallow season weed pressure. Even one less required herbicide application, particularly in no-till systems, would be financially beneficial to a producer's operation and potentially offset the cost of planting the cover crops.

INTRODUCTION

Weeds present a major detriment to production in all cropping systems. Soybean systems are no exception to this. Although several herbicide technologies are available for in-season applications in soybean crops, the economic feasibility, as well as the increased resistance and efficacies of applying those herbicides, are becoming more uncertain. Due to unforeseen global events, herbicide production and availability have decreased rapidly leading to a sharp increase in prices. The combination of rising prices, the ever-growing potential for herbicide resistance in common weed species, and further regulatory changes and restrictions are causing growers to refrain from relying solely on chemical control for weed management within their systems. As a means to relieve the continual pressures on agricultural chemicals, agronomic means to aid in weed control has been evaluated. One potential practice is the use of cover crops throughout the fallow periods in a rotation. Cover crops can decrease weed species by competing for light, water, and nutrient resources. Reddy (2003) found that rye as a cover crop in the winter season resulted in significantly lower density of two major weeds in that particular soybean system due to the high biomass that rye produces throughout the winter. Another study by Lou, Davis, and Yannarell (2015) suggests that allelochemical activity from certain cover crops can promote weed control in the short term for the cash crop season. Allelopathic chemicals released by plants have been studied and determined to reduce weed seed emergence and growth; however, there is still much to be learned about this area of weed control. A portion of this study aimed to determine: 1) if various cover crop mixes have different effects on weed pest abundance throughout the cover crop season and 2) if the planting of cover crop mixes reduce weed presence within the cash crop season.

MATERIALS AND METHODS

Field Trial

The data to be discussed in this chapter were collected from the Oklahoma field trials explained in Chapter III. The cover crop and soybean management were identical to those discussed in the previous chapter. Methods for data collected and shared in this chapter are given below.

Data Collected

Pre-Season and In-Season Weed Management

Biomass samples were collected from each plot immediately before cover crop termination. All above ground matter was clipped at the soil surface from a 0.25 m^2 area. The plant biomass from each plot was separated into a cover crop category and a weed category. The weed category was further separated into several subcategories of prominent weed species/weed groups present at that trial location. Those weed subcategories changed between location and year as specific weed species and groups varied. Once all plant materials were separated into paper bags, they were placed into drying ovens and dried at 115^{o}C for at least 96 hours. After being completely dried, each bag was weighed to quantify the amount of each category for each plot. All cover crop biomass in the fallow treatments equaled 0 g as no cover crops were planted in those plots. The weeds that remained in the field were terminated along with the cover crops before soybean planting.

Before each in-season soybean herbicide application was made, qualitative weed ratings were taken for each plot following. The weed ratings were made on a 0-10 scale with 0 representing plots with 0% identifiable weed cover and 10 representing plots with approximately 100% weed coverage. In these ratings, any remaining cover crops that were not successfully terminated by the burndown or successive chemical application. These qualitative ratings will be used to determine differences in weed management properties of the various cover crop mixes.

Data Analysis

All data was analyzed using SAS v. 9.4 (SAS Institute Inc., Cary, NC) to evaluate impacts of cover crop treatments on fallow season cover crop and weed biomass and in-season percent weed coverage. Cover crop treatments were considered fixed effects while replication and its interactive effects were considered random effects. Both year and location had a significant impact on the influence of treatments on weed counts, as verified by analysis, therefore further analysis was carried out separately for both location and year. Analysis of variance was conducted using Procedure Mixed (PROC MIXED). Post-hoc analysis was done with a Tukey adjustment to determine differences between individual mean values. An $\alpha = 0.05$ was used for all analysis.

RESULTS

Biomass Weights

Bixby 2019

Significant differences in cover crop biomass amounts were present among the different treatments at the Bixby location in 2019 (Figure 12). The highest biomass producing treatment was the combination rye-oats weighing 306.2 g 0.25m^{-2} and was significantly higher than the other treatments. The lowest biomass producing cover crop treatments were the spring planted treatments of the chicory mix and the sunn hemp mix with weights of 10.4 and 4.3 g 0.25m^{-2} respectively. Important to note, little biomass was produced in the fall planted cover crops throughout winter with the majority of biomass growing in the spring (Image 1). Both mixes were significantly less than all other treatments apart from the fallow treatment which was not significantly different in biomass weight. The other fall planted treatments, canola, buckwheat, and kitchen sink produced significantly less biomass than the rye-oats mix, but significantly higher than the spring planted and fallow treatment (Image 2).

There were also significant differences in weed biomass weights between the different cover crop treatments at the time of cover crop termination (Figure 13). Almost inversely, the highest weed biomass weights were found in the spring planted cover crop treatments and the fallow treatment. The sunn hemp treatment had the highest weed biomass of any cover crop treatment with a weight of 11.4 g $0.25m^{-2}$. Chicory and fallow treatment had slightly lower, but not significantly different weed biomass amounts present from the sunn hemp mix. Significant differences did occur with the fall planted cover crop mixes resulting in significantly lower weed amounts. The rye-oats mix and the kitchen sink mix had the lowest weed biomass amount at 0.3 g $0.25m^{-2}$. The canola and buckwheat mixes had slightly higher weed amounts but were not significantly different from the rye-oats and kitchen sink mixes and were still significantly lower than the chicory, sunn hemp, and fallow treatments.

When looking at three predominant weed types, grasses, mustards (Shephard's purse (*Capsella bursa-pastoris*), flixweed (*Descurainia sophi (L.) Webb ex Prantl*), and tansymustard (*Descurainia pinnata (Walt.) Britt.*)), and henbit (*Lamium amplexicaule*), there were significant differences between cover crop mixes and the amounts of those particular weed types present (Figure 14). All cover crop treatments resulted in significantly less grass biomass when compared to the fallow treatment. This includes the sunn hemp and chicory treatments which did not differ significantly from the fallow treatment in regard to total weed biomass. Sunn hemp had significantly higher mustard biomass than any of the fall cover crop treatments but did not differ significantly from the fallow and chicory treatments. The fallow and spring cover crop mixes all had significantly higher henbit biomass when compared to the fall planted treatments. The fall cover crop treatments had no significant differences in the weights of the different types of weeds.

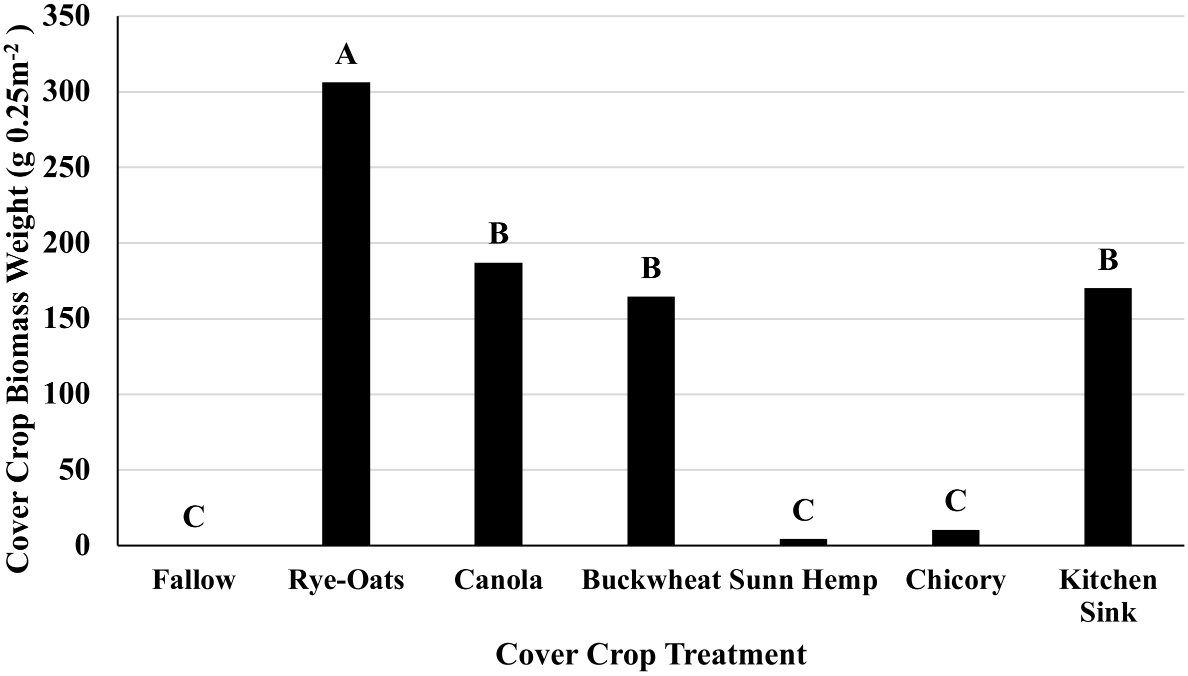

Figure 12. Total cover crop biomass collected at cover crop termination for the Bixby 2019 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

Image 1. Examples of fall planted cover crop biomass growth from February 1 (left), March 13 (middle), and May 13 (right).

Image 2. Differences in biomass between spring planted cover crops (middle) and fall planted (left side and right side).

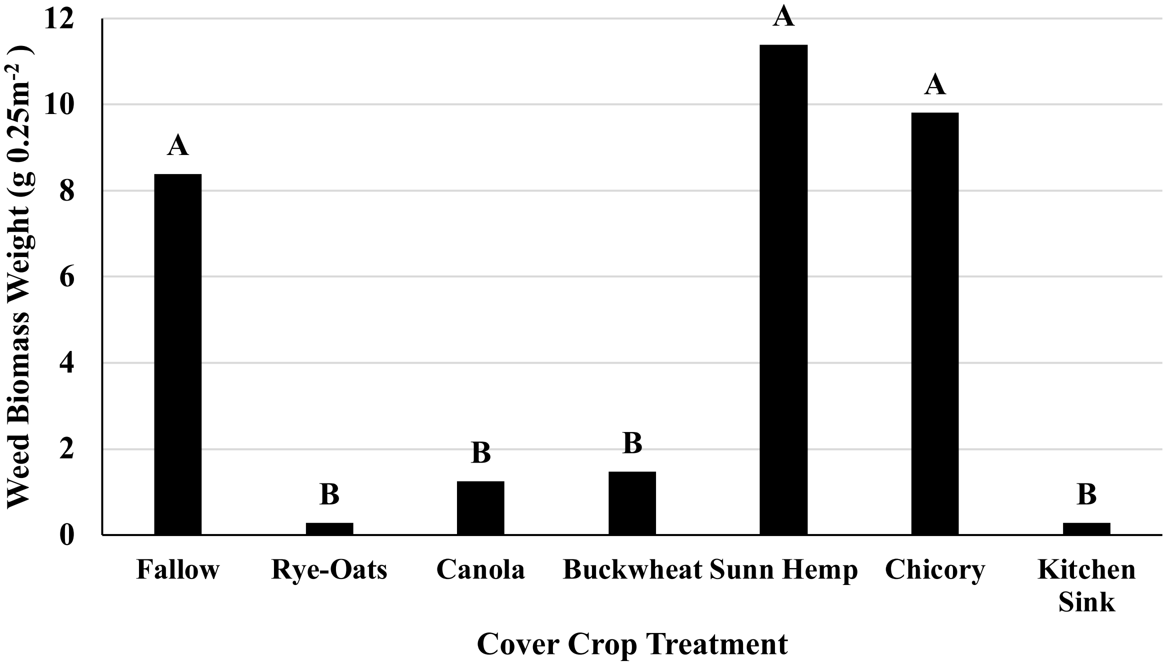

Figure 13. Total weed biomass collected at cover crop termination for the Bixby 2019 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

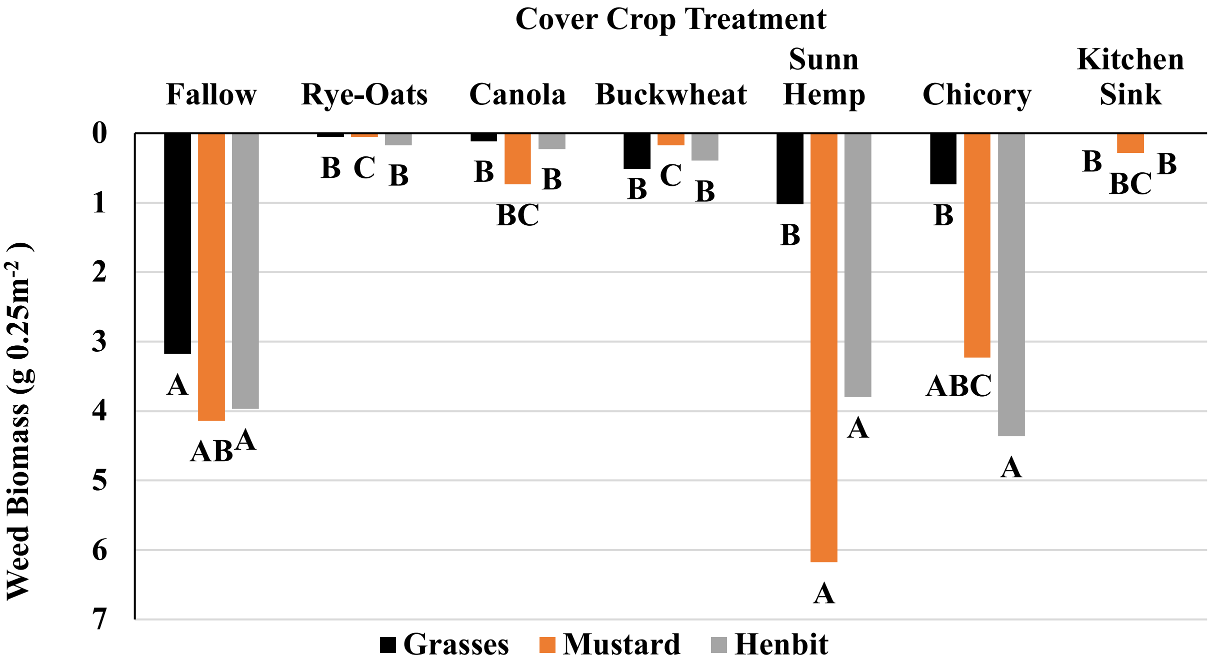

Figure 14. Weights of grasses, mustards, and henbit present in different treatments collected at cover crop termination for the Bixby 2019 location. Differing letters denote significant differences in weights between cover crop mixes within specific weed types due to the main effect of cover crop treatment (*a* = 0.05).

Perkins 2019

The cover crop biomass production significantly differed between cover crop treatments at the Perkins location in 2019 (Figure 15). Much like the 2019 Bixby location, the rye-oats mix yielded the highest amount of cover crop biomass at a weight of 136.1 g $0.25m^{-2}$. The rye-oats mix yielded significantly higher than all other treatments except for the kitchen sink mix which, although had a lower biomass weight, was not significantly different. Once again, the fallow treatment along with the spring planted mixes, chicory and sunn hemp, produced the lowest biomass throughout their season and was significantly less than the fall planted treatments. The chicory and sunn hemp treatments produced 7.6 and 5.6 g $0.25m^{-2}$ respectively, not significantly different from the fallow treatment. The canola and buckwheat mixes had biomass weights that were significantly less than the rye-oats mix, but not significantly different than the kitchen sink mix.

Significant differences in weed biomass weight varied significantly between cover crop treatments (Figure 16). The fallow treatment had the highest accumulation of weed biomass when compared to all other treatments with a weight of 49.8 g $0.25m^{-2}$. This difference was significant, even in regard to the sunn hemp and chicory treatments. The sunn hemp and chicory mixes had significantly lower weed biomass weights than the fallow treatment; however, these weights were significantly higher than all four fall planted treatments. The fall planted mixes, rye-oats, canola, buckwheat, and kitchen sink did not have any significant differences in weed biomass when compared to each other. The rye-oats mix again had the lowest amount of weed biomass at cover crop termination with a weight of 1.5 g $0.25m^{-2}$.

There were three predominant weed types at the Perkins location in 2019: grasses, cutleaf evening primrose (*Oenothera laciniata*), and henbit (*Lamium amplexicaule*). Significant differences between cover crop treatments were observed in both cutleaf evening primrose and henbit (Figure 17). No significant differences were found in grass biomass weights between cover crop treatments, although the fallow treatment had the highest amount of grass biomass. The fallow treatment had significantly higher biomass of cutleaf evening primrose than all other cover crop treatments with a weight of 22.6 g 0.25m^{-2}. The chicory mix had significantly higher amounts of cutleaf evening primrose than the rye-oats, canola, and buckwheat mixes. The chicory mix also had higher amounts than both the sunn hemp and kitchen sink mixes, but those differences were not significant. The sunn hemp mix had the highest amount of henbit out of all treatments with a weight of 13.0 g 0.25m^{-2}. This amount was significantly higher than all other treatments, except for the chicory treatment which although had a lower weight, the difference was not significant. The fall treatments did not have any significant differences in the weights of the different types of weeds when compared to each other.

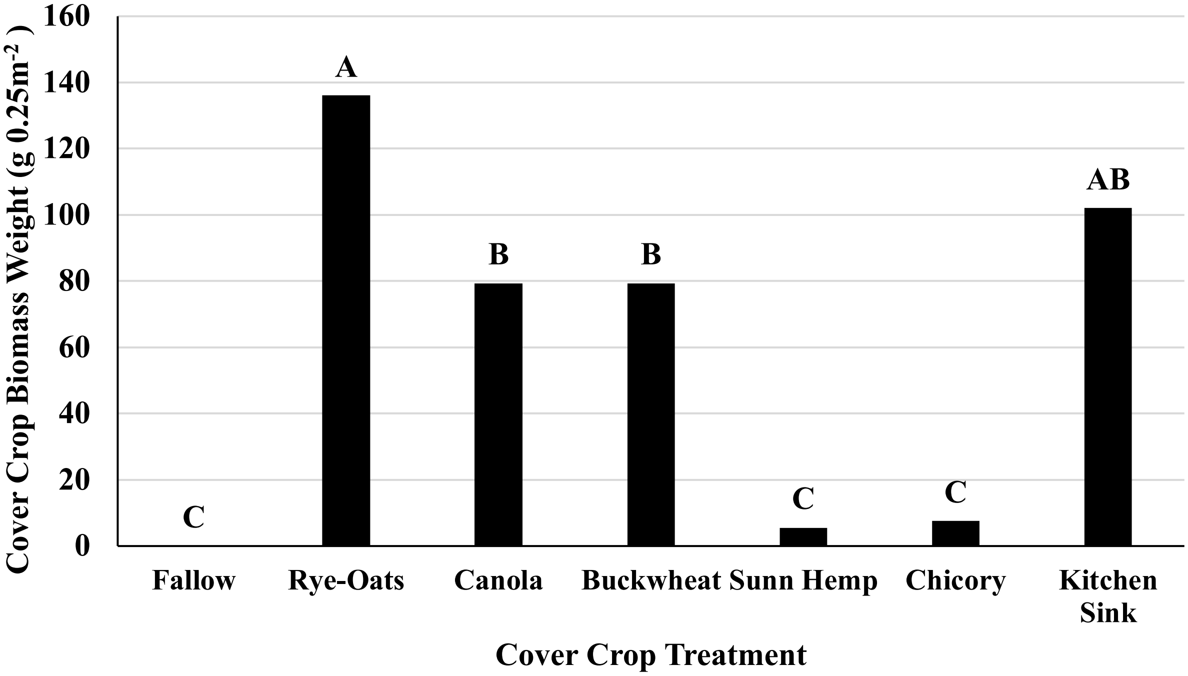

Figure 15. Total cover crop biomass collected at cover crop termination for the Perkins 2019 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

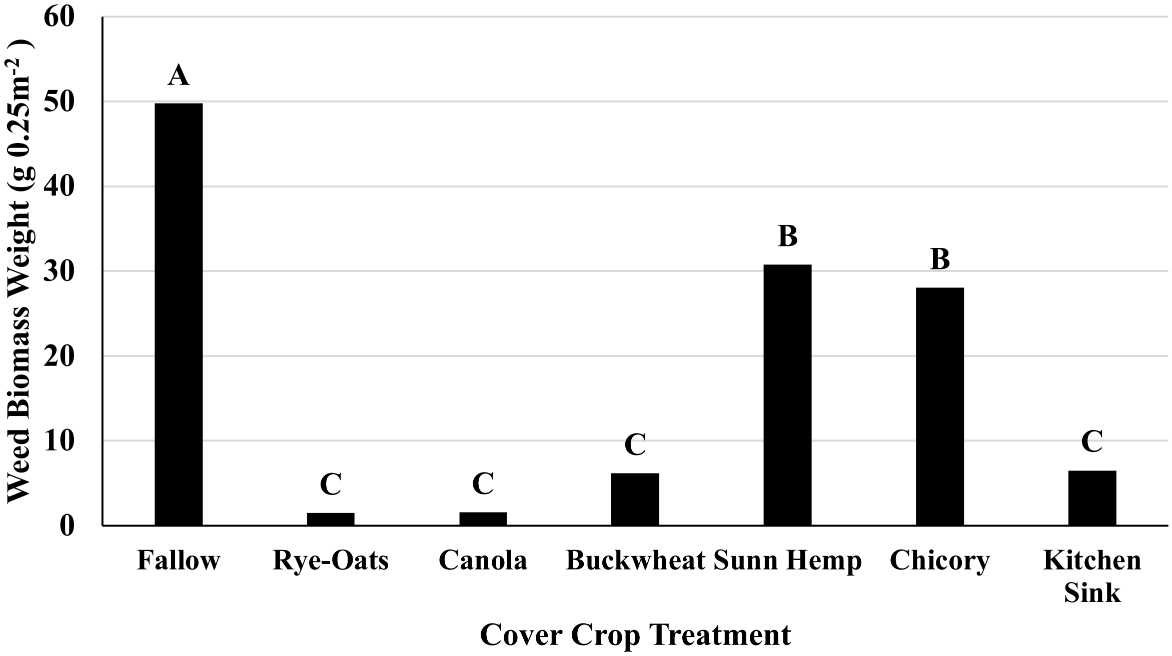

Figure 16. Total weed biomass collected at cover crop termination for the Perkins 2019 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

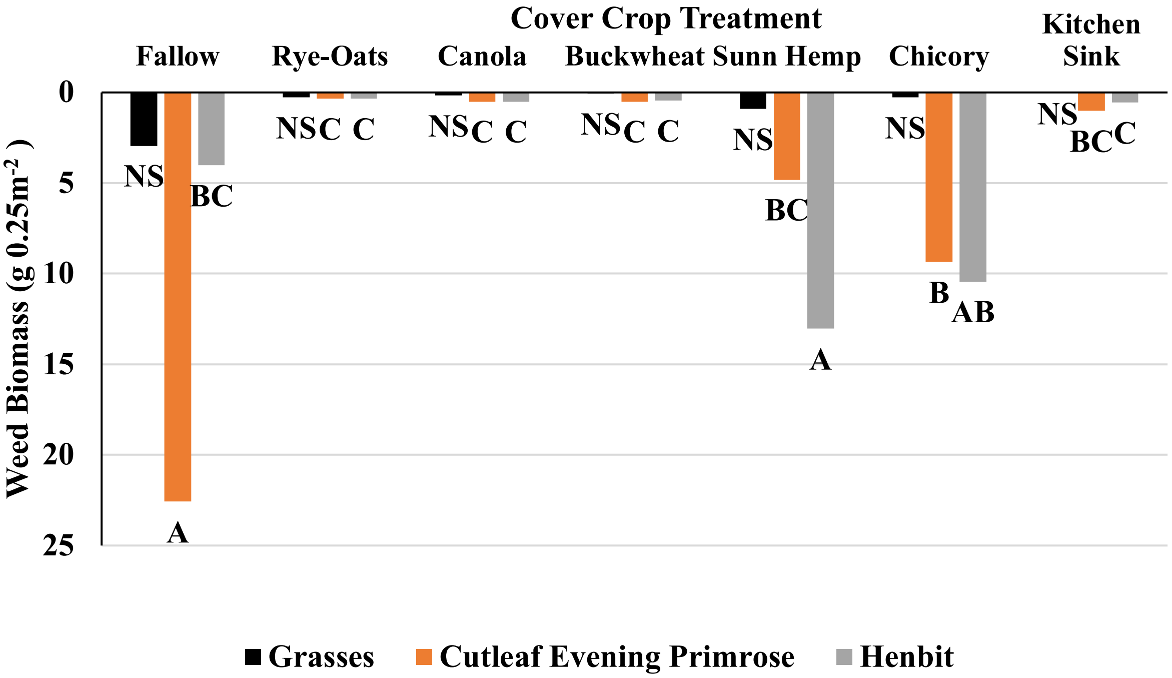

Figure 17. Weights of grasses, cutleaf evening primrose, and henbit present in different treatments collected at cover crop termination for the Perkins 2019 trial. Differing letters denote significant differences in weights between cover crop treatments averaged across weed types due to the main effect of cover crop treatment (*a* = 0.05). NS denotes non-significance.

Perkins 2020

Total cover crop biomass weights significantly differed between cover crop treatments at the Perkins location in 2020 (Figure 18). Much like both locations in 2019, the fall planted cover crops yielded significantly higher biomass than the fallow and spring planted treatments. The kitchen sink mix had the highest cover crop biomass at a total weight of 47.6 g 0.25m^{-2}. The fall planted buckwheat mix had significantly less biomass than the kitchen sink mix but was not significantly different than either the rye-oats or the canola mixes. The buckwheat mix still yielded significantly higher biomass than the fallow and spring planted treatments. The rye-oats and canola mixes produced numerically less biomass than the kitchen sink treatment but did not significantly differ.

When looking at the weed biomass weights for the Perkins 2020 location, there was a significant difference between the fallow treatment and the fall planted cover crops (Figure 19). The fallow treatment had the highest amount of weed biomass with a total weight of 13.6 g $0.25m^{-2}$. The fall planted rye-oats mix resulted in the lowest amount of weed biomass at a weight of 3.4 g $0.25m^{-2}$. Inconsistent with previous site years, although the weed biomass weights in the spring planted cover crop mixes were lower than the fallow treatment, they did not significantly differ. Also differing from previous results, the spring planted cover crops did not have significantly more weed biomass when compared with the fall planted cover crops.

Shepherd's purse was the only major weed pest at the Perkins location in 2020 that showed significant differences in total biomass between cover crop treatments (Figure 20). Grasses were present, but due to high variability, no significances were found. Both the fallow treatment and the spring planted sunn hemp mix had significantly higher Shepherd's purse biomass than the rye-oats, canola, and kitchen sink mixes. The fall planted buckwheat mix along with the spring planted chicory mix had higher Shepherd's purse biomass than the rye-oats, canola, and kitchen sink mixes but lower biomass than the fallow and sunn hemp treatments. However, these differences were not significant.

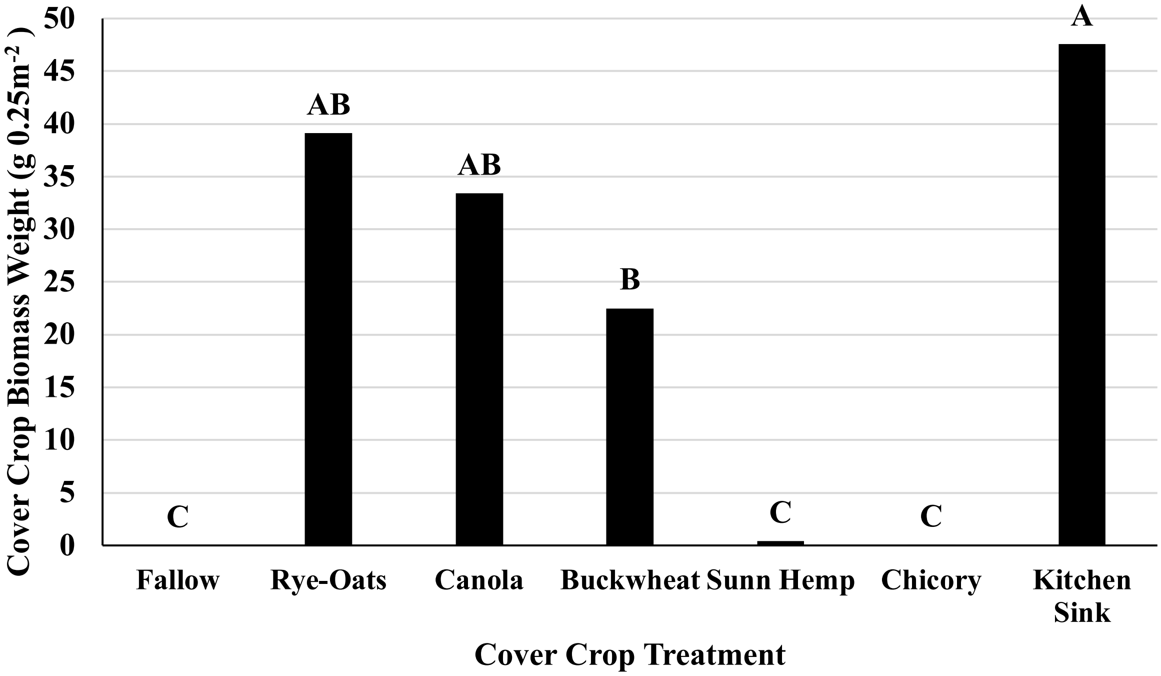

Figure 18. Total cover crop biomass collected at cover crop termination for the Perkins 2020 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

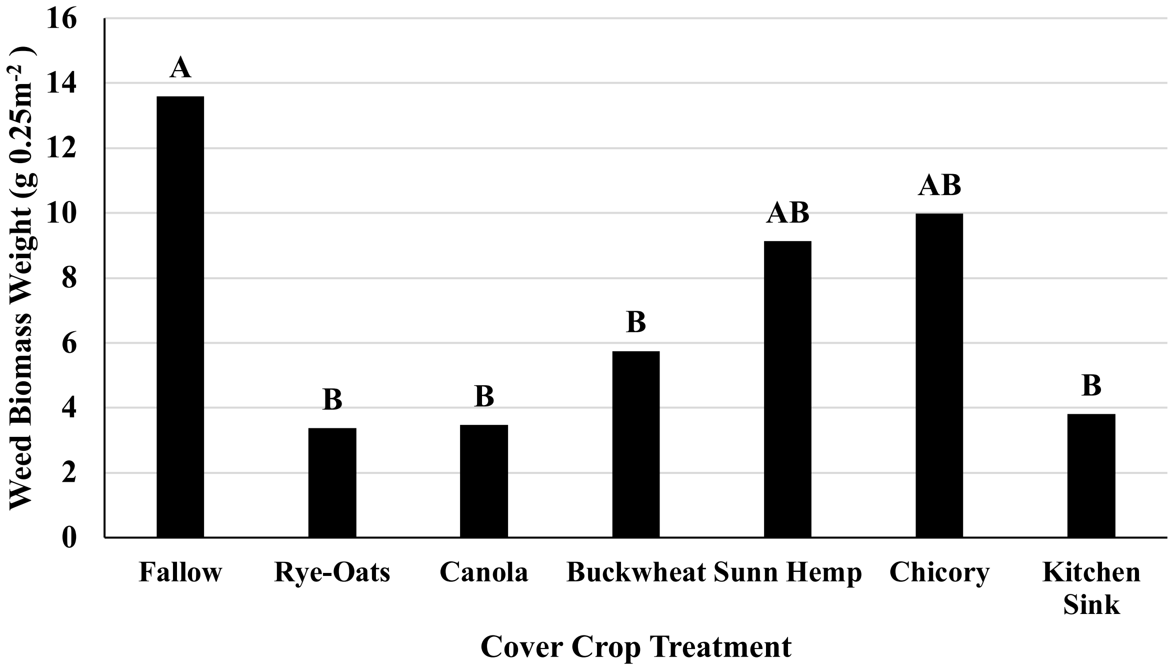

Figure 19. Total weed biomass collected at cover crop termination for the Perkins 2020 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

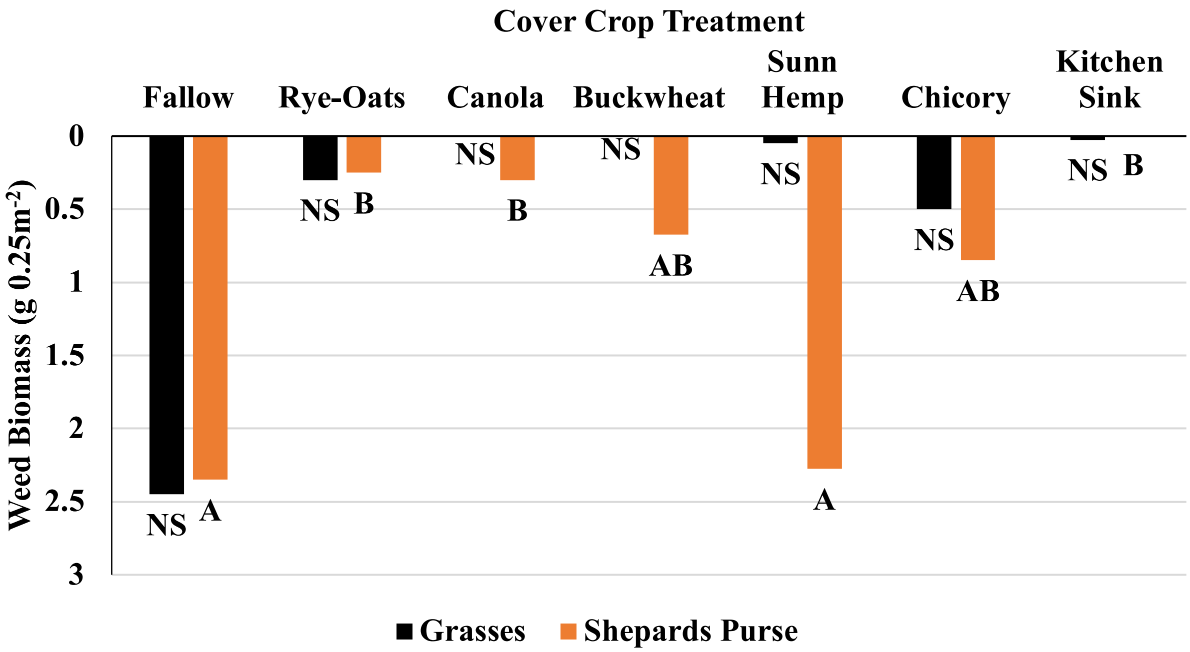

Figure 20. Weights of grasses and Shepherd's purse present in different treatments collected at cover crop termination for the Perkins 2020 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05). NS denotes non-significance.

Perkins 2021

The Perkins 2021 location had significant differences in cover crop biomass weights between different cover crop treatments (Figure 21). The rye-oats mix had significantly higher biomass than all other treatments, including the other fall planted mixes. However, similar to all previous site years, the fall planted cover crop treatments had significantly higher cover crop biomass production than the fallow and spring planted treatments.

Unlike the other site years, there were no significant differences in weed biomass weights at the Perkins 2021 trial (Figure 22). The chicory had the highest weed biomass weight at 24.4 g 0.25m^{-2}. The treatment with the lowest weed biomass present was the kitchen sink mix at a total of 7.7 g 0.25m^{-2}.

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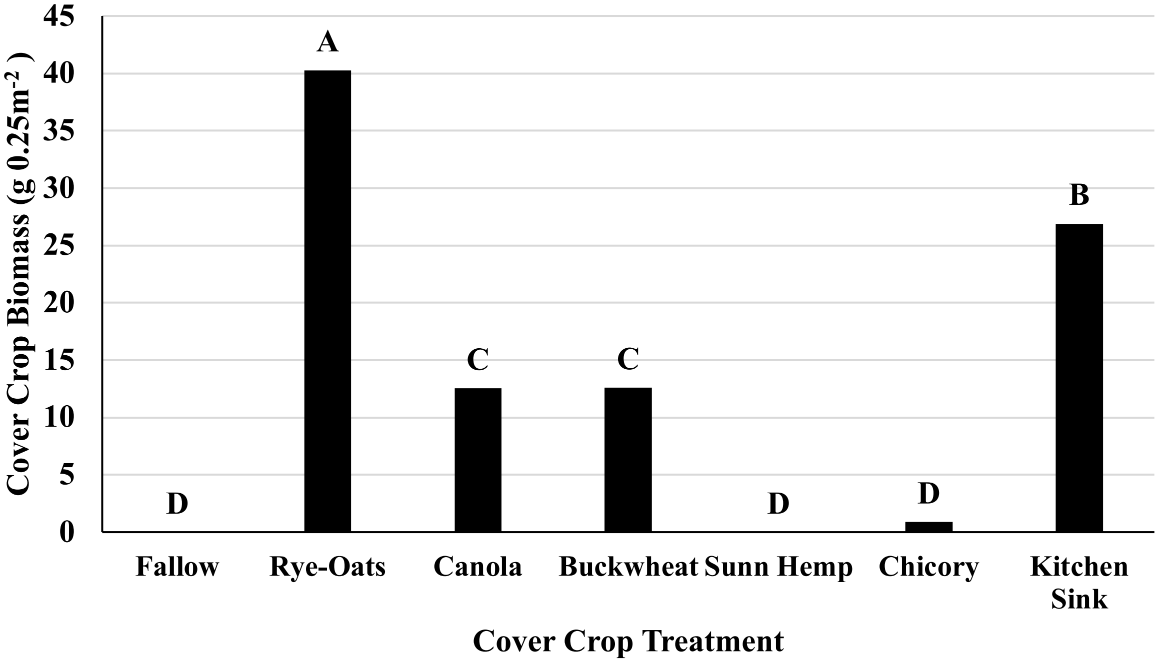

Figure 21. Total cover crop biomass collected at cover crop termination for the Perkins 2021 trial. Differing letters denote significant differences in weights between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

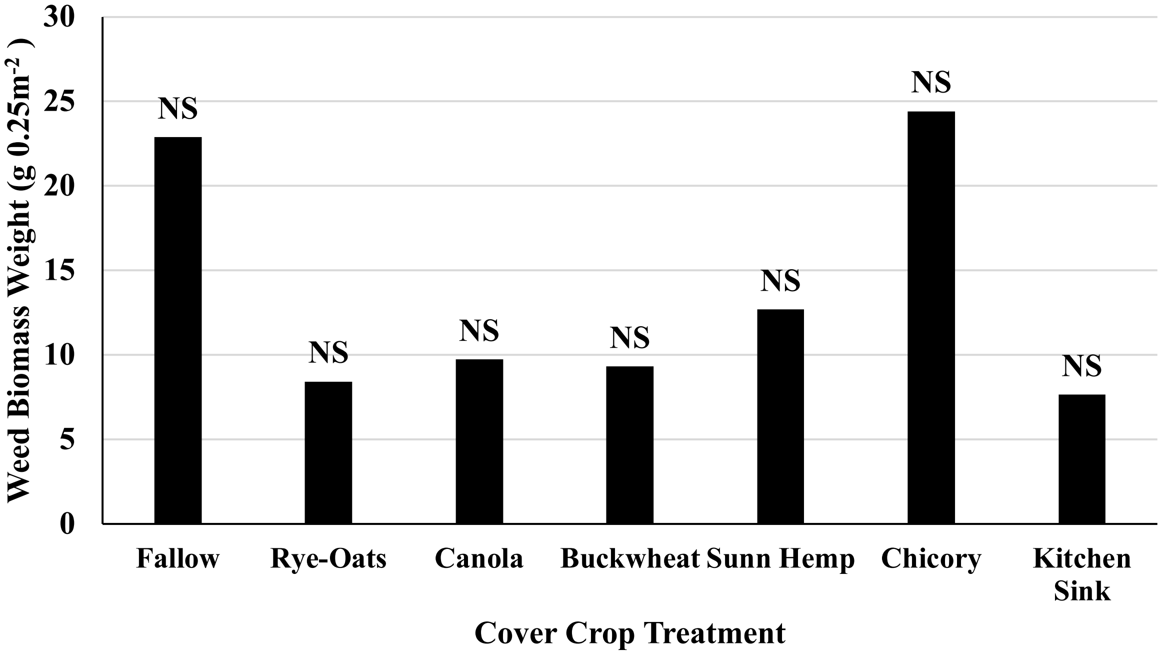

Figure 22. Total weed biomass collected at cover crop termination for the Perkins 2021 trial.

In-Season Percent Weed Coverage

In-season ratings were taken periodically throughout the soybean season before herbicide applications were made, therefore, the dates of ratings were not consistent between years (Table 16). There were significant differences in percent weed coverage at the Bixby location in 2019; however, all other site years had no significant differences between treatments. As noted through the CVs in Table 16, the variation of percentages within most treatments were high with some even around 90%. At the Bixby 2019 location, the canola and kitchen sink mixes had significantly higher percent weed pressure than all other treatments except for the sunn hemp treatment. The canola treatment had the highest percent weed coverage at an average of 40% while the lowest percent weed coverage was observed in the chicory mix which averaged between 10-20%. For the first herbicide application made in Perkins 2020, the highest percent weed coverage was found in the rye-oats mix at an average of 40% while the lowest was found in the buckwheat treatment at an average between 10-20% lying closer to 20%. At the second herbicide application made in 2020, the canola treatment had the highest average percent weed coverage of 20%. The rye-oats, buckwheat, and chicory mixes all had the lowest percent weed coverage with an average percentage of 10% each. For the first herbicide application at the Perkins location in 2021, the highest percent weed coverage was observed in the canola and chicory mixes at an average between 50-60% with the majority being closer to 60%. The lowest percent weed coverage was in both the fallow treatment and buckwheat mix at an average between 40-50% with the majority lying closer to 40%. And for the last herbicide application made in 2021, the rye-oats mix had the highest percent weed coverage with an average between 50-60% with most being closer to 50% and the fallow treatment had the lowest percent coverage at 20%.

Table 16. Average in-season percent weed coverage (%) for each treatment and their respective coefficients of variation for each scouting event across the length of the trial.

	Bixby 2019 (8/7/19)		Perkins 2019 (8/7/19)		Perkins 2020-1 (6/4/20)		Perkins 2020-2 (7/22/20)		Perkins 2021-1 (6/4/21)		Perkins 2021-2 (7/23/21)	
	Weed Coverage (%)	CV	Weed Coverage (%)	CV	Weed Coverage (%)	CV	Weed Coverage (%)	CV	Weed Coverage (%)	CV	Weed Coverage (%)	CV
Fallow	15.0 B*	38.5	43.3	81.0	30.0	66.7	13.3	43.3	43.3	53.3	20.0	86.6
Rye-Oats	17.5 B	54.7	40.0	66.1	40.0	90.1	10.0	0.0	50.0	60.0	56.7	44.4
Canola	40.0 A	28.9	16.7	34.6	36.7	15.8	20.0	50.0	56.7	20.4	40.0	25.0
Buckwheat	20.0 B	40.8	23.3	65.5	16.7	34.6	10.0	0.0	43.3	26.7	43.3	35.3
Sunn Hemp	30.0 AB	27.2	43.3	74.2	26.7	57.3	13.3	43.3	50.0	52.9	43.3	13.3
Chicory	15.0 B	38.5	46.7	61.9	23.3	24.7	10.0	0.0	56.7	27.0	50.0	40.0
Kitchen Sink	37.5 A	55.0	20.0	86.6	23.3	65.5	16.7	34.6	53.3	10.8	36.7	15.8

*Different letters denote significant differences in percent weed coverage between cover crop treatments (*a*=0.05).

DISCUSSION

Fallow season weed control is often accomplished using tillage machinery and/or herbicide applications. With the increasing adoption of no-tillage, the reliance on herbicide applications for weed control throughout the fallow periods has risen to numerous applications each fallow season (Kumar et al., 2020). The heavy dependence on herbicides for weed management can place extra financial constraints on producers through application and rising chemical costs. In addition, overuse of herbicides, especially those with the same mode of action (MOA), is known to produce herbicide resistance in certain weeds (Norsworthy, 2012). To combat these growing issues, cover crops have been suggested as a means to reduce the need for extensive herbicide use within the fallow period and early in the cash crop seasons (Bunchek et al., 2020; Kumar et al., 2020).

Results of this study show that various cover crop mixes resulted in significantly different total weed biomass amounts at cover crop termination for three out of four site years. Consistently throughout the trials a distinct trend held true: the higher the cover crop biomass, the lower the weed biomass. Although this seems like an obvious conclusion, it is an important one when it comes to species/mix selection. Similar research resulted in the same conclusion that cover crop biomass is the driving factor in weed suppression throughout the cover crop season (Florence et al., 2019; MacLaren et al., 2019; Mirsky et al., 2011; Osipitan et al., 2019). Florence et al. (2019) found that regardless of the number of species within the cover crop mixture, the total biomass of the weed was inversely related to the overall biomass of the cover crops. MacLaren et al. (2019) found high biomass cover crops were best at suppressing weeds due to limiting available resources. Osipitan et al. (2019) conducted a meta-analysis of 53 different studies and concluded that weed biomass was inversely related to cover crop biomass with an r^2=0.67.

Throughout this study, the fall planted cover crops produced significantly higher biomass than the spring planted cover crops and the fallow treatment at every site year. The increase in biomass is due to the longer growing season associated with earlier planting in the fall crops. Throughout the Perkins 2021 site year, overall biomass production was low due to poor growing conditions. Although the fall planted cover crops produced significantly higher biomass than the spring biomass, it did not translate into significant weed biomass reductions. This underscores the importance of high cover crop biomass accumulation throughout the fallow period. The total accumulated spring cover crop biomass, although was numerically greater than 0 g, did not significantly differ from the fallow treatment (0 g) for any site year. Within the fall planted cover crops, there were differences in accumulated cover crop biomass with some of those differences being significant. Numerically, the rye-oats mix resulted in the highest total cover crop biomass in three of the four site years with the kitchen sink mix resulting in the highest cover crop biomass the other year. These results were the opposite for the weed biomass with either the rye-oats mix or the kitchen sink mix having the lowest total weed biomass at each site year. Similarly, MacLaren et al. (2019) found that mixes consisting of mainly cereal cover crops resulted in the highest biomass accumulation and the lowest weed biomass. Osipitan et al. (2019) also noted that grass cover crops suppressed weeds better than broadleaf cover crops. As each cover crop mixture used within the study contained wheat, it suggests that the inclusion of rye and oats in the mixes resulted in the greater biomass compared to the broadleaves in the other mixes.

The spring planted cover crops only significantly reduced weed biomass compared to the fallow treatment once throughout the study in Perkins 2019. This significant difference is likely due to the significant reduction in cutleaf evening primrose (*Oneothera laciniata*) biomass present in the spring cover crop treatments compared to the fallow treatment. Although the chicory and sunn hemp cover crops significantly reduced weed biomass from the fallow treatment, they did not produce significantly higher biomass over the fallow treatment. This lack of significant difference in cover crop biomass may suggest that a weed suppression mechanism other than competition resulted in the weed biomass reduction. There is not enough evidence from this study to determine the cause; however, allelopathic activity in both chicory and sunn hemp has been discussed in literature (Bianchini, 2019; Bundit, Ostlie, and Prom-U-Thai, 2021; Skinner et al., 2012). Hypothetically, cutleaf evening primrose, could be susceptible to allelochemicals released from the spring planted cover crops. Further research would be needed to verify the interaction.

Generally, living, growing cover crops can significantly reduce weed biomass; however, when it comes to post-termination control with cover crop residues, the weed control is limited (Teasdale et al., 2007). Osipitan et al. (2018) found that terminated cover crop residues can suppress weeds into the early cash crop season. Cover crop residues in high amounts have the ability to postpone or reduce weed seed emergence in the early stages of the cash crop season, potentially delaying or eliminating an early season post-emergence herbicide application (Saini, Price and van Santen, 2006). Mirsky et al. (2019) share the value of delaying cover crop termination as a means to increase total biomass which could lead to altering competitive weed species' germination allowing for greater early season crop growth.

Results from the in-season weed percent coverage ratings were not as straightforward and conclusive as those from the biomass collections. There were significant differences in the Bixby 2019 site year although those were not consistent throughout the remainder of the trial. However, those significant differences do shed light on one potential problem associated with cover crop systems. In certain situations, cover crops grown during the fallow season can become a major weed pest throughout the cash crop season (Ingels et al., 1994). The canola and kitchen sink cover crop treatments had significantly higher weed coverage than all other treatments except for the sunn hemp mix. When taking weed percent coverage ratings, it was noted that the majority of weeds within the canola mix plots and the sunn hemp mix plots were canola and sunn hemp respectively. This was also observed in the canola treatments throughout the three years at the Perkins location, although those did not result in significant differences. The chemicals used for cover crop termination and post-emergence weed control in this study did not terminate the larger canola plants and in the case of Bixby 2019, the larger sunn hemp plants. Similar results would be expected in the sunn hemp plots for the Perkins location; however, due to climatic differences between locations, the plants did not grow to be as large.

The weed percent coverage ratings in this study were taken when weed pressure throughout the trial on average warranted an application. One herbicide application was made in both locations during the 2019 season compared to two applications in the 2020 and 2021 trials. The applications made in 2019 occurred around 9 and 11 weeks after soybean planting at Perkins and Bixby respectively. In both 2020 and 2021, the first herbicide applications were made around 3 and 4 weeks after soybean planting respectively. The differences in application timings between years was partially due to high rainfall events/flooding that occurred in May 2019 shortly after planting the soybeans at both locations. Soybean emergence and early season growth was delayed and weed pressure was not an issue during this time. Another potential reason for the lack of weed pressure early in-season in 2019 could be the higher amounts of biomass associated with this year at both locations. As mentioned earlier, higher amounts of cover crop residues have a much greater effect on suppressing weed species (Mirsky et al., 2019; Osipitan et al., 2019; Teasdale et al., 2007).

Delaying the emergence of weed species in the early season of the soybeans allows for the crop to obtain a competitive advantage over the weed pests. Potentially observed within this study, but also highly confirmed throughout literature, this delay in weed emergence can allow the producer to eliminate an early season herbicide application. Using current and locally available herbicide prices of \$14.00 L^{-1} for glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri) and \$16.64 L^{-1} for dicamba (XTENDIMAX; Bayer; St. Louis, Missouri) with application rates of 1,259.7 g a.e. ha^{-1} of glyphosate mixed with 39.5 oz ha^{-1} of dicamba, one application of herbicide would cost \$52.09 ha^{-1}. This savings from eliminating one in-season herbicide application would cover the cost of seed for the lower price cover crop mixtures such as the rye-oat mix or buckwheat mix.

CONCLUSION

Cover crops have been suggested as a means to aid in weed management throughout the fallow season and early in the cash crop season. As herbicide prices and weed resistance to herbicides have been increasing, any option to limit herbicide applications can prove to be beneficial financially and ecologically. This study was conducted to determine the effects of cover crops on fallow-season and in-season weed pressure. Significant differences were observed in both fallow season weed biomass weights and one in-season weed rating. The most influential factor controlling fallow season weed biomass was cover crop biomass. High biomass producing cover crops consistently reduced fallow season weed presence. Fall planted cover crops consistently produced higher biomass than the spring planted cover crops resulting in significant differences in weed biomass except for in one site year. In-season weed ratings were not as consistent with significant differences observed in just one site year. Further research on in-season impacts of previously grown cover crops should be explored with greater emphasis on the first few weeks of the cover crop season. Planting high biomass producing cover crops in the fall can significantly suppress fallow season weed pressure. Any reduction in herbicide applications in no-till operations would be financially beneficial to a producer's operation and potentially offset the cost of planting the cover crops. Weed management, particularly through the fallow season, is a benefit of cover crops that may validate the practice of cover cropping.

CHAPTER V

THE EFFECTS OF COVER CROP MIXES ON SOIL HEALTH OF A SOYBEAN SYSTEM

ABSTRACT

The implementation of cover crops has been promoted and incentivized by the NRCS and other entities as a way to improve the soil health of agricultural systems. Cover crops have been shown to result in improved soil structure and increases in water infiltration, biological presence and activity, as well as nutrient cycling. However, literature does not consistently show these results in all environments or time-frames. To better understand the effects of cover crops on soybean growth and yield in Oklahoma soybean systems, trials were conducted in Bixby, OK in 2019 and Perkins, OK in 2019, 2020, and 2020. Treatments within the trials included four fall-planted cover crop mixes, two spring-planted cover crops, and a fallow treatment. The objective of this study was to determine the effects of various cover crop mixes on the overall soil health of a system when planted during the fallow season consistently for three years. Infiltration rates, bulk density, 24 hr CO_2 respiration amounts, and aggregate stability were determined for each treatment. In addition soil samples were sent to Ward Laboratories (Ward Laboratories

Inc.; Kearney, Nebraska) for the Haney Soil Health Test and a permanganate oxidizable carbon test. Results of this study showed few significant differences between cover crop treatments in the tested soil health properties. Significant differences were observed in CO_2 respiration, but those differences were not consistent across sampling timings. Significant differences were also observed in total, inorganic, and available P contents likely due to greater uptake in high biomass producing cover crops. Overall, significant differences in soil health indicators between cover crop treatments were rarely detected throughout the three year study. These findings can help producers gauge their expectations for the response of soil health to cover crops in a three year time frame.

INTRODUCTION

The concept of soil health aims to quantify the potential productiveness and sustainability of a given soil. The idea itself is complex as it attempts to simultaneously evaluate physical, chemical, and biological properties of the soil to form a guidance of management practices for producers. The incorporation of cover crops has been highly encouraged by the NRCS and other entities as a means to improve soil health. As intensive management practices of cropping systems, including regularly employed tillage, have been destructive to soil structure throughout time, it also has negatively impacted the overall health of the soil. Cover crops have historically been used to add diversity to systems, maintain ground cover to aid against erosion, control weed species in fallow seasons, and more (Groff, 2015). Recently, scientists and commercial soil testing research services have focused on understanding soil microbiology to improve testing for soil health and soil microbe populations. The understanding of complex relationships between soil, microbes, and plants is leading to advancements in management practices throughout agricultural production systems. One such advancement can be seen through the utilization of cover crops for the specific purposes of improving soil organic matter, soil microbial populations, microbial diversity, soil structure, etc. Kelly et al. (2021) found that cover crops improved soil health by increasing soil aggregation and decreasing soil bulk density in the short term. Wulanningtyas et al. (2021) also found improved soil health associated with the incorporation of cover crops particularly through an increase in soil organic carbon. However, inconsistent responses of soil health to different soil management practices reveal that our current understanding of factors used to determine soil health is clearly not complete. Therefore, a trial was established to determine the effects of different cover crop mixes on numerous soil health parameters over 3 years.

MATERIALS AND METHODS

Field Trial

The data shown in this chapter were collected from the Oklahoma trials discussed in Chapter III. The management of the cover crops and the soybean were identical to those previously mentioned. Methods for the collection of data presented in this chapter are given below.

Data Collected

Soil samples were collected on November 19, 2020 and 2021 to determine soil health parameters including pH, fertility, composition of microbial communities, CO_2 respiration, total C, P, and S contents, organic C content, POXC carbon content, bulk density, infiltration, and aggregate stability. In 2018, analysis of composite soil samples was conducted across each of the two trials to obtain a baseline analysis of the trial location. Table 17 displays baseline soil test results. In 2019, 2020, and 2021 composite soil samples were taken for each individual plot to evaluate the impact on a plot-by-plot basis. To attain the composite samples, 25 soil cores were taken from 0-15.24 cm with a 2.54 cm soil probe and were mixed. The samples taken from each plot in 2019 were submitted to the Oklahoma State University Soil, Water, and Forage Analytical Laboratory (SWFAL) for pH, and soil P and K contents. Upon arrival at SWFAL the soil samples were dried at 65°C for 6 to 12 hours and ground and sieved through 2mm sieves. The pH value of each sample was determined by adding 10 mL of water to 10 g of soil, letting the mixture equilibrate for 30 minutes, and then read with a glass electrode pH meter. To quantify the P and K levels within the soil, 20 ml of Mehlich-3 solution mixed with 2 g of soil, shaken for five minutes before being filtered and analyzed by an inductively coupled plasma (ICP) instrument.

Table 17. Baseline soil test results for beginning of trial.

	Bixby	Perkins
pH	6.6	5.9
N (kg ha^{-1})	12.7	8.7
P (kg ha^{-1})	77.6	76.5
K (kg ha^{-1})	298.3	394.1

The soil samples from the Perkins 2020 and 2021 trials were submitted to Ward Labs (Ward Laboratories Inc.; Kearney, Nebraska) for the Haney Test and permanganate oxidizable carbon (POXC) analyses. According to Ward Labs (Ward Laboratories Inc., 2019) for the Haney Test, as the samples are received at the lab, they are dried at 50°C, ground, and sieved through 2 mm sieves. Once sieved, 8 g of each sample are evenly separated into two flasks and 40 g into a perforated beaker. Twenty mL of deionized water is added to a glass jar that contains the perforated beaker, allowing for wetting of the sample. A lid is placed on the jar and for 24 hours the sample is incubated at 24ºC. After incubation, an infrared gas analyzer, the Li-Cor 84-A (LI-COR Biosciences; Lincoln, Nebraska), is used to analyze the gas that is in the jar. This instrument provides the CO2-C measurements. One of the two remaining samples in the flasks is extracted with 40 mL of deionized water while the other is extracted with 40 mL of H3A. Each sample is shaken for ten minutes and centrifuged for five minutes. They are then filtered and the extracts are analyzed using a Lachat 8000 flow injection analyzer (Hach Company; Loveland, Colorado). The Lachat 8000 instrument provides values for NO_3-N, NH_4-N, and PO_4-P. The extracts from the water are also analyzed for organic C and total N values using the Teledyne-Tekar Torch C:N analyzer.

The Solvita CO_2 Burst Test Kit (Solvita; Mt. Vernon, Maine) was used to determine the rate of CO_2 respiration of each soil sample from the Perkins 2020 and 2021 trials. To prepare for the CO_2 burst test, samples were air-dried at 27ºC for 48 hrs and ground to pass through a 2 mm sieve. Thirty cubic centimeters of sieved soil from each sample were then placed in a 50 cc plastic beaker and between 9 and 10 mL (depending on the bulk density of the sample) of water was evenly added to each beaker. Once the water fully and evenly infiltrated the soil, a CO_2 detector probe was placed in each beaker which was now in a larger container promptly sealed with a lid. The beakers were left untouched for 24 hours at a constant 27ºC. After 24 hours, the CO_2 detector probe was inserted into a Solvita Digital Color Reader Instrument (Solvita; Mt. Vernon, Maine) to determine color and mg kg^{-1} of CO_2.

Further soil health data was collected in the Perkins 2020 and 2021 trials through bulk density and infiltration measurements. Bulk density cores were collected from 0 to 5.08 cm from each plot. Each core had a diameter of 5.08 cm and a height of 5.08 cm. The cores were oven-dried at 46ºC for 72 hours and then weighed. To find the bulk density values, the mass of each core was divided by the volume, 103 cm^3. To quantify infiltration rates, double-ring infiltrometers of 10 cm in height were driven 3 cm into the soil in each plot. The remaining 7 cm above ground of both rings were filled with water and a stopwatch was set. Measurements were taken every two minutes from the top of the inner ring to the water surface to record the displacement over time. Measurements were taken for 30 minutes. For the 2020-2021 season, the bulk density core samples were ground and used to determine wet aggregate stability for each plot. The method used for wet aggregate stability was by Kemper and Rosenau (1986). Oven-dried soil was passed through a 2 mm and 1 mm sieve. Four grams of soil aggregates that passed through the 2 mm sieve (<2mm) but remained in the 1 mm sieve (>1 mm) were used for the analysis. The soil was placed on the sieving apparatus and lowered into canisters containing 100 ml of deionized water. The sieving apparatus was submerged into the distilled water for 10 min so that the water covered the soil. After submersion, the sieving apparatus raised and lowered the sieve 1.3 cm, 35 times min^{-1} for 3 min. The cans were then removed from the apparatus with the soil particles and fragments that broke off and traveled through the sieve. New cans were added to the machine containing 100 ml of a dispersing solution containing 2 g of NaOH L^{-1}. The soils were then lowered and raised into the dispersing solution for 5 min. At the end of the 5 min interval, if any aggregates remained on the sieve, the aggregates were rubbed across the screen to ensure that only sand particles remained on the sieve. The 5 min sieving process was repeated twice more. Following the sieving intervals, both cans that collected soil particles throughout the sieving process were placed in a convection oven and dried at 110°C until all water had evaporated. The weight of the dried soil remaining in the cans was determined and recorded. For the canister that contained the dispersing agent, 2 g was subtracted to account for the dispersing agent solutes left on the soil. To determine the aggregate stability, the mean weight diameter was found using the following formula by Moncada et al., 2015:

(1) $MWD = \frac{Ws*d}{Wt}$;

Where:

MWD = mean weight diameter
Ws = weight of stable aggregates
d = mean diameter of aggregate (1.5 mm)
Wt = sum of Ws and the weight of the unstable aggregates

At the end of the study, a particle size analysis test was conducted to determine % sand, % silt, and % clay for the trial. As treatments would have no influence on the soil texture, one composite sample was collected for the entire trial and was submitted to Oklahoma State University SWFAL for textural classification using the hydrometer method (Zhang, Henderson, and McCray, 2019).

Data Analysis

All data was analyzed using SAS v. 9.4 (SAS Institute Inc., Cary, NC) to determine significant impacts of cover crops on soil health indicators. Cover crop treatments were considered fixed effects while replication and its interactive effects were considered random effects. Both year and location had a significant impact on the influence of treatments on soil health indicators, as verified by analysis, therefore further analysis was carried out separately for both location and year. Analysis of variance was conducted using Procedure Mixed (PROC MIXED). Post-hoc analysis was done with a Tukey's adjustment to determine differences between individual mean values. An $\alpha = 0.05$ was used for all analysis.

RESULTS

Particle Size Analysis

The composite sample taken across the Perkins trial location was determined to be a sandy loam. The soil was comprised of 60% sand, 28.8% silt, and 11.2% clay.

Soil Infiltration Rates

Infiltration rates varied between treatments at both the Perkins 2020 and Perkins 2021 site years. These variations were only numeric and did not result in significant differences. At the Perkins location in 2020, the chicory treatment resulted in the highest total amount infiltrated over 30 min at an average total of nearly 29 mm (Figure 23). The rye-oats mixture averaged the least total amount infiltrated after 30 min at just over 14 mm. When infiltration amounts were analyzed at the intervals of 0-10 min, 10-20 min, and 20-30 min no significant differences between cover crop treatments existed (Table 18). The canola mix and the chicory mix both had infiltrated the same amount at an average of nearly 18 mm at 10 min. At 20 min, the chicory mix had infiltrated just over an average of 6 mm while the canola mix had only allowed for an average of 5 mm to infiltrate during that time. For the final interval, 20-30 min, the chicory mix had allowed for nearly 5 mm of water to infiltrate while just over 1 mm infiltrated in the canola mix. The rye-oats mix had the least amount of infiltration in all three intervals.

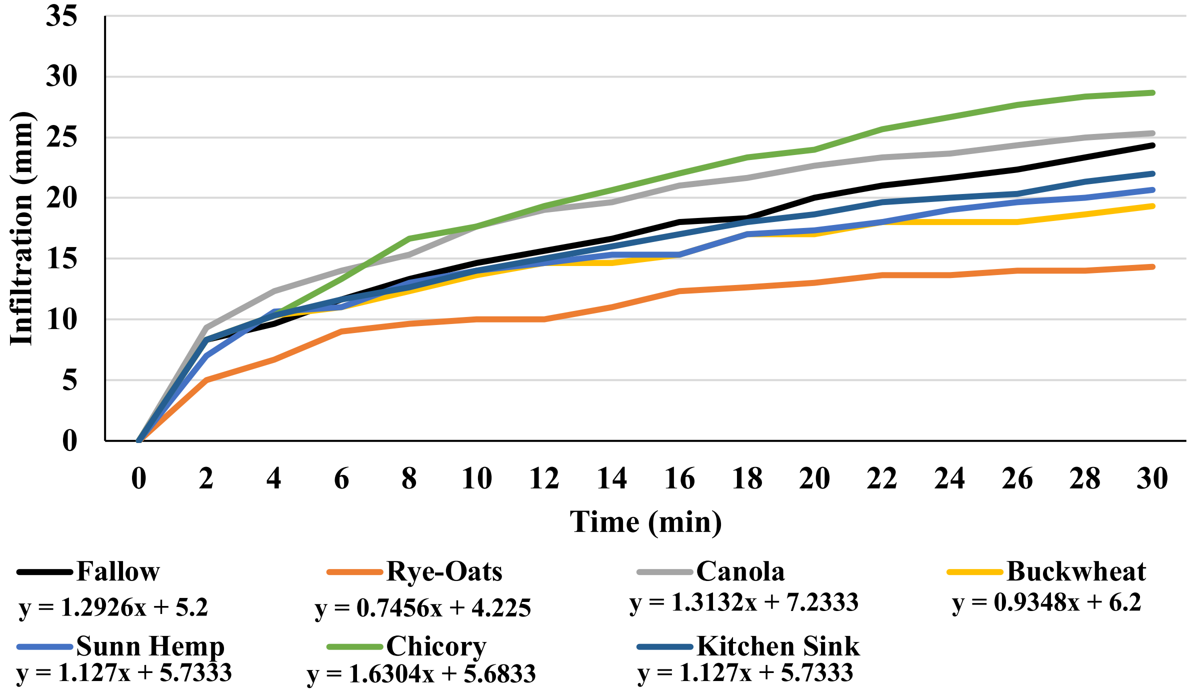

Figure 23. Infiltration amounts throughout 30 min. for each cover crop treatment at the Perkins 2020 location.

Table 18. Infiltration rates for 0-10 min, 10-20 min, 20-30 min intervals and total infiltration over 30 min. at Perkins in 2020.

	Infiltration (mm)			
	0-10 min	**10-20 min**	**20-30 min**	**Ending**
Fallow	14.7	5.3	4.3	24.3
Rye-Oats	10.0	3.0	1.3	14.3
Canola	17.7	5.0	2.7	25.3
Buckwheat	13.7	3.3	2.3	19.3
Sunn Hemp	14.0	3.3	3.3	20.7
Chicory	17.7	6.3	4.7	28.7
Kitchen Sink	14.0	4.7	3.3	22.0

Infiltration amounts differed numerically between treatments at Perkins in 2021, however, these differences were not significant. The cover crop treatment that resulted in the highest final amount of infiltration over the 30 min interval was the canola mix with an average total infiltration of just over 31 mm (Figure 24). The fallow treatment had the lowest overall average infiltration of 19 mm. There were no significant differences in infiltration amounts between cover crop treatments for the intervals 0-10 min, 10-20 min, and 20-30 min (Table 19). The canola mix had the highest average infiltration amount throughout the 0-10 min interval at 20 mm while the fallow treatment had the lowest average infiltration amount of nearly 12 mm. For the 10-20 min time interval, the canola mix once again had the greatest infiltration of just over 7 mm while unlike the first 10 min, the rye-oats mixture had the least infiltration of just under 3 mm. And finally, the buckwheat mixture showed the most infiltration through the 20-30 min interval at an average total of 5 mm. The lowest average infiltration throughout the last 10 min interval was found in the kitchen sink mix at in between 1 and 2 mm.

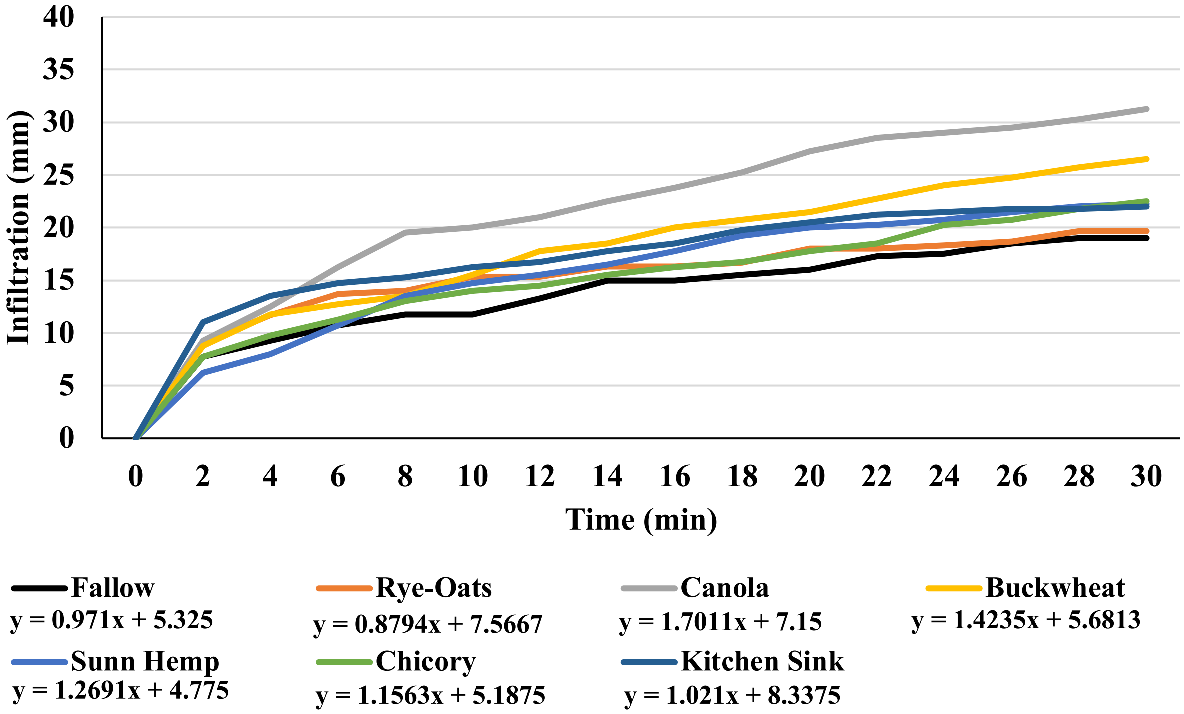

Figure 24. Infiltration amounts throughout 30 min. for each cover crop treatment at the Perkins 2021 location.

Table 19. Infiltration rates for 0-10 min, 10-20 min, 20-30 min intervals and total infiltration over 30 min. at Perkins in 2021.

	Infiltration (mm)			
	0-10 min	**10-20 min**	**20-30 min**	**Total**
Fallow	11.8	4.3	3.0	19.0
Rye-Oats	15.3	2.7	1.7	19.6
Canola	20.0	7.3	4.0	31.3
Buckwheat	15.5	6.0	5.0	26.5
Sunn Hemp	14.8	5.3	2.3	22.3
Chicory	14.0	3.8	4.8	22.5
Kitchen Sink	16.3	4.3	1.5	22.0

Bulk Density

Slight differences were observed in bulk density values between cover crop treatments and between years; however, no differences were statistically significant

(Figure 25). Across the Perkins location in 2020, bulk densities were very similar with a range of only 0.05 g cm^{-3}. The rye-oats mix had a slightly higher bulk density than all other mixes while the kitchen sink mix had the lowest. Bulk densities decreased overall in 2021 except for in the kitchen sink mix which increased by a negligible amount. The buckwheat mix resulted in the largest decrease of just over 9%, for a bulk density of 1.26 g cm^{-3}.

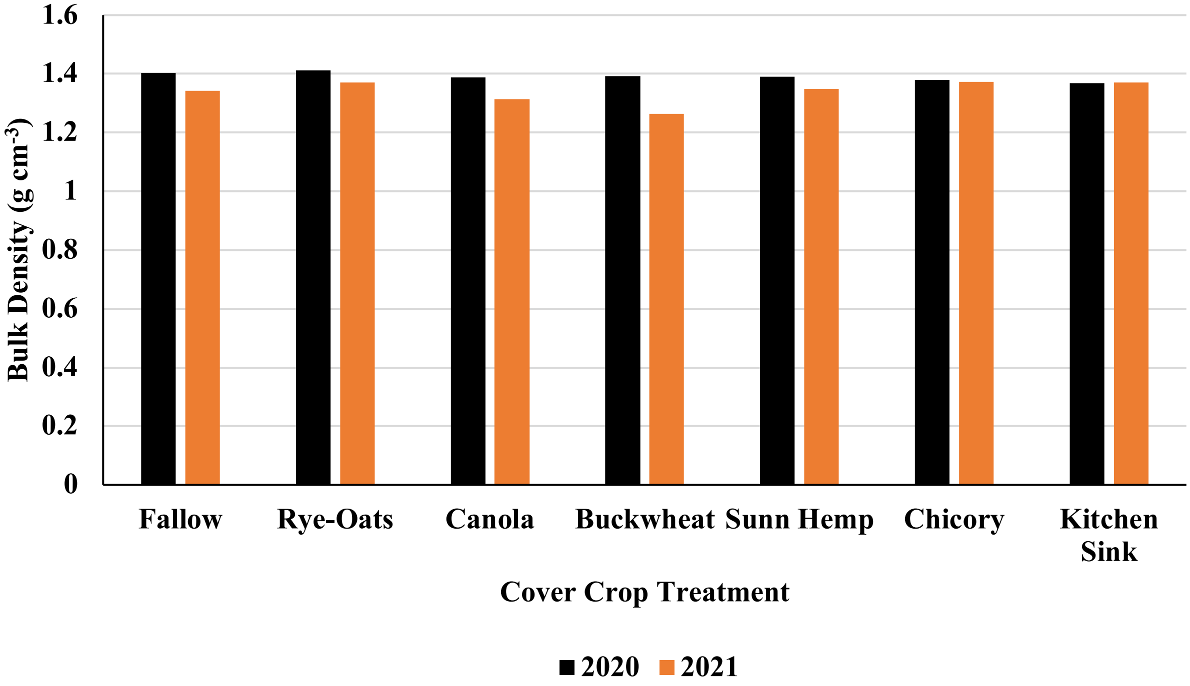

Figure 25. Soil bulk density values for different cover crop treatments from the Perkins 2020 and 2021 trials.

CO_2 Burst Test

Significant differences in CO_2-C concentrations existed between cover crop treatments at Perkins in both 2020 and 2021. In 2020 the sunn hemp mix resulted in the highest average CO_2-C production at 18.6 ppm (Figure 26). The treatment resulting in the lowest amount of CO_2-C was the rye-oats mix with an average of 8.7 ppm. The sunn hemp mix had significantly higher CO_2-C amounts than all other treatments except for the kitchen sink treatment. The rye-oats mix produced significantly less CO_2-C compared to the buckwheat, sunn hemp, and kitchen sink mixes. In 2021 the chicory and canola mixes resulted in the highest and lowest CO_2-C amounts respectively (Figure 27). The chicory mix had an average total of 15.6 ppm and was significantly higher than all treatments except for the rye-oats mix. The canola mix produced an average of 9.1 ppm CO_2-C, but was only significantly less than the chicory mix.

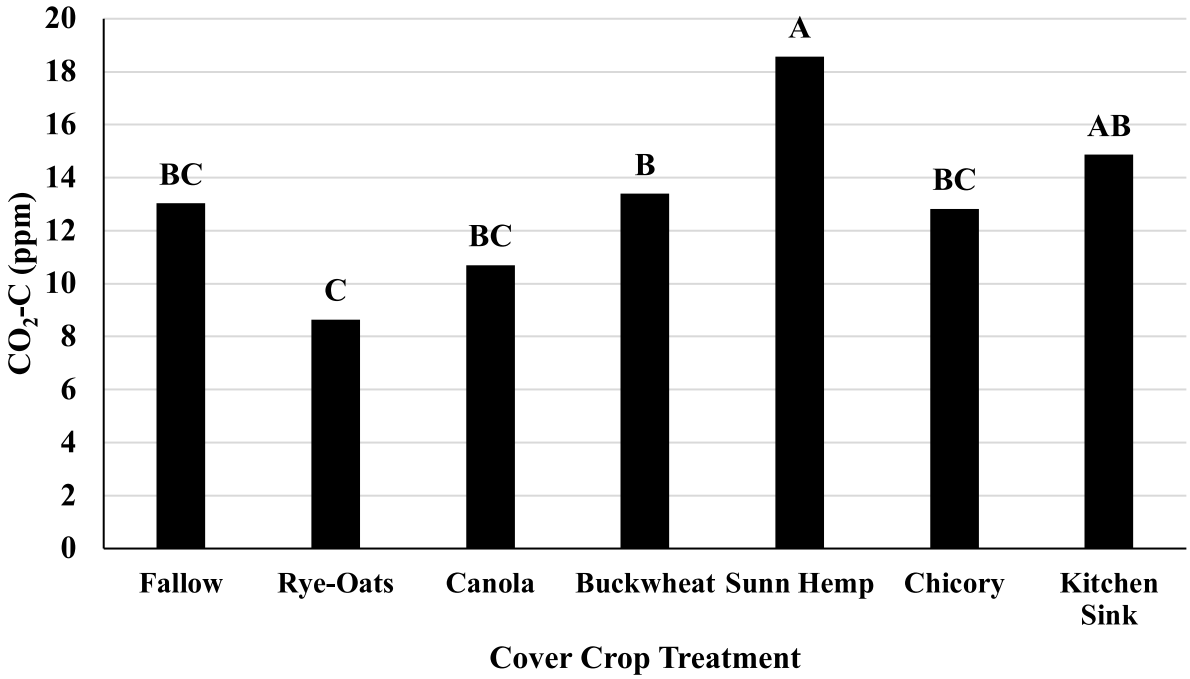

Figure 26. Average total CO_2-C (ppm) respired throughout the 24-hr Solvita CO_2-burst test for each treatment in the Perkins 2020 trial. Differing letters denote significant differences in total CO_2-C between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

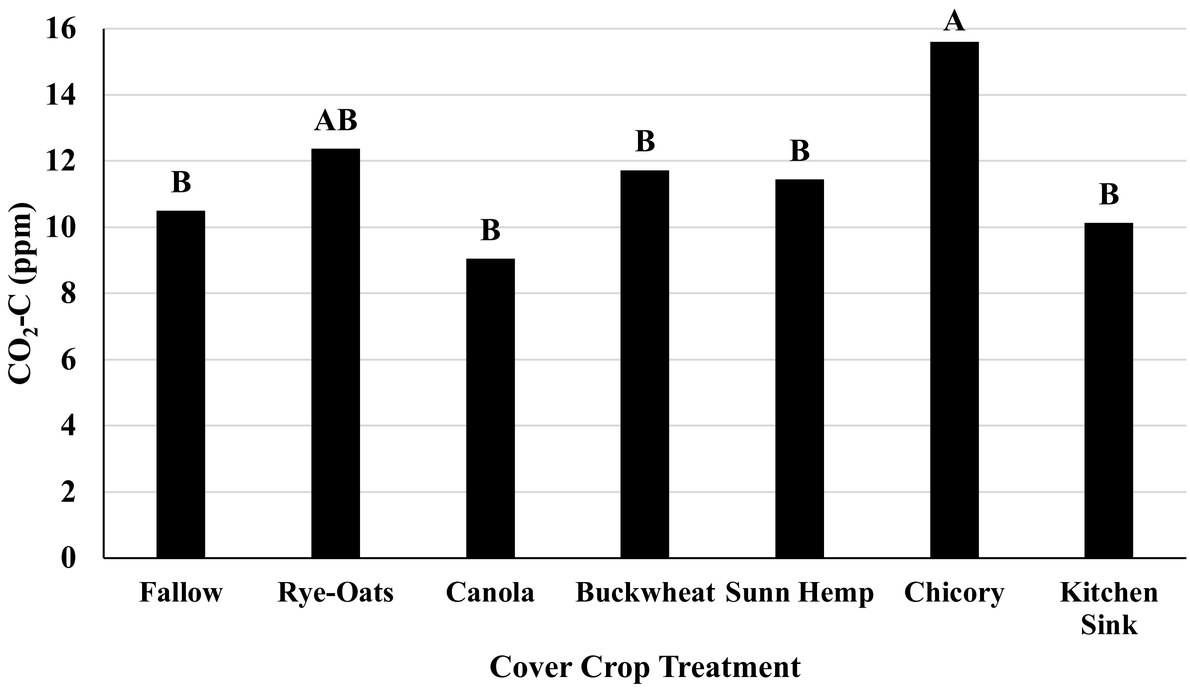

Figure 27. Average total CO_2-C (ppm) respired throughout the 24-hr Solvita CO_2-burst test for each treatment in the Perkins 2021 trial. Differing letters denote significant differences in total CO_2-C between cover crop mixes due to the main effect of cover crop treatment (*a*=0.05).

Haney Soil Health Test Results

Significant differences in several components of the Haney soil health test were present throughout the trial (Table 20 and 21). The main effect of year had the greatest impact on the soil health components. Soil pH and buffer pH values significantly decreased from 2020 to 2021 by 0.4 and 0.2 respectively. Organic matter also significantly declined from 1.0% to 0.9%. Of the three water extractable nutrients, H_2O organic C decreased significantly by 67% from 2020 to 2021, H_2O total N and H_2O organic N did not significantly differ. Several H3A extracted nutrients significantly differed between years as well. Total P, inorganic P, ICAP K, ICAP Mn, and ICAP Na significantly decreased from 2020 to 2021 while the ICAP Fe significantly increased. Microbially active carbon significantly increased from 2020 to 2021 from 19.9 to 57.5%

MAC. The available P, available K, and nutritive values significantly decreased from 2020 to 2021 by 8.4%, 18.6%, and 19.3% respectively. H3A organic P differed significantly due to a two-way interaction between year and treatment (Table 22). All treatments in 2021 had significantly higher amounts of H3A organic P than every treatment in 2020. The chicory treatment in 2020 had the overall lowest average H3A organic P amount with only 1.8 ppm P and was significantly less than the buckwheat and kitchen sink mixture in 2020 and all treatments in 2021. The treatment with the highest average amount of H3A organic P was the fallow treatment in 2021 at 10 ppm P. The fallow treatment had a significantly higher average H3A organic P amount than the buckwheat mixture in 2021 and all treatments in 2020.

For all soil health indicators that were significantly influenced by the main effect of year, further analysis was conducted within each year separately (Table 23). Through these analyses, it was found that H3A total P, H3A inorganic P, and available P values were significantly different between cover crop treatments in 2021. For all three indicators, the fallow treatment had the highest average totals. These average values from the fallow treatment were significantly higher than the average values of the rye-oats, buckwheat, and kitchen sink mixes consistently for the H3A total P, H3A inorganic P, and available P. The fallow treatment also had significantly higher average available P than the canola mix. The kitchen sink mix tied with the buckwheat mix for the lowest average H3A total P but did have the lowest H3A inorganic P and available P compared to all other treatments. The kitchen sink mix had a significantly lower average amount of H3A total P than the fallow treatment, the rye-oats mix, and the chicory mix. It also had significantly lower amounts of H3A inorganic P on average compared to the fallow treatment and the chicory mix. And finally, the kitchen sink mix had significantly lower available P than the fallow treatment and the chicory treatment.

The overall soil health score reported by the Haney Soil test is determined by the following equation (Ward Laboratories Inc., 2019):

$$(2)\quad Soil\ Health\ Score = \frac{24\ hour\ CO_2{-}C}{H_2O\ Organic\ C{:}H_2O\ Organic\ N} + \frac{H_2O\ Organic\ C}{100} + \frac{H_2O\ Organic\ N}{100}$$

There were no significant differences in the soil health score detected between cover crop treatments; however, there was a significant decline from 2020 to 2021. According to Ward Laboratories Inc. (2019) a soil health score >7 is deemed acceptable, so the score for 2021 fell well below the acceptable range at 4.95.

Table 20. ANOVA table for soil health indicators that had significant differences due to a main effect of year, a two-way interaction between treatment and year, and a main effect of treatment in 2021.

	P-Values for Combined Data			2020	2021
Soil Property	**Treatment**	**Year**	**Treatment* Year**	**Treatment**	**Treatment**
Soil pH	0.37	**0.01**	0.69	0.58	0.29
WDRF Buffer	0.72	**0.02**	0.94	0.83	0.86
Organic Matter (%LOI)	0.39	**0.01**	0.75	0.88	0.16
H_2O Organic C (ppm C)	0.33	**<0.01**	0.20	0.84	0.19
H3A Total Phosphorous (ppm P)	0.12	**0.01**	0.35	0.57	**0.04**
H3A Inorganic Phosphorous (ppm N)	0.05	**<0.01**	0.59	0.20	**0.04**
H3A Organic Phosphorous (ppm P)	0.54	**<0.01**	**0.02**	0.09	0.12
H3A ICAP Potassium (ppm K)	0.32	**0.01**	0.64	0.67	0.28
H3A ICAP Iron (ppm Fe)	0.99	**0.01**	0.59	0.73	0.91
H3A ICAP Manganese (ppm Mn)	0.75	**0.01**	0.17	0.17	0.84
H3A ICAP Sodium (ppm Na)	0.84	**0.03**	0.28	0.56	0.55
Microbially Active Carbon (% MAC)	0.87	**<0.01**	0.57	0.47	0.80
Soil Health Calculation	0.77	**0.01**	0.56	0.51	0.88
Available P (kg P_2O_5 ha^{-1})	0.08	**0.01**	0.37	0.40	**0.03**
Available K (kg K_2O ha^{-1})	0.32	**0.01**	0.63	0.67	0.27
Nutrient Value	0.94	**<0.01**	0.89	0.92	0.90

Table 21. Haney Soil Health Test values for the Perkins 2020 and 2021 trials.

Soil Health Indicator	**Test Values***		**CV Values (%)**	
	2020	**2021**	**2020**	**2021**
Soil pH	5.7 A**	5.3 B	4.9	3.6
WDRF Buffer pH	6.8 A	6.6 B	1.5	0.9
1:1 Soluble Salt (mmho cm^{-1})	0.11	0.09	22.1	34
Organic Matter (%LOI)	1.0 A	0.9 B	12.6	12.5
H_2O Total N (ppm N)	32.5	19.3	48.6	39.7
H_2O Organic N (ppm N)	19.8	5.8	85.6	82.9
H_2O Organic C (ppm C)	174 A	58 B	11.7	15.6
H3A Nitrate (ppm NO_3-N)	8.5	10.6	54.4	39.7
H3A Ammonium (ppm NH_4-N)	5.6	4.6	52.8	19.6
H3A Inorganic Nitrogen (ppm N)	14.2	15.3	25.9	26.6
H3A Total Phosphorus (ppm P)	28 A	22 B	14	15.4
H3A Inorganic Phosphorus (ppm P)	25.6 A	12.9 B	11.8	20.4
H3A ICAP Potassium (ppm K)	112 A	91 B	8.7	12.5
H3A ICAP Calcium (ppm Ca)	253	247	18.1	19.5
H3A ICAP Aluminum (ppm Al)	318	352	11.7	11.4
H3A ICAP Iron (ppm Fe)	181 B	225 A	13.3	11.8
H3A ICAP Sulfur (ppm S)	3	3.4	17.8	14.4
H3A ICAP Zinc (ppm Zn)	0.65	0.79	24.1	9.8
H3A ICAP Manganese (ppm Mn)	18.8 A	15.2 B	10.3	9.7
H3A ICAP Copper (ppm Cu)	0.67	0.68	17.1	14.1
H3A ICAP Magnesium (ppm Mg)	77	82	12.3	10.8
H3A ICAP Sodium (ppm Na)	17 A	13 B	7.5	11.7
Microbially Active Carbon (%MAC)	19.9 B	57.5 A	43.1	15.2
Organic C : Organic N	12	11.8	42.3	26.5
Organic N : Inorganic N	1.5	0.4	82.4	68.2
Organic N Release (ppm N)	12.6	5.8	50.6	82.9
Soil Health Calculation	8.40 A	4.95 B	13.7	15
Available N (kg N ha^{-1})	54.0	41.2	30.2	33.7
Available P (kg P_2O_5 ha^{-1})	69.7 A	56.9 B	12.1	15.6
Available K (kg K_2O ha^{-1})	150.4 A	122.4 B	8.7	12.5
Nutrient Value \$ ha^{-1}	338.4 A	273.2 B	8.8	9.7

***H3A organic phosphorus was excluded from the table as it was significantly affected by a two-way interaction between year and cover crop treatment. ** Differing letters denote significant differences in soil test values between years of the trial due to the main effect of year (*a*=0.05).**

Table 22. Average H3A Organic P values with significant differences due to a two-way interaction between year and treatment.

Year	Treatment	H3A Organic P (ppm P)
2020	**Fallow**	2.6 DE*
2020	**Rye-Oats**	2.8 CDE
2020	**Canola**	2.4 DE
2020	**Buckwheat**	3.8 C
2020	**Sunn Hemp**	2.6 DE
2020	**Chicory**	1.8 E
2020	**Kitchen Sink**	3.5 CD
2021	**Fallow**	10.0 A
2021	**Rye-Oats**	9.1 AB
2021	**Canola**	9.2 AB
2021	**Buckwheat**	8.7 B
2021	**Sunn Hemp**	9.1 AB
2021	**Chicory**	9.5 AB
2021	**Kitchen Sink**	9.0 AB

***Differing letters denote significant differences in average H3A organic P values between year by cover crop combinations due to the two-way interaction between year and cover crop treatment(*a*=0.05).**

Table 23. Indicators with significant differences between different cover crop treatments for Perkins in 2021.

	H3A Total P	H3A Inorganic P	Available P
Fallow	24.3 A*	14.4 A	62.6 A
Rye-Oats	21.0 B	12 BC	54.4 BC
Canola	22.3 ABC	12.9 ABC	56.8 BC
Buckwheat	20.8 C	12.3 BC	53.8 BC
Sunn Hemp	22.3 ABC	13.2 ABC	57.5 ABC
Chicory	23.3 AB	13.7 AB	59.6 AB
Kitchen Sink	20.8 C	11.7 C	53.4 C

***Differing letters denote significant differences in soil test values between cover crop treatments due to the main effect of cover crop treatment(*a*=0.05).**

POXC Test Results

No significant differences were detected in POXC measurements between years or treatments (Table 24). In 2020 POXC measurements ranged from 734 ppm C (fallow) to 396 ppm C (sunn hemp). In 2021, POXC values ranged from 578 ppm C (buckwheat) to 502 ppm C (sunn hemp).

Table 24. Average POXC measurements and corresponding CV values for each treatment within the 2020 and 2021 trials at Perkins.

Treatment	2020		2021	
	POXC (ppm C)	CV(%)	POXC (ppm C)	CV(%)
Fallow	734	26.9	535	26.6
Rye-Oats	537	7.0	571	26.2
Canola	681	44.1	571	24.9
Buckwheat	558	29.2	578	30.4
Sunn Hemp	396	63.8	502	18.5
Chichory	650	36.3	545	29.8
Kitchen Sink	485	38.7	526	10.3

Aggregate Stability

Differences in aggregate stability were observed between treatments at the end of the 3-year trial in Perkins; however, these differences were not significant (Table 25). Mean weight diameter values ranged from 0.81 mm (buckwheat) to 0.69 mm (sunn hemp).

Table 25. Aggregate stability for different cover crop treatments at Perkins in 2021.

Treatment	MWD (mm)
Fallow	0.73
Rye-Oats	0.76
Canola	0.80
Buckwheat	0.81
Sunn Hemp	0.69
Chicory	0.80
Kitchen Sink	0.78

DISCUSSION

Cover crops have been shown to improve the overall soil health of a system through influencing soil properties that contribute to crop production and the sustainability of the system (Blanco-Canqui and Ruis, 2020). Through assessing different soil health indicators, it is possible to detect changes in soil health due to shifts in management practices, such as the implementation of cover crops. However, the extent that cover crops effect soil health properties as well as the amount of time required to detect changes are inconsistent. These inconsistent responses likely are caused by the inherent complexity involved in assessing the physical, chemical, and biological properties of soil together. Lehmann et al. (2020) discusses that skepticism surrounding the concept of soil health can be attributed to the difficulties involved in the development of a consistent and standardized assessment for soil health. They offer several examples of such difficulties, such as the need for specific regional recommendations, the variability in soil characteristics, and the potential of antagonistic ecological processes in a system (Lehmann et al., 2020). Even the currently available commercial soil health tests have been found to be inconsistent in detecting differences between management practices in medium-term trials (Chalal and Van Eerd, 2018).

Throughout this 3-year study, cover crop treatments had very little effect on overall soil health with few significant differences between treatments detected in the indicators assessed. No significant differences were observed between cover crop treatments in infiltration rates, bulk densities, POXC results, wet aggregate stability, and most soil chemical properties including organic matter as well as all N and K measurements. Cover crop treatments did have a significant effect on CO_2-burst results, H3A total P, H3A inorganic P, H3A organic P, and available P.

The lack of significant differences in the soil physical and chemical properties could be attributed to several different reasons. One possibility for few significant detections made between treatments is the relatively short time-frame of the study. Blanco and Ruis (2020) conducted a meta-analysis on research regarding the impact of cover crops on soil physical properties. They found that long-term studies (>10 years) showed a much greater impact of cover crop mixes on soil physical properties compared to medium or short-term studies and noted that several such properties are not rapidly responsive to management changes. Another potential explanation of the lack of differences in the majority of indicators is the scale of the plot trial. Wood and Bowman (2021) conducted large-scale farm research over several states and determined they were able to detect differences in soil health indicators quicker and more often than is commonly observed in plot-size research. It is important to also understand that the Haney Soil Health Test was developed through farm-scale research to better represent scenarios in which producers would make decisions (Haney et al., 2018). However, a study by Chu et al. (2019) that was designed to determine the effectiveness of the Haney Soil Health Test determined that although the concept of the test is thorough, it could benefit from more region-specific indicator selection or shifts in algorithms as the test did not determine differences between management practices as would be expected.

Further potential reasons for the absence of significant differences between cover crop treatments are the coarse soil at the location site, the sampling dates, as well as the weather leading up to sampling. As the trial was conducted in a coarse soil, certain soil health indicators may not be as affected as they would in a medium to fine textured soil (Blanco-Canqui and Ruis, 2020). In addition, the soil samples were taken a few weeks following soybean harvest each year. This date was intentional and aimed to evaluate the persistent effects of the cover crops to soil health indicators rather than the fleeting effects common directly following an introduction of residue to the soil. Hsiao et al. (2019) found high variability in sample timings throughout the year for both soil chemical and biological properties, particularly in no-till systems. Weather can also play a role in temporal variability between samples. Soil temperature and moisture play a large role in microbial abundance throughout time with hot/dry conditions often limiting certain fungal populations (Castano et al., 2017).

Significant differences between cover crop treatments were present in CO_2-burst results in both 2020 and 2021, however these differences were not consistent between years. Throughout the two years, the chicory and the sunn hemp mixes both produced significantly higher CO_2-C amounts when compared to the fallow treatment suggesting that in certain situations, cover crops can lead to greater microbial activity compared to the fallow treatment. The inconsistency between effects of cover crop treatments over the two years are not necessarily surprising as Crookston et al. (2021) found that microbial respiration results had high CV values from year to year. The temporal CVs associated with microbial respiration were much higher than OM and C:N ratios suggesting that more repetitive sampling may be needed across time to fully detect changes in biological components (Crookston et al., 2021).

Throughout this three year trial, few soil health indicators exhibited significant differences in response to cover crop treatments. The length of the trial could be a large factor in the absence of differences, as long-term trials seem to show greater effects of cover crops on soil health. Many Oklahoma producers only allow 2-3 years of a new practice (no-till, cover crops, crop rotation, etc.) to have a positive return before discontinuing the practice. The improvement of soil health is a noble plight, but in general, producers do not and cannot continue to implement a practice that costs financially and does not return financially, especially if that non-monetary return takes around 10 years to detect or benefit from.

CONCLUSION

The incorporation of cover crops into a system's rotation has been suggested as a means to improve the physical, chemical, and biological properties of the soil. Inconsistencies on the effects of cover crops on soil health throughout literature raise questions on the efficacy of such a practice. The results of this 3-year study did not show consistent measurable impacts on soil health indicators by different cover crop mixes. The individual years of the trial had more influence on soil health indicators than the imposed cover crop treatments. The significant differences observed between treatments in the CO_2 burst test suggest that cover crops can result in higher microbial respiration compared to the fallow, but no particular cover crop had consistent results. A few potential reasons for the lack of significant differences are the short-term nature of this trial, the plot sizes, the soil texture at the test site, and the lack of multiple soil sample times each year. Future research regarding cover crops and soil health could benefit from larger-scale, long-term trials on fine-medium textured soil. Sampling several times throughout each year could also allow for further distinguishing between treatments. When planting high biomass cover crops, such as for weed suppression, supplemental phosphorus may be needed to compensate for cover crop uptake. Overall, Oklahoma producers should not expect to see soil health improvements in the first three years of including cover crops into rotation.

CHAPTER VI

LATE SEASON MANAGEMENT OF SOYBEAN SYSTEMS

ABSTRACT

Challenges that arise late in the soybean season have the potential to cause drastic yield and seed quality losses. Common late season issues for soybean growers in Oklahoma include peak infestations of stinkbug insects (Heteroptera: Pentomidae) as well as delays in harvest. Oklahoma soybean harvest typically occurs during the months of October and November, busy months for wheat producers within the state. Lack of workforce or available machinery in conjunction with drastic differences in weather conditions, common within these months, can leave producers unable to harvest at the ideal time. These challenges are fairly uncontrollable; therefore, mitigation methods are necessary for yield maintenance in the late season. To determine strategies for limiting the yield reductions caused by late season complications, a study was conducted to determine the effects of a late-season insecticide treatment, a desiccation application, and delays in harvest on both soybean yield and seed quality. These trials were in Bixby and Perkins, OK in 2019, 2020, and 2021. Treatments included two levels of insecticide timing (through R5 growth state and through R7 growth stage), two levels of desiccation treatments (treated and non-treated), and three levels of harvest delays (timely harvest, 14

days delayed, and 28 days delayed). Various yield components were collected and analyzed to attempt to determine the causes of yield differences between treatments. Results of this trial showed that harvest delays negatively impact yield with average losses found up to 55 kg ha^{-1} day^{-1} when delayed 28 days. The driving factor causing these yield losses was pre-harvest pod shatter. Pre-harvest pod shatter ratings showed significant increases with each harvest delay. Another trend observed throughout the trial was that applying a late season insecticide in addition to a mid-season insecticide generally resulted in greater yield maintenance, although this additional application may not be economically justified if soybean prices are less than \$0.44 kg^{-1}. The application of a desiccant showed no consistent effects on yield. It is imperative for producers to ensure timely harvest to collect the maximum available yield. In years with high soybean commodity prices, a late-season insecticide application would be beneficial.

INTRODUCTION

Soybean production has been increasing throughout the state of Oklahoma. Much of this growth in acreage can be seen in regions of the state that have not traditionally grown soybean. Due to the added acres of soybean grown in the region, producers have encountered an increased number of challenges. Increased pressure from the stinkbug insect (Heteroptera: Pentomidae) pest has been seen in soybean growing areas. Stinkbugs can cause reductions in yield and seed quality when not managed throughout the growing season. Not only are stinkbugs a common issue in soybean systems, but time management within operation practices can be as well. Generally, soybean harvest within the state occurs in October and November. These months are typically very busy for Oklahoma producers as it is often when they will be planting winter wheat, the primary crop grown in the state. These months, especially October, are often variable in terms of temperature and rainfall. These unpredictable weather events along with the concurrence of harvest and winter crop planting, soybean harvest can often be delayed past the ideal harvest time. The delay in harvest can cause reductions in yield and seed quality through the degradation of the seed pod and or pod shatter. Managing insect pests through the beginning of seed maturity, or later than what is commonly practiced, as well as applying a desiccant can potentially aid in mitigating the potential losses due to unforeseeable harvest delays. A study was conducted to determine the effects of a late-season insecticide treatment, a desiccation application, and delaying harvest on both soybean yield and seed quality. Various yield components were collected and analyzed to attempt to determine the causes of yield differences between treatments.

MATERIALS AND METHODS

Field Trial

Field experiments were established at the Cimarron Valley Research Station in Perkins Oklahoma and the Mingo Valley Research Station in Bixby Oklahoma in 2019, 2020, and 2021. Table 26 includes the dominant soil series and their descriptions as well as the geographic coordinates for each location of the study. While the trials were located at the same stations and had the same soil series, trials were not in the same location year to year. Climatic conditions for each site year are given in Figures 28-29.

Table 26. Locations, soil series, and soil descriptions for trials in Perkins and Bixby, OK.

Location	Soil Series	Description
Perkins, OK	TELLER	FINE-LOAMY, MIXED, ACTIVE, THERMIC UDIC ARGIUSTOLLS
Bixby, OK	WYNONA	FINE-SILTY, MIXED, ACTIVE, THERMIC CUMULIC EPIAQUOLLS

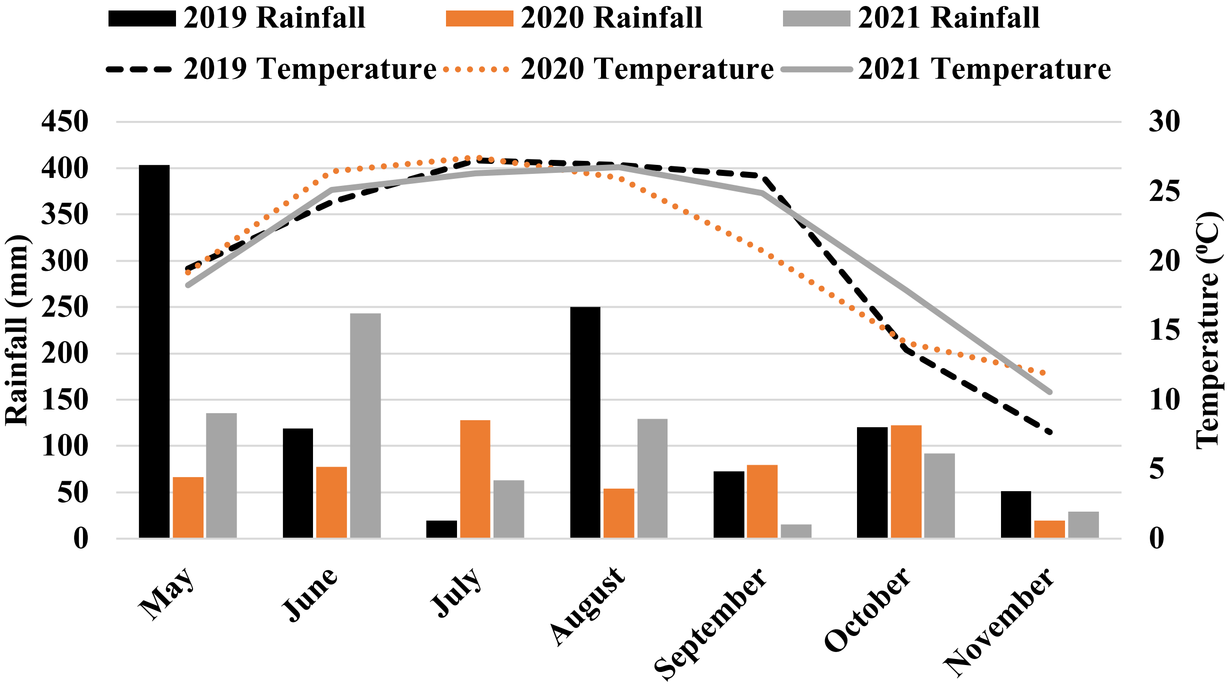

Figure 28. Average monthly temperature (right axis) and total rainfall (left axis) for the Perkins location in 2019, 2020, and 2021.

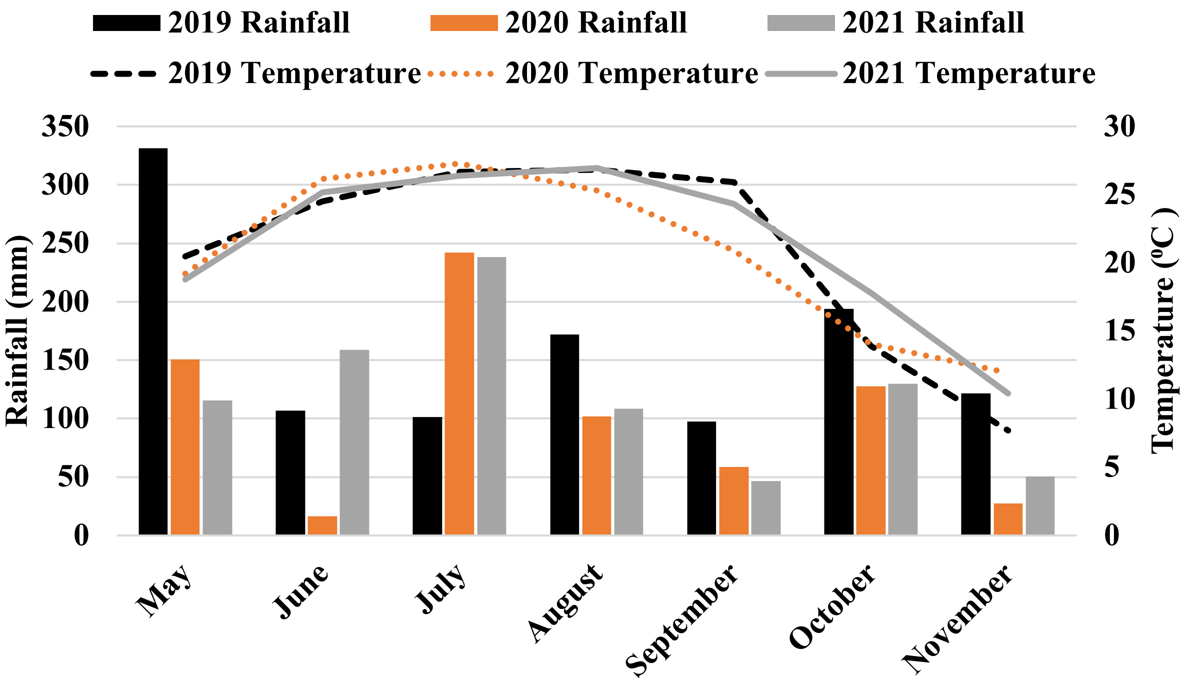

Figure 29. Average monthly temperature (right axis) and total rainfall (left axis) for the Bixby location in 2019, 2020, and 2021.

The trials were arranged in a randomized complete block design with a complete three-way factorial treatment structure. The three treatments were two levels of insecticide application timings, two levels of desiccation applications, and three levels of harvest timings resulting in twelve treatment combinations (Table 27), each replicated four times. Important dates for each trial are given in Table 28.

Table 27. Treatment levels for late season management trials.

Treatment	Levels
Insecticide Application Timings	Through R5 stage Through R7 stage
Desiccation Applications	Non-Desiccated Desiccated
Harvest Timing	Timely Delayed 14 days Delayed 28 days

Table 28. Important dates for Bixby and Perkins late-season management trials in 2019, 2020, and 2021.

Activity	Bixby			Perkins		
	2019	2020	2021	2019	2020	2021
Planted soybeans	5/21	5/20	5/14	5/17	5/20	5/17
Sprayed Insecticide (all)	8/22	7/20	N/A	8/19	7/22	N/A
Sprayed Insecticide (R7 treatment)	9/20	9/18	9/2	9/18	9/15	8/23
Desiccated soybeans (desiccation treatment)	10/4	9/30	9/23	9/30	10/1*	9/17
Timely harvest	10/28	10/16	10/21	10/7	10/16	9/28
2 week delayed harvest	11/4	11/6	11/10	10/22	11/3	10/19
4 week delayed harvest	11/19	11/19	11/18	11/4	11/17	11/1

*All plots were desiccated.

Soybean Management

Soybean seed was planted using a four row Monosem vacuum planter (Monosem Inc., Edwardsville, Kansas) set on 76.2 cm spacing at a rate of 258,362 seeds ha^{-1} at each location both years. Plot sizes were 6.10 m by 1.52 m. The Asgrow (Creve Coeur, Missouri) variety AG48X7 was planted in 2019 and 2020; however, due to lack of seed availability the variety LGS4808XF (Westfield, Indiana) was planted in 2021. In-season weed management was conducted in accordance with the Oklahoma Cooperative

Extension Service's best management practices. Varying rates of glyphosate (Roundup PowerMAX; Monsanto; St. Louis, Missouri) and dicamba (XTENDIMAX; Bayer; St. Louis, Missouri) were applied when needed based on label suggestions and size of targeted weeds. Insecticide applications were made as necessary throughout the season. When soybean plants reached physiological maturity, plots assigned to receive a desiccation treatment were desiccated using 24.7 oz ha^{-1} of paraquat (Solera; Yuma, Arizona) applied by a tractor and sprayer. All plots were desiccated at the Perkins location in 2020; therefore, no data for non-treated plots are presented. Two weeks later, based on labeled preharvest interval, plots corresponding to the 'Timely' harvest treatment were mechanically harvested using a Wintersteiger plot combine (Wintersteiger; Ried im Innkreis, Austria). Plot weights were used to estimate yield on a per hectare basis. Around two weeks following the first harvest, the '14 days delayed' harvest occurred in an identical process and around two weeks later, the '28 days delayed' harvest was completed. Rainfall received by each location in the periods between harvests is given in Table 29.

Table 29. Rainfall amounts (mm) received at each location between harvests of late-season management trials.

Time Interval	Bixby			Perkins		
	2019	2020	2021	2019	2020	2021
1st Harvest-2nd Harvest	27.4	127.0	56.9	32.3	121.9	85.3
2nd Harvest-3rd Harvest	63.8	8.10	31.49	87.4	3.00	19.3

Insecticide Treatments

Trials were surveyed using a sweep net for insects bi-weekly during reproductive growth and insecticide applications of 24.7 oz ha^{-1} of Besiege (Syngenta; Basel, Switzerland) were made when critical thresholds were met. At least 15 random 6.1 meter rows were swept with 20 sweeps throughout the trials at each scouting activity. Detailed counts were taken in 2020. Early season (prior to R5) insecticide applications were triggered by the economic threshold of grasshoppers in 2019 and three-cornered alfalfa hoppers in 2020 while late-season (R7 or later) applications were due to the presence of stinkbugs in both 2019 and 2020. In 2019 an infestation of grasshoppers present at both Perkins and Bixby locations required insecticide application. An insecticide application was made in 2020 at both locations to control three-cornered alfalfa hopper infectations. Applications made after GS R7 were initiated when counts reached >2 stinkbugs per 6.1 m or approximately 12 sweeps at all site years. All early season insecticide applications were made via a tractor and sprayer while late-season applications were applied with a backpack sprayer as only plots with the R7 insecticide treatment received insecticide.

Data Collected: Soybean physiology, quality, and yield

To understand the effects of the different cover crop treatments on soybean production and quality, several data were collected on growth parameters, seed size and quality, as well as yield. Stand counts were taken from each plot to quantify soybean populations for each treatment. These values were collected by counting each plant within 1-m of row from two rows in each plot. The counts were averaged between the two rows and then averaged over like treatments to attain one average plant population value. This value was used for comparison between different treatments.

After desiccation of the soybeans, physiological measurements including plant height, height to first harvestable node (HFN), number of nodes per plant, number of nodes per mainstem, total number of pods per plant, and number of 0, 1, 2, 3, and 4 bean pods per plant were taken from each plot. Shatter ratings of each plot were also taken immediately before the plots were harvested by visually estimating the percent shatter across the plot and were recorded on a scale of 0-10 with 0 meaning 0% and 10 meaning 100%. The shatter ratings for the 28 days delayed harvest are not available at either location in 2021. Plant height measurements were taken from the soil surface to the top node of three random plants per plot. On those same five plants, HFN was recorded as the measurement from the soil surface to the lowest seeded pod. Additional physiological measurements were taken on three plant subsamples that were randomly collected from each plot before soybean harvest. The height and HFN measurements were not necessarily taken from the same plants that were collected for plant samples. Once the plant samples were collected nodes were counted on the mainstem as well as the entire plant. After counting nodes, all pods were removed from the plant, separated into 0, 1, 2, 3, and 4 bean groups, and counted.

Soybean seed yield was collected at harvest along with a subsample of seed from each plot. The seed collected was then used to attain 100 seed weight, quality ratings, oil content, and protein content. The 100 seed weight value was determined by randomly counting 100 seeds from each subsample and weighing them. Visual seed quality ratings were taken on the 100 seeds used to attain the weight measurement. These visual ratings were taken on a 0-5 scale with 0 represented seed samples that had nearly 0% abnormal seeds while 5 represented samples with 100% abnormal seeds. “Abnormal seeds” refers to seeds that were shriveled or shrunken, were green, were brown, had purple seed stain, were covered in white powdery mold, or if the seed coat was ripping. These abnormalities are often symptoms of damage caused by insects, diseases, or environmental conditions, therefore important to understanding the imposed treatments for this trial. In addition to the visual quality ratings, the 100 seeds from each plot were separated into damage categories mentioned above. The method used to do this was to visually separate all seeds that met one damage category, count those seeds, and record the number. Those separated seeds were then added back to the rest of the seed and the process was redone with a different category. Oil and protein contents were determined through the use of a Perten Model DA7250 At-Line Near-Infrared (NIR) instrument (PerkinElmer, Inc.; Waltham, Massachusetts).

Data Analysis

All data was analyzed using SAS v. 9.4 (SAS Institute Inc., Cary, NC) to determine significant impacts of the imposed treatments on physiological parameters, seed quality, and yield. Insecticide treatment, desiccation treatment, and harvest timing were considered fixed effects while replication and its interactive effects were considered random effects. Both year and location had a significant impact on the influence of treatments on collected data, as verified by analysis, therefore further analysis was carried out separately for both location and year. Analysis of variance was conducted using Procedure Mixed (PROC MIXED). Post-hoc analysis was done with a Tukey adjustment to determine differences between individual mean values. An $\alpha = 0.05$ was used for all analysis.

RESULTS

Yield

Bixby 2019

A three-way interaction between insecticide timing, desiccation treatment, and harvest timing significantly affected soybean yield at the Bixby location in 2019 (Figure 30). Overall there was a negative trend in yields as harvest was delayed. The highest yield for the trial was found in the R7, desiccated, timely harvest treatment with an average yield of 4887 kg ha^{-1}. The lowest average yield was 3571kg ha^{-1} found in the R5, non-desiccated, 28 days delayed harvest treatment. With one exception, the R7 insecticide timings resulted in significantly higher yields than their respective R5 treatment combinations. The one exception to this occurred between the non-desiccated plots in the 14 days delayed harvest which although the R7 treatment did yield higher than the R5 treatment, this difference was not significant. Generally, the desiccated plots yielded higher than the non-desiccated with a significant difference seen in the R7, 28 days delayed harvest treatments.

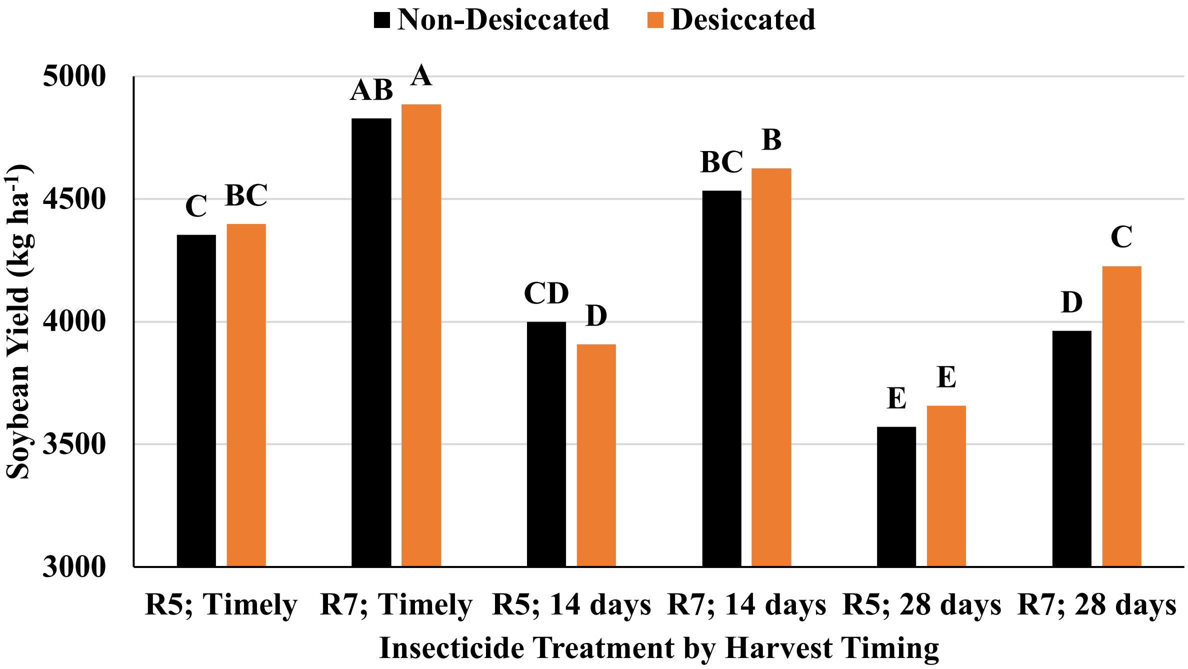

Figure 30. Yield results from the Bixby location in 2019. Differing letters denote significant differences in yield due to a three-way interactive effect of insecticide treatment (R5 or R7), harvest timings (timely, 14 days, or 28 days delayed), and desiccation treatments (treated or non-treated) (*a*=0.05).

Perkins 2019

A two-way interaction between insecticide timings and harvest date significantly affected yield at the Perkins location in 2019 (Figure 31). Yield generally declined as harvest date was delayed. The R7 insecticide timing in the timely harvest date produced the highest yield at an average of 3117 kg ha^{-1}. The R5 insecticide timing in the 28 days delayed harvest yielded significantly less than all other treatment combinations, with the exception of the R5 insecticide timing in the 14 days delayed harvest, at a total average yield of 2299 kg ha^{-1}. However, there were no significant differences in yield between the R7 treatments at any harvest date, including the 28 days delayed harvest.

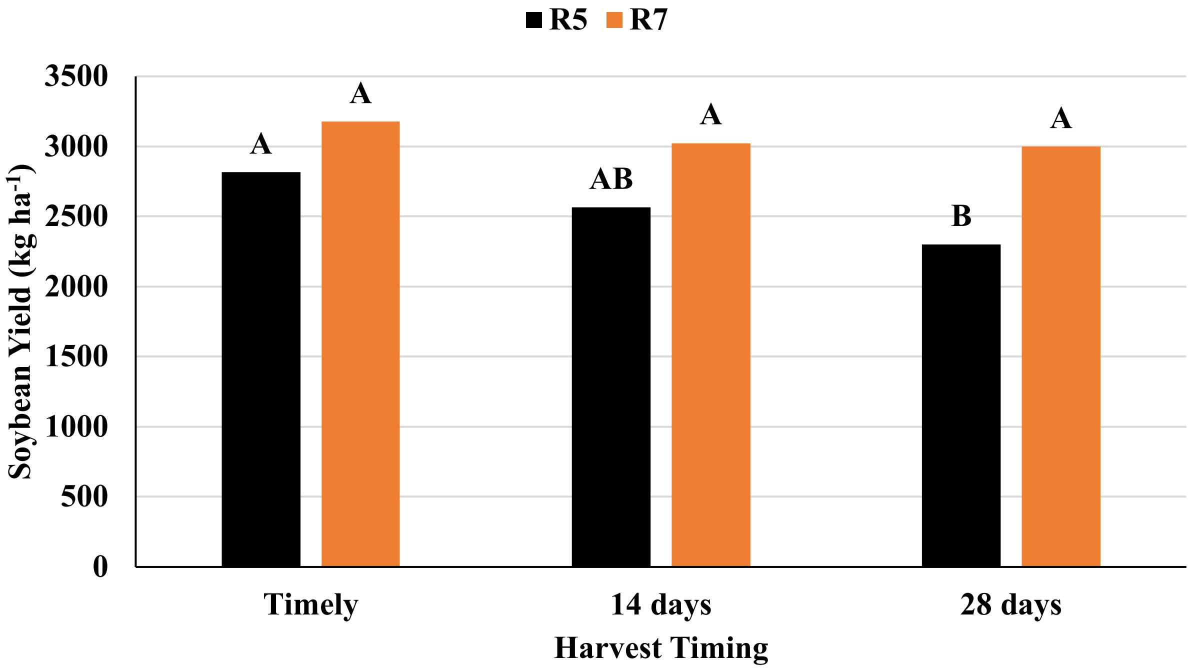

Figure 31. Yield results from the Perkins location in 2019. Differing letters denote significant differences in yield due to a two-way interactive effect of harvest timing (timely, 14 days, and 28 days) and insecticide treatments (R5 and R7) (*a*=0.05).

Bixby 2020

Similar to the Bixby location in 2019, a three-way interaction between treatments existed at the Bixby location in 2020 (Figure 32). The highest yield came from the R7, non-desiccated, 14 days delayed treatment with an average yield of 5869 kg ha^{-1}. Unlike the previously discussed locations, there was not an overall negative trend in yield. In fact, the lowest yielding treatment combination was the R5, non-treated, timely harvest treatment with an average yield of 4335 kg ha^{-1} which yielded significantly less than all R7 treatments within the timely harvest and all treatment combinations in both the 14 and 28 days delayed harvests except for the R7, treated, 28 days delayed harvest treatment. There were slight decreases in yield from the 14 days delayed harvest to the 28 days delayed harvest. The only significant decreases, however, were from the R7, treated, 28 days delayed harvest treatment yielding significantly less than the R5, non-treated and R7, non-treated plots in the 14 days delayed harvest.

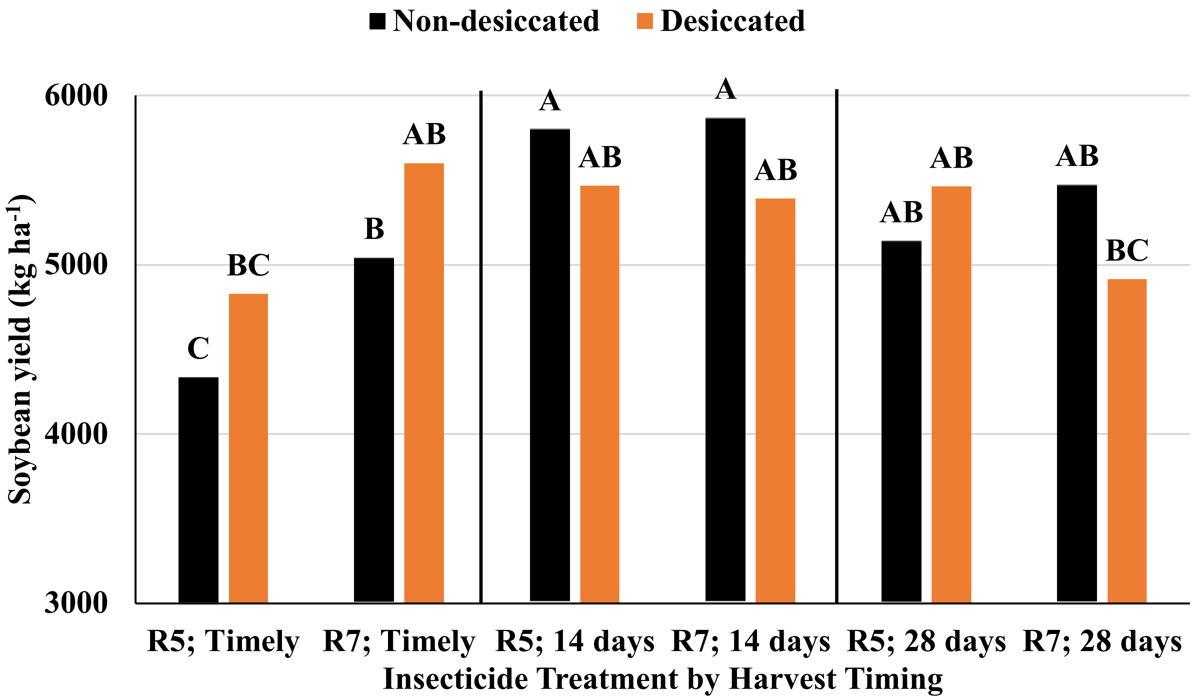

Figure 32. Yield results from the Bixby location in 2020. Differing letters denote significant differences in yield due to a three-way interactive effect of insecticide treatment (R5 or R7), harvest timings (timely, 14 days, and 28 days delayed), and desiccation treatments (treated or non-treated) (*a*=0.05).

Perkins 2020

Soybean yield at the Perkins location in 2020 behaved similarly to the yield at the same location in 2019. There was a two-way interaction between insecticide timing and harvest date that impacted soybean yield (Figure 33). Once again, there was an overall downward trend in yield as harvest was delayed. The yield was highest in the R7, timely harvest date treatment at a total average yield of 2060 kg ha^{-1}. The lowest yield was the R5, 28 days delayed treatment at an average of 1312 kg ha^{-1}. Unlike the Perkins 2019 yield, there were significant differences between yields for the R7 treatments as harvest was delayed. The R7, 28 days delayed harvest yield was significantly less than the R7, timely harvest yield by 34.1%.

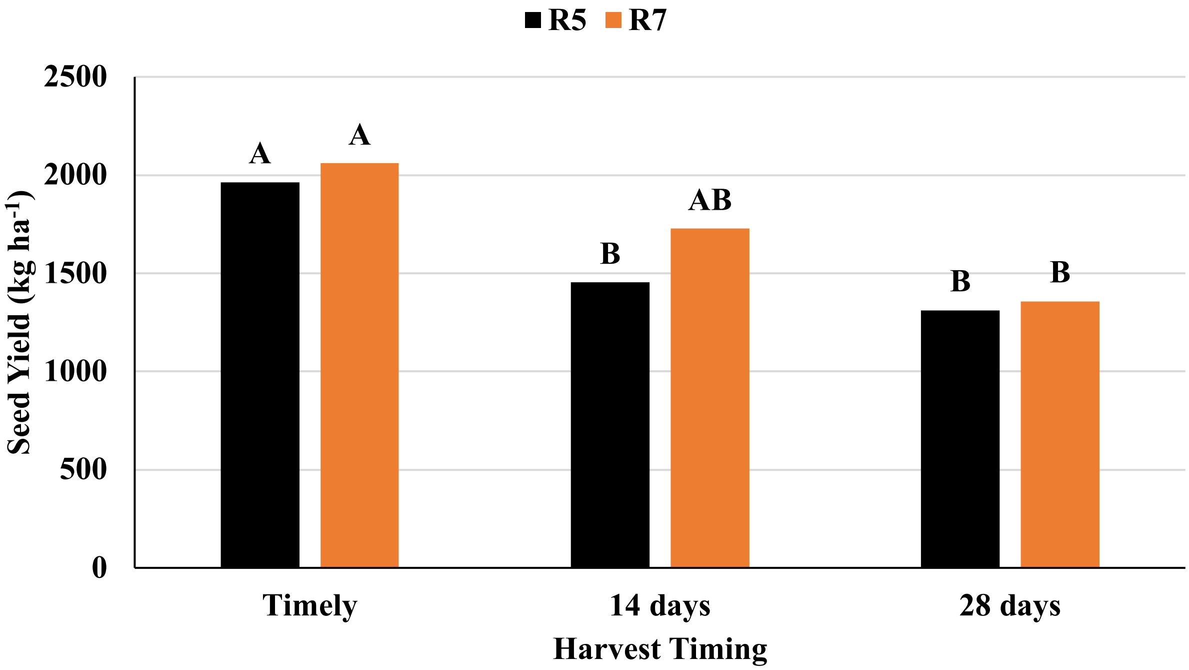

Figure 33. Yield results from the Perkins location in 2020. Differing letters denote significant differences in yield due to a two-way interactive effect of harvest timing (timely, 14 days, and 28 days delayed) and insecticide treatments (R5 or R7) (*a*=0.05).

Bixby 2021

Yield at Bixby in 2019 was significantly affected by the main effect of harvest timing (Figure 34). The highest yield was observed in the timely harvest at an average of 4695 kg ha^{-1} while significantly lower, the 28 days delayed harvest yielded the least at an average of 2845 kg ha^{-1}. The 14 days delayed harvest was less than the timely, but not significantly different. It was, however, significantly higher than the average yield at the 28 days delayed harvest.

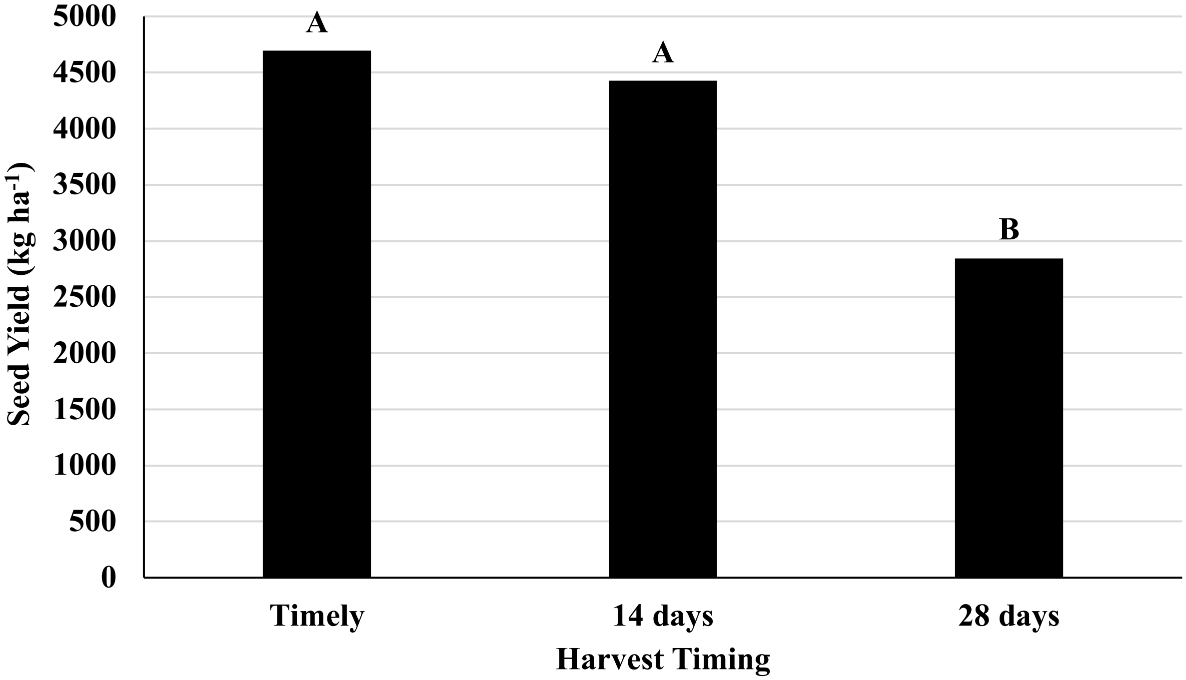

Figure 34. Yield results from the Bixby location in 2021. Differing letters denote significant differences in yield due to the main effect of harvest timing (timely, 14 days, and 28 days delayed) (*a*=0.05).

Perkins 2021

Yield was significantly affected by the main effect of insecticide timing (Figure 35). The plots that received the late season insecticide treatment yielded significantly higher than those that just received insect control throughout the R5 growth stage. The R7 treatment yielded 1895 kg ha^{-1} while the R5 treatment yielded 1636 kg ha^{-1}.

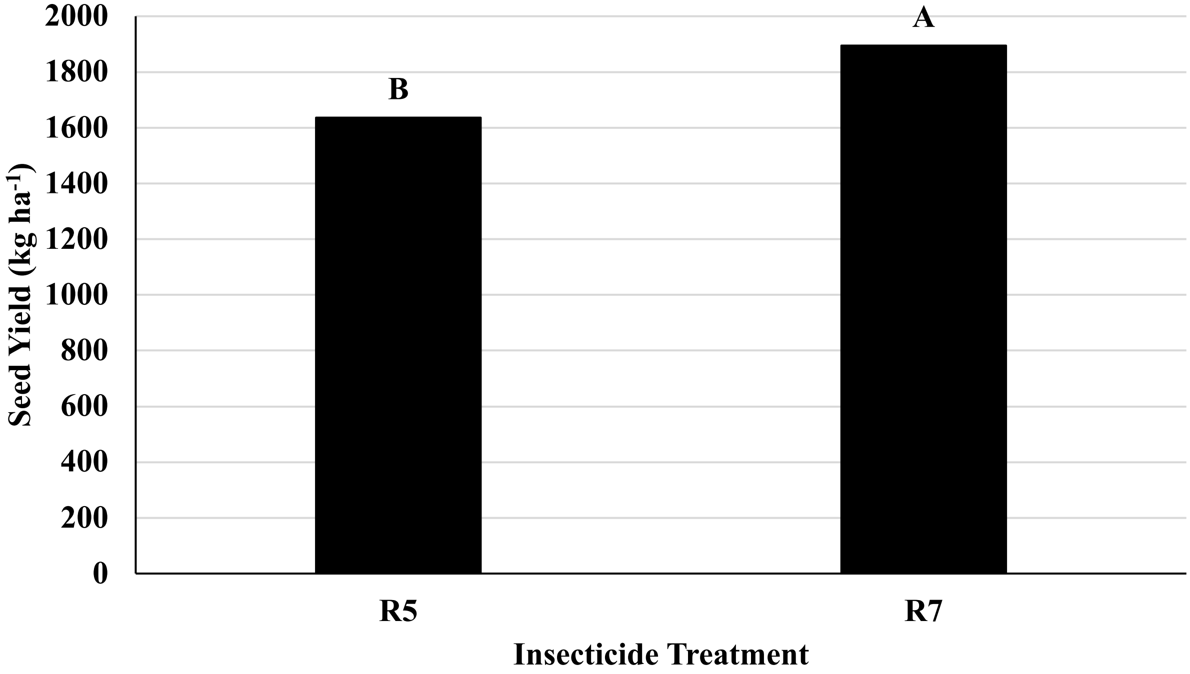

Figure 35. Yield results from the Perkins location in 2021. Differing letters denote significant differences in yield due to the main effect of insecticide treatment (*a*=0.05).

100-Seed Weights

Significant differences in 100-seed weights were present at the Bixby and Perkins locations in 2020 (Figure 36). The 100-seeds used for this data were randomly selected and could be a split or partial seed. The highest average 100-seed weight at Bixby in 2020 was found in the timely harvest at an average of 16.5 g which was significantly higher than the 14 days and 28 days delayed harvest. The average 100-seed weight at the 28 days delayed harvest was significantly lower than the two earlier harvest dates at an average of 9.0 g. For the Perkins 2020 site year, once again the highest 100-seed weight was observed in the timely harvest at an average of 13.5 g. Both the 14 and 28 days delayed 100-seed weights were significantly less than the timely harvest. The 28 days delayed had the lowest 100-seed weight at an average of 8.2 g, but was not significantly different from the 14 days delayed harvest.

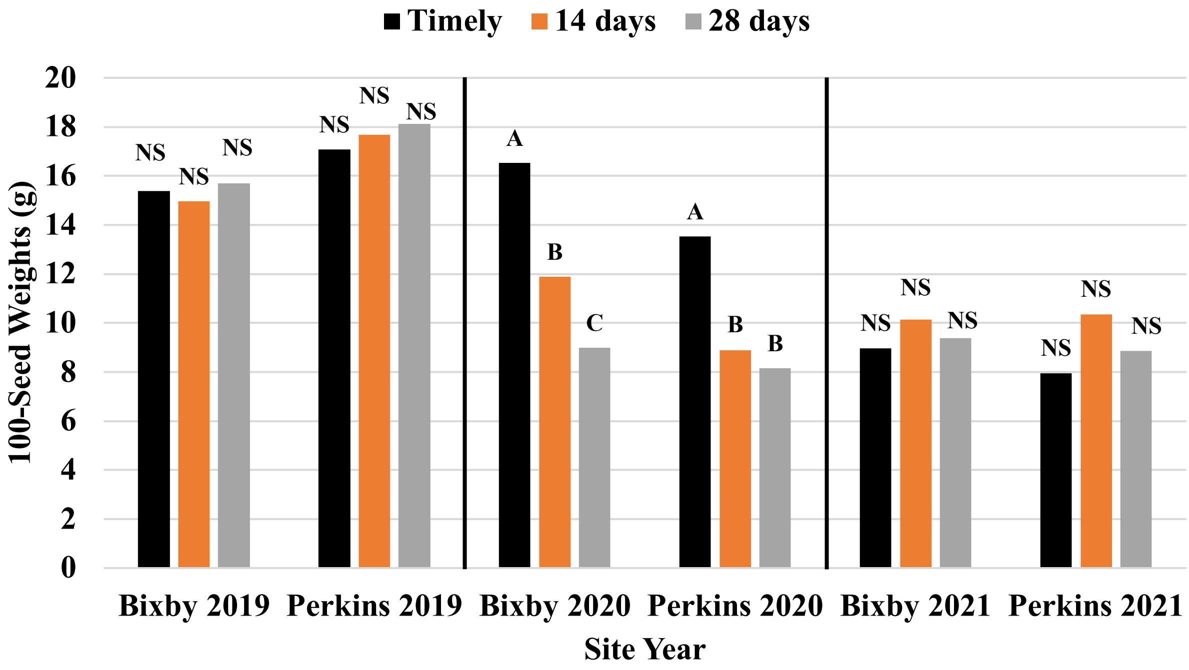

Figure 36. Estimated 100-seed weights averaged across harvest timings for each site year. Differences in letters denote significant differences between harvest timings due to the main effect of harvest timing (*a*=0.05).

Shatter Ratings

At each site year except for Bixby 2020, there were significant increases in pod shatter every time harvest was delayed past the timely harvest (Figure 37). For both locations in 2019, there was no shatter present at the timely harvest, but significantly higher shatter at both the 14 days delayed harvest and the 28 days delayed harvest. The average percent shatter at the 28 days delayed harvest was 20% and nearly 60% for the Bixby and Perkins locations respectively. Although there were not significant differences in percent shatter for the Bixby 2020 location, there was a similar trend in percent shatter increasing as harvest was delayed. The percent shatter at the timely harvest was 10% and in between 30-40% for the 28 days delayed harvest. For the Perkins 2020 location there was nearly 20% shatter at the timely harvest which then significantly increased to nearly 90% at the 28 days delayed harvest. At both locations in 2021 the percent shatter at the timely harvest was in between 10-20% while the percent shatter for the 14 days delayed harvest significantly increased to in between 20-30% for Bixby and just near 50% at Perkins.

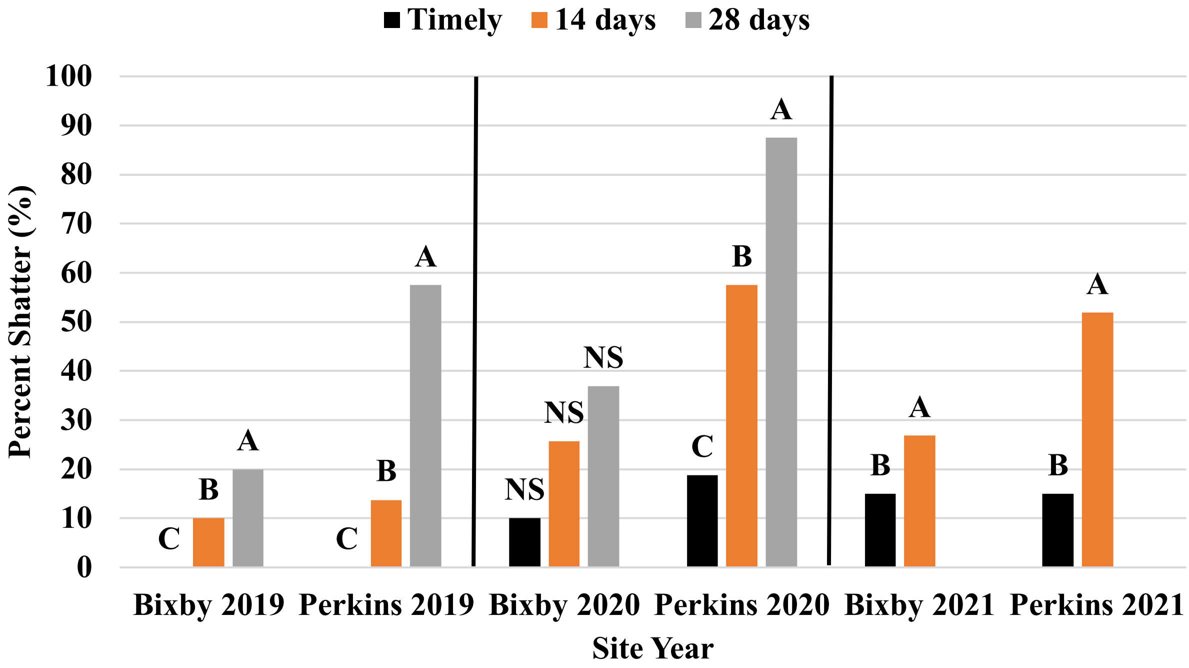

Figure 37. Shatter ratings averaged across harvest timings for each site year. Differences in letters denote significant differences between harvest timings due to the main effect of harvest timing (*a*=0.05). No ratings are available for the 28 day delayed harvest treatment for either location in 2021.

Pod Partitioning and Node Data

There were differences in pod partitioning and node count results between treatment combinations at each site year of the trial, with some of those differences being significant. There were also differences across treatments between different bean number groups. The significant differences between bean number groups due to the main effect of harvest will be discussed due to the noted importance of harvest date on yield.

Bixby 2019

No significant differences were observed between total pods, mainstem nodes, or total nodes at Bixby in 2019. There were significant differences in percent 0 bean pods between different treatment combinations due to a three-way interaction between imposed treatments (Table 30). No other significant differences were observed in other bean number groups. The treatment combination with the highest percent of zero bean pods was the R7; treated; timely treatment at an average of 3.6%. This average was significantly higher than the R7; non-treated; timely treatment, the R5; treated; timely treatment, and the R5; non-treated; 28 days delayed treatment. The R5; non-treated; 28 days delayed treatment resulted in the lowest average percent of 0 bean pods at an average of 0.4%.

Significant differences did exist in percent of total pods between bean number groups across each harvest timing (Appendix B- Figure 41). Regardless of harvest timing, the highest percent of total pods was observed in the 3 bean pods. Nearly 50% of all pods were 3 bean pods across all harvest timings. The percent of total pods for 2 bean pods was significantly less than 3 bean pods, but significantly higher than all other bean number groups. The 0 bean pods and 4 bean pods accounted for the least percent of total pods.

Table 30. Percent of total pods, total pods, mainstem nodes, and total nodes for Bixby 2019. The ANOVA table is also given for all treatments and treatment combinations.

			Percent of Total Pods (%)							
Insecticide Treatment	**Desiccation Treatment**	**Harvest Timing**	**0 Bean Pod**	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
R5	**NT**	**Timely**	1.6 AB	9.9	39.7	46.5	2.2	53.6	15.1	22.1
R7	**NT**	**Timely**	0.7 B	9.8	37.0	50.1	2.4	59.0	16.8	24.0
R5	**T**	**Timely**	0.5 B	6.8	35.0	54.3	3.4	65.4	16.1	24.3
R7	**T**	**Timely**	3.6 A	9.9	38.7	46.0	1.8	65.1	16.0	29.6
R5	**NT**	**14 days**	1.1 AB	9.4	40.8	45.6	3.2	73.6	19.3	36.0
R7	**NT**	**14 days**	1.3 AB	6.6	42.4	47.3	2.3	59.1	16.7	29.9
R5	**T**	**14 days**	2.7 AB	7.3	35.7	50.3	4.1	65.7	17.2	32.6
R7	**T**	**14 days**	1.4 AB	9.1	41.7	45.9	1.8	63.6	18.4	32.6
R5	**NT**	**28 days**	0.4 B	10.7	36.8	49.1	2.9	57.7	18.0	28.4
R7	**NT**	**28 days**	2.1 AB	8.4	36.1	50.4	3.1	68.7	17.6	32.3
R5	**T**	**28 days**	1.0 AB	8.5	39.2	48.7	2.7	67.7	15.9	33.4
R7	**T**	**28 days**	3.1 AB	8.6	42.8	43.9	1.7	58.4	17.1	30.9

ANOVA Table

	Percent 0 Bean	**Percent 1 Bean**	**Percent 2 Bean**	**Percent 3 Bean**	**Percent 4 Bean**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
Insect Timing	0.17	0.98	0.20	0.44	0.33	0.80	0.86	0.84
Desiccation Treatment	0.19	0.59	0.98	1.00	0.85	0.78	0.52	0.50
Harvest Timing	1.00	0.70	0.24	0.58	0.92	0.80	0.16	0.09
Insect by Desiccation	0.27	0.19	0.13	0.17	0.17	0.72	0.41	0.80
Insect by Harvest	0.14	0.50	0.46	0.96	0.81	0.71	0.63	0.39
Desiccation by Harvest	0.99	0.69	0.08	0.33	0.67	0.72	0.64	0.75
Insect by Desiccation by Harvest	**0.049**	0.85	0.89	0.66	0.95	0.54	0.27	0.39

***Different capital letters denote significant differences in percent of total pod values across treatment or treatment combinations (*a*=0.05).**

Perkins 2019

There were no significant differences in total pods, mainstem nodes, and total nodes at Perkins 2019. There were two bean number groups that showed significant differences in percent of total pods between different treatments (Table 31). There were significant differences in percent of 0 bean pods due to a main effect of harvest timing. The highest percent of 0 bean pods resulted from the 28 days delayed harvest with an average of 2.3% which was significantly higher than the percent of 0 bean pods from the timely harvest which was 0.8%. There was also a significant difference in percent of 1 bean pods due to a two-way interaction between insecticide timing and desiccation treatments. The R5; non-treated combination resulted in the highest percent of 1 bean pods at an average of 22.0% which was significantly higher than the R5; treated combination which had the lowest percent of 1 bean pods at an average of 17.7%. Both R7 treatments were neither significantly different from each other or either non-treated treatment.

Like Bixby 2019, there were significant differences in percent of total pods between bean number groups across each harvest timing (Appendix B- Figure 42). At this location, the highest percent of total pods was seen through the 2 bean pods regardless of harvest timing with 2 bean pods making up nearly 45% of all pods for each harvest. Percent of 3 bean pods was significantly less, however, was significantly higher than all other bean number group for each harvest. The only significant difference between percent 0 bean pods and percent 4 bean pods was in the 28 days delayed harvest with the percent 4 bean pods being significantly less than percent 0 bean pods.

Table 31. Percent of total pods, total pods, mainstem nodes, and total nodes for Perkins 2019. The ANOVA table is also given for all treatments and treatment combinations.

	Percent 0 Bean	Percent 1 Bean	Percent 2 Bean	Percent 3 Bean	Percent 4 Bean	Total Pods	Mainstem Nodes	Total Nodes
Timely	0.8 B*	19.2	44.1	35.3	0.5	54.8	17.0	40.8
14 days	1.3 A	18.6	43.7	35.7	0.8	53.6	17.3	39.1
28 days	2.3 A	18.5	43.8	34.7	0.7	47.4	17.4	35.8
R5;NT	2.6	22.0 A	44.3	30.6	0.5	42.1	16.6	31.8
R7;NT	3.7	18.1 AB	42.6	34.8	0.7	59.9	17.4	43.6
R5;T	3.5	17.7 B	44.7	33.6	0.5	51.8	17.7	37.9
R7;T	5.5	21.3 AB	41.3	31.0	0.9	50.2	17.6	35.5

ANOVA Table

	Percent 0 Bean	Percent 1 Bean	Percent 2 Bean	Percent 3 Bean	Percent 4 Bean	Total Pods	Mainstem Nodes	Total Nodes
Insect Timing	0.20	0.88	0.28	0.76	0.29	0.33	0.70	0.38
Desiccation Treatment	0.30	0.40	0.86	0.79	0.87	0.99	0.36	0.77
Harvest Timing	**0.01**	0.69	0.85	0.13	0.60	0.11	0.30	0.16
Insect by Desiccation	0.74	**0.02**	0.57	0.08	0.63	0.23	0.34	0.11
Insect by Harvest	0.68	0.54	0.85	0.68	0.40	0.10	0.36	0.15
Desiccation by Harvest	0.77	0.73	0.64	0.27	0.95	0.84	0.12	0.77
Insect by Desiccation by Harvest	0.28	0.61	0.57	0.48	0.57	0.40	0.59	0.11

***Different capital letters denote significant differences in percent of total pod values across treatment or treatment combinations (*a*=0.05).**

Bixby 2020

Once again there were differences in percent of total pods between different treatment combinations across different bean number groups, as well as in total pods, mainstem nodes, and total nodes at the Bixby 2020 site year; however, none of these differences were significant (Appendix B- Table 54). There were significant differences in percent of total pods between bean number groups across different harvest timings (Appendix B- Figure 43). At this location, there were no significant differences between percent of 2 and 3 bean pods for any harvest timing with both bean number groups having significantly higher percentages than all other groups. The 4 bean group accounted for the lowest percent of total pods for each harvest timing with those in the timely and 28 days delayed harvest being significantly less than the percent of total pods of 0 bean pods.

Perkins 2020

No significant differences in total pods, mainstem nodes, or total nodes were seen in any treatment combination at the Perkins 2020 site year. Significant differences in percent of total pods were observed across treatments in 0, 3, and 4 bean pods due to the main effect of harvest timing (Table 32). The 28 days delayed harvest had the highest percent of 0 bean pods at an average of 32.1% of all pods. Significantly less 0 bean pods were observed in both the timely and 14 days delayed harvests with averages of 6.7% and 13.3% respectively. Conversely, the timely harvest had the highest percentage of 3 bean pods at 41.3%. The 14 days delayed harvest had a lower average percent of 3 bean pods, however this difference was not significant. Significantly less than both earlier harvests, the 28 days delayed harvest had the lowest percent of 3 bean pods at an average of 19.6%. Similar results were observed in the percent of 4 bean pods with the timely harvest having the highest percent of 4 bean pods at an average of 1.5%. The percent of total 4 bean pods in the 14 days delayed harvest did not significantly differ from either other harvest timing. However, the 28 days delayed harvest resulted in significantly less percent of 4 bean pods compared to the timely treatment at an average of 0.6%.

Differences in percent of total pods were observed between bean number groups across each different harvest timing (Figure 38). Three bean pods accounted for the highest percent of total pods within the timely harvest treatment. This was significantly higher than all other bean group except for the 2 bean pods which had a lower average percent of total pods, but the difference was not significant. The lowest percent of total pods in the timely harvest resulted from the 4 bean pods at an average of 1.5%. Unlike the timely harvest, in the 14-days delayed harvest, the 2 bean pod group accounted for the highest average percent of total pods at 37.4%. Percent of 3 bean pods was less, though the difference was not significant. Four bean pods accounted for the smallest percentage of total pods in the 14 days delayed harvest at an average percentage of 0.9% with percent 0 bean pods being significantly higher at an average of 13.3% of all pods. Drastically different results were observed in the 28 days delayed harvest with the 0 bean pods making up the highest percentage of total pods when compared to all other bean number groups. The 0 bean number group made up 32.1% of all pods. The percent 2 bean pods was lower, but the difference was not significant. There was a significant reduction in 3 bean pods when compared to both 0 and 2 bean pods with 3 bean pods accounting for only 19.6% of all pods. Once again the lowest percent of total pods was found in the 4 bean number group at an average percentage of 0.6%.

Table 32. Percent of total pods, total pods, mainstem nodes, and total nodes for Perkins 2020. The ANOVA table is also given for all treatments and treatment combinations.

	Percent of Total Pods (%)							
Harvest Timing	**0 Bean Pod**	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
Timely	6.7 B*	12.0	38.5	41.3 A	1.5 A	373.5	26.5	173.3
14 days	13.3 B	14.0	37.4	34.4 A	0.9 AB	412.8	27.5	213.8
28 days	32.1 A	18.7	29.1	19.6 B	0.6 B	436.0	26.5	212.6

ANOVA Table

	0 Bean Pod	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
Insect Timing	0.87	0.99	0.52	0.83	0.88	0.99	0.39	0.57
Harvest Timing	**<0.01**	0.07	0.07	**<0.01**	**0.04**	0.95	0.60	0.73
Insect*Harvest	0.20	0.08	0.69	0.07	0.11	0.63	0.33	0.93

***Different capital letters denote significant differences in percent of total pod values across treatment or treatment combinations (*a*=0.05).**

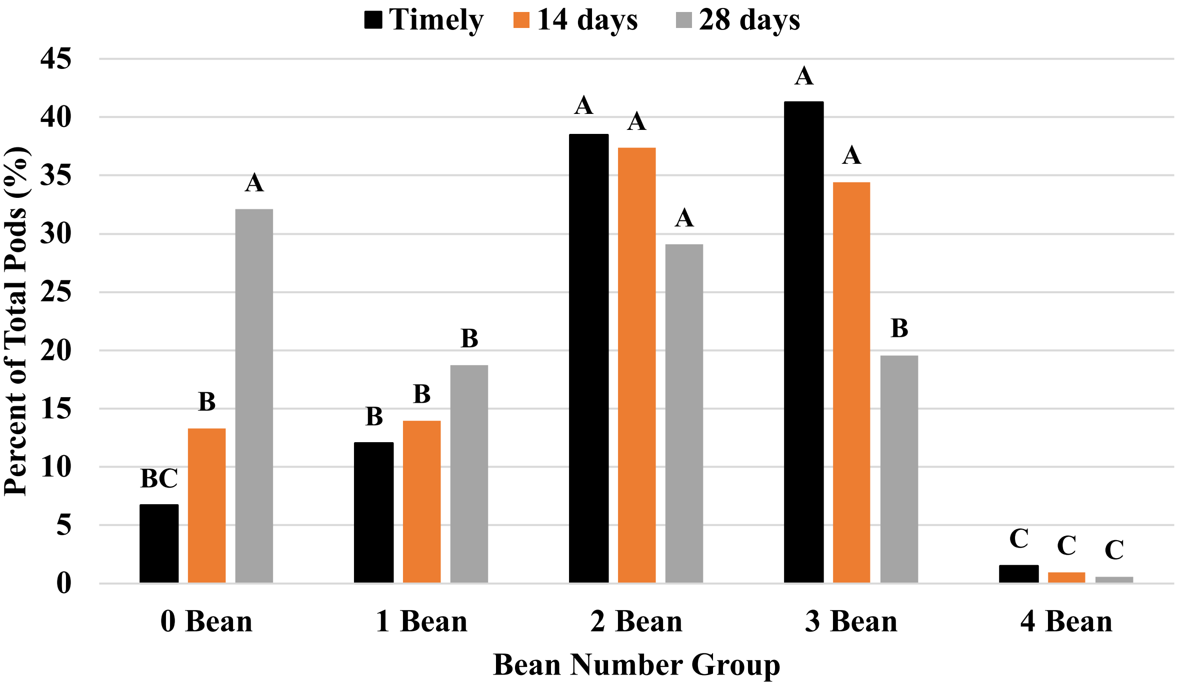

Figure 38. Percent of total pods for the Perkins 2020 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05).

Bixby 2021

Like all other site years, there were no significant differences in total pods, mainstem nodes, or total nodes at Bixby in 2021 (Table 33). There was a significant difference in percent of total pods with the 1 bean number group being affected by a three-way interaction between all imposed treatments. The significant difference occurred between the R7; non-treated treatments at both the 14 days delayed and the 28 days delayed harvests. The highest percent 1 bean pods was found in the R7; non-treated; 28 days delayed treatment at an average of 7.7% while the lowest resulted from the R7; non-treated; 14 days delayed treatment at an average of 2.4%. There were no other significant differences between any treatment combination.

When analyzing differences in percent of total pods between bean number groups within the different harvest treatments, it was found that 3 bean pods accounted for the highest percentage of total pods regardless of harvest timing with averages just above 25% (Appendix B- Figure 44). These percentages were significantly higher than all other bean number groups. The 2 bean number group although less than the 3 bean group, was significantly higher than the 0, 1, and 4 bean groups. There were significant differences between the 1 bean number group and the 4 bean number group in the 14 days and 28 days delayed harvests with the 4 bean pods having a significantly lower average percent of total pods compared to 0 bean pods.

Table 33. Percent of total pods, total pods, mainstem nodes, and total nodes for Bixby 2021. The ANOVA table is also given for all treatments and treatment combinations.

			Percent of Total Pods (%)							
Insecticide Treatment	**Desiccation Treatment**	**Harvest Timing**	**0 Bean Pod**	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
R5	**NT**	**Timely**	2.0	6.5 AB*	19.7	24.5	1.5	154.1	22.4	48.3
R7	**NT**	**Timely**	3.8	3.3 AB	17.6	30.8	0.9	127.0	18.3	37.2
R5	**T**	**Timely**	2.2	4.8 AB	18.6	25.9	1.0	141.0	21.5	45.6
R7	**T**	**Timely**	4.0	3.3 AB	13.6	29.1	1.2	123.8	18.3	42.3
R5	**NT**	**14 days**	2.8	7.0 AB	19.8	21.4	0.7	136.1	20.0	45.0
R7	**NT**	**14 days**	4.5	2.4 B	16.5	26.8	0.8	128.8	20.3	42.6
R5	**T**	**14 days**	5.2	4.7 AB	15.9	25.6	0.3	131.2	19.3	43.3
R7	**T**	**14 days**	3.8	7.2 AB	19.6	27.6	0.9	172.4	19.7	48.3
R5	**NT**	**28 days**	2.7	5.2 AB	17.5	30.8	1.6	174.3	21.0	49.7
R7	**NT**	**28 days**	3.1	7.7 A	18.3	23.6	1.4	148.8	21.2	46.7
R5	**T**	**28 days**	2.2	4.5 AB	17.2	27.4	1.5	148.8	20.7	49.3
R7	**T**	**28 days**	2.1	5.2 AB	14.9	26.5	0.8	125.0	20.3	41.3

ANOVA Table

	0 Bean Pod	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
Insect Timing	0.26	0.4	0.47	0.60	0.68	0.41	0.27	0.25
Desiccation Treatment	0.13	0.67	0.94	0.86	0.15	0.58	0.6	0.71
Harvest Timing	0.85	0.81	0.39	0.85	0.52	0.70	0.56	0.98
Insect*Desiccation	0.35	0.05	0.40	0.28	0.45	0.20	0.07	0.43
Insect*Harvest	0.24	0.37	0.93	0.98	0.65	0.41	0.90	0.56
Desiccation*Harvest	0.45	0.56	0.71	0.91	0.90	0.24	0.99	0.81
Insect*Desiccation*Harvest	0.37	**0.04**	0.16	0.42	0.56	0.57	0.78	0.55

***Different capital letters denote significant differences in percent of total pod values across treatment or treatment combinations (*a*=0.05).**

Perkins 2021

No significant differences in total pods, mainstem nodes, and total nodes between any treatment combination were observed at the Perkins 2021 site year (Appendix B-Table 55). There were also no significant differences in percent of total pods across bean number groups between any treatment combination. There were however significant differences in percent of total pods between bean number groups across the different harvest timings (Figure 39). For both the timely and 14 days delayed harvests, the 3 bean pods accounted for the highest percent of total pods, significantly higher than all other bean number groups. However, for the 28 days harvest, the 0 bean pods had a slightly higher percent of total pods than the 3 bean pods, but this difference was not significant. The 2 bean number group had a lower average percent of total pods than both the 0 and 3 bean pods, but was not significantly different than either. Four bean pods had a significantly lower average percent of total pods than the 0 bean pods for all harvest treatments. The four bean pods in the 28 days delayed harvest had a significantly lower average percent of total pods compared to the 1 bean pods. This was not observed in the earlier harvest timings.

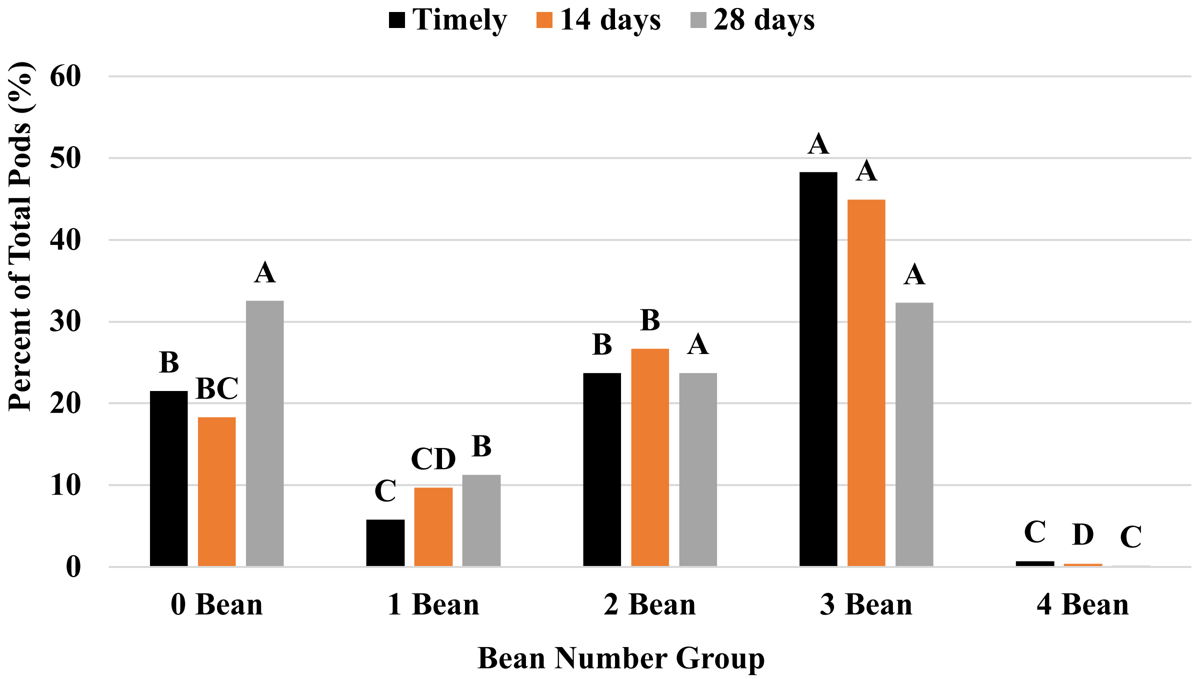

Figure 39. Percent of total pods for the Perkins 2021 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05).

Quantitative Seed Quality

Differences between percent of beans visually displaying signs of seed quality damage were present at each site year throughout the trial (Table 34). Significant differences in percent of affected seed across damage types were observed at the Bixby location in 2019 due to a main effect of harvest timing. These significant differences were observed in shriveled, green, and brown seeds. The 14 and 28 days delayed harvests resulted in significantly higher percents of shriveled seed compared to the timely harvest. The 28 days delayed harvest had an average percent shriveled seed between 41% and 42% compared to in-between 24% and 25% at the timely harvest. Conversely the timely harvest had a significantly higher average percent of green seeds than both delayed harvests. The timely harvest had an average of 5-6% green seeds compared to an average of 2-3% in the 14 days delayed harvest. Very similar to the shriveled seed, the delayed harvests had significantly higher average percent of brown seeds compared to the timely harvest. The 28 days delayed harvest had an average percentage of brown seed between 15% and 16% compared to the timely harvest with an average between 5% and 6%. Significant differences in percent of brown seeds were present at the Perkins 2019 trial as well; however, these differences were affected by a three-way interaction between the imposed treatments (Figure 40). The treatment combination that resulted in the highest percentage of brown seeds was the R5; treated; 28 days delayed treatment with an average percentage of 10%. This percentage was significantly higher than the R5; treated; timely treatment, the R7; non-treated; 14 days delayed treatment, and the R5; non-treated; 28 days delayed treatment. The R7; non-treated; 14 days delayed treatment resulted in the lowest average percent of brown seeds at in between 1-2%. This percentage was also significantly lower than both the R5; non-treated; 14 days delayed treatment and the R7; treated and non-treated; 28 days delayed treatment.

Table 34. Percent of seeds displaying seed quality damage based on type for Bixby in 2019, 2020, and 2021 and Perkins in 2019 and 2020.

Damage Type	Bixby 2019			Perkins 2019			Bixby 2020			Perkins 2020			Bixby 2021		
	Timely	14 days	28 days	Timely	14 days	28 days	Timely	14 days	28 days	Timely	14 days	28 days	Timely	14 days	28 days
Shriveled	24.2 B*	37.8 A	41.7 A	22.3	19.2	23.1	28.7	21.4	17.1	35.3	27.1	31.0	31.0	29.3	30.0
Green	5.2 A	3.2 B	2.6 B	8.3	4.1	2.9	8.4	4.5	4.3	7.9	5.5	6.3	9.2	6.6	3.6
Purple	3.2	3.6	5	11.5	14.0	12.1	1.1	0.8	0.5	1.5	1.3	1.1	0.3	0.2	0.0
Brown	6.3 B	15.4 A	15.6 A	4.7	4.5	6.6	8.6	11.5	9.4	6.1	6.9	9.4	8.4 B	13.3 A	10.2 AB
Seed Coat Tear	4.9	4.9	4.2	8.6	12.4	11.1	6.1	5.1	4.9	7.3	7.4	6.8	3.7	4.2	4.4
White	7.8	4.3	6.3	19.9	19.1	17.7	8.1	6.2	6.0	5.8	5.1	5.4	7.9	10.9	7.5

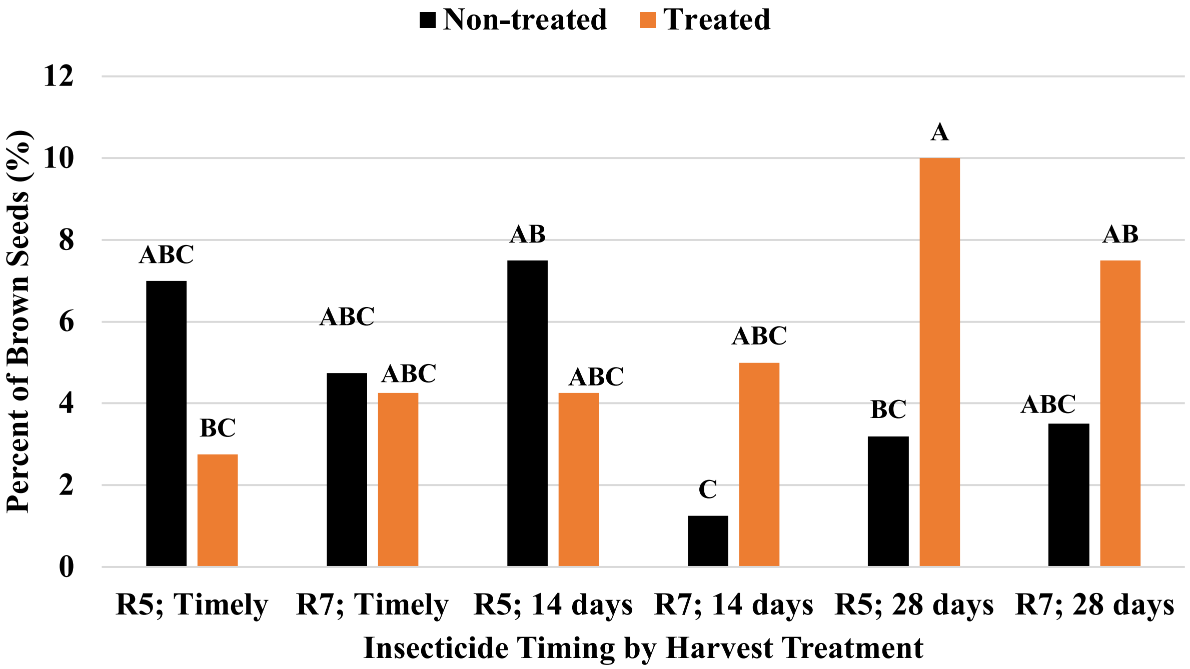

Figure 40. Percent of seeds displaying brown discoloration at Perkins in 2019 due to a three-way interaction between all imposed treatments. Differences in capital letters denote significant differences in number of brown seeds between treatment combinations.

Seed Quality Ratings

Differences in seed quality ratings existed at each site year of the trial. These differences were not significant at the Perkins 2019 and 2020 trials as well as the Bixby 2021 trial. There was a significant main effect of harvest date on seed quality ratings for the Bixby trials in 2019 and 2020 as well as the Perkins trial in 2021 (Table 35). At the Bixby location in 2019, the lowest quality rating, which is the higher quality seed, was found in the timely harvest at an average rating between 2 and 3. This was significantly lower than the seed quality at the 14 days delayed trial which had an average overall quality rating between 3 and 4, with most ratings being 4. For Bixby 2020, once again the timely treatment had the lowest average quality rating at an average between 2 and 3 with most ratings being 2; however, the highest average rating was observed in the 28 days delayed harvest at an average between 3 and 4 with most ratings being 4. At Perkins in 2021 it was observed that the seed quality within the 14 days harvest timing was the lowest at an average between 2 and 3 with more ratings being 3. The highest seed quality rating was observed in the timely harvest at an average rating between 4 and 5 with more ratings being 4.

Table 35. Seed quality ratings for each year and location of the trial.

Harvest Timing	**Site Year**					
	Bixby 2019	**Perkins 2019**	**Bixby 2020**	**Perkins 2020**	**Bixby 2021**	**Perkins 2021**
Timely	2.5 B	3.4	2.3 C	3.8	2.3	4.2 A
14 days	3.7 A	3.3	3.3 B	3.8	3.3	2.9 B
28 days	3.2 AB	3.2	3.9 A	4.3	3.0	3.7 A

Seed Oil and Protein Content

Soybean seed oil and protein contents varied between treatments and their combinations at each site year throughout the trial. The differences in protein contents were small and did not significantly differ from each other for any site year (Appendix B-Table 56). However, oil contents did significantly differ due to a main effect of harvest timing at the Perkins location in 2019, 2020, and 2021 and the two-way interaction of desiccation treatment by harvest timing at the Bixby location in 2020 (Table 36).

Oil contents at the Perkins location in 2019 differed significantly between harvest timings with the 28 days delayed harvest having the highest average oil content at 19.3% which was significantly higher than the oil content for both the timely and the 14 days delayed harvests. For the Perkins location in 2020, the seeds from the 14 days delayed harvest contained the most oil at an average content of 21.6% which was significantly higher than the other two harvest timings. The 28 days delayed harvest, though less than the 14 days delayed harvest, resulted in higher average oil contents than the timely harvest by 1.6%. For Perkins in 2021 the 28 days delayed harvest once again resulted in significantly higher average seed oil contents than the 14 days delayed treatment. The high oil content at 18.6% was higher than the average oil content of the timely harvest, though the difference was not significant. The difference between the timely harvest and 14 days delayed harvest was also not significant. For the Bixby location in 2020, a two-way interaction between desiccation treatment and harvest timing significantly affected average seed oil contents. The treated, 14 days delayed harvest resulted in the highest average oil content at 20.8% which was significantly higher than all other treatment combinations. The remaining treated treatments had significantly higher contents than all non-treated plots regardless on harvest timing. Within the non-treated plots, the 28-days delayed plots had a significantly higher oil content than the two earlier harvests.

Table 36. Seed oil contents (%) for each site year averaged across harvest timings and desiccation*harvest timings.

	Bixby 2019	**Perkins 2019**	**Bixby 2020**	**Perkins 2020**	**Bixby 2021**	**Perkins 2021**
Timely	20.0	18.4 B	18.1	19.0 C	18.6	18.3 AB
14 days	19.8	18.5 B	19.8	21.6 A	18.6	18.0 B
28 days	19.8	19.3 A	20.5	20.6 B	19.1	18.6 A
NT;Timely	20.1	18.4	18.1 D	-	18.5	18.2
NT;14 days	19.8	18.4	18.1 D	-	18.7	18.4
NT; 28 days	19.8	18.5	19.5 C	-	18.8	18.0
T;Timely	19.8	18.5	20.1 B	19.0	18.5	18.1
T;14 days	19.9	19.3	20.8 A	21.6	18.8	18.6
T;28 days	19.6	19.2	20.2 B	20.6	19.3	18.7

***Different capital letters denote significant differences in percent of total pod values across treatment or treatment combinations (*a*=0.05).**

DISCUSSION

Yield

Yield loss associated with delays in harvest was observed in all years. Significant differences in yield due to either a main effect of harvest timing or an interactive effect including harvest timing were determined in five of the six site years. This strong influence of harvest date on soybean yield has been noted throughout literature. In a similar study conducted in 1989, Philbrook and Oplinger (1989) observed up to 11 kg ha^{-1} day^{-1} loss in soybean yield as harvest was delayed past the ideal harvest. Lamp et al. (1962) observed losses of 1% yield day^{-1} when seed moisture was below 10%. Lee et al. (2020) found that as harvest was delayed 40 days past harvest maturity, yield of soybeans decreased by 0.8 kg ha^{-1} day^{-1} to 3.4 kg ha^{-1} day^{-1} depending on amount of irrigation received through the harvest delay period. In another study, yield loss of up to 28% of total yield ha^{-1} was observed as harvest was delayed by just 3 weeks (Tukamuhabwa et al., 2002). In this study, average yield loss for the R5 treatment was 12 kg ha^{-1} day^{-1} in between the first and second harvest and 45 kg ha^{-1} day^{-1} in between the second and third harvest. Average yield loss for the R7 treatment was 10 kg ha^{-1} day^{-1} in between the first and second harvest and 55 kg ha^{-1} day^{-1} in between the second and third harvest.

Pod shatter has been attributed to be the leading cause of yield reduction in soybean crops that are not harvested timely (Lamp et al., 1962; Lee et al., 2020; Philbrook and Oplinger, 1989; and Tukamuhabwa, 2002). Certain publications noted significant yield loss due to pod shatter that occurred by the combine during harvest (Lamp et al., 1962; Philbrook and Oplinger, 1989); however, this type of loss was evaluated the first year of the study, but due to no loss that harvest, it was discontinued. Pre-harvest shatter, or shatter that naturally occurs due to environmental causes, was found to contribute to the majority of yield loss when plants were left in the field past harvest maturity (Lee et al.,2019; Tukamuhabwa et al., 2002). Similarly, the results of this trial suggest that the increase in pre-harvest pod shatter observed at each site year likely led to the yield reductions associated with delayed harvests. Total percent shatter found in the 28 days delayed harvests throughout the site years ranged from 20% at Bixby in 2019 to nearly 90% at Perkins in 2020. With any amount of pod shattering, seed loss to the ground is likely and less seed harvested is inherently less potential yield acquired. The pod partitioning data, particularly for the Perkins 2020 location, underscore the detrimental role pod shatter plays on loss of yield potential in the late season. The data shows that pod distribution tends to shift from high bean number groups to low bean number groups as shattering occurs. This shift in distribution numerically shows the loss of harvestable seed from the pods.

A reduction in overall seed weight is another potential, yet less discussed factor in yield reduction as harvest is delayed. Lee et al. (2020) observed slight decreases in 100-seed weight over the delayed harvests, although these differences were not statistically different. Throughout this study, significant reductions in 100-seed weights were observed at both locations in 2020. As yield is a measurement of mass, any reductions in seed mass can contribute to major yield reductions. The lower 100-seed weights found in the later harvests at Bixby and Perkins in 2020 certainly had an impact on yield reductions, but in the case of Perkins in 2020, the effect would be minimal compared to the high shatter rates. One potential reason for reduced 100 seed weights could be attributed to the ice storm that occurred after maturation that year. It is also worth noting that cracked or partial seeds would have been considered as whole seed in the 100-seed count.

The unsuspected yield increase from the first to second harvest at Bixby in 2020 can be explained by weather events that occurred just before the first harvest. As mentioned before, weather around soybean harvest in Oklahoma can be unpredictable and very different from year to year. A major ice storm event occurred one week following the application of desiccation. It is believed that the freezing event caused any green material that had yet to dry down to essentially remain stagnant for the few days leading up to the first harvest. Any green material that remains in the soybean plants at harvest cause inefficiencies with mechanical harvest and lead to yield losses (Egli and Bruening, 2014; Hobbs et al., 2006). Any green material remaining at the first harvest after the freeze a few days before may have decreased harvest efficiency and reduced the yield. Further maturation and dry down could have continued leading up to the second harvest. This theory is supported by the fact that for regardless of insecticide timing within the timely harvest, the desiccated plots yielded higher than the non-desiccated plots suggesting that some plant dry-down did occur in the desiccated plots through the week following desiccation and before the ice storm event.

The application of a late season insecticide also had a consistent influence on soybean yield suggesting that insect pressure throughout the R6 and R7 growth stages can cause significant reductions in yield when not treated. Stinkbugs were the most prevalent insect in the late season period and were the insect of interest in this trial. These results differed from those by Musser et al. (2011) which did not show consistent significant yield reductions caused by stinkbug infestations during the R7 growth stage, but the authors still stated a need for an economic injury threshold specifically for the R7 growth stage as any yield loss, statistically significant or not can lead to real economic loss. They did suggest that thresholds for applying an insecticide to control stinkbugs in the late season should be higher than those in the early season. Similarly, Thomas et al. (1974) found no effect on yield when stinkbug populations arrived during either the R5 or R7 growth stage. They attributed this to the lack of time for insect maturation before plant maturation.

Due to no distinct trends in yield component data being present between insecticide timings, the direct cause for yield loss in the late season is unknown. Even in the case of Perkins 2021 where yield loss was affected by the main effect of insecticide treatments, no significant differences in pod partitioning results or 100-seed weights associated with insecticide timings were noted. Similar results were observed by Todd and Turnipseed (1973) when they found significant differences in yield when soybeans were infected with as little as 1 stinkbug $0.3m^{-1}$. but did not observe significant decreases in seed weight until soybeans were infected with 3 stinkbugs $0.3m^{-1}$. Russin et al. (1987) also noted yield reductions as stinkbug pressure increased, but there was a lack of significant 100 seed-weight differences associated with the yield decline. The authors found that stinkbug damage was localized in the upper half of the plant but the bottom of the plant was rather untouched by the stinkbugs. They also noted that the undamaged seeds found in the lower half of the plant compensated for the damaged seed by up to 48% increase in seed weight over average seed weights from unaffected plants (Russin et al., 1987). This phenomenon along with the potential of several seemingly insignificant factors acting in conjunction could explain the higher yields with the longer period of control.

Overall desiccation had little to no effect on soybean yield throughout this trial. At two site years the treatment was part of a three-way interaction with all other treatments, but the noticeable effect of the desiccant was negligible in yield. As mentioned previously, though the difference was not significant, the treated plots in the timely harvest in Bixby 2020 did maintain yield potential better than the non-treated plots likely due to hastened dry down in the days leading to the ice storm. In the case of high late season weed pressure, large amounts of green stem syndrome, or need of an early harvest, desiccating soybeans can prove beneficial to maximizing yield potential (Boudreaux and Griffin, 2011; Griffin, Boudreaux, and Miller, 2010).

Seed Quality

Throughout literature it is established that both delays in harvest and heavy stinkbug pressure can cause significant seed quality reductions. The results of this study are inconsistent in both scenarios. Seed quality issues were present at all locations, though very few significant differences between treatments were present and of those significant differences, even fewer were consistent. Harvest delays had the most impact on seed quality degradation of any of the imposed treatments. Visual quality ratings showed significant differences in quality due to a main effect of harvest at three site years. Each harvest timing had the poorest seed quality rating throughout those three site years, showing no consistent trends. Through the quantitative bean quality data, it was found that shriveled seeds were the most common quality issue observed at each site year. However, significant differences in percent of shriveled seed only occurred at the Bixby 2019 site year due to the main effect of harvest date with the 14 and 28 days delayed harvest having significantly higher amount of shriveled seed compared to the timely harvest. Shriveled seeds are a result of temperatures greater than 30°C and drought conditions during the seed fill growth stage (Franca Neto et al., 1993). Inconsistent treatment effects on seed shriveling suggest that environmental factors such as a lack of moisture and high temperatures had the greatest effect on seed quality issues throughout this trial.

Economic Feasibility

Management decisions made by producers are often financially driven to maintain stability within their operation. Yield losses associated with both harvest delays and late season insect pressure can diminish the operation's net return for each soybean crop. It was determined that late season insecticide treatments consistently maintained yield when compared to mid-season applications alone. However, with high chemical, fuel, and equipment prices, the question becomes which option is financially 'less risky'? To attempt to answer this question using yield data observed through this trial, differences in net returns between an operation that made a mid- and late season insecticide application compared to an operation that only applied mid-season. To derive these numbers, the following formula was used:

(3)

$$Difference = [(Yield_1 * Price) - (2 * Application\ Cost)] - [(Yield_2 * Price) - Application\ Cost]$$

Where:

Difference = The overall cost (-) or return (+) of applying an additional late season insecticide (\$ ha^{-1})

$Yield_1$ = Soybean yield averaged across the R7 treatment respective of site year

Price = Soybean commodity price

Application cost = Example costs of an insecticide and custom application (\$80.00 ha^{-1})

$Yield_2$ = Soybean yield averaged across the R5 treatment respective of site year

Based on the results of the cost analysis, when soybean prices are at or below \$0.29 kg^{-1}, negative returns on the investment of a second insecticide application are likely (Table

37). When soybean prices are \$0.44 kg^{-1} or greater, the application of an added insecticide treatment would likely prove beneficial.

Table 37. Difference in net return between when both an early and late season insecticide were applied versus just a mid-season application. Different commodity prices and average yields for respective insecticide treatments for all site years were used in the cost analysis.

Site Year		Soybean Price (\$ kg^{-1})						
		\$0.15	**\$0.22**	**\$0.29**	**\$0.37**	**\$0.44**	**\$0.51**	**\$0.59**
Perkins	2019	-\$5.67	\$31.50	\$68.67	\$105.83	\$143.00	\$180.17	\$217.34
	2020	-\$60.64	-\$50.96	-\$41.28	-\$31.59	-\$21.91	-\$12.23	-\$2.55
	2021	-\$41.99	-\$22.99	-\$3.98	\$15.02	\$34.03	\$53.03	\$72.04
Bixby	2019	-\$2.18	\$36.73	\$75.65	\$114.56	\$153.47	\$192.38	\$231.30
	2020	-\$49.31	-\$33.97	-\$18.62	-\$3.27	\$12.07	\$27.42	\$42.76
	2021	-\$48.67	-\$33.01	-\$17.34	-\$1.67	\$13.99	\$29.66	\$45.33

CONCLUSION

The overall objective of this study was to determine if and how the applied late-season practices could mitigate the detrimental effects of production challenges and stresses on soybean yield and seed quality. The purpose of the implemented treatments within the trial was not to increase yield or improve seed quality, but to maintain them throughout late-season uncertainties. Due to the nature of the potential late-season challenges such as insect pressure and unpredictable harvest delays due to weather, no two years will ever be the same. Because of this, overall trends present in the data can aid producers in their management decisions regarding the late-season period. Through the results of this trial, two major trends remained consistent in their effects to yield. First and foremost, delays in harvest resulted in reductions in yield. Significant losses in yield were caused by pre-harvest shatter losses that also occurred in the delayed harvests. Secondly, the application of a late season insecticide helped maintain yield over applications only made through the beginning seed fill growth stage. The exact causes of this difference were not determined; however, the differences were consistently present. Further studies are needed on a large-scale area to clarify the impact of insecticide treatments and their effects.

REFERENCES

Acharya, J., T.B. Moorman, T.C. Kaspar, A.W. Lenssen, and A.E. Robertson. 2020. Cover crop rotation effects on growth and developments, seedling disease, and yield of corn and soybean. *Plant Disease,* 104, 677-687. https://doi.org/10.1094/PDIS-09-19-1904-RE.

Acuna, J.C.M., and M.B. Villamil. 2014. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. *Agron. J.,* 106(3): 860-870. https://doil.org/10.2134/agronj13.0370.

Allen, D.E., B.P. Singh, and R.C. Dalal. 2011. Soil health indicators under climate change: a review of current knowledge. *Soil Health and Climate Change,* Soil Biology 29. https://doi.org/10.1007/978-3-642-20256-8_2.

Amezketa, E. 2018. Soil aggregate stability: A review. *Journal of Sustainable Agriculture,* 14(2-3):83-151. https://doil.org/10.1300/J064v14n02_08.

Andraski, T.W. and L.G. Bundy. 2005. Cover crop effects on corn yield response to nitrogen on an irrigated sandy soil. *Agron. J.,* 97, 1239-1244. https://doi.org/agronj2005.0052.

Argawal, A.P., P.W. Basarkar, P.M. Salimath, and S. Patil. 2002. Role of cell wall degrading enzymes in pod shattering process of soybean. *Curr. Sci.* 82(1):10.

Arias, M.E., J.A. Gonzalez-Perez, F.J. Gonzalez-Vila, A.S. Ball. 2005. Soil health-a new challenge for microbiologists and chemists. *International Microbiology*, 8:13-21.

Assefa, T., P.I. Otyama, A.V. Brown, S.R. Kalberer, R.S. Kulkarni, and S.B. Cannon. 2019. Genome-wide associations and epistatic interactions for internode number, plant height, seed weight and seed yield. *BMC Genomics*, 20:527. https://doil.org/10.1186/s12864-019-5907-7.

Bara, N., D. Khare, and A.N. Shrivastava. 2013. Studies on the factors affecting pod shattering in soybean. *Indian Journ. of Gen. and Plant Breed.,* 73(03): 270-277. https://doi.org/10.5958/j.0975-6906.73.3.040.

Beyer, B.A., R. Srinivasan, P.M. Roberts, and M.R. Abney. 2017. Biology and management of the threecornered alfalfa hopper (Hemiptera: Membracidae) in alfalfa, soybean, and peanut. *Journal of Integrated Pest Management*, 8(1). https://doi.org/10.1093/jipm/pmx003.

Bhor, T.J., V.P. Chimote, and M.P. Deshmukh. 2014. Inheritance of pod shattering in soybean [*Glycine max* (L.) Merrill]. *Electronic Journal of Plant Breeding,* 5(4): 671-676. https://ejplantbreeding.org/index.php/EJPB/article/view/275.

Bianchini, A., P.V. Dutra de Moraes, J.B. Jakubski, C.B. Rankrape, E. Gadyel, M.C. Schuster, and P. Rossi. 2019. Allelopathy of cover crops on the germination and initial development of *Euphorbia heterophylla*. *Journal of Agricultural Science,* 11(14): 74-82. https://doi.org/10.5539/jas.v11n14p74.

Bianchi, J.S., A. Quijano, C.O. Gosparini, and E.N. Morandi. 2020. Changes in leaflet shape and seeds per pod modify crop growth parameters, canopy light environment, and yield components in soybean. *The Crop Journal,* 8(2020):351-364. https://doi.org/10.1016/j.cj.2019.09.011.

Bjorkman, T., and J.W. Shail Jr. 2013. Using buckwheat cover crop for maximum weed suppression after early vegetables. *HortTech,* 2013 23(5). https://doi.org/10.21273/HORTTECH.23.5.575.

Blanco-Canqui, H. 2018. Cover crops and water quality. *Agron. J.,* 110, 1633-1647. https://doi.org/10.2134/agronj2018.02.0077.

Blanco-Canqui, H., and S.J. Ruis. 2020. Cover crop impacts on soil physical properties: A review. *Soil Sci. Soc. Am. J.* 84:1527-1576. https://doi.org/10.1002/saj2.20129.

Board, J.E. 1987. Yield components related to seed yield in determinate soybean. *Crop Science*, 27(6):1296-1297. https://doi.org/10.2135/cropsci1987.0011183X002700060041x.

Boudreaux, J.M., and J.L. Griffin. 2011. Application timing of harvest aid herbicides affects soybean harvest and yield. *Weed Tech.* 25:38-43. https://doi.org/10.1614/WT-D-10-00045.1.

Bundit, A., M. Ostlie, and C. Prom-U-Thai. 2021. Sunn hemp (*Crotalaria juncea*) weed suppression and allelopathy at different timings. *Biocontrol Science and Technology,* 31(7): 694-704. https://doi.org/10.1080/09583157.2021.1881446.

Bunchek, J.M., J.M. Wallace, W.S. Curran, D.A. Mortensen, M.J. VanGessel, and B.A. Scott. 2020. Alternative performance targets for integrating cover crops as a proactive herbicide-resistance management tool. *Weed Sci.* 68: 534-544. https://doi.org/10.1017/wsc.2020.49.

Burnside, O.C., G.A. Wicks, D.D. Warnes, B.R. Somerhalder, and S.A. Weeks. 1969. Effect of weeds on harvesting efficiency in corn, sorghum, and soybeans. *Weed Sci.,* 17: 438-441. https://doi.org/10.1017/S0043174500054473.

Castano, C., J.G. Alday, J. Parlade, J. Pera, J. Martinez de Aragon, and J.A. Bonet. 2017. Seasonal dynamics of ectomycorrhizal fungus *Lactarius vinosus* are altered by changes in soil moisture and temperature. *Soil Biology and Biochemistry,* 115: 253-260. https://doi.org/10.1016/j.soilbio.2017.08.021.

Castiglioni, M.G. and F.B. Kraemer. 2019. Short-term effect of cover crops on aggregate stability assessed by two techniques. *Cienc. Suelo (Argentina)* 37(2): 298-314.

Chalise, K.S., S. Singh, B.R. Wegner, S. Kumar, J.D. Perez-Gutierrez, S.L. Osborne, T. Nleya, J. Guzman, and J.S. Rohila. 2018. Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agron. J.* 110:99-108 (2018). https://doi.org/10.2134/agronj2018.03.0213.

Chu, M., S. Jagadamma, F.R. Walker, N.S. Eash, M.J. Buschermohle, and L.A. Duncan. 2017. Effect of multispecies cover crop mixture on soil properties and crop yield. *Agric. Environ. Lett.* 2:170030. https://doi.org/10.2134/ael2017.09.0030.

Chu, M., S. Singh, F.R. Walker, N.S. Eash, M.J. Buschermohle, L.A. Duncan, and S. Jagadamma. 2019. Soil health and soil fertility assessment by the Haney Soil Health Test in an agricultural soil in West Tennessee. *Communications in Soil Science and Plant Analysis,* 50(9): 1123-1131. https://doi.org/10.10800/00103624.2019.1604731.

Creamer, N.G., M.A. Bennett, B.R. Stinner, J. Cardina, and E.E. Regnier. 1996. Mechanisms of weed suppression in cover crop-based production system. *Hort. Sci.* 31(3): 410-413. https://doi.org/10.21273/HORTSCI.31.3.410.

Crookston, B.S., M.A. Yost, M. Bowman, K. Veum, G. Cardon, and J. Norton. 2021. Soil health spatial-temporal variation influence soil security on Midwestern, U.S. farms. *Soil Security*, 3:100005. https://doi.org/10.1016/j.soisec.2021.100005.

Dabney, S.M. 1998. Cover crop impacts on watershed hydrology. *Soil and Water Cons.*, 53(3) 207-213.

Dalal, R.C., D.E. Allen, K.Y. Chan, and B.P. Singh. 2011. Soil organic matter, soil health, and climate change. *Soil Biology,* 29. https://doi.org/10.1007/978-3-642-20256-8_5.

Dapaah, H.K., and T.J. Vyn. 1998. Nitrogen fertilization and cover crop effects on soil structural stability and corn performance. *Commun. Soil Sci. Plant Anal.* 29(17&18): 2557-2569. https://doi.org/10.1080/00103629809370134.

De Bruin, J.L., P.M. Porter, and N.R. Jordan. 2005. Use of a rye cover crop following corn in rotation with soybean in upper Midwest. *Agron. J.,* 97, 587-598. https://doi.org/10.2134/agronj2005.0587.

DeLaune, P.B., P. Mubvumba, S. Ale, and E. Kimura. 2020. Impact of no-till, cover crop, and irrigation on cotton yield. *Agricultural Water Management,* 232, 106038. https://doi.org/10.1014/j.agwat.2020.106038.

Delouche, J.C. 2021. Maintaining soybean quality. *Seed Technology Papers,* 101. https://scholarsjunction.msstate.edu/seedtechpapers/101.

Depieri, R.A., and A.R. Panizzi. 2010. Duration of feeding and superficial and in-depth damage to soybean by selected species of stinkbugs (Heteroptera: Pentatomidae). *Neotrop. Entomol.* 40(2):197-203.

Dhima, K.V., I.B. Vasilakoglou, I.G. Eleftherohorinos, and A.S. Lithourgidis. 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. *Crop Sci.* 46:345-352. https://doi.org/10.2135/cropsci2005-0186.

Ding, G., X. Liu, S. Herbert, J. Novak, D. Amarasiriwardena, and B. Xing. 2006. Effect of cover crop management on soil organic matter. *Geoderma,* 130, 229-239. https://doi.org/10.1016/j.geoderma.2005.01.019.

Doran, J.W., and M.R. Zeiss. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology,* 15, 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6.

Dunn, G.H., and R.E. Phillips. 1991. Macroporosity of a well-drained soil under no-till and conventional tillage. *Soil Sci. Soc. Amer. J.,* 55(3): 817-823. https://doi.org/10.2136/sssaj1991.03615995005500030031x.

Duval, M.E., J.A. Galantini, J.M. Martinex, and F. Limbozzi. 2018. Labile soil organic carbon for assessing soil quality: influence of management practices and edaphic conditions. *Catena*, 171:316-326. https://doi.org/10.1016/j.catena.2018.07.023.

Egli, D.B. 2013. The relationship between the number of nodes and pods in soybean communities. *Crop Sci.* 53:1668-1676. https://doi.org/10.2135/cropsci2012.11.0663.

Egli, D.B., and W.P. Bruening. 2014. Depodding causes green-stem syndrome in soybean. *Crop Management.* https://doi.org/10.1094/CM-2006-0104-01-RS.

Fageria, N.K., V.C. Baligar, and B.A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analaysis.* 36(19-20), 2733-2857. https://doi.org/10.1080/00103620500303939.

FAO STAT. 2021. Statistical Database. http://www.fao.org/faostat/en/#data/QC. (accessed 1 Jun. 2021).

Fierer, N., S.A. Wood, and C.P.B. de Mesquita. 2020. How microbes can, and cannot, be used to assess soil health. *Soil Biology and Biochemistry,* 153. https://doi.org/10.1016/j.soilbio.2020.108111.

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

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Harwood, J.M. Squire, and C.C. Sheaffer. 2001. Weed suppression by annual legume cover crops in no-tillage corn. *Soil and Crop Management,* 93(2), 319-325. https://doil.org/10.2134/agronj2001.932319x.

Florence, A.M., L.G. Higley, R.A. Drijber, C.A. Francis, and J.L. Lindquist. 2019. Cover crop mixture diversity, biomass productivity, weed suppression, and stability. *PLoS ONE,* 14(3): e0206195. https://doi.org/10.1371/journal.pone.0206195.

Folorunso O.A., D.E. Rolston, T. Prichard, and D.T. Louie. 1992. Soil surface strength and infiltration rate as affected by winter cover crops. *Soil Technology,* 5, 189-197. https://doi.org/10.1016/0933-3630(92)90021-R.

Franca Neto, J.B., F.C., Krzyzanowski, A.A. Henning, S.H. West, and L.C. Miranda. 1993. Soybean seed quality as affected by shriveling due to heat and drought stresses during seed filling. *Seed Sci. and Tech.* 21:107-116.

Ghahreman, S., A. Ebadi, A. Tobeh, M. Hashemi, M. Sedghi, A. Gholipoouri, and A.V. Barker. 2021. Short-term impact of monocultured and mixed cover crops on soil properties, weed suppression, and weed suppression, and lettuce yield. *Communications in Soil Science and Plant Analysis,* 52(4):400-409. https://doi.org/10.1080/00103624.2020.1854295.

Ghimire, R., B. Ghimire, A.O. Mesbah, U.M. Sainju, and O.J. Idowu. 2019. Soil health response of cover crops in winter wheat-fallow system. *Agron. J.* 111, 2108-2115. https://doi.org/10.2134/agronj2018.08.0492.

Griffin, J.L., J.M. Boudreaux, and D.K. Miller. 2010. Herbicides as harvest aids. *Weed Science,* 58:355-358. https://doi.org/10.1614/WS-09-108.1.

Groff, S. 2015. The past, present, and future of the cover crop industry. *Journal of Soil and Water Conservation.* 70(6), 130A-133A. https://doi.org/10.2489/jswc.70.6.130A.

Haruna, S.I., S.H. Anderson, R.P. Udawatta, C.J. Gantzer, N.C. Phillips, S. Cui, and Y. Gao. 2020. Improving soil physical properties through the use of cover crops: a review. *Agrosyst Geosci Environ.* 2020;3:e20105. https://doi.org/10.1002/agg2.20105.

Haney, R.L., W.F. Brinton, and E. Evans. 2008. Soil CO_2 respiration: Comparison of chemical titration, CO_2 IRGA analysis and the Solvita gel system. *Renewable Agriculture and Food Systems,* 23(2): 171-176. https://doi.org/10.1017/S174217050800224X.

Haney, R.L., E.B. Haney, D.R. Smith, R.D. Harmel, and M.J. White. 2018. The soil health tool—Theory and initial broad-scale application. *Applied Soil Ecology*, 125:162-168. https://doi.org/10.1016/j.apsoil.2017.07.035.

Haney, R.L., E.B. Haney, L.R. Hossner, and J.G. Arnold. 2010. Modifications to the new soil extractant H3A-1: A multinutrient extractant. *Commun. Soil Sci. Plant Anal.,* 37: 11-12. https://doi.org/10.1080/00103624.2010.482173.

Heatherly, L.G., and H.F. Hodges. 1998. Soybean insect management. In: Heatherly, L.G., and H.F. Hodges (eds) Soybean Production in the Midsouth.

Helms, D. 1992. Readings in the History of the Soil Conservation Service. USDA SCS. *Historical Notes Number 1.* https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043484.pdf (Accessed 12 Oct. 2021).

Hepperly, P.R., and J.B. Sinclair. 1978. Quality losses in *Phomopsis*-infected soybean seeds. *Phytopathology* 68:1684-1687.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. *Soil & Tillage Research,* 44, 109-120. https://doi.org/10.1016/S0167-1987(97)00043-3.

Herzog, D.C. 1980. Sampling soybean looper on soybean. In: Kogan, M., Herzog, D.C. (eds) Sampling methods in soybean entomology. *Springer Series in Experimental Entomology*. https://doi.org/10.1007/978-1-4612-9998-1_7.

Hobbs, H.A., C.B. Hill, C.R. Grau, N.C. Koval, Y. Wang, W.L. Pedersen, L.L. Domier, and G.L. Hartman. 2006. Green stem disorder of soybean. *Plant Dis.* 90:513-518. https://doil.org/10.1094/PD-90-0513.

Hoffman, M.L., L.A. Weston, J.C. Snyder, and E.E. Regnier. 1996. Allelopathic influence of germinating seeds and seedlings of cover crops on weed species. *Weed Science,* 44(3): 579-584. https://www.jstor.org/stable/4045639.

Hsiao, C.-J., G.F. Sassenrath, L.H. Zeglin, G.M. Hettiarachchi, and C.W. Rice. 2019. Temporal variation of soil microbial properties in a corn-wheat-soybean system. *Soil Sci. Soc. Am. J.* 83:1696-1711. https://doi.org/10.2136/sssaj2019.05.0160.

Hunt, T.E., L.G. Higley, and J.F. Witkowski. 1994. Soybean growth and yield after simulated bean leaf beetle injury to seedlings. *Agron. J.,* 86:140-146. https://doi.org/10.2134/agronj1994.00021962008600010026x.

Hunter, M.C., A.R. Kemanian, D.A. Mortenson. 2021. Cover crop effects on maize drought stress and yield. *Agriculture, Ecosystems, and Environmnent,* 311(2021); 107294. https://doi.org/10.1016/j.agee.2020.107294.

Hunter, M.C., M.E. Schipanski, M.H.Burgess, J.C. LaChance, B.A. Bradley, M.E. Barbercheck, J.P. Kaye, and D.A. Mortensen. 2019. Cover crop mixture effects on maize, soybean, and wheat yield in rotation. *Agric. Environ. Lett.* 4:180051. https://doi.org/10.2134/ael2018.10.0051.

Ingels, C., M.V. Horn, R. Bugg, and P.R. Miller. 1994. Selecting the right cover crop gives multiple benefits. *Calif. Agr.*, 45(5):43-48.

Janzen, H.H. 2006. The soil carbon dilemma: shall we hoard it or use it? *Soil Biology & Biochemistry*, 38: 419-424. https://doi.org/10.1016/j.soilbio.2005.10.008.

Janzen, H.H., C.A. Campbell, B.H. Ellert, and E. Bremer. 1997. Soil organic matter dynamics and their relationship to soil quality. *Developments in Soil Science,* 25, 277-292 in Soil Quality for Crop Production and Ecosystem Health.

Kelly, C., M.E. Schipanski, A. Tucker, W. Trujillo, J.D. Holman, A.K. Obour, S.K. Johnson, J.E. Brummer, L. Haag, and S.J. Fonte. 2021. Dryland cover crop soil health benefits are maintained with grazing in the U.S. high and central plains. *Agriculture, Ecosystems, and Environment,* 313(2021); 107358. https://doi.org/10.1016/j.agee.2021.107358.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. *Physical and Mineralogical Methods,* Agronomy Monograph no. 9.

Kogan, M., and S.G. Turnipseed. 1987. Ecology and management of soybean arthropods. *Ann. Rev. Entomol.* 32:507-538.

Kokubun, M., and K. Watanabe. 1984. Analysis of the yield-determining process of field-grown soybean in relation to canopy structure. *Japan. Jour. Crop Sci.,* 52(2): 215-219.

Krueger, E.S., T.E. Ochsner, P.M. Porter, and J.M. Baker. 2011. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. *Agron. J.,* 103:316-323. https://doi.org/agronj.2010.0327.

Kumar, V., A. Obour, P. Jha, R. Liu, M.R. Manuchehri, J.A. Dille, J. Holman, and P.W. Stahlman. Integrating cover crops for weed management in semiarid U.S. Great Plains: opportunities and challenges. *Weed Sci.* 68:311-323. https://doi.org/10.1017/wsc.2020.29.

Lamp, B.J., W.H. Johnson, K.A. Harkness, and P.E. Smith. 1962. Soybean harvesting—approaches to improved harvesting efficiencies. *Research Bulletin* 899. Ohio Agricultural Experiment Station.

Langdale, G.W., R.L. Blevins, D.L. Karlen, D.K. McCool, M.A. Nearing, E.L. Skidmore, A.W. Thomas, D.D. Tyler, and J.R. Williams. 1991. Cover crop effects on soil erosion by wind and water. *Cover Crops for Clean Water.* 15-22.

Larkin, R.P. 2019. Effects of cover crops, rotation, and biological control products on soil properties and productivity in organic vegetable production in the Northeastern US. *Org. Agr.* https://doi.org/10.1007/s12165-019-00257-3.

Lawley, Y.E., J.R. Teasdale, and R.R. Weil. 2012. The mechanism for weed suppression by a forage radish cover crop. *Agron. J.* 104:205-214. https://doi.org/10.2134/agronj2011.0128.

Lee, I., M.-J. Seo, M.R. Park, N.-G. Kim, G. Yi, Y.-Y. Lee, M. Kim, B.W. Lee, and H.-T. Yun. 2020. Yield and seed quality changes according to delayed harvest with rainfall treatment in soybean (*Glycine max* L.). *Korean J. Crop Sci.* 65(4): 353-364. https://doi.org/10.7740/kjcs.2020.65.4.353.

Lehmann, J., D.A. Bossio, I. Kogel-Knaber, and M.C. Rillig. 2020. The concept and future prospects of soil health. *Nat. Rev. Earth Environ.* 1(10): 544-553. https://doi.org/10.1038/s43017-020-0080-8.

Li, C., A. Cano, V. Acosta-Martinez, K. S Veum, and J. Moore-Kucera. 2020. A comparison between fatty acid methyl ester profiling methods (PLFA and EL-FAME) as soil health indicators. *Soil Sci. Soc. Am. J., 84:1153-1169.* https://doi.org/10.1002/saj2.20118.

Liu, A., B.L. Ma, and A.A. Bomke. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. *Soil Sci. Soc. Am. J.* 69:2041-2048. https://doi.org/10.2136/sssaj2005.0032.

Liu, X., S.J. Herbert, A.M. Hashemi, X. Zhang, and G. Ding. 2006. Effects of agricultural management on soil organic matter and carbon transformation- a review. *Plant Soil Environ.,* 52(12): 531-543.

Lou, Y., A.S. Davis, and A.C. Yannarell. 2015. Interactions between allelochemicals and the microbial community affect weed suppression following cover crop residue incorporation into soil. *Plant Soil*, 399, 357-371. https://doi.org/10.1007/s11104-015-2698-8.

MacLaren, C., P. Swanepoel, J. Bennett, J. Wright, and K. Dehnen-Schmultz. 2019. Cover crop biomass production is more important than diversity for weed suppression. *Crop Sci.* 59(2): 733-748. https://doi.org/10.2135/cropsci2018.05.0329.

Mirsky, S.B., W.S. Curran, D.M. Mortenseny, M.R. Ryany, and D.L. Shumway. 2011. Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. *Weed Science*, 59(3):380-389. https://doi.org/10.1614/WS-D-10-00101.1.

Mitchell, J.P., A. Shrestha, K. Mathesius, K.M. Scow, R.J. Southard, R.L. Haney, R. Schmidt, D.S. Munk, and W.R. Horwarth. 2015. Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. *Soil and Tillage Research,* 165(2017):325-335. http://dx.doi.org/10.1016/j.still.2016.09.001.

Miura, T., K. Makoto, S. Niwa, N. Kaneko, and K. Sakamoto. 2017. Comparison of fatty acid methyl ester methods for characterization of microbial communities in forest and arable soil: Phospholipid fraction (PLFA) versus total ester linked fatty acids (EL-FAME). *Pedobiologia,* 63:14-18. https://doi.org/10.1016/j.pedobi.2017.04.002.

Moncada, M.P., D. Gabriels, W. Cornelis, and D. Lobo. 2013. Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation and Development,* 26(8):843-852. https://doi.org/10.1002/ldr.2225.

Moore, M.J., T.J. Gillespie, and C.J. Swanton. 1994. Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. *Weed Technology. 8:512-518.* https://www.jstor.org/stable/3988021.

Musser, F.R., A.L. Catchot, B.K. Gibson, and K.S. Knighten. 2011. Economic injury levels for southern green stinkbugs (Hemiptera: Pentatomidae) in R7 growth stage soybeans. *Crop Protection*. 30:63-69. https://doi.org/10.1016/j.cropro.2010.09.011.

Nascente, A.S., and C.A.C. Crusciol. 2012. Cover crops and herbicide timing management on soybean yield under no-tillage system. *Pesq. Agropec. Bras.* 47(2): 187-192. https://doi.org/10.1590/S0100-204X2012000200006.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In D.L. Sparks (Ed.), *Methods of soil analysis: Part 3. Chemical methods.* SSSA and ASA. https://doi.org/10.2136/sssabookser5.3.c34.

Nielson, D.C., D.J. Lyon, R.K. Higgins, G.W. Hergert, J.D. Holman, and M.F. Vigil. 2016. Cover crop effect on subsequent wheat yield in the central great plains. *Agron. J.* 108:243-256. https://doi.org/10.2134/agronj2015.0372.

Norsworthy, J.K., S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, T.M. Webster, K.W. Bradley, G. Frisvold, S.B. Powles, N.R. Burgos, W.W. Witt, and M. Barrett. 2012. Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science, 2012: 31-62.* https://doi.org/10.1614/WS-D-11-00155.1.

Ochsner, T. 2021. Rain or Shine. *Oklahoma State University Library Open Textbook Initiative.*

Osipitan, O.A., J.A. Dille, Y. Assefa, E. Radicetti, A. Ayeni, and S.Z. Knezevic. 2019. Impact of cover crop management on level of weed suppression: a meta-analysis. *Crop Sci.* 59:833-842. https://doi.org/10.2135/cropsci2018.09.0589.

Philbrook, B.D., and E.S. Oplinger. 1989. Soybean field losses as influenced by harvest delays. *Agron. Journ.*, 81(2): 251-258. https://doi.org/10.2134/agronj1989.00021962008100020023x.

Rankoth, L.M., R.P. Udawatta, C.J. Gantzer, S. Jose, K. Veum, and H. Dewanto. 2019. Cover crops on temporal and spatial variations in soil microbial communities by phospholipid fatty acid profiling. *Agron. J.* 111:1693-1704. https://doi.org/10.2134/agronj2018.12.0789.

Reddy, K. 2001. Effects of cereal and legume cover crop residues on weed, yield, and net return in soybean (*Glycine max*). *Weed Technology,* 15(4): 660-668. https://www.jstor.org/stable/3988546.

Reddy, K. 2003. Impact of cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean (*Glycine max). Weed Technology,* 17(1): 28-35. https://doi.org/10.1614/0890-037X(2003)017[0028:IORCCA]2.0.CO;2.

Reddy, K.N., R.M. Zablotowicz, M.A. Locke, and C.H. Koger. 2003. Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. *Weed Science*, 51(6):987-994. https://doi.org/10.1614/P2000-169.

Romkaew, J., and T. Umezaki. 2006. Pod dehiscence in soybean: Assessing methods and varietal difference. *Plant Prod. Sci.,* 9(4): 373-382. https://doi.org/10.1626/pps.9.373.

Royer, T.A. 2021. Management of insect and mite pest in soybean. *Oklahoma Cooperative Extnesion Service* CR-7167.

Royer, T.A., D. Arnold, and B. Hellie. 2016. Common insects of field crops in Oklahoma. *Oklahoma Cooperative Extension Service* E-1043.

Russin, J.S., M.B. Layton, D.B. Orr, and D.J. Boethel. 1987. Within-plant distribution of, and partial compensation for, stinkbug (Heteroptera: Pentatomidae) damage to soybean seeds. *J. Econ. Entomol.* 80: 215-220. https://doi.org/10.1093/jee/80.1.215.

Ryan, M.R., W.S. Curran, A.M. Grantham, L. K. Hunsberger, S.B. Mirsky, D.A. Mortenson, E.A. Nord, and D.O. Wilson. 2011. Effects of seeding rate and poultry litter on weed suppression from a rolled cereal rye cover crop. *Weed Science*, 59(3):438-444. https://doi.org/10.1614/WS-D-10-00180.1.

Saini, M., A. Price, and E. Van Santen. 2006. Cover crop residue effects on early-season weed establishment in a conservation-tillage corn-cotton rotation. In: 28th Annual Southern Conservation Systems Conference. *USDA-ARS Conservation and Production Research Laboratory Rep*., 175-182.

Schutter, M.E., and Richard P. Dick. 2000. Comparison of fatty acid methyl ester (FAME) methods for characterizing microbial communities. *Soil Science Society of America Journal* 64(5), 1659-1668. https://doi.org/10.2136/sssaj2000.6451659x.

Shah, A.N., M. Tanveer, B. Shahzad, G. Yang, S. Fahad, S. Ali, M.A. Bukhari, S.A. Tung, A. Hafeez, and B. Souliyanonh. 2017. Soil compaction effects on soil health and crop productivity: an overview. *Environ Sci Pollut Res*, 24:10056-10067. https://doi.org/10.1007/s11356-017-8421-y.

Skinner, E.M., J.C. Diaz-Perez, S.C. Phatatk, H.H. Schomberg, and W. Vencill. 2012. Allelopathic effects of sunnhemp (*Crotolaria juncea*) on germination of vegetables and weeds. *Hort. Sci.*, 47(1):138-142. https://doi.org/10.21273/HORTSCI.47.1.138.

Solvita. 2022. CO_2 method-standard lab protocol measure CO_2 respiration. https://solvita.com/co2-burst/

Teasdale, J.R., L.O. Brandsaeter, A. Calegari, and F. Skora Neto. 2007. Cover crops and weed management. *Non-chemical Weed Management,* 4: 49-64.

Tekrony, D.M., D.B. Egli, and A.D. Phillips. 1980. Effect of field weathering on the viability and vigor of soybean seed. *Agron. Journ.* 72(5): 749-753. https://doi.org/10.2134/agronj1980.00021962007200050014x.

Tiwari, S.P., and P.S. Bhatnagar. 1991. Genetics of pod shattering in soybean. *Soybean Genet. Newsl.* 18:150-153.

Thomas, G.D., C.M. Ignoffo, C.E. Morgan, and W.A. Dickerson. 1974. Southern green stinkbug: Influence on yield and quality of soybeans. *Journ. of Econ. Entomol. 67(4):* 501-503. https://doi.org/10.1093/jee/67.4.501.

Todd, J.W., and S.G. Turnipseed. 1973. Effects of Southern green stinkbug damage on yield and quality of soybeans. *Journ. of Econ. Ento.* 67(3):421-426. https://doi.org/10.1093/jee/67.3.421.

Tukamuhabwa, P., K.E. Dashiell, P. Rubaihayo, and M. Nabasirye. 2002. Determination of field yield loss and effect of environment on pod shattering is soybean. *African Crop Sci. Journ.* 10(3): 203-209. https://hdl.handle.net/20.500.12478/3809.

Turnipseed, S.G. 1972. Management of insect pests of soybeans. *Proc. Tall Timbers Conf. Ecol. Anim. Contr. Habitat Manage.* 4:189-203.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. *Jornal of Soil and Water Conservation,* 53(3): 200-207.

USDA RMA. 2018. Cover Crops and Crop Insurance. USDA RMA. https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/State-Offices/Iowa/pdfs/Cover_Crop_Fact_Sheet.pdf (accessed 12 Oct. 2021).

USDA FAS. 2021. World Agricultural Production. USDA FAS. https://apps.fas.usda.gov/psdonline/circulars/production.pdf (accessed 1 Jun. 2021).

USDA NASS. 2021. 2020 State Agriculture Overview. Quick Stats. USDA. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=OKLAHOMA (accessed 6 Mar. 2021).

USDA NRCS. 1996. Soil quality resource concerns: compaction. USDA NRCS Soil Quality Inst., Ames, IA. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051594.pdf (accessed 3. Jan. 2022).

USDA NRCS. 2014. NRCS Conservation Practice Standard: Cover Crop. USDA NRCS. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1263176.pdf (accessed 12 Oct. 2021).

USDA NRCS. 2021. Soil Health Glossary. USDA NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/?cid=nrcs142p2_053848 (accessed 18 Oct. 2021).

Ward Laboratories Inc. 2019. Haney/Soil Health Test Information Rev. 1.0. https://www.wardlab.com/wp-content/uploads/2019/09/Haney-Rev-1.0-Information.pdf. (accessed 15 Apr. 2021).

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruever, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, 18(1): 3-17. https://www.jstor.org/stable/44503242.

Weston, L.A. 1996. Utilization of allelopathy for weed management in agroecosystems. *Agron. J.* 88: 860-866. https://doi.org/10.1.1.473.3515.

Whigham, D.K. and E.W. Stoller. 1979. Soybean desiccation by paraquat, glyphosate, and ametryn to accelerate harvest. *Agron. J.,* https://doi.org/10.2134.agronj1979.00021962007100040027x.

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. *Soil Sci. Soc. Am. J.,* 68: 1403-1409. https://doi.org/10.2136/sssaj2004.1403.

Williams II, M.M., D.A. Mortensen, and J.W. Doran. 2000. No-tillage soybean performance in cover crops for weed management in the western Corn Belt. *Journal of Soil and Water Conservation,* 55(1):79-84.

Wood, S.A., and M. Bowman. 2021. Large-scale farmer-led experiment demonstrates positive impact of cover crops on multiple soil health indicators. *Nature Food,* 2:97-103. https://doi.org/10.1038/s43016-021-00222-y.

Wulanningtyas, H.S., Y. Gong, P. Li, N. Sakagami, J. Nishiwaki, and M. Komatsuzaki. 2021. A cover crop and no-tillage system for enhancing soil health by increasing soil organic matter in soybean cultivation. *Soil and Tillage Research,* 205(2021) 104749. https://doi.org/10.1016/j.still.2020.104749.

Zhang, B., Q.G. Zhao, R. Horn, and T. Baumgartl. 2000. Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and Tillage Research,* 59: 97-106. https://doi.org/10.1016/S0167-1987(01)00163-5.

Zhang, H., K. Henderson, and B. McCray. 2019. Testing services and price list. *Oklahoma Cooperative Extension Service,* L-241. https://agriculture.okstate.edu/departments-programs/plant-soil/soil-testing/site-files/docs/price-list-brochure.pdf. (accessed 10 Oct. 2021).

APPENDICES

APPENDIX A

Cover Crop Trial- Yield Components

Table 38. Average soybean seed protein contents (%) for each cover crop treatments for all years.

	Bixby 2019	Perkins 2019	Perkins 2020	Perkins 2021
Fallow	33.99	33.81	34.49	33.61
Rye-Oats	34.84	33.79	35.22	34.22
Canola	33.92	33.89	34.95	33.66
Buckwheat	34.61	33.95	34.86	33.51
Sunn Hemp	34.13	33.85	35.08	33.80
Chicory	34.03	34.10	34.75	33.62
Kitchen Sink	34.90	34.15	35.25	33.53

Table 39. Average soybean seed oil contents (%) for each cover crop treatments for all years.

	Bixby 2019	Perkins 2019	Perkins 2020	Perkins 2021
Fallow	18.87	19.33	17.98	18.29
Rye-Oats	18.84	19.23	17.12	18.16
Canola	19.18	19.13	17.73	18.31
Buckwheat	18.58	19.06	17.88	18.59
Sunn Hemp	18.83	19.00	17.39	18.05
Chicory	19.00	19.12	17.86	18.34
Kitchen Sink	19.18	18.88	17.40	18.07

Table 40. Coefficients of variation for the yield of each cover crop treatment at each site year.

	Bixby 2019	Perkins 2019	Perkins 2020	Perkins 2021
Fallow	10.92	9.74	19.43	18.24
Rye-Oats	3.74	36.13	35.04	7.89
Canola	20.08	11.92	33.48	16.33
Buckwheat	5.60	27.38	13.69	8.22
Sunn Hemp	22.93	29.82	15.16	23.97
Chicory	13.46	25.19	24.45	27.32
Kitchen Sink	16.27	12.60	4.45	6.61

Figure 41. Coefficients of variation for percent of 0, 1, 2, 3, and 4 bean pods of total pods, number of total pods, mainstem nodes, and total nodes for each treatment at each site year. Highlighted cells represent treatments with high levels of variation for the given variable.

		0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
Bixby 2019	**Fallow**	51.67	28.64	8.35	6.33	18.76	26.10	13.19	21.59
	Rye-Oats	97.28	25.71	8.18	8.57	47.21	15.33	8.68	18.14
	Canola	71.96	16.29	13.70	11.80	58.98	17.81	12.78	2.22
	Buckwheat	98.00	30.42	4.61	9.85	34.53	12.67	4.97	10.05
	Sunn Hemp	60.71	41.79	6.56	12.16	24.99	29.95	5.66	9.21
	Chicory	47.89	3.40	4.42	1.53	75.84	6.90	12.84	15.32
	Kitchen Sink	42.54	68.07	14.15	11.10	24.79	30.97	1.93	15.77
Perkins 2019	**Fallow**	45.64	13.52	4.99	4.27	87.38	18.73	14.34	7.77
	Rye-Oats	39.17	27.07	7.79	2.00	36.54	3.09	8.91	11.70
	Canola	79.44	31.46	8.41	12.16	52.63	13.33	14.63	9.75
	Buckwheat	63.35	12.06	10.19	11.76	173.21	10.05	2.98	9.94
	Sunn Hemp	80.81	13.89	1.43	3.65	87.46	8.15	4.62	9.90
	Chicory	72.58	32.49	3.66	15.45	173.21	10.72	3.57	9.16
	Kitchen Sink	82.76	70.32	18.11	24.51	73.71	57.25	4.45	28.57
Perkins 2020	**Fallow**	47.00	2.56	8.78	13.08	32.54	6.38	8.87	10.58
	Rye-Oats	10.15	30.61	10.22	20.96	56.06	18.16	12.04	33.02
	Canola	85.98	23.90	22.02	11.21	24.37	70.10	9.06	51.32
	Buckwheat	49.17	39.64	11.72	12.46	68.83	21.67	8.75	7.58
	Sunn Hemp	69.53	6.85	19.02	6.22	93.49	22.60	3.35	7.85
	Chicory	34.48	14.44	9.09	17.11	98.43	5.27	17.53	12.29
	Kitchen Sink	39.41	7.37	8.00	7.04	54.64	20.07	3.81	10.99
Perkins 2021	**Fallow**	104.05	49.90	21.38	74.61	173.21	60.03	18.80	35.55
	Rye-Oats	57.79	120.72	6.28	24.00	95.91	18.86	18.48	7.36
	Canola	46.23	92.65	9.04	3.75	173.21	44.27	27.09	35.54
	Buckwheat	70.65	104.74	32.74	25.83	N/A	30.28	43.98	16.32
	Sunn Hemp	80.59	22.46	6.24	8.79	102.98	50.59	10.33	26.98
	Chicory	111.83	91.34	2.81	40.65	N/A	40.86	17.95	16.20
	Kitchen Sink	45.59	9.76	18.78	9.69	149.58	66.43	44.26	61.91

Seed Quality Ratings

Table 42. Visual seed quality ratings for all site years.

	Bixby 2019	Perkins 2019	Perkins 2020	Perkins 2021
Fallow	1.7 C	4.5 A	2.8	4.0
Rye-Oats	2.3 AB	3.3 C	3.0	3.9
Canola	2.0 BC	3.8 BC	3.0	3.8
Buckwheat	2.7 A	4.0 AB	2.5	3.7
Sunn Hemp	2.3 AB	4.0 AB	2.8	3.8
Chicory	2.3 AB	4.0 AB	3.0	4.0
Kitchen Sink	2.7 A	3.5 BC	2.5	3.8

APPENDIX B

Late Season Management

Table 43. Insect counts for scouting events at Bixby in 2020.

Scouting Date	Bean Leaf Beetle	Three-Cornered Alfalfa Hopper	Green Stinkbug	Stinkbug Nymphs	Grasshoppers	Loopers
7/15/2020*	0.38	8.63	0.63	0	0	0.25
8/4/2020	0	2.36	0.93	0	0.07	0
8/20/2020	0	0	0.38	0	0	0.15
8/27/2020	0	0	0.80	0.25	0	0
9/15/2020*	0	0	1.30	10+	0	0
9/30/2020	0	0	1.00	0.90	0	0

*Insect counts triggered spray application.

Table 44. Insect counts for scouting events at Perkins in 2020.

Scouting Date	Bean Leaf Beetle	Three-Cornered Alfalfa Hopper	Green Stinkbug	Stinkbug Nymphs	Grasshoppers	Loopers
7/16/2020*	0.67	4.83	0.17	0	0	0
8/25/2020	0	0	1.54	0.23	0	0
9/8/2020	0	0	0.44	0.87	0	0.13
9/14/2020*	0	0	2.11	2.33	0	0

*Insect counts triggered spray application.

Table 45. Insect Counts for scouting events at Bixby in 2021.

Scouting Date	Bean Leaf Beetle	Three-Cornered Alfalfa Hopper	Green Stinkbug	Stinkbug Nymphs	Grasshoppers	Loopers	Brown Stinkbug	Japanese Beetle
7/7/2021	0.75	0.25	0	0	0	0	0	0
7/22/2021*	0	1.2	0.7	0	0	0.6	0.5	0.5
8/5/2021	0	0	1.13	0	0.27	1.73	0	0
8/31/2021*	0	0	4.8	12.4	0	0	0	0
9/15/2021	0	0	1.15	2.25	0	0	0	0

*Insect counts triggered spray application.

Table 46. Insect Counts for scouting events at Perkins in 2021.

Scouting Date	Bean Leaf Beetle	Three-Cornered Alfalfa Hopper	Green Stinkbug	Stinkbug Nymphs	Grasshoppers	Loopers	Brown Stinkbug	Japanese Beetle
7/6/2021	0.45	0.09	0	0	0	0	0.09	0
7/23/2021*	0.3	0.1	0	0	0.3	0	0	0
8/5/2021	0	0	0	0	0	0	0	0
8/23/2021*	0	0	0.27	1.18	0	0	0	0

*Insect counts triggered spray application.

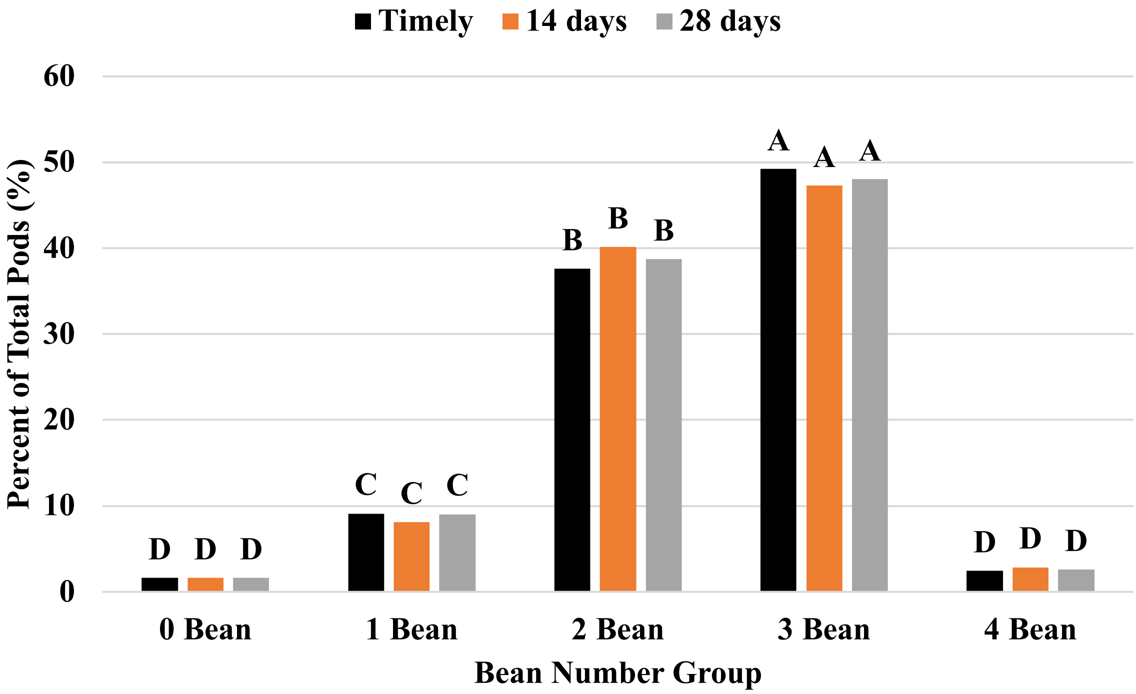

Figure 41. Percent of total pods for the Bixby 2019 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05).

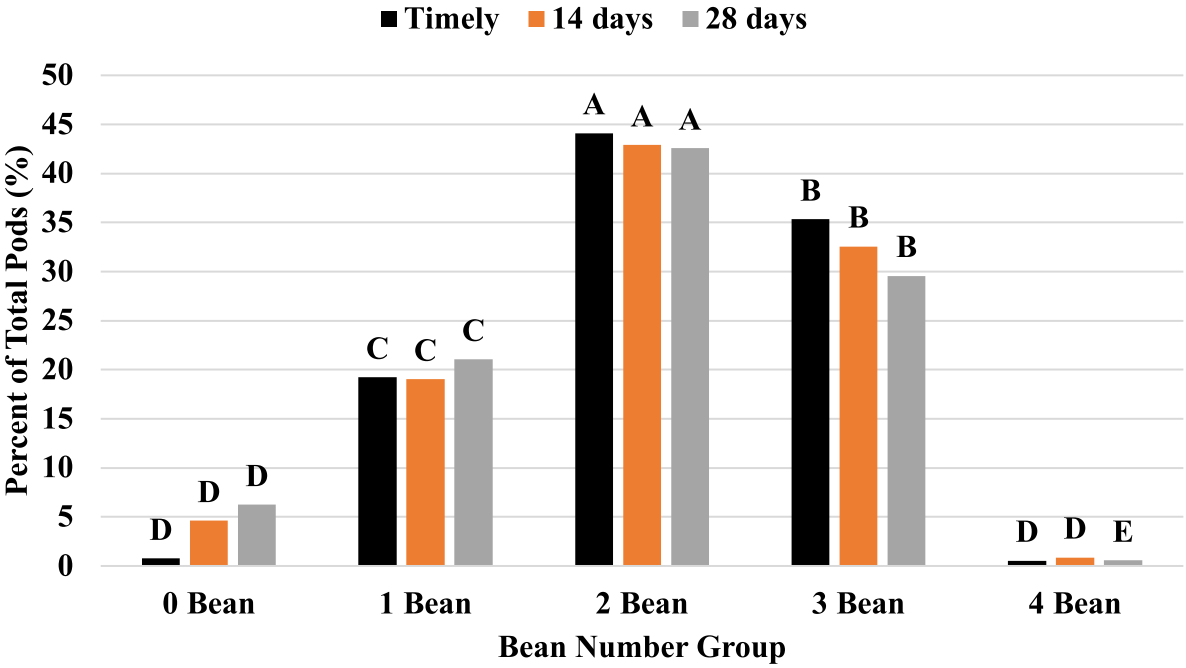

Figure 42. Percent of total pods for the Perkins 2019 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05).

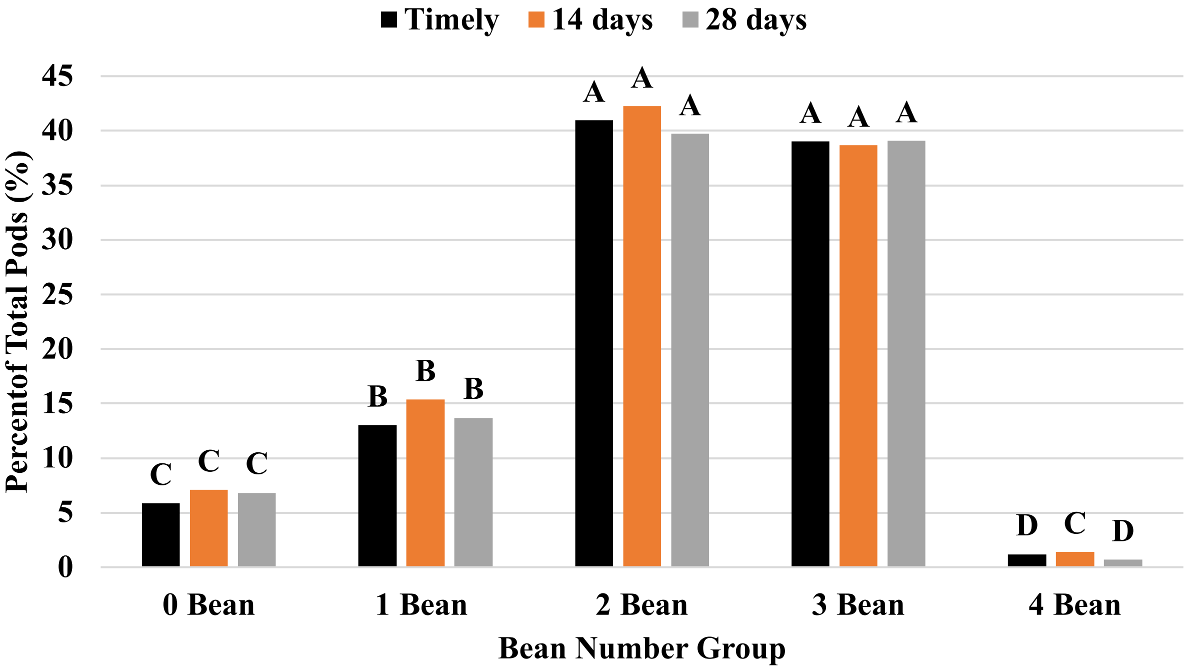

Figure 43. Percent of total pods for the Bixby 2020 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05)

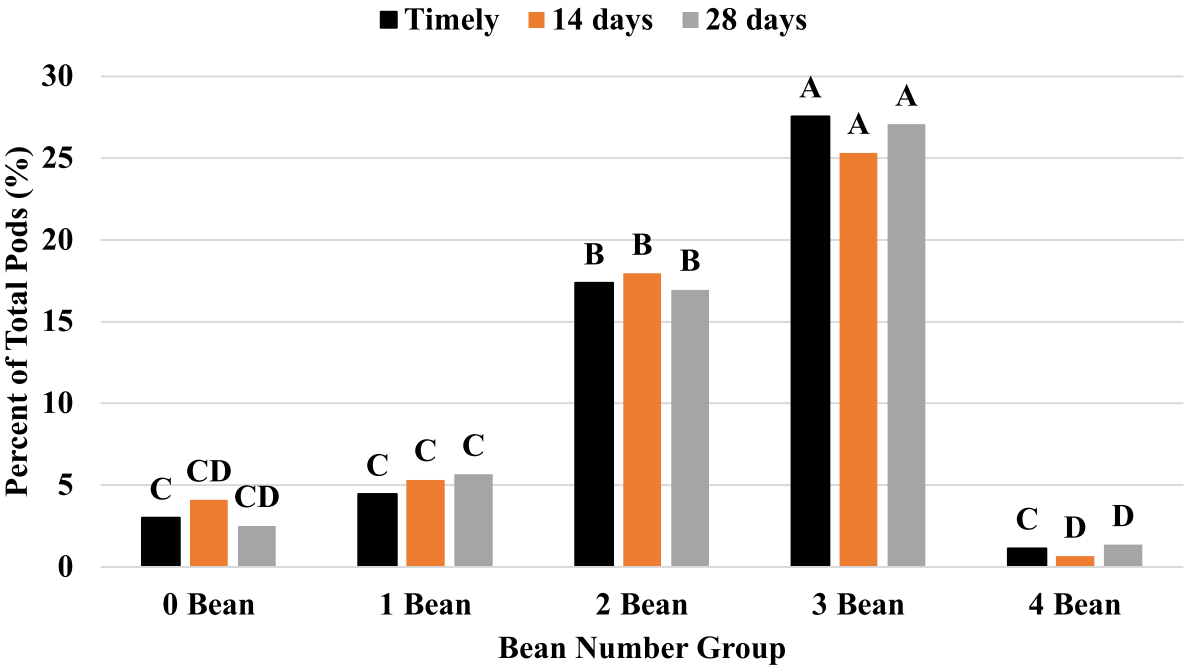

Figure 44. Percent of total pods for the Bixby 2021 location. Capital letters denote significant differences in percent of total pods between bean number groups within each individual harvest timing (*a*=0.05)

Table 47. Percent of total pods, total pods, and node counts averaged across treatments for the Bixby 2020 location.

Insecticide Treatment	Desiccation Treatment	Harvest Timing	Percent of Total Pods (%) 0 Bean Pod	1 Bean Pod	2 Bean Pod	3 Bean Pod	4 Bean Pod	Total Pods	Mainstem Nodes	Total Nodes
R5	**NT**	**Timely**	6.40	16.31	41.78	34.98	0.52	154.25	26.17	78.25
R7	**NT**	**Timely**	5.19	10.40	40.17	41.54	2.70	129.75	25.08	73.17
R5	**T**	**Timely**	5.44	11.00	40.24	42.79	0.53	132.08	23.67	75.58
R7	**T**	**Timely**	6.40	14.28	41.63	36.73	0.96	154.83	26.08	88.25
R5	**NT**	**14 days**	7.44	13.18	41.75	36.35	1.27	130.22	25.83	64.44
R7	**NT**	**14 days**	7.68	16.69	38.65	39.33	0.63	123.59	26.42	52.04
R5	**T**	**14 days**	7.32	14.85	45.20	43.48	1.66	152.00	25.75	71.58
R7	**T**	**14 days**	5.61	15.67	42.82	33.65	2.25	123.11	26.42	72.00
R5	**NT**	**28 days**	6.46	15.29	39.10	38.57	0.58	141.08	25.33	82.17
R7	**NT**	**28 days**	7.17	18.48	39.23	34.71	0.41	159.25	24.75	81.75
R5	**T**	**28 days**	8.52	10.04	38.76	41.75	0.93	135.08	26.08	73.21
R7	**T**	**28 days**	5.12	10.98	41.73	41.29	0.87	117.58	24.67	68.92

ANOVA Table

	Percent 0 Bean	Percent 1 Bean	Percent 2 Bean	Percent 3 Bean	Percent 4 Bean	Total Pods	Mainstem Nodes	Total Nodes
Insect Timing	0.5389	0.6355	0.6593	0.5007	0.403	0.8807	0.7689	0.6334
Desiccation Treatment	0.6605	0.7418	0.6632	0.9076	0.2748	0.8141	0.583	0.7518
Harvest Timing	0.6309	0.3174	0.5085	0.1786	0.6376	0.5305	0.178	0.8056
Insect*Desiccation	0.884	0.5648	0.3955	0.7083	0.2028	0.4975	0.4172	0.9105
Insect*Harvest	0.5892	0.7273	0.3484	0.0999	0.8963	0.4015	0.7202	0.7937
Desiccation*Harvest	0.7302	0.4056	0.8267	0.572	0.1577	0.7135	0.2182	0.5391
Insect*Desiccation*Harvest	0.4486	0.1915	0.9719	0.1094	0.1987	0.2886	0.6433	0.3941

Table 48. Percent of total pods, total pods, and node counts averaged across treatments for the Perkins 2021. location.

			Percent of Total Pods (%)							
Insecticide Treatment	**Desiccation Treatment**	**Harvest Timing**	**0 Bean Pod**	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
R5	**NT**	**Timely**	24.08	4.03	26.50	44.24	1.15	31.92	13.83	26.67
R7	**NT**	**Timely**	16.43	4.02	22.35	57.20	0.00	26.83	13.50	25.92
R5	**T**	**Timely**	19.11	10.17	24.64	46.08	0.00	27.08	12.67	22.42
R7	**T**	**Timely**	26.47	4.98	21.36	45.46	1.74	26.75	13.50	24.92
R5	**NT**	**14 days**	27.38	8.54	22.74	41.10	0.24	26.75	9.92	22.75
R7	**NT**	**14 days**	15.96	7.95	26.97	48.35	0.76	27.75	12.00	26.75
R5	**T**	**14 days**	9.80	12.23	30.18	47.09	0.70	28.17	17.00	26.33
R7	**T**	**14 days**	19.98	9.98	26.75	43.29	0.00	25.42	16.00	23.42
R5	**NT**	**28 days**	40.03	10.40	20.03	29.54	0.00	24.17	11.83	19.17
R7	**NT**	**28 days**	23.88	13.00	28.45	34.67	0.00	28.92	14.75	25.58
R5	**T**	**28 days**	40.21	11.26	21.58	26.66	0.29	26.58	12.08	23.33
R7	**T**	**28 days**	26.03	10.35	24.87	38.45	0.30	27.33	10.83	22.00

ANOVA Table

	0 Bean Pod	**1 Bean Pod**	**2 Bean Pod**	**3 Bean Pod**	**4 Bean Pod**	**Total Pods**	**Mainstem Nodes**	**Total Nodes**
Insect Timing	0.3299	0.6954	0.7035	0.2343	0.8758	0.8768	0.8261	0.6801
Desiccation Treatment	0.2136	0.1675	0.7726	0.0722	0.3822	0.7726	0.8798	0.7382
Harvest Timing	0.8836	0.2885	0.8923	0.8151	0.6894	0.7121	0.5162	0.7697
Insect*Desiccation	0.3750	0.6577	0.2326	0.7586	0.8577	0.4386	0.9914	0.9467
Insect*Harvest	0.2129	0.3135	0.3982	0.4486	0.4037	0.7813	0.5267	0.4276
Desiccation*Harvest	0.6256	0.3719	0.7025	0.8191	0.8071	0.7743	0.0931	0.7968
Insect*Desiccation*Harvest	0.6295	0.8562	0.6925	0.4725	0.0662	0.5069	0.651	0.3907

Table 49. Protein content (%) of soybean seed from each site year averaged across 3-way treatment combinations.

Insecticide Treatment	Desiccation Treatment	Harvest Timing	Protein Content (%)					
			Bixby 2019	Perkins 2019	Bixby 2020	Perkins 2020	Bixby 2021	Perkins 2021
R5	**NT**	**Timely**	32.83	34.21	32.86	-	35.53	33.08
R7	**NT**	**Timely**	32.45	34.11	32.90	-	34.67	33.17
R5	**T**	**Timely**	32.62	33.77	33.13	32.17	35.25	33.07
R7	**T**	**Timely**	32.78	34.61	33.00	32.71	35.50	33.10
R5	**NT**	**14 days**	32.76	32.98	33.20	-	34.97	32.86
R7	**NT**	**14 days**	32.65	32.97	33.07	-	34.91	33.30
R5	**T**	**14 days**	33.39	34.11	33.22	30.85	35.44	33.23
R7	**T**	**14 days**	33.11	33.68	33.27	31.31	35.26	32.99
R5	**NT**	**28 days**	33.38	33.98	32.99	-	35.28	33.05
R7	**NT**	**28 days**	33.16	34.24	33.15	-	35.43	33.10
R5	**T**	**28 days**	32.72	34.36	33.19	31.82	35.49	33.00
R7	**T**	**28 days**	33.24	34.16	32.67	31.77	35.08	33.05

VITA

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