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ESTABLISHMENT OF PERENNIAL LEGUMES WITH AN ANNUAL WARM-SEASON GRASS AS A COMPANION CROP

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by

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The yields of perennial forage legumes are often hindered during the establishment year due to slow germination rates and weed competition. This study was conducted to determine if sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. sudanese*) is a compatible annual companion crop for increased forage production, weed suppression, and legume establishment. In 2016, sorghum-sudangrass was paired with alfalfa (*Medicago sativa* L. 'Ranger'), birdsfoot trefoil (*Lotus corniculatus* L.), Illinois bundleflower [*Desmanthus illinoensis* (Michx.) MacMill. ex B.L. Rob. & Fernald], purple prairie clover (*Dalea purpurea* Vent.), red clover (*Trifolium pratense* L.), and roundhead lespedeza (*Lespedeza capitata* Michx.). We studied effects of a sorghum-sudangrass companion crop with a varying number of harvests (three vs. four harvests) collected per plot throughout the summer and compared yields to the yield of a weeded legume treatment, and a non-weeded legume treatment. In 2017, we studied effects of the application of four seeding rates for sorghum-sudangrass at 5 pure live seed per m^2 (PLS/m^2), 10 PLS/m^2, 20 PLS/m^2, and 40 PLS/m^2 paired with only the alfalfa perennial legume and compared yields to the yield of an oat-alfalfa control treatment, a weeded alfalfa treatment, and a non-weeded alfalfa treatment. Total dry matter yields along with the yield of each legume, weeds,

sorghum-sudangrass, and oats (second year only) were collected for each treatment. In both years, we found the addition of sorghum-sudangrass increased overall dry matter yield and significantly decreased weed abundance. The increase in total dry matter yield came at a cost to the legume yield; as treatments planted with sorghum-sudangrass or oats had lower legume/alfalfa yields than weeded legume/alfalfa treatments. These results suggest that sorghum-sudangrass is a viable option for weed suppression but is not ideal as a companion crop with an establishing legume stand for weed control as it decreases the success of legume establishment. These results demonstrate the importance of selecting a companion crop that is compatible with the crop of interest to achieve production goals.

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CHAPTER 1: LITERATURE REVIEW OF PERENNIAL LEGUMES AND A POTENTIAL COMPATIBLE WARM-SEASON COMPANION CROP FOR THE NORTH CENTRAL UNITED STATES

Introduction

Perennial legumes provide nutrient-rich feed for livestock. As a forage option, perennial legumes are valued for their high crude protein levels, low lignin content, and ease of digestibility by livestock. Additionally, their growth provides forage matter for many years (Lithourgidis *et al.*, 2011; McGraw, 2004). However, establishing perennial legumes is difficult because of their slow establishment rates and the aggressive competition from weeds for resources such as light, water, and soil nutrients. In the north central United States, management techniques such as tilling, applying herbicides, and implementing companion cropping techniques are used to improve the establishment success of perennial legumes (Lenssen & Cash, 2011; Zimdhal, 2007). The use of companion crops with perennial legumes is an especially popular choice as it allows producers to increase forage production during the legume's establishment year. However, the success of this measure has been variable and proven to be inconsistent for weed control (Hall *et al*., 1995).

Cool-season annual grasses are typically used as a companion crop with perennial legumes. However, using a warm-season annual companion crop would offset the timing of production and offer an alternative forage source during the summer slump of production observed in cool-season species. A warm-season annual to facilitate the establishment of perennial legumes while being consistent with weed control would be the most optimal measure to implement. However, it is important to understand the agricultural practices associated with intercropping and the use of companion crops, as well as cost-effective and efficient ways to manage pasture weeds in relation to the climate and soil conditions of the north central region of the U.S.

Methods

We conducted a literature review of various perennial legumes that are suitable for sowing with companion crops. Information was sourced from peer-reviewed scientific publications, unpublished literature, US Federal agency reports, U.S. County and State extension office reports, and online databases. For background, we gathered information on the practice of intercropping and on the use of companion crops, especially in relation to the north central region of the US. Information was also sourced on the various management strategies used for weed control, specifically in relation to economics and the environment. We further researched and assessed perennial legume species of interest that are commonly grown in the region. Last, we compiled information on the warm-season sorghum-sudangrass as a potential companion crop in relation to its compatibility with perennial legumes, specifically, its tolerance to the north central regional growing conditions, ability to perform as a natural weed suppressant, and ability to increase production yields.

Results – Background Information

Intercropping Practices and the Use of Companion Cropping

Intercropping is defined as the growth of two or more crops that are either sown together or at different times but are grown simultaneously in the same field for a substantial proportion of their growing periods (Ofori and Stern, 1987; Pappa *et al.*, 2012). Intercropping can be categorized into four groups: (1) two or more annual crops/forages sown together, (2) companion cropping in establishing perennial forage crops, (3) annual forages drilled into an existing stand to boost short-term yields

(Thorsted *et al.* 2002), and (4) perennial legumes sown in between the rows of an arable crop (Zemenchik *et al.* 2000, Ćupina *et al.*, 2011).

Intercropping of crop and forage species for production has previously been limited to tropical regions of the world because of limited economic and mechanical reasons. The adaptation of intercropping into the temperate regions of the globe has been slow due to the highly mechanized and industrialized agricultural systems in this region. Equipment utilized in industrialized agriculture is tailored to monocropping systems and faces challenges in the adaptation of intercropping from the mechanics of the drill, the complexities of harvesting, and the application of pesticides and fertilizers (Anil *et al.*, 1998), making intercropping less practical in the temperate regions of the world.

The implementation of intercropping within temperate regions has received increased attention due to a growing interest in more sustainable farming from both producers and consumers. Other reasons for shifting to intercropping practices in agricultural systems include: (1) the possible marketing and financial benefits associated with home-grown forage, (2) the utilization of crops with complementary growth cycles to reduce the need for extra inputs; (3) reproach of the monoculture systems; (4) the advancement in technology capable of more effectively drilling and harvesting intercrops; (5) the physiological and agronomical benefits of pairing crops for the efficient production of forage (Anil *et al.*, 1998). Through continued explorations, more and more discoveries have been made about the applicability and suitability of intercrops into the conventional agricultural system and the many additional benefits this system can offer a producer.

The capability of intercropping systems to suppress weed growth is one of the most striking benefits available. Intercropping practices have led to an understanding in using functionally diverse crops to fill available niches and in optimizing the utilization of resources to decrease the need for direct weed control measures such as tillage and herbicides (Bybee-Finley *et al.*, 2017). The practice of intercropping provides an important benefit to producers that can potentially suffer substantial crop loss due to the competition from weeds for water, inorganic nitrogen, light, and other resources that are necessary for hearty crop yields (Lenssen & Cash, 2011), while improving land use efficiency (Hauggaard-Nielsen *et al.*, 2001).

When intercropping pairs together compatible species to reach optimal land-use efficiency, the practice creates an environment for the crops to fully utilize available resources (Picasso *et al.*, 2008). As the intercrops continue to grow, they develop a full canopy which will block the available light from reaching the soil and developing weeds (Anil *et al.*, 1998). The increased uptake of water, nutrients, and light by the crops creates an environment undesirable for weeds and will suppress their germination and growth (Bastiaans *et al.*, 2008). The competition for resources from intercropping has proven to be one of the cheapest forms of weed control available (Anil *et al.*, 1998) and has proven to have less harvestable weed biomass than that of a monocrop stand (Mugabe *et al.*, 1983; Liebman and Dyck, 1993).

Aside from increased land use efficiency and weed suppression, intercropping management has other advantages over monocrop systems. One advantage is the increase in productivity and yield stability that occurs when growing crops in an intercropped mix (Bybee-Finley *et al.*, 2016; Anil *et al.*, 1998). More root growth occurs with intercropping practices, which can improve soil conditions in ways that facilitate plant growth. For example, crops with deep penetrating roots would allow for the breakup of hardpans in the soil, while crops with shallow roots will help to create aeration near the soil surface (Lithourgidis *et al.*, 2011). These rooting qualities aid in improving overall soil health, stability, and porosity creating a more stable soil. A stable soil is more resistant to wind and water erosion and is better able to keep nutrients and minerals in place (Anil *et al.*, 1998; Kilcher & Heinrich, 1959; Lithourgidis *et al.*, 2011).

The benefits of intercrops are not restricted to the soil. Intercrops also provide positive effects to the above ground region of the plant as well by reducing the occurrence of severity of plant pests and diseases (Lin *et al.*, 2011; Sanderson *et al.*, 2004; Lithourgidis *et al.*, 2011). By adding an additional plant species to a stand, the system can hinder the presence and effects of pests and diseases to the main crop plants through two mechanisms. First, the introduction of another plant species will alter the environment of the first crop plant, and second, the quality (morphological and chemical conditions) of the first crop plant becomes altered as well (Langer *et al.*, 2007). There are also three ways in which an intercrop can cause attack escape from a pest as well. First, the intercrop causes the main crop that is susceptible to attack to be a less habitable host. Second, the intercrop can interfere with attacker, the pathogen or pest, activities. Lastly, intercrops can alter the environment so that natural enemies of the attacking pest are favored (Trenbath, 1993).

Viewing the benefits available through the use of an intercropping system, it becomes clear the intercrops may provide high insurance against conditions for crop failure, especially in regions with extreme weather conditions of frost, flood, drought, and heat. This system can provide increased financial stability as the crops act as a buffer for one another and help ensure production even in low yielding years (Lithourgidis *et al.*, 2011).

As with any management technique, it is important to have a good understanding of the system and recognize the challenges associated with it upfront to ensure success of the desired outcomes. One of the biggest considerations to highlight when considering an intercropping mixture is the compatibility of the intercropped species. Interaction between the intercropped species and hence the productivity is dependent on many components of each species including the plant morphology and physiology, and the density and spatial arrangement of the crops in relation to the climatic, edaphic, and biotic environment (Anil *et al.*, 1998). Intercropping two species may alter the growth patterns from that found in a monocrop (Ahmad *et al.*, 2007) and may create new complementary and competitive aspects (Anil *et al.* 1998). In fact, if not carefully considered, the selection and pairing of some species could lead to reductions in plant vigor and stand density, and hence, subsequent reduced forage yields. In addition, the increased land use efficiency may be considered a double-edged sword in production. While the higher resource partitioning inhibits the growth of weeds, if nutrient and soil moisture levels are not adequate, this increase could be costly to the growth of one or both intercrops as they must now compete against each other for the limited resources (Ahmad *et al.*, 2007; Kilcher & Heinrich, 1959).

Another big disadvantage to the use of intercropping is the difficulty faced with practical management measures. This is especially challenging when the intercrops have differing fertilization, herbicide, insecticide, fungicide, sowing, and harvesting requirements (Lithourgidis *et al.*, 2011). More challenges might be faced during and after harvesting. Issues with lodging, grain lost, additional cost to separate mixed grains, and the lacking market for mixed grains can be serious drawbacks. The difficulties faced during harvest can be more easily overcome in a forage system where the intercrops can be grazed, and the need for machine use is limited.

Despite the challenges faced, there is a wide variety of species that are utilized within intercropping systems. This includes the use of annuals, perennials, cereals, grain, legumes, shrubs, and trees (Lithourgidis *et al.*, 2011). The choice of intercrop species and their symbiotic success are strongly influenced by the length of each species' growing season; the adaptation of crops to differing environments, the combination of crops, and the variation found among geographical regions are also influential factors for success (Ofori and Stern, 1987). In the north central region of the US, favored options for intercropping include the use of legumes with either forage grasses or cereal crops. The intercropping use of these plants varies, though they are commonly used as a companion crop during an establishment period or as a mixed pasture stand.

Forage producers across the north central region are often looking for ways to increase productivity and nutritive value of pastures. One common practice is for forage producers to interseed a perennial legume into an existing grass pasture to increase the nutritional value of the pasture grass by increasing the crude protein concentration and the intake potential of the forage (Anil *et al.*, 1998; Lithourgidis *et al.*, 2011). Favored pairings of intercrops for this production goal include alfalfa with bermudagrass (Cinar & Hatipoglu, 2014), alfalfa with smooth bromegrass or switchgrass (Berdahl, *et al.*, 2001), and native warm-season grasses like Indian grass and switchgrass with the native legumes of purple prairie clover and roundhead lespedeza (Posler *et al.*, 1993), and red clover with big bluestem or switchgrass (Jakubowski *et al.*, 2017).

Another technique utilized by forage producers is to combine a cereal crop as a companion crop into an establishing legume stand. This is a popular choice as it allows the producer to increase forage production during the establishment year when yields are typically lower, and it offers necessary protection for the smaller, slower growing legume seedlings from weeds (Kilcher & Heinrich, 1959). Some traditional choices for a companion crop with perennial legume establishment include many small grains such as wheat, oat, triticale, rye, and barley (Kilcher & Heinrich, 1959; Tesar & Marble, 1988; Sulc *et al.*, 1993; Wiersma *et al.*, 1999).

Weed Control

When establishing a crop or forage, one of the greatest challenges for producers is the undesired establishment and growth of weeds within the stand. Weeds will have a greater economic cost on pastures than the combination of costs expended to manage insects and pathogens (Quimby *et al.*, 1991). There have been many techniques and mechanisms utilized by producers to combat weeds. Approaches to weed management have changed over time from cultural control to mechanical and industrial techniques. Cultural control techniques include row spacing, crop rotation, cultivar selection, residue management, seeding density, fertility manipulation, planting pattern, cover crops, intercropping, and thermal weed control (Lenssen & Cash, 2011; Radicetti, 2012). Mechanized and industrial tactics for combating weeds include the use of tillage, cultivation, cutting/mowing, and herbicides.

Upon entering an era with increased mechanization and intensive cropping systems, the principal component in controlling weeds has been through the use of herbicides. Herbicide use easily allows producers to reach increased yield goals and simultaneously reduce production costs. As with any tool, herbicides provide benefits that have associated costs. In addition to increased yields and decreased production costs, herbicides have benefited crop production by decreasing the need for tillage, allowing for earlier planting dates, and providing farm management with more time to perform other required tasks (Moss, 2008). Some of the costs associated with using herbicides include training of herbicide handlers, certifications for large-scale use, proper storage facilities, and personal safety equipment. Costs further include providing medical and emergency training and services to those who directly handle and apply herbicides. Further, any significant adverse impacts to fish, non-target plants, and/or wildlife would come as an often-irreversible environmental cost, as well as an economic cost if it results in clean-up and mitigation efforts (Zimdhal, 2007). Other costs result when non-target plants are altered or affected because of drift or incorrect chemical application. Further, the over-reliance, improper use, and dosage of herbicides has led to reported resistance in 233 different weed species, which further increases production costs as newer and stronger herbicides must be developed and used for effective application (Heap, 2000).

With increased herbicide resistance, costly economic factors from increasing prices, and an ever-increasing awareness of environmental costs, many researchers and producers are using other management practices in the battle against weeds. These practices are more reliant on biological, ecological and cultural components of the environment, such as species competition, allelopathy, and soil disturbance (Liebman and Gallandt, 1997). More commonly this approach is known as ecological weed management and requires careful planning of the cropping system using one or multiple tools such as diversified cash crop rotations, cover crops, grazing livestock, and intercropping. Through the use of these techniques, the main goal of ecological weed management is to regulate the density, growth, and competitive ability of weeds (Liebman and Gallandt, 1997) along with managing the weed seed bank, seedling establishment, and seed production (Anderson, 2007).

But just as with herbicides, there are obstacles in the implementation of ecological weed management, such as the applicability, efficacy, reliability, and compatibility of the methods within the cropping system. Often, ecological weed management has to come from a combination of methods in order to reach efficacy, and this furthers the complexity of the system by making it more challenging to manage. Through the strategic use of multiple small components, there is the advantage of a reduced risk of weeds developing a resistance and a reduced risk of drastic crop loss (Bastiaans *et al.*, 2008).

Analysis – Perennial Legumes and Sorghum-sudangrass

Perennial Legumes

The legume family has over 16,000 unique species, which are commonly grouped by their life cycle of annual, biannual, or perennial. The most valuable of these as forage crops have a perennial life cycle, as a comparable or greater agronomic and environmental advantage can come from the use of perennial legumes compared to annual legumes. Perennial legumes offer many advantages to agricultural systems through added organic matter, recycled nutrients, continuous ground cover, higher water infiltration, increased soil fertility, long-term carbon storage, and the elimination of yearly seeding costs (Sheaffer *et al.*, 2003). One of the greatest secondary advantages of legumes is their ability to fix atmospheric nitrogen through their association with *Rhizobium* bacteria. This association provides the macronutrient nitrogen to neighboring plants in the ecosystem and has been shown to improve the yield of subsequent crops (Becker & Crocket, 1976; Radović *et al.*, 2009).

Perennial legumes have a long history of use in agricultural systems. In the north central region of the United States, perennial legumes play a vital role in supplying high-quality feed, seed, nectar, green manure, and soil cover (Sheaffer *et al.*, 2003). Many forage production systems and livestock producers favor the inclusion of perennial legumes as they fill a niche in providing cheap forage that has high nutritive value and digestibility (Radović *et al.*, 2009). They hold high importance in ruminant feeding due to their high buffering effect that reduces risk of acidosis, high energy content, and they contain higher protein concentrations and less fiber than grasses at corresponding growth stages (Frame, 2005; Barnes *et al.*, 2007; Cherney & Allen, 1995).

While there is a diverse selection of perennial legumes that have potential to be grown for forage, the species of interest is relatively narrow (Annicchiarico *et al.*, 2015). Introduced perennial legumes are the main species of interest by livestock producers for hay and pasture across the north-central United States (McGraw & Nelson, 2003). Many producers favor the use of introduced species, such as alfalfa, red clover, and birdsfoot trefoil as there is a greater amount of development and research put into these species. This allows for a wide selection of cultivars and genetics that aid in the use of introduced species across many environmental conditions and stresses. However, recent years have seen a shift from producers and end consumers in agronomic practices towards more sustainable and ecological management practices.

Native perennial legumes were at one point an integral component of the Midwest prairie ecosystem, providing beneficial forage to wildlife and livestock (Weaver, 1954). Today, the majority of legumes that are utilized across the north central US by livestock producers for hay and pasture are introduced species (McGraw & Nelson, 2003), and many native legumes are now utilized as components for conservation and restoration plantings (Tilman *et al.*, 1999). The lack of cost-effective and dependable establishment methods to create a vigorous stand along with the limited evaluation of their biomass and seed yield present a roadblock in the utilization of many native legumes (Fischbach, 2006). However, in recent years native perennial legumes have received increased interest in their agronomic potential as grain and forage crops (Tilman *et al.*, 1999). This is due to their higher feed value compared to traditional native grass pastures; native perennial legumes will provide higher concentrations of crude protein and lower levels of neutral detergent fiber (McGraw *et al.*, 2004).

We compiled information on six perennial legumes of interest: three introduced and three native species. They are alfalfa (*Medicago sativa*), red clover (*Trifolium pratense*), birdsfoot trefoil (*Lotus corniculatus*), Illinois bundleflower (*Desmanthus illinoensis*), roundhead lespedeza (*Lespedeza capitata*), and purple prairie clover (*Dalea purpurea*). We further present information on sorghum-sudangrass as a potential warm-season grass for intercropping and weed control.

1. Alfalfa

Alfalfa is known by several names throughout the world including Lucerne, purple medick, common purple Lucerne, the queen forage, and purple alfalfa (Frame, 2005). Alfalfa is often referred to as the queen forage as it is the most commonly produced forage crop across the world with approximately 30 million hectares primarily located in North America, Europe and South America (Yuegao & Cash, 2009) and with continuing expansion throughout China and Australia (Annicchiarico *et al.*, 2015). The popular use of alfalfa dates to B.C.E. when its first known domestication was through seed trading by merchants around 4000 B.C.E. (Prosperi *et al.*, 2001) with cultivation dating to 500 B.C. in Persia (Radović *et al.*,2009). Roughly 57% of all alfalfa production in the United States is produced in the north-central states as a main source for forage material (Barnes *et al.*, 1995).

Today, alfalfa is the favored forage legume for cultivation throughout the Great Plains and many temperate zones around the world. As a perennial, alfalfa is a top performing legume that can be expected to produce high yields for 4-6 seasons

(Frame, 2005). The most productive conditions for alfalfa growth include highly fertile, well-drained soils with a pH range of 6.5-7.0 (Stubbendieck & Conrad, 1989) and an optimal temperature range of 20-25 ℃ (Annicchiarico *et al.*, 2015). Alfalfa has been found to be productive outside of these ranges due to its rich and variable genetics that provide a wide range of cultivars allowing the plant to adapt in various growing conditions and environments (Frame, 2005; Radović *et al.*, 2009). Most commonly grown between latitudes 55° north and 50° south, alfalfa is found to be tolerant of extreme temperatures ranging from -25 °C up to 50 °C (Barnes *et al.*, 1995). Additionally, it is productive on soils with pH levels of 5.9 up to 7.5 and is moderately tolerant in more alkaline soils (Kemp *et al.*, 1999; Annicchiarico *et al.*, 2015). When compared to other favorable perennial legumes, such as red clover and birdsfoot trefoil, alfalfa has a narrower range of growing conditions for highly productive yields, but it is incredibly drought resistant compared to red clover and birdsfoot trefoil (Frame, 2005; Barnes *et al.*, 1995). A strong and deep taproot system also can enable alfalfa to withstand periods of low precipitation and high temperatures for lengths of one or two years by inducing itself into a dormant state (Annicchiarico *et al.*, 2015; Barnes *et al.*, 1995).

The wide adaptability and cultivar selection of alfalfa combined with its erect growth, high protein content, high forage yield potential, and good nutritional quality make it a highly utilized feed source for many classes of livestock (Li *et al.*, 2007). When sourced as feed for livestock alfalfa is primarily grown for use as hay, but it is also ensiled as silage, or grazed as fresh forage. Rapid recovery period of alfalfa after defoliation allows the legume to be one of the top-yielding forage sources by producing close to 20 T ha^{-1} of dry matter (Nešić *et al.*, 2005, Radović *et al.*, 2004). High yields, long persistence, and environmental stress tolerance make alfalfa an economically significant companion crop. One drawback to using alfalfa is its potential to cause bloating in livestock and, if left untreated, can be fatal. This is mainly an issue of concern when young, short, or injured alfalfa is grazed by livestock (Undersander *et al.*, 2011).

While alfalfa is primarily produced as a forage source, it also provides important economic and biological functions. Alfalfa serves as a good predecessor to agricultural crops since this legume acts as a desalination crop, will increase soil fertility, and enrich the soil nitrogen levels through rhizobium activity (Radović *et al.*, 2009). The growth of alfalfa will also reduce wind and water erosion by binding with the soil (Liu *et al.*, 2009a); lastly, it is a great source for a nectar-producing crop and as a green-manure source (Radović *et al.*, 2009).

2. Red Clover

There are over 250 species within the *Trifolium* genus that have Eurasian, American, and African origins (Ellison *et al.*, 2006). One species of common interest in forage production is red clover (*Trifolium pratense*). The red clover species can be further divided into three different groups: early-flowering, late flowering, and wild red (Barnes *et al.*, 1995). The red clover species that occur throughout the United States are typically of the early-flowering type and collectively known as, medium red clover (Barnes *et al.*, 1995). The late-flowering type mammoth red clover, however, can also be located throughout the US (Barnes *et al.*, 1995). Red clover originated in Asia Minor and southeastern Europe and is believed to have been carried to the US by English colonists (Barnes *et al.*, 1995).Red clover in the US extends from areas of eastern Iowa west into the eastern edges of Montana and Wyoming, and reaches from southern Canada down to the northern boundary of Texas (Stubbendieck & Conrad, 1989).

The red clover species is a biennial or short-lived perennial legume that can maintain a strong, persistent stand for two to three years followed by a steep decline (Frame, 2005; Kemp *et al.*, 1999). Optimum growing conditions for red clover include temperatures between 20 -25°C and well-drained soils with a pH range of 6.0-6.5 (Annicchiarico *et al.*, 2015; Stubbendieck & Conrad, 1989). However, this legume can survive ±15°C of the optimum range and is also moderately tolerant to acidic soils with a minimum pH of 5.5 (Frame *et al.*, 1998; Kemp *et al.*, 1999; Annicchiarico *et al.*, 2015).

Within the clover family, red clover is the most widely grown out of all the true clovers (Barnes *et al.*, 1995). Due to its high quality and palatability, red clover has become a significant pasture legume in temperate agricultural systems around the world (Frame, 2005; Sheaffer *et al.*, 2003). The high quality of red clover has also made it a widely utilized forage plant throughout the globe in the form of silage or hay for conservation feed and is often fed to all classes of livestock (Abberton & Marshall, 2005; Sheaffer *et al.*, 2003; Stubbendieck & Conrad, 1989). In addition to its use as feed in livestock operations, red clover is commonly used for its soil improvement benefits (Barnes *et al.*, 1995). Lastly, in previous centuries, red clover had a use medicinally as the dried flowers could be used to cure whooping cough and ulcers (Stubbendieck & Conrad, 1989).

While red clover is used widely across the world, its hectares of production are less than alfalfa due to some limitations of the species. One limitation comes from its susceptibility to cause bloating and reproductive issues when grazed by livestock, particularly for pure stands of red clover (Frame, 2005; Kemp *et al.*, 1999). Perhaps a greater limitation, though, may be attributed to the short life span of red clover stands, as the profitability of a pasture is based principally upon the yield and persistence of the stand (Ford & Barrett, 2011).

3. Birdsfoot Trefoil

Birdsfoot trefoil (*Lotus corniculatus*) is a warm-season perennial legume that was first introduced to North America from Eurasia (Stubbendieck & Conrad, 1989) and is now commonly grown in many areas including Asia, New Zealand, Australia, North Africa, South America, Canada, Europe, and the United States (Grant and Marten, 1985; Grant and Small, 1996). The production of birdsfoot trefoil throughout various locations across the globe can be contributed to its wide range of growing conditions. Birdsfoot trefoil will successfully grow in many types of soils including clays, sandy loams, shallow, droughty, infertile, and acidic or mildly alkaline, and also grows well under saline and waterlogged conditions (Barnes *et al.*, 1995; Sheaffer *et al.*, 2003). The most productive conditions for this perennial legume are moderately to well-drained, fertile soils with a pH of 6.2 to 6.5 (Barnes *et al.*, 1995).

While birdsfoot trefoil is well adapted to a wide range of soil conditions, it has a much narrower range of tolerable temperatures. Birdsfoot trefoil is not well adapted to extremely high temperatures (Turkington and Franko, 1980), and it is highly susceptible to severe winter conditions and winter-killing. In fact, when located at latitudes greater than north-south 40°, a layer of winter snow cover becomes critical for the winter survival of birdsfoot trefoil (Barnes *et al.*, 1995).

Growth of birdsfoot trefoil can be distinguished by its lush, low growing, rhizomatous features. Birdsfoot trefoil can be grouped into two main types. The first group is the Empire-type and is defined by its low prostate growth and fine stems. This low-growing group is also distinguished by its late-season flowering and increased winter-hardiness (Sheaffer *et al.*, 2003). The second group is the European-type, which is noted for its upright growth and quicker establishment and regrowth

(Sheaffer *et al.*, 2003). With more erect growth the European type is better suited for usage in hay and pasture and the Empire group is best suited for pasture use only (Grant & Marten, 1985).

The use of birdsfoot trefoil has increased in recent years as niche uses for it are discovered. Due to its lush and rhizomatous features birdsfoot trefoil is a great resource for ground-cover in the stabilization of gullies, roadsides, and dunes (Stubbendieck & Conrad, 1989). It is also growing in popularity as an alternative to alfalfa and red clover when soil conditions have low pH levels or high moisture levels (Seaney & Henson, 1970; Piano & Pecetti, 2010). Interest in the use of birdsfoot trefoil is also increasing because of a unique compound of condensed tannins found within the plant prevents bloat, which is a common issue when using other legumes; further, it aids in the rumen bypass of digestible proteins (Min *et al.*, 2003; Waghorn *et al.*, 1998).

Despite the increasing interest and wide adaptability of birdsfoot trefoil, there are still barriers that limit its use. When compared to other legumes, birdsfoot trefoil has very poor seedling vigor and slow stand establishment; this is mainly due to its small seed size (Laskey & Wakefield, 1978). These characteristics often result in birdsfoot trefoil being very susceptible to early competition from weeds, further increasing the difficulty to establish a successful stand (Chapman *et al.*, 2008). However, establishment success can be increased prior to planting by subjecting seeds to scarification and inoculation with rhizobial bacteria (Stubbendieck & Conrad, 1989). Once a stand is established, it can be limited for use in hay production despite its high quality because it is prone to lodging, making it difficult to cut (Sheaffer *et al.*, 2003). If all characteristics are carefully considered, birdsfoot trefoil could prove to be an incredible source of forage.

4. Illinois Bundleflower

Illinois bundleflower (*Desmanthus illinoensis*) is a warm-season perennial legume native to the Great Plains of North America (Stubbendieck & Conrad, 1989). Illinois bundleflower is the most widely distributed species of the *Desmanthus* genus found within the United States. This plant ranges from Minnesota and South Dakota over to Colorado and New Mexico, south into Texas, eastward into Florida, and up into North and South Carolina, Tennessee, Kentucky and Ohio (Latting, 1961). This perennial legume was once one of the dominant species within North American prairies. Today it is sparse throughout the plains and most commonly found in the margins of cultivated fields, upland swales, along roadside ditches, and on low, open ground (Latting, 1961). Regardless, it adapts to growing in many conditions including a wide temperature tolerance, and the moist or dry soils of the prairies in open wooded slopes, ravines, waste places, and roadsides (Latting, 1961; Stubbendieck & Conrad, 1989).

With forage quality similar to that of alfalfa, and seed yield comparable to soybean, Illinois bundleflower has potential for use as both a forage and grain crop (Kulakow *et al.*, 1990; DeHaan *et al.*, 2003; Fischbach *et al.*, 2006). All classes of livestock will readily consume Illinois bundleflower as a forage; in fact, cattle will preferentially graze this legume. However, it should be noted that Illinois bundleflower must be carefully grazed as heavy grazing will negatively impact the legume and can lead to complete disappearance (Stubbendieck & Conrad, 1989; Latting, 1961; Fischbach *et al.*, 2005). As a warm-season legume, Illinois bundleflower produces a single harvest for hay or silage during the height of the summer slump (Fischbach *et al.*, 2005). The total yield produced during a season is typically less than most cool-season legumes but is found to be ranked among the top for native warm-season legumes (Fischbach *et al.*, 2005; McGraw *et al.*, 2004).

5. Roundhead Lespedeza

There are eleven species of *Lespedeza* that are native to North America (Clewell, 1966). Of these 11 species, roundhead lespedeza (*Lespedeza capitata*) has the greatest geographical spread. It is commonly found from the western edge of the Midwest over to the east coast and down into portions of Texas up into Canada (Stubbendieck & Conrad, 1989). This warm-season perennial species has a rigidly, upright profile and is capable of growing in many diverse habitats including dry wooded areas, sandy dunes, dry fields, prairies, and along roadsides (NRCS, 2011; Stubbendieck & Conrad, 1989). Roundhead lespedeza preforms best in rocky, well-drained soils (NRCS, 2011). The greatest chance for germination and establishment occurs at temperatures ranging 15-30 °C (McGraw *et al.*, 2003). While this plant is moderately drought tolerant, it performs best with precipitation of at least 50 cm annually (NRCS, 2011).

Roundhead lespedeza can be utilized in many ways. It has been used by Native Americans to make tea and medicines, by upland game bird managers as a wildlife-feed source, and livestock managers as cultivated forage (NRCS, 2011). Roundhead lespedeza serves as an excellent, palatable, and nutritious source of forage for many classes of livestock (Stubbendieck & Conrad, 1989; NRCS, 2011). When utilized as forage for livestock, it is critical that seeds are scarified before planting in order to weaken the hard shell and ensure soil stabilization for a successful establishment (Stubbendieck & Conrad, 1989). Livestock owners must also closely monitor roundhead lespedeza in pasture and rangeland use because it is very susceptible to overgrazing and is often slow to reseed under natural conditions (Kneebone, 1959). Additionally, this legume provides benefits to the soil through rhizobial symbiosis, producing nitrogen that becomes available to the next crop or current mixed-species crops. The extensive root system, reaching depths of one and a half to two and a half meters, aids in the breakup of compaction and soil hardpans (NRCS, 2011).

6. Purple Prairie Clover

Purple prairie clover (*Dalea purpurea*) is a warm-season perennial legume that is native to North America. It belongs to the *Dalea* L. genus, which has over 160 species that range from South America northward into Canadian prairies (Barneby 1977). Throughout the Great Plains, this legume is commonly found in dry prairies (Stubbendieck & Conrad, 1989). It reaches across the span of the Great Plains, extending from Texas to the Canadian Prairie Provinces and from the eastern part of the Rocky Mountains through the U.S. Midwest (Great Plains Flora Association, 1986).

Purple prairie clover can provide excellent forage for ruminants (Stubbendieck & Conrad, 1989). This plant is also a favorable choice for the restoration and improvement of rangelands (Sheaffer *et al.*, 2009). The high levels of protein and overall good forage quality of purple prairie clover make this plant a viable option for improving forage nutritive value, increasing pasture productivity, and extending the grazing period of native pastures (Schellenber & Banerjee, 2002; Stubbendieck & Conrad, 1989). Like birdsfoot trefoil, purple prairie clover contains condensed tannins in its tissue that provide animal health benefits (Liu *et al.*, 2013; Jin *et al.*, 2015). Tannin levels in purple prairie clover have been shown to be some of the highest among legumes (Iwaasa *et al.*, 2014), and aid in higher feed efficiency in cattle and greater protein utilization (Iwaasa *et al.*, 2014). They have also been shown to play a vital role in reducing the level of E. coli activity in cattle (Jin *et al.*, 2015; Iwaasa *et al.*, 2014).

<u>*Grass*</u>

1. Sorghum-sudangrass

Sorghum is a warm-season annual grass originating from Africa where it was first cultivated roughly 3,000 years ago (Harlan and de Wet, 1972). Worldwide, sorghum is the sixth most produced crop (Martin *et al.*, 2006) and in the US, an estimated seven million hectares annually are devoted to forage grain sorghum production (Rooney *et al.*, 2007). Historically, the introduction of sorghum to the Americas and Australia is relatively new, as it only arrived in these regions within the last 200 to 300 years (Rooney *et al.*, 2007). The selection and distribution of sorghum by humans over time has led to several modern types of sorghum being developed, specifically, sweet, grain, forage, and sorghum x sudangrass hybrids. These four types of sorghum are used throughout the world primarily as a seasonal forage crop in livestock production, as a grain crop, and as a potential feedstock for cellulosic ethanol production (Rooney *et al.*, 2007). Sorghum is a favored crop of choice for these uses due to its ability to produce large quantities of biomass with minimal inputs.

Sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. sudanese*) is a cross between dwarf sorghum and sudangrass, creating a hybrid with the height of forage sorghum crossed with the intermediate stem and leaf texture, and increased tillering abilities of sudangrass (Pedersen & Rooney, 2004; Sanderson *et al.*, 1995). These characteristics and many traits of sorghum-sudangrass make it well suited for biomass production and hence a valuable forage option. One of the key traits that contribute to the biomass production of sorghum-sudangrass is that it is a warm-season annual grass, giving it the ability to produce high yields throughout a short growing season (McCaughey *et al.*, 1995). As a warm-season grass, sorghum-sudangrass is traditionally associated with hot and dry subtropical and tropical areas with a mean average temperature of 37°C, but it can also be grown up to the north-south 45° latitudes (Cothren *et al.*, 2000). Fribourg (1995) found sorghum-sudangrass to exhibit a tolerance for heat and low moisture stress factors, and to be capable of productive yields in environments with as little as 400-650 mm of annual rainfall. Sorghum-sudangrass can survive in semi-arid environments with minimal precipitation due to its xerophytic characteristics and C_4 photosynthetic pathway (Ahmad *et al.*, 2007). While sorghum-sudangrass is grown in a variety of climatic areas, it is limited to growth in soils with a pH of 5.0 to 8.3 as it does not tolerate acidic soils (Cothren *et al.*, 2000).

Sorghum-sudangrass has found a valuable spot in many production systems due to its multitude of uses and benefits. Within forage systems, producers utilize sorghum-sudangrass as hay, silage, green chop, or pasture production (Rooney, 2004; Fribourg, 1985). But throughout the United States, sorghum-sudangrass is most commonly grown as hay and silage crops. The fodder of sorghum can be fed to nearly every class of livestock as either hay or silage (Ahmad *et al.*, 2007). Sorghum-sudangrasses are desirable as forage for livestock due to their smaller stems and increased tillering capacity, along with the tendency to accumulate less soluble sugars in their culms, compared to sweet sorghum and grain sorghum (Pedersen and Rooney, 2004).

Sorghum-sudangrass has additional advantages outside of its nutritive benefits and increased interest in its potential to succeed as a cover crop and companion crop in agricultural systems is due to this plant's rapid growth and recovery features, natural tolerance to drought and high temperatures, and the risks posed by plant insects and diseases (Lang, 2001). Sorghum-sudangrass also offers benefits in weed control through its allelopathic qualities; it helps in the prevention of soil erosion; and it is a source of additional soil organic matter (Marchi *et al.*, 2008).

While sorghum-sudangrass has many beneficial reasons to be utilized as a forage crop, it is worth noting that it is to be used cautiously. Sorghum-sudangrass has the potential for acute toxicity within cattle because it releases hydrogen cyanide (HCN), also referred to as prussic acid (Gorz *et al.*, 1979; Haskins *et al.*, 1979). Aspects influencing the release of HCN are plant genotype, plant age, plant morphology, and environmental factors. Sorghum-sudangrass will accumulate high amounts of HCN in the leaves of young plants, in new growth, and in frost or drought damaged tissue (Pedersen & Rooney, 2004). To avoid issues with HCN within livestock it is recommended to: 1) graze sorghum-sudangrass at a height of at least 60 cm, 2) avoid feeding frost or drought damaged stands to animals, or 3) to harvest as a chop, hay, or silage to reduce HCN up to 50 percent (Fjell *et al.*, 1990; Schneider & Anderson, 1986).

Due to the multitude of uses of sorghum-sudangrass as green chop, hay, pasture, and silage, the production of biomass and harvest techniques vary depending on the producer's end goal. Forage sorghum, such as sorghum-sudangrass, gains maximum yield as the crop reaches the hard dough stage in maturity (Pedersen & Rooney, 2004). However, the value that comes with top yields must be balanced with the quality of the forage as well. Nutritive value for sorghum-sudangrass is best while the crop is in its late vegetative stage (Fribourg & Waller, 2002). Once the plant matures past the vegetative stage, an increase of lignification begins to occur. The amount of lignin in the plant is significant as elevated levels lead to substantial decreases in digestibility (Rooney, 2004). For a productive harvest that gains the maximum yield without sacrificing too much nutritive value potential, a balance would be reached if harvesting is timed during the boot stage. By implementing techniques to improve the quality of forage, yields of 22-28 Mg ha^{-1} can be achieved (Venuto & Kindiger, 2007; Miller *et al*., 1989).

Discussion

Use of intercropping provides a wide array of benefits to producers. By including intercrops into a production plan a producer can gain marketing and financial benefits. By combing two or more favorable crop together a producer has now given himself a buffer against the ever-changing markets of commodities by adding diversity into his crop portfolio. Intercropping also provides increased financial stability as intercrops provide insurance against extreme weather conditions as the crops act as a buffer to each other.

Producers also gain an advantage in increased production and yield stability through intercropping. The growing of two or more complementary crops will utilize resources more optimally by fulfilling available niches, and therefore supporting the additional biomass production. Through the proper selection and utilization of complementary crops producers can decrease their need for direct weed control measures, as the increased demand for resources and add competition will create an unfavorable growing environment for weeds.

The use of perennial legumes is a favored forage option among producers as many legumes provide quality feed and high yields throughout their lifespan. However, when planted in the spring perennial legumes tend to have lower yields during the establishment year and increased pressure from weeds. Through the practice of intercropping and selecting an appropriate companion crop producer can offset this year of lower production.

Sorghum-sudangrass appears to be a promising warm-seasonal companion crop option for perennial legumes through its ability to naturally suppress weeds, increase forage yields, and has multiple uses in forage systems. The rapid establishment and allelopathic characteristics of sorghum-sudangrass combine to help combat against the strong weed pressure often present in spring established perennial legumes. As a productive, high tillering, warm-season annual sorghum-sudangrass appears to be a prospective companion crop option that will increase total forage production during the low yielding establishment year for perennial legumes. Lastly, the diversity of uses of sorghum-sudangrass as green chop, hay, pasture, and silage give it great flexibility to be paired with a perennial legume in many forage systems.

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Figures and Tables

Table 1-1: Descriptive table highlighting growing conditions and characteristics of the species of interest; alfalfa, red clover, birdsfoot trefoil, Illinois bundleflower, roundhead lespedeza, purple prairie clover, and sorghum-sudangrass for intercropping purposes.

Species	Scientific Name	Type of Plant	Growing Season	Tolerances	Soil preference	Optimal Temperature (°C)	Optimal pH Range	Uses
Alfalfa	*Medicago sativa*	Legume	Perennial	Extreme temperatures and drought	Highly fertile; well-drained	20-25	6.5-7.0	Forage material; Feed source
Red Clover	*Trifolium pratense*	Legume	Biennial or short-lived perennial	Soils ≥ pH of 5.5 Temperatures ± 15°C of optimal range	Well-drained	20-26	6.0-6.5	Forage plant
Birdsfoot Trefoil	*Lotus corniculatus*	Legume	Warm season perennial	-	Fertile; moderately to well-drained	7.6-23.7	6.2-6.5	Hay and pasture (European-type) Pasture (Empire-type)
Illinois bundleflower	*Desmanthus illinoensis*	Legume	Warm season perennial	Moist or dry soils Wide temperature ranges	Medium textured soils; rocky; well drained	20-30	6.0-7.0	Forage; Grain crop; Hay and silage (single summer crop)
Roundhead lespedeza	*Lespedeza capitata*	Legume	Warm season perennial	Moderate drought (≥ 50 cm rainfall)	Rocky; well-drained	15-30	5.7-8.2	Forage
Purple prairie clover	*Dalea purpurea*	Legume	Warm season perennial	-	dry prairies	15-30	6.4-6.7	Rangeland restoration and improvement Forage
Sorghum-sudangrass	*Sorghum bicolor x S. bicolor*	Grass	Warm season annual	Hot temperatures and low moisture (minimum 400-650 mm of annual rainfall)	-	37	6.0-6.5	Forage grain; Seasonal forage crop; Grain crop; Potential feedstock for cellulosic ethanol production; Hay and sileage

Table 1-2: Opportunities and obstacles in the growth and utilization of alfalfa, red clover, birdsfoot trefoil, Illinois bundleflower, roundhead lespedeza, purple prairie clover, and sorghum-sudangrass for intercropping purposes.

Species	Pros	Cons
Alfalfa	- Produce high yields for 4-6 seasons - Productive even outside of optimal growing condition - Adapts to various growing conditions and environments - Good predecessor to agricultural crops	- Potential to cause bloating in livestock
Red Clover	- Can maintain a strong, persistent stand for 3 years - Tolerates temperatures +/- 15°C of optimal range	- Short life span of a stand (2-3 years followed by a steep decline) - Causes bloating and reproductive issues in livestock
Birdsfoot Trefoil	- Can adapt to a wide range of growing conditions - Will successfully grow in many types of soils - Does not cause bloating in livestock - Aids in rumen bypass of digestible proteins	- Not well adapted to high temperatures - Very poor seedling vigor - Slow stand establishment - Susceptible to early competition from weeds
Illinois bundleflower	- Will successfully grow in many habitats - Livestock will readily consume	- Heavy grazing will negatively impact the legume
Roundhead lespedeza	- Capable of growing in many diverse habitats - Increases soil nitrogen content	- Seeds need scarification before planting - Susceptible to overgrazing - Often slow to reseed itself
Purple prairie clover	- Contains high levels of protein - Does not cause bloating in livestock - Aids in rumen bypass of digestible proteins	- Seeds need scarification before planting - Susceptible to overgrazing
Sorghum-sudangrass	- Naturally suppresses weeds - Produces high yields throughout a short growing season - Provides high amounts of forage during “summer-slump” of production - Enhances soil properties of pastures Multitude of uses/roles in forage production systems	- Does not tolerate acidic soils - Potentially toxic to cattle because it releases hydrogen cyanide

CHAPTER 2: ESTABLISHMENT OF PERENNIAL LEGUMES WITH SORGHUM-SUDANGRASS AS A COMPANION CROP

Introduction

Many legume species are commonly grown throughout the world and the United States as a nutritious source of forage material for many livestock kinds and classes. In the northern region of the United States, commonly grown perennial forage legumes include red clover (*Trifolium pratense* L.), alfalfa (*Medicago sativa* L.), and birdsfoot trefoil (*Lotus corniculatus* L.). While these three perennial legumes produce high quality hay and are valuable additions in pasture seedings in this region, recent years have shown an increasing interest in the use of native legume species for forage and pasture use due to a social shift in values and increasing knowledge in ecology (Khanal *et al*., 2016). Additionally, producers have an interest in native perennial legumes as they may have beneficial adaptations to the area and the capacity to grow better in adverse conditions of the region. The northern region of the United States is home to many native perennial legume species including roundhead lespedeza (*Lespedeza capitata* Michx.), Illinois bundleflower [*Desmanthus illinoensis* (Michx.) MacMill. ex B.L. Rob. & Fernald], and purple prairie clover (*Dalea purpurea* Vent.).

The use of perennial legumes, native or introduced, can come with a set of challenges during the establishment year. One of the challenges to establishing a perennial legume is their very small seed size which makes them highly prone to drought before they even emerge from the topsoil (Ćupina *et al*., 2011). While perennial legumes can be planted during both the spring or during the summer/fall, it is important to note that a spring sowing often leads to a significantly lower yield during the establishment year compared to a summer/fall sown legume crop (Ćupina *et al*., 2000, 2004). The difference in yield observed between spring and fall sown legume crops can be attributed to the competition emerging legumes face against weeds during the establishment period. Due to the slow emergence rate of legumes, many weeds can quickly establish and gain a strong foothold in the field before the legumes. A strong weed presence will compete with the small legume seedlings for resources, and stunt or halt the growth of the legume. However, if a spring planting is desired, there are resources available for producers to help combat weeds during the establishment time of the legume crop.

Often times a producer may select an herbicide or tillage practice to help suppress weed growth in an establishing crop, but another popular choice, particularly within legumes, is the use of a companion crop. Since many legumes, including those commonly used in the northern United States, have a slow emergence rate and lengthy establishment period they are often paired with a fast-emerging crop to help combat and suppress weed growth during this period (Hall *et al.*, 1995). The use of companion crops is widely utilized throughout crop establishment as an alternative to chemical applications for weed suppression. Companion crops provide benefits in the prevention of soil erosion, pest management, and increased plant resource utilization (Simmons *et al*., 1995; Anil *et al*., 1998). Companion crops are also beneficial within the establishment year of legumes as they increase the forage yield during the season by providing additional plant material (Simmons *et al*., 1995; Pappa *et al*., 2012; Dane and Laugale, 2014).

But as with many farming practices, companion cropping must be approached properly to reach production goals. The companion crop must be carefully considered as not every companion crop is universally beneficial to all crops. If a highly competitive companion crop is selected it will compete just as greatly if not more than a stand of weeds, creating an unfavorable environment for establishing the main crop of interest. A competitive companion crop then creates risk for poor legume establishment, especially if the companion crop were to become lodged (Nielsen *et al*., 1981; Tesar and Marble, 1988; Lanini *et al*., 1991). Additionally, the success of companion crops will be dependent on the ability of the co-seeded legume to capture light and develop under the shade of the companion crop's canopy (Tan *et al*., 2004). All in all, the best companion crop is one that is least competitive with the establishing forage seedling while providing adequate weed control.

Small grain cereal crops, such as oats (*Avena sativa* L.), have been identified as companion crops of choice in forage production systems as they tend to be highly competitive against weed growth but favorable for the growth of the legume (Simmons *et al*., 1995). Cereal crops, especially those used as companion crops, tend to be cool-season annuals. These provide control over weeds during establishment and offer extra forage production during the early summer months. During the growing season, forage production systems tend to face a "slump" during the peak of summer when production slows from cool-season species and legumes. To create a more consistent production of forage, producers could incorporate the use of warm-season species into their system as these species reach peak production during this "slump". However, there are few studies that have explored the compatibility of a warm-season annual as a companion crop during the legume establishment period.

Sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. sudanese*) is an annual warm-season grass that may serve as a beneficial companion crop. The use of sorghum-sudangrass as a companion crop could significantly boost forage production during the legume establishment year, while increasing production during the summer "slump". Previous studies have found sorghum-sudangrass to effectively suppress weeds due to allelopathic qualities of the grass (Marchi *et al*., 2008; Weston, 1989). It has also been shown to effectively reduce weed abundance and growth when utilized as a cover crop prior to the planting of a cash crop (Smith *et al*., 2015; Lenssen & Cash, 2011). However, the use of sorghum-sudangrass as a companion crop with an establishing perennial legume is yet to be explored.

The aim of this study is to determine the compatibility of sorghum-sudangrass as a companion crop with six different perennial legumes. Specifically, this study tests the ability of sorghum-sudangrass to suppress weed growth, boost forage yields, and allow a successful establishment of a perennial legume. Compatibility was approached by analyzing different sorghum-sudangrass harvesting times among different perennial legume species through identifying the yield of the legumes, sorghum-sudangrass, and weeds of each treatment. The goal of this study was to provide practical information on the applicability of sorghum-sudangrass as a warm-season companion crop for perennial legumes during their establishment year.

Materials and Methods

Research Location

This study was conducted at the University of Nebraska-Lincoln Horticulture Research Garden in Lincoln, NE (40°49’40” N 96°39’26” W, and 358 m ASL). The 30-year average annual precipitation at the site is 735 mm with 38% of precipitation occurring June through August (High Plains Regional Climate Center, 2018) (Figure 2-1). The 30-year mean (1981-2010) temperature was 11° C with the average temperature in June, July, and August at 22.6° C, 25.3° C, and 24.1° C, respectively (High Plains Regional Climate Center, 2018) (Figure 2-2). Forage establishment experimental plots were formed in the University Research Garden (2023.4 m^2) in an area that until the fall of 2015 was a regularly mowed sod that mainly consisted of tall fescue [*Schedonorus* arundinaceus (Schreb.) Dumort., nom. cons.] and smooth bromegrass (*Bromus* inermis Leyss). The dominant soil was a deep, moderately well drained urban land-Wymore complex (fine, smectitic, mesic Aquertic Argiudolls) with moderate permeability (USDA NRCS Web Soil Survey 2018).

Experimental Design

The forage establishment experiment design was randomized complete block design with three blocks and a split-plot arrangement of six legume species and four companion crop treatments, creating 24 treatments per block (Figure 2-3). The main plot consisted of six legume treatments of alfalfa cv. Ranger, birdsfoot trefoil cv. Norcen, and common varieties of a medium-type of red clover, Illinois bundleflower, roundhead lespedeza, and purple prairie clover (e.g. varieties not stated). The subplot factor was companion crop treatment consisting of four treatments including a legume plot that was hand-weeded, a legume plot that was non-weeded, and two plots where the legume was seeded with sorghum-sudangrass as a companion crop. Of the two treatments receiving a sorghum-sudangrass companion crop, one had the sorghum-sudangrass harvested three times and the other treatment had the sorghum-sudangrass harvested four times throughout the growing season. All treatments were seeded on 19 May 2016 with sorghum-sudangrass cv. Super Sugar at a pure live seed (PLS) rate of 10.92 kg PLS ha^{-1}, alfalfa at 10.8 kg PLS ha^{-1} (36% hard seed), red clover at 10.6 kg PLS ha^{-1} (4% hard seed), birdsfoot trefoil at 5.8 kg PLS ha^{-1} (9% hard seed), Illinois bundleflower at 17.0 kg PLS ha^{-1} (54% hard seed), roundhead lespedeza at 11.6 kg PLS ha^{-1} (hard or dormant seed not determined), and purple prairie clover at 9.8 kg PLS ha^{-1} (71% dormant seed). Legume seed was purchased from Stock Seed Farms (Murdock, NE) and inoculated with the appropriate rhizobium strain prior to planting.

Planting

Preparation for 2016 spring planting began in fall of 2015 with tilling and disking of the site to kill the existing sod and provide a smooth seedbed. The site was tilled again and culti-packed two days before planting on 17 May 2016. All seed was planted with a Great Plains 3P600 drill (Kincade Equipment Manufacturing, Haven, KS) equipped with a cone-seeder to accurately meter the seed in plots that were 1.5 m wide x 6 m long. Each plot contained nine rows with 15.25-cm row spacing and a planting depth of 1.25 cm. Ttall fescue was planted in the borders around each block to minimize soil erosion and compaction during harvesting operations throughout the experiment.

Stand Establishment

Early establishment data were gathered from all treatments roughly one month after planting, on 10 June 2016. For this collection, a frequency frame method was utilized (Vogel and Masters, 2001). The method consists of placing a metal frame that contains 25 cells, with each cell measuring 15 x 15 cm, over the plant material to be assessed cells containing one or more of the seeded species were counted. The grid was systematically placed within the seeded plot so that a total of four frames were collected to gather a total of 100 cells of frequency from each plot. The total frequency count of a species from a plot is then converted into a frequency of occurrence by dividing the number by 100. To arrive at a conservative density estimate (seedlings m^{-2}), number of cells with the target plant species (frequency) was multiplied by a factor of 0.4 (Vogel and Masters, 2001).

Harvesting and Clipping

Treatments with the sorghum-sudangrass companion crop had the sorghum-sudangrass harvested either three times or four times throughout the summer. The legumes from each plot, regardless of treatment, were harvested at the end of the growing season following a hard freeze, this harvest occurred on 25 October 2016. Harvesting of the sorghum-sudangrass occurred on 27 June, 4 August, and 25 October for the three-cut treatment, and on 27 June, 4 August, 20 September, and 25 October for the four-cut treatment. The 25 October harvest date was the final harvest of the season, and during this harvest, all plant material, including legumes, sorghum-sudangrass, and weeds were removed.

Harvesting the sorghum-sudangrass treatments consisted of collecting a total plot weight using a Carter Plot Harvester with a 0.91-meter flail head (Carter Manufacturing Company in Brookston, IN) once the sorghum-sudangrass reached the boot-stage of growth. Harvests on 27 June, 4 August, and 20 September were all harvested with the harvester head placed 25.5 cm above the ground so that the only plant material removed was sorghum-sudangrass, leaving the legume of interest intact. Each plot was harvested in one pass, and as the harvester moved across the plot, forage material was collected in the bucket of the harvester which provided the total fresh weight of the harvested material. From this, a subsample was collected from each plot by placing two handfuls of harvested material into a large paper bag. Wet weight was recorded by weighing each subsample bag immediately following harvest. Wet subsamples were then placed in a SMO28-2 SHEL LAB Forced Air Oven (Sheldon Manufacturing, Inc., Cornelius, OR) at a temperature of 60° C for five days and reweighed to obtain a dry weight. The dry weight was divided by the wet weight for each sample to determine the dry matter weight of the collected forage. The dry matter weight was then multiplied by the total plot fresh weight to calculate the dry matter yield per plot, and then multiplied out on a per hectare basis.

On 24 October 2016, the day prior to the final machine harvest, hand-clipped samples were collected from each treatment to determine forage composition. Two

30.5 x 30.5 cm sample frames were randomly collected per plot by clipping the plant material within the frame to ground level. Forage material inside the frame was separated and placed into different weeds, legume of interest, and sorghum-sudangrass for each plot. The samples were then placed into the drying oven at 60°C for five days. Following the drying period, samples were weighed, and a dry weight was recorded. The dry weight of the weeds, legume of interest, and sorghum-sudangrass were then used to estimate the total composition for each plot.

The final harvest on 25 October consisted of harvesting the sorghum-sudangrass, legume, and any weed growth from each of the 24 treatments. Plots were harvested with one pass of the harvester through the center of the plot with the harvesting head at a height of 5 cm above the ground to collect all growth of the sorghum-sudangrass, legume of interest, and weeds. Harvested material was again collected with the total plot weight was calculated and recorded. From this, a subsample was gathered from each plot, weighed, placed into the oven at 60°C for five days, and reweighed to collect a dry weight. The wet weight and dry weight were once again used to calculate the dry matter production for each plot.

Year Two Harvest

The following season, on 24 May 2017, the legumes in plots that were originally seeded in the spring of 2016 were harvested to gather yield data for the first cutting of the second year of growth. Regrowth was harvested from the alfalfa, red clover, and birdsfoot trefoil treatments only, as the Illinois bundleflower, purple prairie clover and roundhead lespedeza failed to produce any growth prior to the timing of the first cutting. Harvesting methods used in 2016 were applied to this harvest where a total plot weight, a wet subsample weight, and a dry subsample weight were collected from each treatment of the three legumes, and a dry matter yield was calculated per plot. Frame clippings were not gathered for this harvest as there was no notable weed growth prior to the timing of the first cutting.

Analysis

The establishment, harvest, clipping, and return-year forage data were analyzed for significant differences between and among treatments using the SAS 9.4 statistical software (SAS Institute, Cary, NC). A Proc Mixed data analysis using contrast statements to account for random effects between treatments and least square means with standard error to determine significant differences (P-value <0.05) among treatments. The fixed variables for these analyses were legume species and companion crop treatment, and the random variables were total dry matter yield, sorghum-sudangrass yield, legume yield, and weed yield.

To determine early establishment (growth) in 2016, data were collected on 10 June for each of the six legume species and the sorghum-sudangrass. To determine if sorghum-sudangrass was a successful suppressor of weed growth during the establishment year, each legume was established with four different treatments, specifically, weeded control (WC), non-weeded control (NWC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3); and dry matter (DM) was calculated as kg DM ha^{-1}. To determine if sorghum-sudangrass boosted forage production, two harvesting treatments were studied, one sorghum-sudangrass treatment was harvested three times (SSG3) and the other was harvested four times (SSG4); and DM was calculated as kg DM ha^{-1}. To determine if there was a compatible companion crop with each of the legume species, each legume species was subjected to four different establishment treatments, specifically, weeded control (WC), non-weeded control (NWC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3); and dry matter (DM) was calculated as kg DM ha^{-1}. To determine if the sorghum-sudangrass companion crop had a lasting effect on the yield of the legumes, the first cutting during the second year of growth was collected from three of the six legumes; alfalfa, red clover, and birdsfoot trefoil (Second year growth data was not collected for roundhead lespedeza, Illinois bundleflower, or purple prairie clover because they failed to produce any growth prior to the timing of the first cutting). Last, legume yields (kg DM ha^{-1}) of the establishment year was compared to that of the second year to determine any significant interaction ($p\text{-value}<0.05$) between years by companion crop treatment and between years by legume treatment.

Results

Early Establishment

Two species had unsuccessful establishment, two species had adequate establishment, and two species had successful establishment (Figure 2-4). Purple prairie clover and roundhead lespedeza were both categorized as unsuccessful establishments with frequencies of occurrence below 25% for all four treatments, which correlates to plant densities lower than 10 plants per m^2 (Vogel and Masters, 2001). Birdsfoot trefoil and Illinois bundleflower were considered to have adequate establishment with frequencies of occurrence between 25-50% for all four treatments, which correlates to plant densities of 10-20 plants per m^2 (Vogel and Masters, 2001). As indicated by frequencies of occurrence greater than 50%, alfalfa and red clover were successful in establishment for the four varying treatments, which correlates to plant densities greater than 20 plants per m^2 (Vogel and Masters, 2001).

All of the sorghum-sudangrass was considered successfully established, as each plot containing sorghum-sudangrass had a frequency of occurrence above 50%

(Figure 2-4), which correlates to a plant density greater than 20 plants per m^2 (Vogel and Masters, 2001).

Dry Matter Production

We found that the production of weeds was dependent only on the companion crop treatment (p-value <.0001, Table 2-1). Weed yield in the SSG3 treatments was not greater than the SSG4 treatment (Table 2-2). The WC legume treatments did not produce a significant difference in weed yield compared to the treatments of legumes receiving sorghum-sudangrass as a companion crop. However, the production of weeds in the NWC legume treatments was significantly higher than weed production in the sorghum-sudangrass companion crop treatments (Figure 2-5). The comparable weed yields gathered from treatments with sorghum-sudangrass as a companion crop and treatments with weeds controlled indicate that sorghum-sudangrass may be an effective strategy to suppress weed growth during legume establishment.

We found that the total dry matter yield was significantly boosted with the addition of sorghum-sudangrass, producing 2782 kg, 6912 kg, 25,038 kg, and 31,956 kg DM ha^{-1} for the WC, NWC, SSG4, and SSG3 treatments, respectively (Table 2-2, Figure 2-6). Furthermore, when harvested three times, sorghum-sudangrass yielded a significantly greater amount compared to four harvests (Table 2-2, Figure 2-7). The sorghum-sudangrass treatment that received three cuttings was able to accumulate more forage because the tillers produced from the second cutting were allowed to reach a later maturity therefore increasing yield. Whereas the sorghum-sudangrass treatment receiving four cuttings was unable to produce high yields following the third cutting. The decreased growth before the fourth cutting of this treatment can be contributed to the shorter growing degree days and lower temperatures during the latter part of the growing season, providing unfavorable conditions for high forage production of the warm-season grass. These findings demonstrate that forage production can be increased through the use of sorghum-sudangrass and the production of sorghum-sudangrass can be influenced by the harvesting frequency.

The legume forage yield depended on a species x companion crop interaction (Table 2-1). Of the six legume species studied two of the species, purple prairie clover and roundhead lespedeza, were found to have no significant differences in their yields between the companion crop treatments (Table 2-3). The four remaining legume species: alfalfa, birdsfoot trefoil, red clover, and Illinois bundleflower, were found to have a significant difference in the yield produced between the WC and the NWC treatments, as well as between the WC and sorghum-sudangrass companion crop treatments (Table 2-3). These four legumes produced their greatest yield in the WC treatment, followed by the NWC treatment, then the SSG3 treatment, and lastly the SSG4 treatment (Figure 2-8). These results indicate the use of sorghum-sudangrass as a companion crop may be more detrimental to legume growth than if the legume was left un-managed for weeds.

Year Two Production

During year two, there was no significant interaction between legume and companion crop treatment on legume yield (P=0.6998), though legume yield was significantly influenced by legume (P=0.001) and companion crop treatment (P<.0001, respectively. Legume yield by companion crop treatment was greatest in the WC treatment, followed by the NWC treatment, then the SSG4, and SSG3 treatmetns (Figure 2-9). Between these treatments, only the NWC and the SSG3 treatments showed no significant difference (Table 2-4). During the second year of growth, alfalfa was the greatest yielding legume, followed by birdsfoot trefoil and then red clover (Figure 2-10).

Year One / Year Two Production

There were significant year by companion crop treatment (P=0.0321) and year by legume treatment (P=0.0003) interactions on legume yields (Figure 2-9 and Figure 2-10). Overall, there was still a significant difference in the yield of legumes between the WC treatment and the NWC treatment, the WC treatment and both the sorghum-sudangrass treatments, and the NWC treatment and both the sorghum-sudangrass treatments (Table 2-5).

Discussion

The application of sorghum-sudangrass as a warm-season annual companion crop reduced first year growth of legumes used in this study, but these legumes were able to emerge and have good production in the second year. While sorghum-sudangrass decreased weed growth in these six perennial legumes during their early establishment, it also inhibited the legume production during the season. These findings do not support the hypothesis that sorghum-sudangrass is an effective option as a warm-season annual companion crop for successfully establishing perennial legumes.

The addition of sorghum-sudangrass increased overall forage production (Table 2-3). Specifically, total dry matter yield in the WC and NWC treatments of alfalfa were 2,782 and 6,912 kg DM ha^{-1}, respectively, while total dry matter yield was 31,956 and 25,038 kg DM ha^{-1} for treatments SSG3 and SSG4, respectively. The higher production in the total dry matter yield of the SSG3 treatment can be attributed to the growth of the sorghum-sudangrass (Figure 2-7). By foregoing the 20 September harvest on the SSG3 treatment, the sorghum-sudangrass was allowed to continue its growth and progress in maturity. This allowed SSG3 treatment to accumulate greater biomass compared to the SSG4 treatment. When the SSG4 treatment was harvested on 20 September regrowth of the plant had to come from growth of new tillers which was drastically decreased compared to earlier harvests. The shorter days and decreasing temperatures during late September and early October are not favorable for growth of the warm-season annual.

Our findings reveal that sorghum-sudangrass reduced weed competition by well over 50% when compared to the NWC control treatment during the establishment year (Figure 2-5). The success found in weed suppression by sorghum-sudangrass aligns with previous studies that have identified other grass-legume pairings to have greater weed suppression than that of a legume monoculture (Akemo *et al*., 2010; Brainard *et al*., 2011; Creamer and Baldwin, 2000; Mohler and Liebman, 1987). This capability is aided by the grass's faster growth rates and ability to tiller, which allows the plant to be more suppressive of weeds than legumes (Haynes, 1980; Bybee-Finley *et al*., 2016). However, while weed suppression is one of the goals when using sorghum-sudangrass as a companion crop, producers may not want the growth of the perennial legumes to be sacrificed for weed control. We found that with the use of sorghum-sudangrass as a companion crop the yield of the perennial legumes suffered significantly in the establishment year (Figure 2-8).

Yields of the legumes were able to recover moderately in the second year of growth, but the negative effects of sorghum-sudangrass were still significant and indicate that sorghum-sudangrass may not be an ideal companion crop option. While alfalfa, birdsfoot trefoil, and red clover had greater production in the first cutting of the second season than the after frost cutting in the establishment year, there was still a significant difference in production across companion crop treatments with the WC treatment outperforming the other three treatments. This suggests that while legumes will recover from a competitive establishment year, they are not able to make a full recovery and match the production of a weed-free environment. A producer may have other options to compensate for the yield decrease suffered by the established legume from the sorghum-sudangrass companion crop. Since the legume was able to produce an adequate stand during the spring of the second-year growth, a producer could look at broadcasting a perennial grass over the alfalfa stand to create a mixed grass-legume stand. Overseeding of perennial grasses and other forages has previously been suggested as a means to improve thin, aging alfalfa stands and could be fitting given the results of this study as well (Canevari et al., 2000).

One interesting result of this study was the general failure of native warm-season perennial legumes to establish. During the establishment year, Illinois bundleflower was able to establish, but purple prairie clover and roundhead lespedeza produced little to no growth all season and were deemed unsuccessful. By the second year of growth, all three of these native legumes failed to produce any biomass regardless of companion crop treatments and were deemed unsuccessful. These findings align with those discovered by McGraw *et al*. (2004) who found the use of native legumes not to be suitable for the replacement of introduced species in forage production. Based on previous studies where these legumes were paired with a perennial warm-season grass and established a productive and promising forage (Posler *et al*., 1993), it was anticipated that these warm-season perennial legumes would pair nicely with the warm-season annual, sorghum-sudangrass. It should be noted, though, that the yield of purple prairie clover and roundhead lespedeza in our study may have been hindered due to a limitation in our study of improper cold stratification of these seeds (Houseal, 2007).

There were some factors that may have contributed to the suppressed growth of the perennial legumes when they were paired with sorghum-sudangrass. A major factor is the possibility of competition between the sorghum-sudangrass and the legumes for resources. The Classical Competition Theory identified by Smith *et al.* (2015), highlights that when pairing species for intercropping there must be favorable timing between the needs for each resource between the crops. If the intercropped species are demanding of the same resources simultaneously, one is likely to outcompete the other. While this study did not address the issue of resource competition, sunlight may be a limiting resource negatively affecting legume growth. Ghosh *et al.* (2006) intercropped sorghum with soybeans and found the shading effect of the tall sorghum crop adversely affected soybean biomass, nitrogen uptake, chlorophyll, and photosynthesis.

An unanticipated factor that also may have led to suppressed legume yield was lodging and residue of sorghum-sudangrass left behind after each harvest. Lodging has previously been cited as the cause of suppressed growth for undersown species when planted with full-leafed pea (*Pisum sativum* L.) cultivar companion crops (Faulkner, 1985; Gilliland and Johnston, 1992). Furthermore, when sorghum-sudangrass residue is left behind the allelopathic compounds found in the plant begin to release during decomposition, negatively affecting the establishing legume crop (Marchi *et al.*, 2008; Weston 1989). These aspects were not a focus within this study and require further investigation to better understand the competitive nature and interactions present between the pairing of sorghum-sudangrass and each of the perennial legumes.

Conclusion

The use of sorghum-sudangrass as a companion crop may be better understood through adjustments to planting and harvesting techniques. The relationship and effectiveness of sorghum-sudangrass as a companion crop might be altered with adjustments to various details in planting technique. For example, the effect of companion crops can be optimized through adjustments to the densities and proportions of the companion crops utilized at planting (Bulson *et al.*, 1997; Carr *et al.*, 1995; Mohler and Liebman 1987).

Given the increased production provided by sorghum-sudangrass in the first year, and the reasonably good legume production in the second year there is opportunity to study this grass-legume pairing further. The potential for seeding perennial grasses into the legumes for a mixed stand from the second year on could provide well-rounded nutritious forage for livestock; however, this direction will require further studies. In conclusion, this study highlights the need to start a discussion regarding the pairing of an establishing legume with a warm-season annual grass and the continued need to identify a suitable forage production plan when utilizing sorghum-sudangrass and perennial legumes to meet production needs.

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Figures and Tables

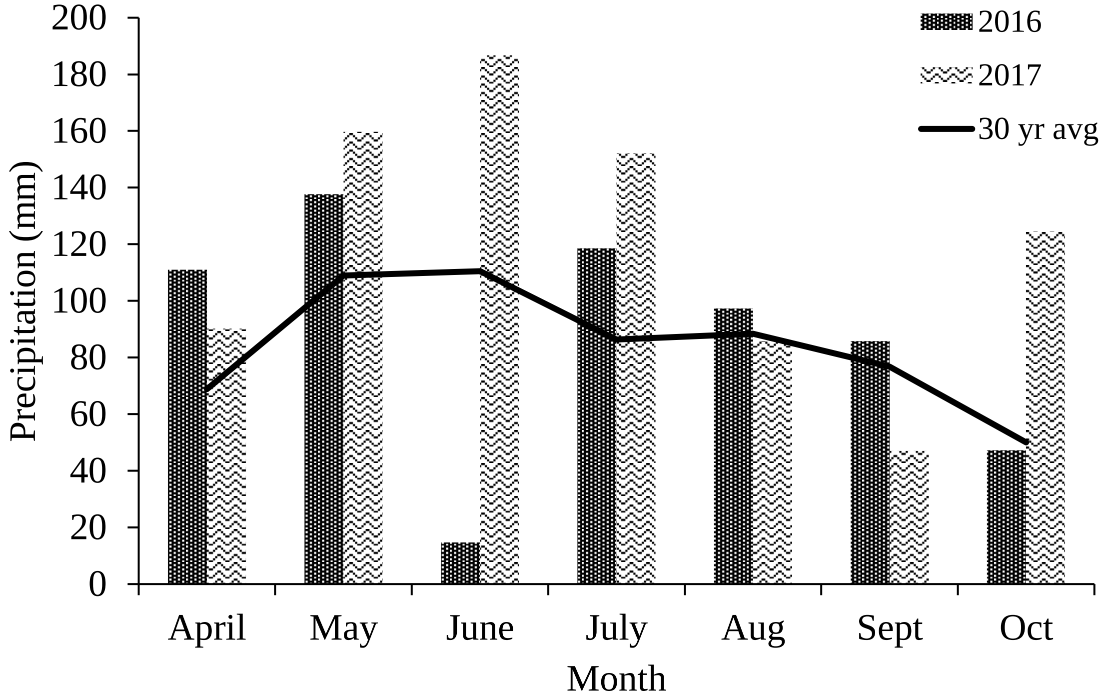

Figure 2-1: Monthly precipitation (mm) from April through October for 2016, 2017, and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska.

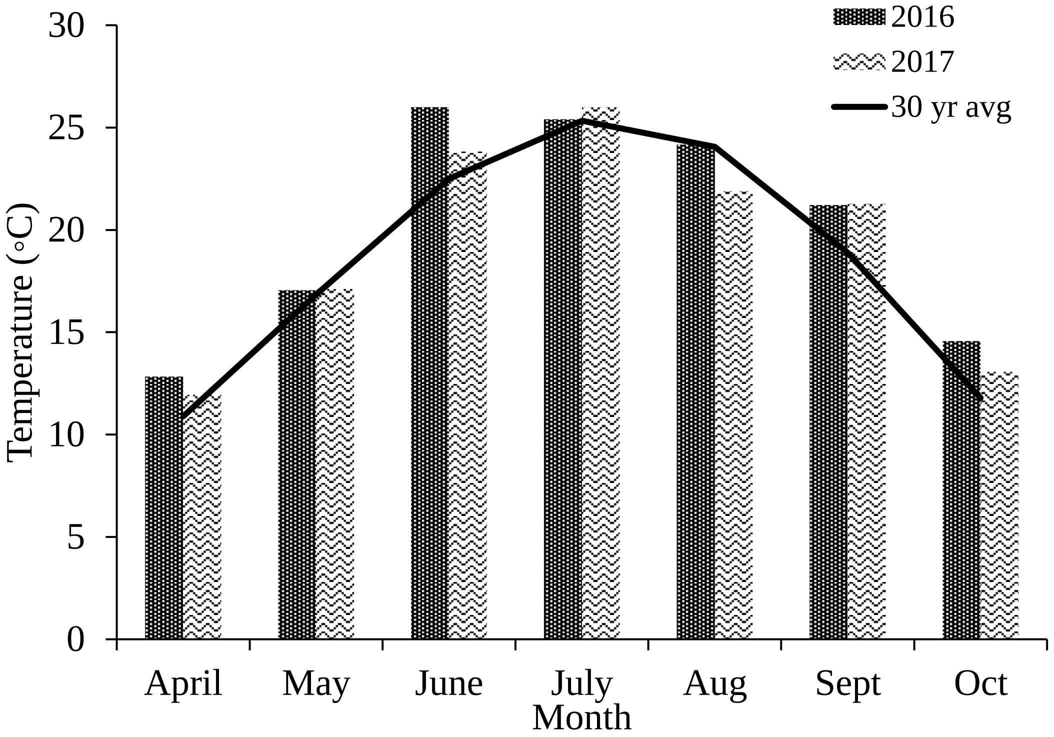

Figure 2-2: Monthly average temperature (degrees Celsius) from April through October for 2016 and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska.

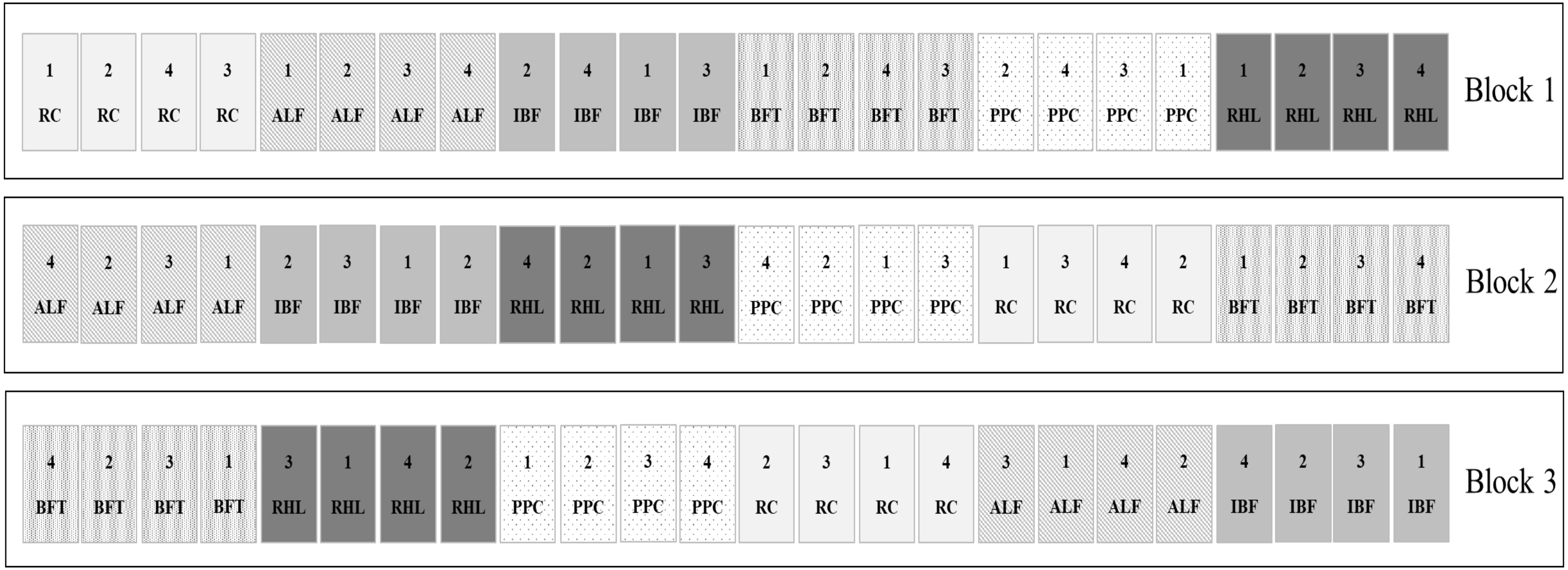

Figure 2-3: Plot diagram of a randomized complete block design with three blocks and a split-plot arrangement of six legume species and four companion crop treatments. The six legume species include alfalfa (ALF), birdsfoot trefoil (BFT), red clover (RC), Illinois bundleflower (IBF), roundhead lespedeza (RHL), and purple prairie clover (PPC). Each legume species received a weeded control (1), a non-weeded control (2), a sorghum-sudangrass companion crop harvested four times (3), and a sorghum-sudangrass companion crop harvested three times (4).

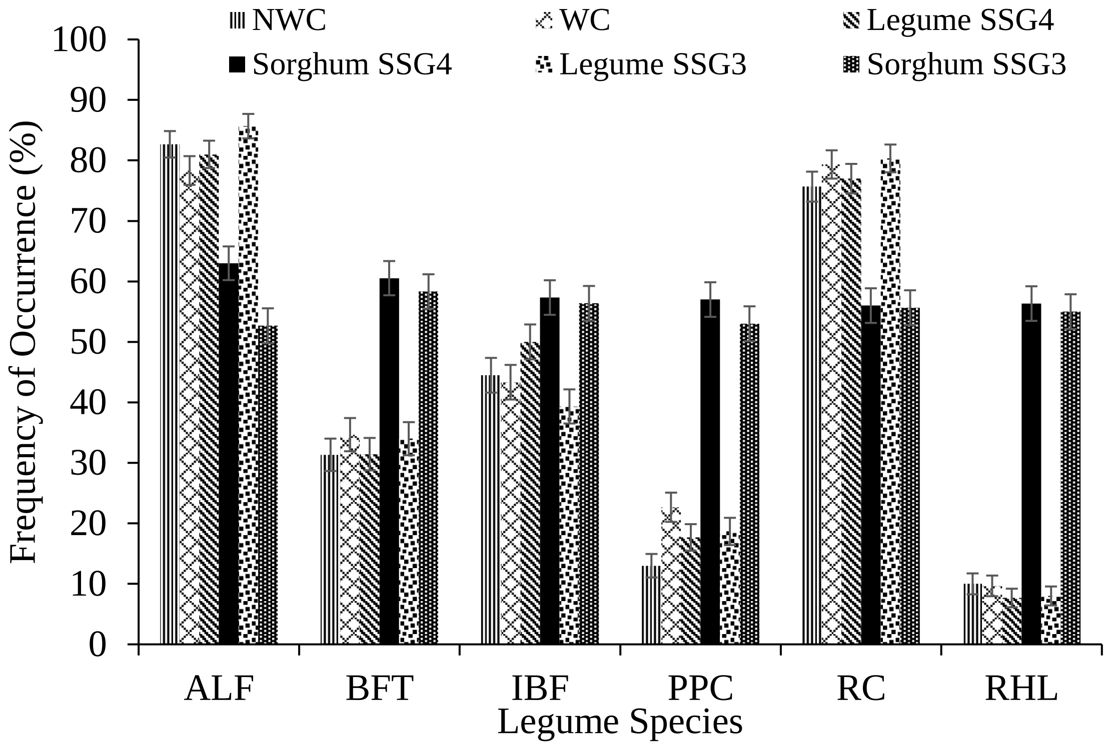

Figure 2-4: Frequency of occurrence (10 June 2016) of alfalfa (ALF), birdsfoot trefoil (BFT), Illinois bundleflower (IBF), purple prairie clover (PPC), red clover (RC), roundhead lespedeza (RHL), and sorghum-sudangrass (SSG) in non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3) companion crop treatments after seeding on 17 May 2016.

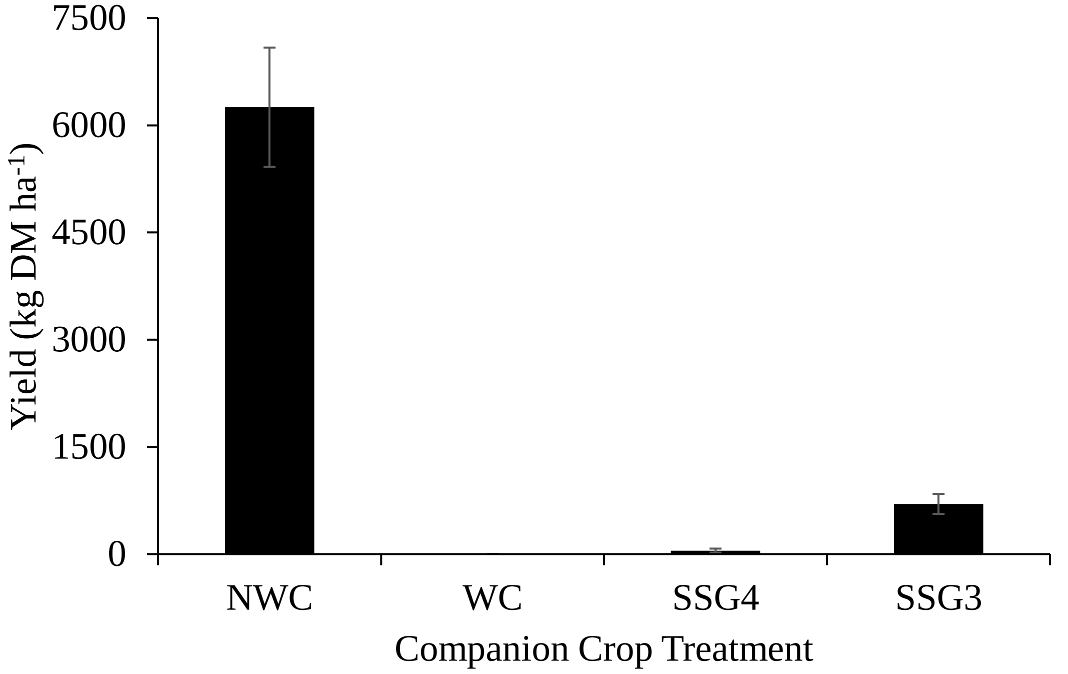

Figure 2-5: Mean weed biomass production (kg DM ha^{-1}) for the companion crop treatment of a non-weeded control (NWC), a weeded control (WC), sorghum-sudangrass companion crop harvested four times (SSG4), and the sorghum-sudangrass companion crop harvested three times (SSG3) during 2016.

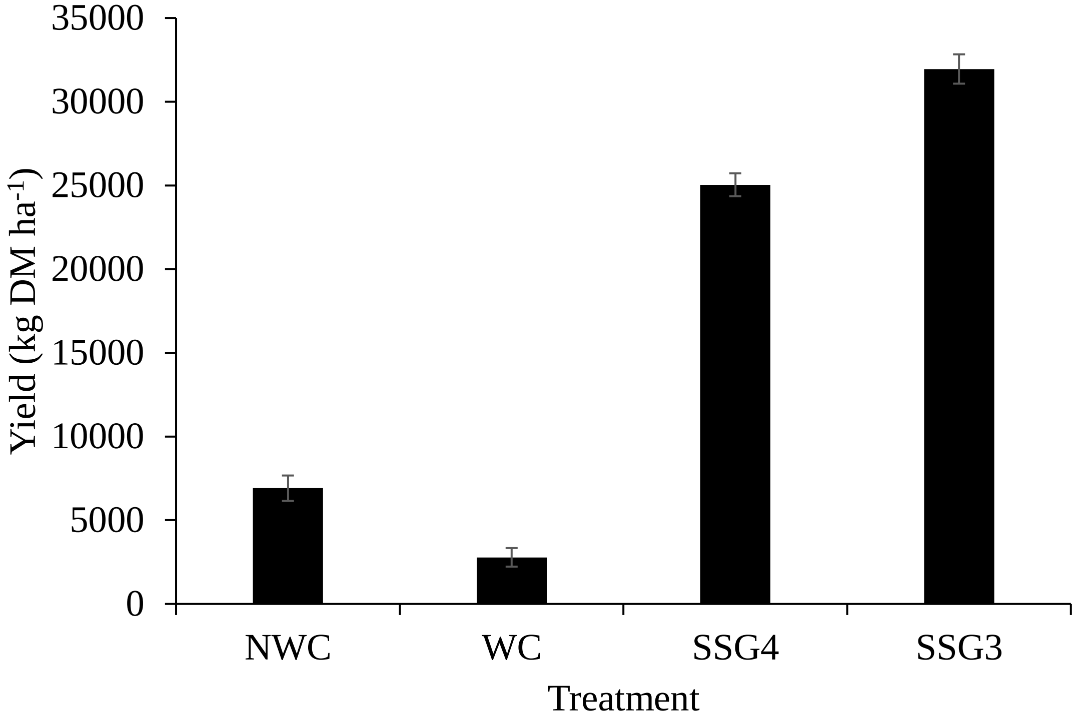

Figure 2-6: Total dry matter yield (kg DM ha^{-1}) for the companion crop treatment of a non-weeded control (NWC), a weeded-control (WC), sorghum-sudangrass companion crop harvested four times (SSG4), and the sorghum-sudangrass companion crop harvested three times (SSG3) during 2016.

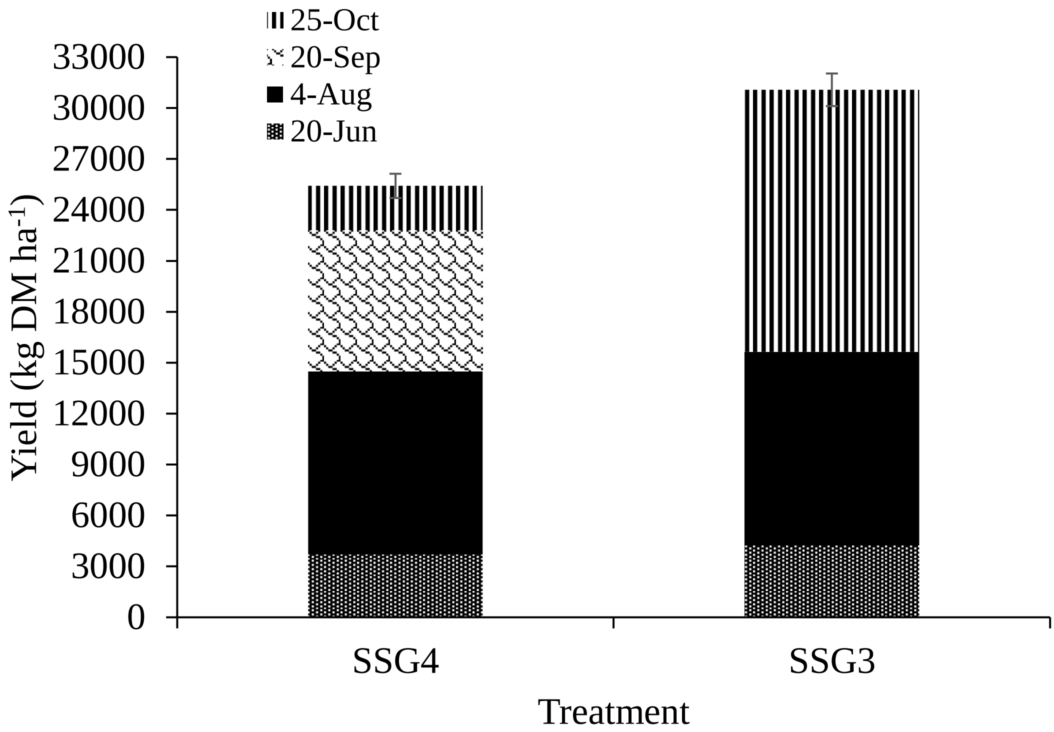

Figure 2-7: Mean yield (kg DM ha^{-1}) for the warm-season annual grass, sorghum-sudangrass, when harvested four times (SSG4) and three times (SSG3) during the 2016 growing season shown per cutting. Dates show yields per cutting.

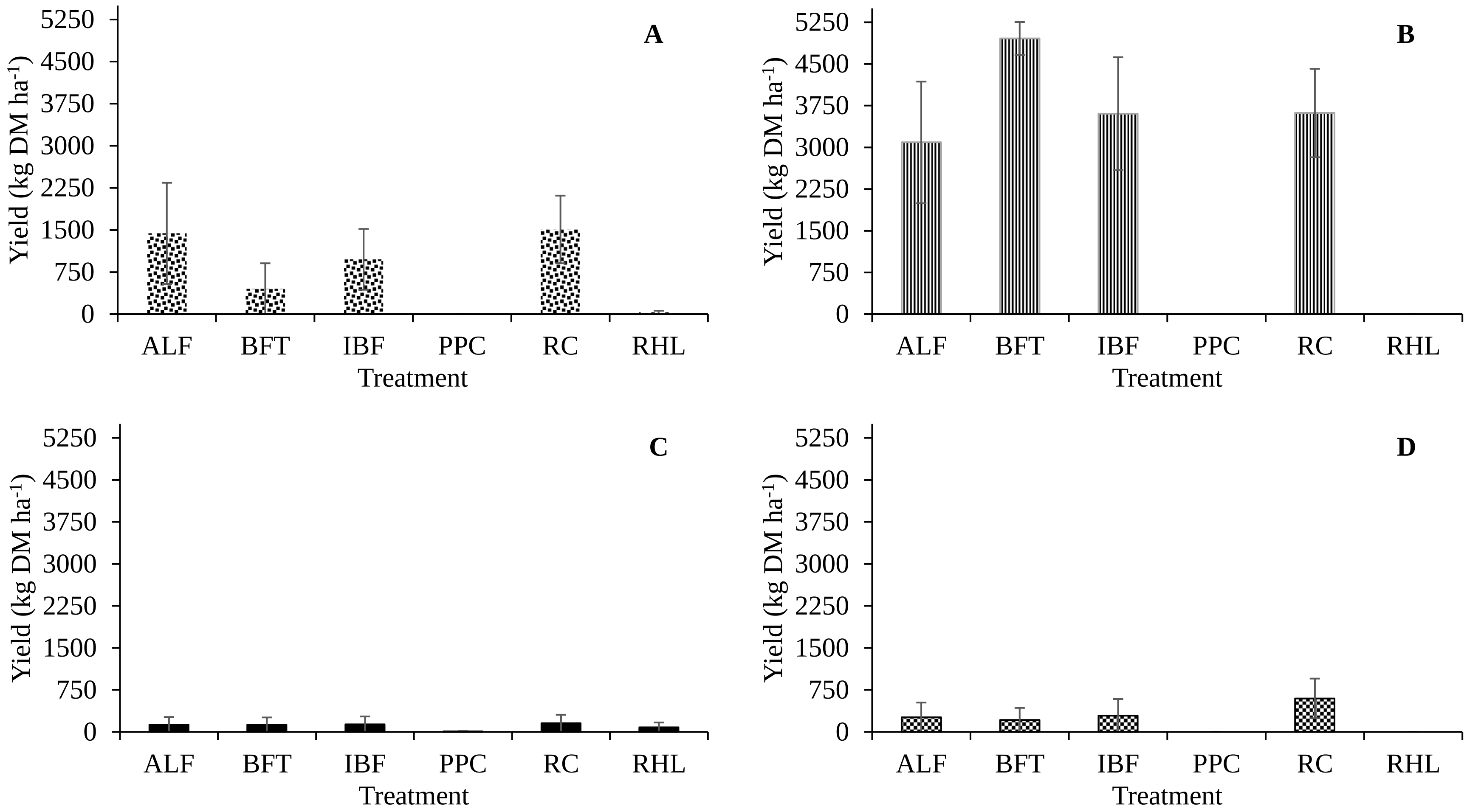

Figure 2-8: Mean yield (kg DM ha^{-1}) of alfalfa (ALF), birdsfoot trefoil (BFT), Illinois bundleflower (IBF), purple prairie clover (PPC), red clover (RC), and roundhead lespedeza (RHL) by companion crop treatment of non-weeded control (A), weeded control (B), sorghum-sudangrass harvested four times (C), and sorghum-sudangrass harvested three times (D) for the 2016 year.

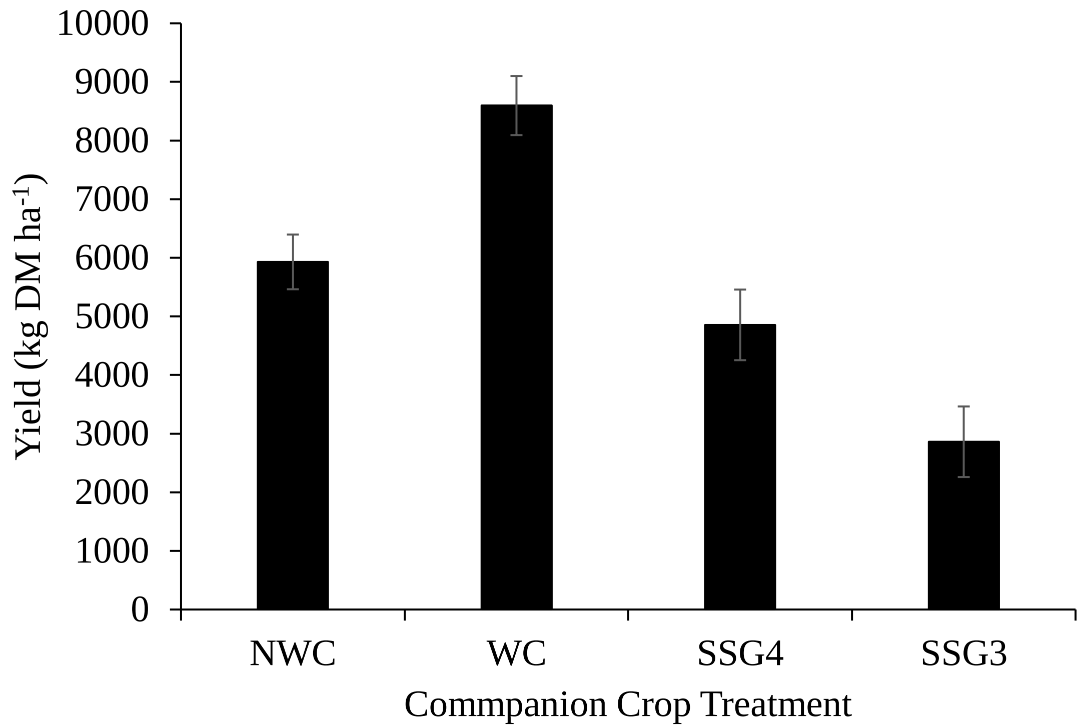

Figure 2-9: Mean legume yield (kg DM ha^{-1}) across alfalfa, red clover, and birdsfoot trefoil for the first cutting (24 May 2017) in the second year of growth by companion crop treatment of non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3).

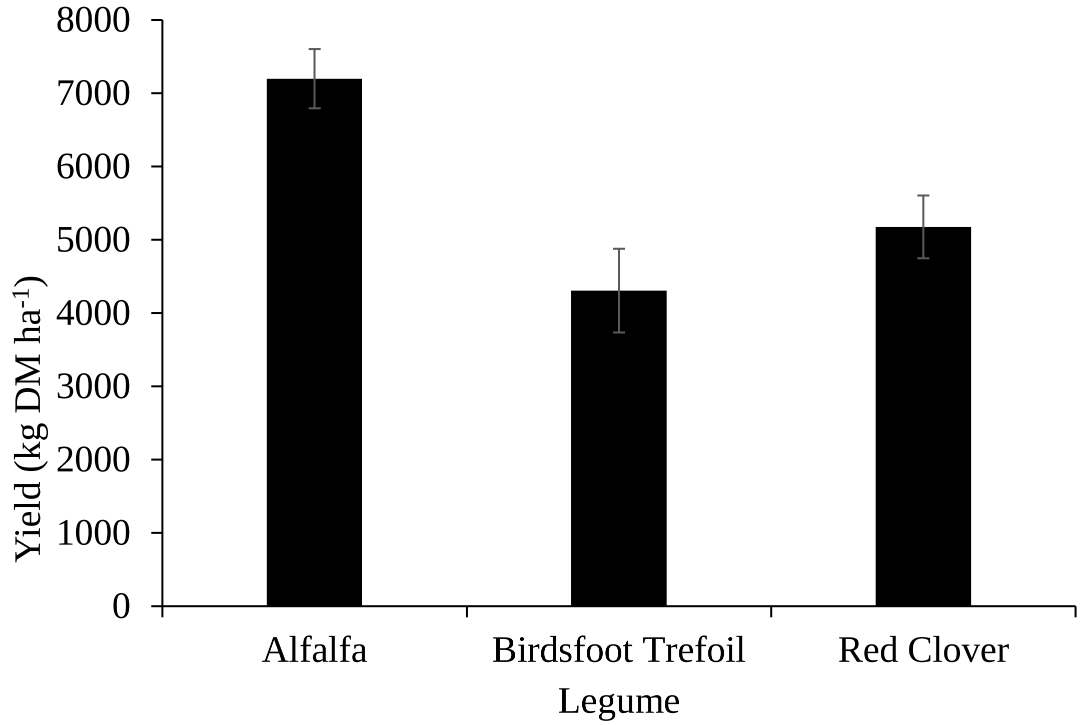

Figure 2-10: Mean yield (kg DM ha^{-1}) of alfalfa, birdsfoot trefoil and red clover across all companion crop treatments for the first cutting (24 May 2017) in the second year of growth.

Table 2-1: Analysis of variance of legume, weed, sorghum-sudangrass (SSG), and total dry matter yield during 2016 based on the effect of legume species (Legume), companion crop treatment (CC), and legume species by companion crop interaction. P-values <0.05 denote a significant difference.

Fixed Effects on Yield in 2016				
	Legume	**Weed**	**Sorghum**	**Total**
Legume	<.0001	0.8357	0.6195	0.2479
CC	<.0001	<.0001	<.0001	<.0001
Legume*CC	<.0001	0.9004	0.4353	0.274

Table 2-2: Mean yield (kg DM ha^{-1}) contrasts for sorghum-sudangrass (SSG), weed, and total dry matter yield (Total Yield) between companion crop (CC) treatments of non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3).

CC	Total Yield	SSG Yield	Weed Yield
	kg DM ha^{-1}		
NWC	6912a†	0.00a	6252a
WC	2782b	0.00a	0.00b
SSG4	25038c	24881b	49b
SSG3	31956d	31026c	702b

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Table 2-3: Average yield in dry matter per hectare (kg DM ha^{-1}) of alfalfa (ALF), birdsfoot trefoil (BFT), Illinois bundleflower (IBF), purple prairie clover (PPC), red clover (RC), and roundhead lespedeza (RHL) by companion crop treatment of non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3). And contrast statements between treatments for yield of each legume species. NS = No Significance, ***= Significant (P<.0001), **= Significant (P<0.01).

Species	NWC	WC	SSG4	SSG3	NWC vs. WC	SSG4 vs SSG3	WC vs SSG4 & SSG3
	kg DM ha^{-1}				Contrasts		
ALF	1439	3377	133	262	**	NS	***
BFT	453	5420	129	214	***	NS	***
IBF	976	3941	138	293	***	NS	***
PPC	0	0	9	0	NS	NS	NS
RC	1059	3954	153	598	***	NS	***
RHL	30	0	84	0	NS	NS	NS

Table 2-4: Analysis of variance on yield contrasts for legume growth prior to first cutting (24 May 2017) during the second year of growth (2017) between companion crop treatments of non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3). P-values <0.05 denote significant difference.

Contrasts	P-value
NWC vs WC	0.0011
NWC vs SSG4	0.031
NWC vs SSG3	0.1756
WC vs SSG3	0.0008
WC vs SSG4	0.0002
SSG4 Vs SSG3	<0.0001

Table 2-5: Yield contrasts for legume growth for the first and second years of growth (2016 and 2017) between companion crop treatments of non-weeded control (NWC), weeded control (WC), sorghum-sudangrass harvested four times (SSG4), and sorghum-sudangrass harvested three times (SSG3). P-values <0.05 denote a significant difference.

Contrasts	**P-value**
NWC vs WC	<.0001
SSG4 vs SSG3	0.0553
NWC vs SSG4 and SSG3	0.0003
WC vs SSG4 and SSG3	<.0001

CHAPTER 3: SUITABILITY OF SORGHUM-SUDANGRASS AS A COMPANION CROP WITH ALFALFA

Introduction

Alfalfa is a major source of hay within the state of Nebraska, accounting for 315,654 ha of forage production, or 30% of the total ha devoted to forage production (United States Department of Agriculture, 2015). As a perennial legume, alfalfa can be challenging to establish due to a slow germination rate and competition from rapidly germinating weeds. Since alfalfa has a slow establishment period, it is often paired with a fast-emerging companion crop as a means to combat and suppress weeds during this period (Hall et al., 1995). Companion crops are widely used during the crop establishment period as an alternative to chemical applications for weed suppression. The selection of a companion crop is often based on traits for rapid germination, emergence, nutrient supply, weed suppression, and ability to prevent soil erosion. Companion crops are also beneficial during the establishment year of alfalfa as they increase the forage yield during the season by providing additional plant material (Pappa et al., 2012; Dane and Laugale, 2014).

Traditionally, spring-established alfalfa has been paired primarily with oats (*Avena sativa* L.) and occasionally with other annual small grain cereal crops as a companion crop (Tesar and Marble, 1988; Smith et al., 1954; Meiss et al., 2010; Sheaffer et al., 2014). When oats and other cool-season annuals are used as companion crops, the increased forage material is primarily available in the early summer months, often times creating a shortage of forage during the peak summer months known as the summer slump. In contrast, warm-season crops have their greatest production during the summer months of July and August to help fill this summer slump. As a warm-season annual, sorghum-sudangrass could become an alternative companion crop to oat during the establishment period of alfalfa and help fill the summer slump of production associated with cool-season legumes (Fischbach et al., 2005).

Currently, there is little knowledge about the compatibility of sorghum-sudangrass with alfalfa. Previous studies have identified sorghum-sudangrass as a suitable cover crop for weed control when used before a fall vegetable crop, such as cabbage (*Brassica oleracea* L. Capitata) and lettuce (*Lactuca sativa* L.) (Creamer & Baldwin, 2000; Finney et al., 2009; Einhellig and Rasmussen, 1989). Sorghum-sudangrass has also been shown to have allelopathic properties during seedling emergence that contribute to combating weed emergence (Weston, 1996; Cheema et al., 2007). With the weed suppression characteristics of sorghum-sudangrass and its high forage yields (Moyer et al., 2004; Lenssen & Cash, 2011), there is a potential for it to be a companion crop when establishing an alfalfa crop. But it has yet to be determined if alfalfa and sorghum-sudangrass are compatible during the establishment year and allow for a successful alfalfa yield during the establishment year.

A potentially confounding factor in the use of sorghum-sudangrass as a companion crop to alfalfa is the differing recommended planting dates between the two species. In the North Central United States, the recommended spring planting date for alfalfa ranges from mid-March through the end of May (Undersander *et al*., 2011). For eastern Nebraska the recommend spring planting date is a bit earlier from early April to early May (Anderson and Nichols, 1983). The recommended planting date of sorghum-sudangrass in eastern Nebraska is late May to early June (Anderson & Volesky, 2013). Pairing alfalfa with sorghum-sudangrass means that the planting date of one or both species must be adjusted to accommodate for the growth of both. By adjusting a planting date, there is potential that the growth and success of one or both crops may be affected negatively or positively. It is an objective of this study to consider the affects that conflicting planting dates will have on the suitability of sorghum-sudangrass as a companion crop with alfalfa.

In addition to facing the challenge in planting dates between alfalfa and sorghum-sudangrass, an alfalfa crop may also face adversity from the potential competition of sorghum-sudangrass. It has been noted that with increasing plant density the weed suppressive ability of a companion crop will increase, but the inter-specific competition between the companion crop and main crop, alfalfa, will also increase (Bastiaans et al., 2008). With the dense, thick canopy of sorghum-sudangrass, it is possible that the alfalfa crop may be hindered most by interspecific competition for sunlight. Additionally, a dense stand of sorghum-sudangrass may compete with alfalfa for nutrients, water, and root space. Due to these possibilities and decreased legume yield noticed when established with a dense sorghum-sudangrass companion crop (La Vallie et al., unpublished data), suggests that seeding rates could be an important factor to consider in companion crop experiments.

The aim of this study is to determine the compatibility of sorghum-sudangrass as a companion crop with the alfalfa. Specifically, this study looks to tests the ability of sorghum-sudangrass in suppressing weed growth, boosting forage yields, and in its ability to allow a successful establishment of alfalfa. Compatibility was approached by analyzing different sorghum-sudangrass seeding rates, adjusted planting dates for alfalfa, and a traditional oat companion crop through identifying the yield of alfalfa, sorghum-sudangrass, oat, and weeds of each treatment. The goal of this study is to provide practical information on the applicability of sorghum-sudangrass as a warm-season crop for perennial legumes during their establishment year.

Materials and Methods

Research Location

This study was conducted at the University of Nebraska-Lincoln Horticulture Research Garden in Lincoln, NE (40°49’40” N 96°39’26” W, 358 m ASL). The 30-year average annual precipitation at the site is 735 mm with 38% of precipitation occurring June through August (High Plains Regional Climate Center, 2018) (Figure 3-1). The 30-year mean (1981-2010) temperature was 11 ℃ with the average temperature in June, July, and August at 22.6 ℃, 25.3 ℃, and 24.1 ℃, respectively (High Plains Regional Climate Center, 2018) (Figure 3-2). Forage establishment experimental plots were established in the University Research Garden (2023.4 m^2) in an area previously managed as a regularly mowed sod that mainly consisted of tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] and smooth bromegrass (*Bromus inermis* Leyss) through 2015, and used in 2016 as cropland consisting of soybean [*Glycine max* (L.) Merr.]. The dominant soil was a deep, moderately well drained urban land-Wymore complex (fine, smectitic, mesic Aquertic Argiudolls) with moderate permeability (USDA NRCS Web Soil Survey 2018).

Experimental Design

The alfalfa cv. Ranger establishment experiment was developed as a randomized complete block design with four blocks of repetition and nine treatments per block (Figure 3-3). Of the nine treatments, three were planted on 11 April 2017 and six were planted on 16 May 2017. One treatment of alfalfa with oat cv. Jerry was planted on 11

April 2017. A weed and non-weeded control treatments of pure alfalfa were planted on both of the following dates, 11 April 2017 and 16 May 2017. The 11 April 2017 planting is a control for the planting date, as the 16 May 2017 planting is slightly later then the recommended planting period of alfalfa to help accommodate for the recommended planting date of sorghum-sudangrass. Four treatments of alfalfa with sorghum-sudangrass cv. Super Sugar were planted on 16 May 2017. These four treatments had varying seeding rates of sorghum-sudangrass (SSG) at 1.37, 2.73, 5.46, and 10.92 kg pure live seed (PLS) per hectare. Alfalfa was seeded at 10.8 kg PLS ha^{-1} in all treatments and oats was seeded at 22.4 kg PLS ha^{-1} in the early-seeded companion crop treatment.

Planting

The 2017 seedbed was prepared two days before planting by tilling, discing, and culti-packing the soil. All seed was planted with a Great Plains 3P600Drill (Kincade Equipment Manufacturing, Haven, KS). One pass was made with the Great Plains 3P600 Drill per plot, planting nine rows with a 15.25 cm row spacing at a depth of 1.25 cm in a 9 m^2 plot (1.5 m x 6 m).

Early Establishment

Early establishment data was gathered from all treatments on 19 June 2017 as a baseline for initial emergence of alfalfa and SSG at the start of the season. For this collection, a frequency frame method was utilized (Vogel and Masters, 2001). The method consists of placing a metal frame containing 25 cells, each cell measuring 15 x 15 cm, over the plant material to be assessed. Cells containing one or more of the seeded species are counted. The grid was systematically placed within the seeded plot so that a total of four frames were collected to gather a total of 100 cells of frequency from each plot. Establishment frequencies are defined as successful (>50%), adequate (ranging 25-

50%), and unsuccessful (<25%). The total frequency count of a species from a plot is then converted into a frequency of occurrence by dividing the number by 100 (Vogel and Masters, 2001).

Oat Harvest

Oats was harvested on 20 June 2017 as forage once the crop reached the boot stage. Forage harvesting consisted of collecting a total plot weight by using a Carter Plot Harvester with a 0.91 m flail head forage harvester (Carter Manufacturing Company in Brookston, IN) with one pass of the harvester over the plot with the harvester head placed 25.5 cm above ground level to leave the full alfalfa plants intact to continue full establishment. As the harvester moved across the plot, the material was collected in the bucket of the harvester which provided the harvested material's fresh weight. From this a subsample was collected by placing two handfuls of harvested material into a large paper bag. From this subsample, a wet weight was recorded by weighing the subsample bag immediately following harvest. Next, subsamples were placed in a SMO28-2 SHEL LAB Forced Air Oven (Sheldon Manufacturing, Inc., Cornelius, OR) at a temperature of 60°C for five days. Following the drying period, subsamples were reweighed, and a dry weight was recorded. The dry weight was divided by the wet weight for each subsample to determine a dry matter weight for the collected forage. The dry matter weight was then multiplied by the total plot fresh weight to calculate the dry matter yield per plot, and then multiplied out on a per hectare basis.

Alfalfa and Sorghum-Sudangrass Harvests

Due to an abundance of weeds, samples were collected from each SSG treatment one day before machine harvest to estimate the composition of the total material harvested. Two 30.5 x 30.5 cm samples were collected per plot by placing a frame randomly in the plot and clipping the plant material that was rooted in the frame. The material inside the frame was cut at 25.5 cm above the ground and separated into individual bags for weeds and SSG. Since a wet weight is not required for sample frames, the samples were placed directly into the oven at 60°C for five days. Once the drying period was completed, samples were weighed, and a dry weight was recorded. The dry weights of the weeds and SSG were then used to estimate the composition for each plot.

The SSG was harvested two times throughout the summer after the plant reached a height of 1.8 m to determine total dry matter yield per plot. The first harvest, on 20 July 2017, was done with the same procedures as for the oat harvest. With the harvesting head placed 25.5 cm above the ground, the SSG material was collected into the bucket where a total plot weight was calculated and recorded. A subsample was collected and weighed for a wet weight, placed into the oven at 60 °C for five days, and reweighed to determine a dry weight.

One day before the second machine harvest (7 September 2017), samples were collected from each treatment to determine plot material composition. Two 30.5 x 30.5 cm sample frames were randomly collected per plot by clipping the plant material rooted within the frame at ground level. Forage material inside the frame was separated and placed into individual bags for weeds, alfalfa, and sorghum-sudangrass. Samples were placed directly into the oven at 60°C for five days. Once the drying period completed, samples were weighed, and a dry weight was recorded.

The second harvest, on 7 September 2017, consisted of harvesting the SSG and alfalfa material from all nine treatments. Plots were harvested with one pass of the harvester through the plot. Forage material was removed from each plot with the harvesting head placed 5 cm above ground level to collect all alfalfa and SSG growth. Harvested material was collected into the bucket where a total plot weight was calculated and recorded. A subsample was collected using the same methods as the previous harvest, weighed for a wet-weight, placed into the oven at 60°C for five days, and reweighed to collect a dry weight. The wet weight and dry weight were once again used to calculate the dry matter production for each plot, and then multiplied out on a per hectare basis.

Year Two Harvest

The following season, on 10 May 2018, the numbers of alfalfa shoots rooted in two 30.5 x 30.5 cm frames per plot were counted, representing the growth of alfalfa that was seeded in the spring of 2017. On 17 May 2018, the alfalfa was harvested to gather yield data on the second year of growth. Harvesting methods previously described were used where a total plot weight, a wet subsample weight, and a dry subsample weight were collected from each treatment and a dry matter yield was calculated per plot.

Analysis

The establishment, harvest, clipping, and return-year forage data were analyzed for significance between treatments using SAS version 9.4 statistical software (SAS Institute). Random variables of the study consist of the yields for total dry matter production, sorghum-sudangrass, oat, weeds, and alfalfa. A mixed-models procedure was used for the ANOVA and included least square means, contrasts statements and polynomial tests to determine significant differences (p-value <0.05) between treatments. Fixed factors in the ANOVA included planting dates, sorghum-sudangrass seeding rate, and companion crop treatment, while block was considered random.

To determine early establishment in 2017, data were collected on 19 June 2017 for all nine treatments. To determine an optimum seeding rate for using SSG as a companion crop, four SSG seeding rates at 1.37, 2.73, 5.46, and 10.92 kg PLS ha^{-1} were used and the growth of SSG, alfalfa, and weeds was measured. Since no significant polynomial relationship was found among the four SSG seeding rate and alfalfa, SSG, or weed production, the average yield across the four seeding rates was taken and used throughout our analysis. To determine whether SSG was an effective companion crop for increasing forage yields, suppressing weeds, and establishing alfalfa the differences in yield were analyzed for the averaged SSG treatments and the five remaining treatments for the total dry matter yield, weed yield, and alfalfa yield, respectively. To determine how the production of alfalfa with a SSG companion crop compares to alfalfa production with a more traditional companion crop, we performed a treatment establishing alfalfa with oat. To evaluate the effect of a recommend alfalfa planting date and a late alfalfa planting date on alfalfa production and weed yield two different planting dates of 11 April 2017 and 16 May 2017 were established for a weeded alfalfa stand and a non-weeded alfalfa stand. To establish if the SSG companion crop had a lasting effect on the yield of the alfalfa, stem counts and yield of the first cutting during second season of growth for alfalfa were collected from all treatments. An important influence in the yield of alfalfa is the number of shoots that are present to support the accumulation of plant growth. To understand the effect of a companion crop on the stand of alfalfa, two sample frames of alfalfa shoots were counted. Last, alfalfa yields (kg MD ha^{-1}) of the establishment year were compared to the yield of the first cutting of alfalfa in the second year to determine any significant interaction (p-value<0.05) between years by companion crop treatment and between years by treatment.

Results

Early Establishment

Of the nine alfalfa treatments, three were considered successfully established and the other six were found to be adequately established (Figure 3-4). The alfalfa from the alfalfa WC, alfalfa NWC, and alfalfa + oats treatments planted on 11 April 2017 were successfully established (>50%) 54%, 66%, and 66%, respectively; these frequencies correlate to plant densities greater than 20 plants per m^2 (Vogel and Masters, 2001). The remaining alfalfa treatments planted on 16 May 2017 had adequate establishment (25-50%); specifically alfalfa WC (49%), alfalfa NWC (36%), alfalfa + SSG at 1.37 kg PLS ha^{-1} (48%), alfalfa + SSG at 2.73 kg PLS ha^{-1} (45%), alfalfa + SSH at 5.46 kg PLS ha^{-1} (47%), and alfalfa + sorghum-sudangrass at 10.92 kg PLS ha^{-1} (47%), these frequencies correlate to plant densities between 10-20 plants per m^2 (Vogel and Masters, 2001).

The SSG had two unsuccessfully established treatments and two adequately established treatments. The lower seeding rate treatments of SSG (1.37 kg PLS ha^{-1} and 2.73 kg PLS ha^{-1}) were unsuccessfully established with frequencies of 12% and 22%, respectively; these frequencies correlate to plant densities below 10 plants/m^2. The higher seeding rate treatments of SSG (5.46 kg PLS ha^{-1} and 10.92 kg PLS ha^{-1}) had adequate establishment with frequencies of establishment at 27% and 35%, respectively; these frequencies correlate with plant densities between 10-10 plants/m^2. The oats companion crop established adequately with a 44% frequency of occurrence; this frequency correlates to a plant density between 10-20 plants/m^2 also.

Dry Matter Production

There was no significant effect of the four SSG seeding rates on the yield of SSG, alfalfa, or weeds. Total dry matter yield was greatest in the 11 April 2017 planted non-weeded control, the oat companion crop, and the SSG companion crop with yields of 20,150, 20,175, and 23,638 kg DM ha^{-1}, respectively (Figure 3-6). There was no significant difference in the yield of these three treatments, or in the total dry matter yield of forage for the April-weeded alfalfa control and the May-weeded alfalfa control (Table 3-1). We found that the SSG companion crop had a significantly lower production of weeds than all other treatments (Figure 3-7). In addition, the alfalfa + oat treatment produced significantly more weeds than the April-WC but also produced significantly fewer weeds than the April-NWC with weed yields of 12,900 kg DM ha^{-1}, 0 kg DM ha^{-1}, and 18,550 kg DM ha^{-1}, respectively (Table 3-1).

There was no significant difference in alfalfa production between the alfalfa + SSG treatment and the May-WC treatment. A significant difference in alfalfa production was found between the alfalfa + SSG treatments and the May-NWC treatment (Table 3-1). Alfalfa production was 1,675 kg DM ha^{-1}, 0 kg DM ha^{-1}, and 963 kg DM ha^{-1} for the May-WC, May-NWC, and the alfalfa + SSG treatments, respectively. The oat companion crop treatment had the lowest alfalfa production compared to the April-non-weeded and April-weeded alfalfa controls, with yields of 0 kg DM ha^{-1}, 1,375 kg DM ha^{-1}, and 3,450 kg DM $^{-1}$, respectively (Table 3-1).

Alfalfa production was also influenced by planting dates in 2017. There was a significant difference in the amount of alfalfa produced in both the weeded and non-weeded controls of the two planting dates (Table 3-1). For the weeded control, the 11 April planting date yielded 3,450 kg DM ha^{-1} of alfalfa, while the 16 May planting date yielded 1,675 kg DM ha^{-1} of alfalfa (Figure 3-8). In the non-weeded control, alfalfa yielded 1,600 kg DM ha^{-1} when planted on 11 April, compared to a yield of 0 kg DM ha^{-1} when planted on 16 May.

Year Two Production

The oat companion crop treatment was found to have a significantly lower yield of alfalfa than the April-WC. Yield of alfalfa collected from the oat treatment was slightly greater than in the April-NWC with a difference of only 727 kg DM ha^{-1}, but the difference was not statistically significant. Like the establishment year, planting date was found to have a significant effect on the yield of alfalfa in both the weeded and non-weeded treatments, with the 11-April planting date of each treatment having a greater alfalfa yield than the 16-May planting date for both treatments (Figure 3-9). With weeds controlled during the later planting date, the alfalfa yield is significantly greater than in the SSG treatments by 4,156 kg DM ha^{-1}. However, when weeds were not controlled during the later planting date there was no significant difference between the yields of alfalfa, although the alfalfa with a SSG companion crop yielded slightly greater than the non-weeded alfalfa (Table 3-2).

The number of shoots in the SSG companion crop was four times less than in the May-WC, and 3.5 times less than the oat companion crop treatment (Table 3-2). In addition, there was a positive quadratic relationship between stems present during the second year of growth for alfalfa and alfalfa production (Figure 3-10).

Year One / Year Two Production

When comparing the alfalfa yields of the establishment year and the second year of growth a year by treatment interaction was found to be significant. Thus, indicating that differences in alfalfa yield are attributed in part to both the year of growth and the weed management treatment (Figure 3-11).

Discussion

The application of sorghum-sudangrass as a warm-season annual companion crop reduced first year growth of alfalfa in this study, but alfalfa was able to emerge and have moderate production in the second year. While sorghum-sudangrass increased dry matter yields and decreased weed growth in the alfalfa during the establishment year, it also reduced alfalfa production during the season as well. These findings do not support our hypothesis that sorghum-sudangrass is an effective option as a warm-season annual companion crop for successfully establishing alfalfa.

With variable sorghum-sudangrass seeding rates, we hoped to identify an optimum rate that would be effective at weed suppression and producing an alfalfa stand. The seeding rate of crops influences the production of both the main crop, alfalfa, and the companion crop, sorghum-sudangrass. Defining an optimum seeding rate where production of alfalfa and sorghum-sudangrass are maximized, and weed production is minimized would provide the greatest economic gain from the companion crop. Instead, there was no treatment effect for the seeding rates and the production of sorghum-sudangrass, alfalfa, and weeds. This observation illustrates that the lowest seeding rate for sorghum-sudangrass at 1.37 kg PLS ha^{-1} would be the optimum rate regarding total dry matter and alfalfa production and the suppression of weeds (Figure 3-5). This opposes previous results where a steady decrease in both weed and alfalfa production was found as the seeding rate of a barley companion crop increased (Erkovan & Tan, 2009). This finding also challenges previous studies where companion crops of barley, crown vetch, and oats were seeded at various rates with alfalfa, and the barley, crown vetch, and oat rates each linearly related to more companion crop production (Sowinski, 2014; Smith *et al*., 1954).

Overall, our findings indicate that sorghum-sudangrass helps increase the total dry matter yields of a stand. However, the total dry matter yield only gives us a broad view of the results. To fully understand the composition of dry matter yields of weeds, alfalfa, and sorghum-sudangrass need to be considered for each treatment.

While this study found no relationship between sorghum-sudangrass seeding rates and weed production, sorghum-sudangrass did effectively suppress weed growth. Schoofs and Entz (2000) also found weed suppression by sorghum-sudangrass to be effective and one of the top contenders of various annual forages for its ability to suppress weeds as a companion crop. Overall, alfalfa production within the sorghum-sudangrass companion crop was comparable to that of the late planted weeded treatment. Thus, using sorghum-sudangrass as a companion crop did not drastically reduce the establishment and growth of alfalfa when similar planting dates were used but did compared to the recommended April planting date (Figure 3-8).

A later planting date contributed to a significantly lower production of alfalfa when compared to the more traditional planting date during mid-April when weeds were controlled. The differing alfalfa yields between planting dates indicate that planting later will negatively affect alfalfa production, regardless of weed control practice and this aligns with previous findings of a later seeding date reducing dry matter yield of alfalfa (Coruh and Tan, 2016). Production of weeds between the two planting dates was also found to be significantly different in the non-weeded controls. However, the 16 May planting date produced fewer weeds by a difference of 4,050 kg DM ha^{-1} compared to the

11 April planting date. This signifies that the timing of planting impacted the yield of weeds, but more greatly impacted production of alfalfa. So even though fewer weeds were produced in the late-planted non-weeded control, no alfalfa was able to successfully grow. Therefore, the benefit of lower weed production is irrelevant when alfalfa production is zero.

Largely, our findings highlight that sorghum-sudangrass outperformed the oat companion crop in weed suppression by 7,800 kg DM ha^{-1} and demonstrates that sorghum-sudangrass is an effective option for the suppression of weed growth within an alfalfa stand. The oat companion crop did not show to be a useful choice in weed suppression, as yield of the weeds in the oat treatment were similar to that of the April-NWC (Figure 3-7). Our findings do not align with the results of Lanini *et al.* (1991), who studied alfalfa establishment and weed suppression using an oat companion crop, and found the use of an oat companion crop was an effective method for weed suppression with alfalfa.

Regarding both alfalfa and weed production, sorghum-sudangrass produced a more successful alfalfa stand than that of oat and the May-NWC (Figure 3-8). The similar alfalfa yields in the alfalfa + sorghum-sudangrass and the May-WC treatments show that alfalfa production does not suffer significantly from sorghum-sudangrass as a companion crop compared to a weed-free environment and helps ensure a more successful stand than a non-weeded stand. The lack of production of alfalfa (0 kg DM ha^{-1}) when paired with an oat companion crop indicates that oat was not a suitable companion for the successful establishment of alfalfa and that sorghum-sudangrass may serve as a better option. However, the decreased production of alfalfa in the oat companion crop during the establishment year may have had more to do with the high production of weeds within the treatment and pests.

During the first month of growth, when early establishment data were gathered, oat and alfalfa appeared to be co-establishing well together. However, once the oat was harvested (20 June 2017) potato leaf hopper moved into the stands and caused great harm and reduction in alfalfa plant growth following establishment. The removal of oat also opened the crop canopy enough for many weeds to gain a strong foot-hold in the area and greatly outcompete the alfalfa through the final harvest in late September. So it appears by the end of the establishment year that sorghum-sudangrass was a better companion crop choice with its great weed suppression and alfalfa yield. However, in the second season of growth, the alfalfa from the OCC treatment yield the third highest at 5,333 kg DM ha^{-1}, behind the early- and late-weeded alfalfa treatments (Figure 3-9). The successful growth of alfalfa can be contributed to the fact that it was able to successfully establish early on in the first year (Figure 3-4), and while the pest and weed pressure resulted in a yield of zero for the first season, the crowns of the alfalfa plants were left unharmed allowing them to grow the next season and produce good yields of alfalfa.

While the effect of decreased alfalfa yield from the sorghum-sudangrass companion crop and late planting date was not overcome in the second year, the alfalfa yield in the sorghum-sudangrass treatments was still ahead of that of a May-NWC treatment in the second year of growth. With the continued effects of decreased alfalfa yield compared to that of the other treatments including the April-WC, April-NWC, May-WC, and an oat companion crop, a producer may be wary of implementing this practice into their forage production system. Before a producer disregards the use of sorghum-sudangrass as a companion crop, they should consider the option of overseeding a perennial cool or warm-season grass with their alfalfa from the second year on. Canevari *et al*. (2000) have previously shown the benefits of overseeding a perennial grass into an alfalfa stand and suggest the use on perennial grasses and other forages to help improve thinning or aging alfalfa stands and it could also prove to be a good fit within the findings of decreased alfalfa yields following a sorghum-sudangrass companion crop in our study. The overseeding a perennial cool or warm-season grass will help compensate for the decreased alfalfa yield following a sorghum-sudangrass companion crop to meet total dry matter yield goals for the following seasons.

Conclusion

The application of sorghum-sudangrass as a companion crop with alfalfa is a plausible option for planting in eastern Nebraska as sorghum-sudangrass allowed for a successful establishment and moderate multi-year growth of alfalfa. Given the increased production from sorghum-sudangrass, producers can reach high production goals during the summer slump with a simple perennial-annual combination during the establishment year and leave them with a moderately-productive alfalfa stand in the subsequent years. Although, the lower production of alfalfa in the establishment year and following year of growth when established with sorghum-sudangrass at a later planting date demonstrates the need to further identify the relationship of its use as a companion crop with alfalfa. This provides opportunities where future research might look at affect from aspects such as changes in row-spacing, harvest height, or mixing grass-legume crops in years following establishment. In conclusion, this study highlights the need to further explore the pairing of an establishing alfalfa crop with a potential warm-season annual grass as a companion crop to successfully meet forage production goals.

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Figures & Tables

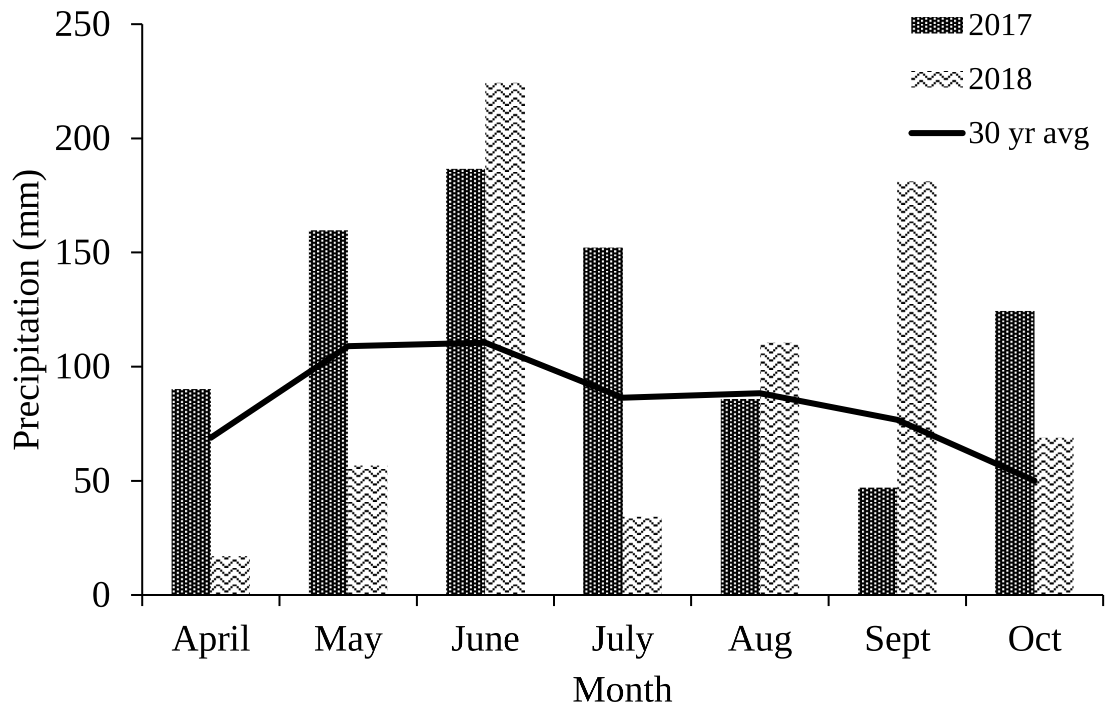

Figure 3-1: Monthly precipitation (mm) from April through October for 2017, 2018, and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska.

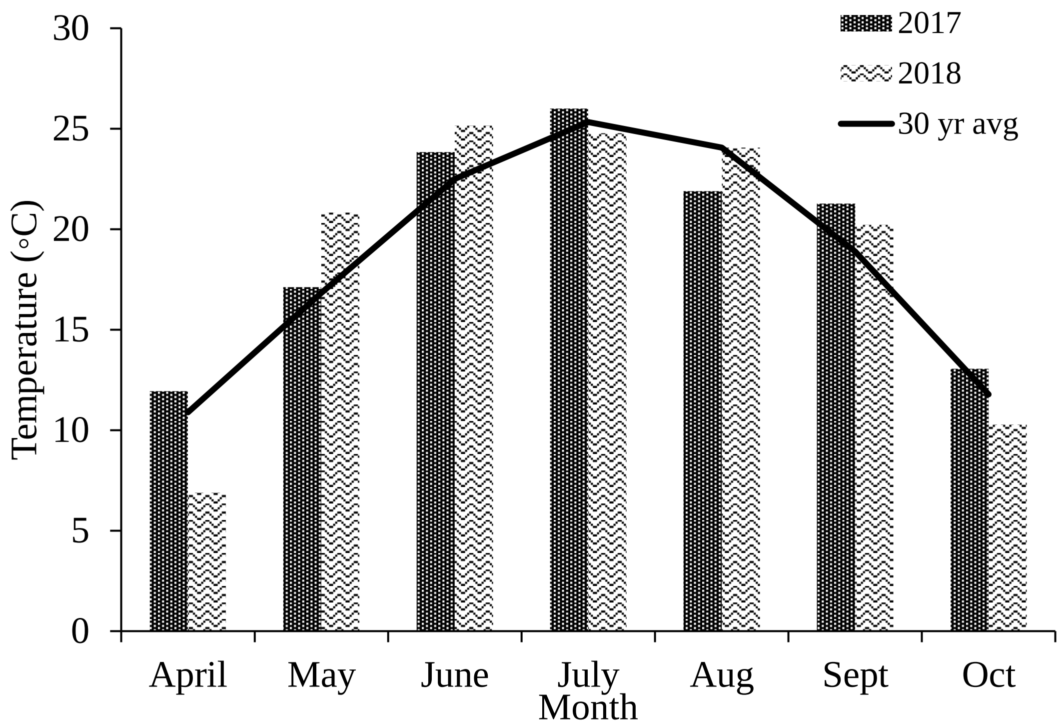

Figure 3-2: Monthly average temperature (degrees Celsius) from April through October for 2017, 2018, and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska.

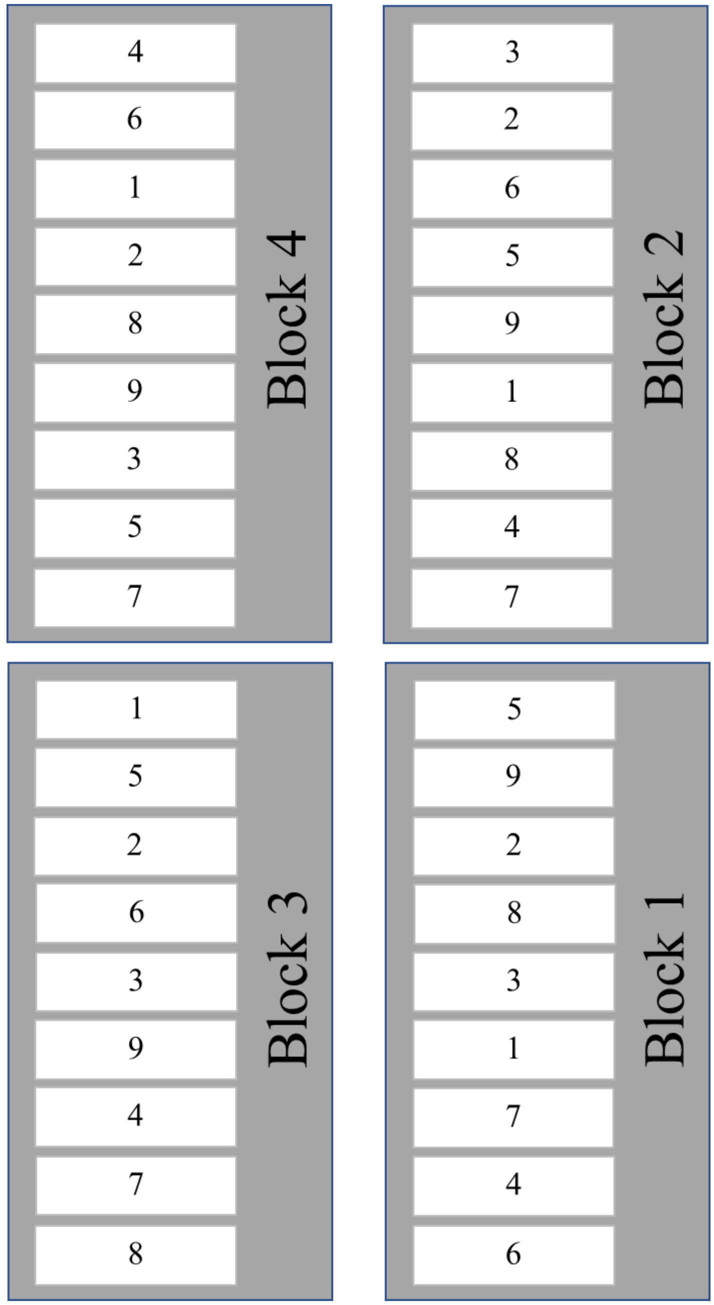

Figure 3-3: Plot diagram of a randomized complete block design with four blocks of replication for the nine studied treatments. Treatments include an April-planted weeded control (1), April-planted non-weeded control (2), oat companion crop (3), May-planted weeded control (4), May-planted non-weeded control (5), alfalfa + sorghum-sudangrass companion crop at 1.37 kg PLS ha^{-1} (6), alfalfa + sorghum-sudangrass companion crop at 2.73 kg PLS ha^{-1} (7), alfalfa + sorghum-sudangrass companion crop at 5.46 kg PLS ha^{-1} (8), and alfalfa + sorghum-sudangrass companion crop at 10.92 kg PLS ha^{-1} (9). Alfalfa was seeded at 10.8 kg PLS ha^{-1} in all treatments and oat was seeded at 22.4 kg PLS ha^{-1} in the early-seeded companion crop treatment.

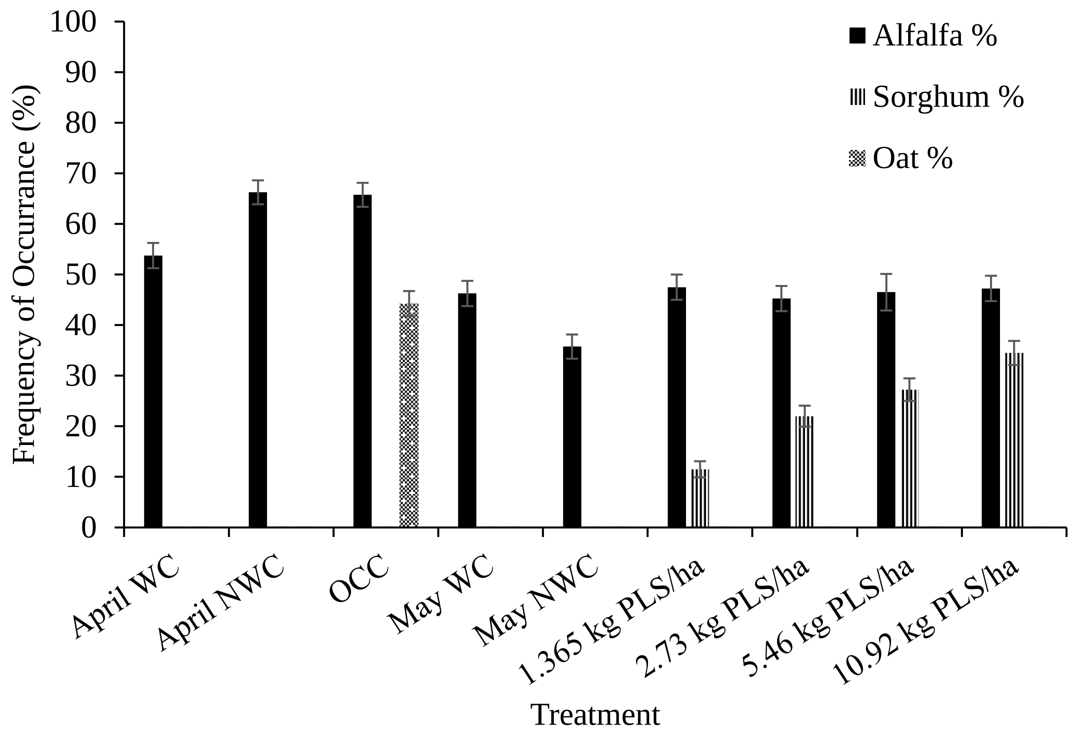

Figure 3-4: Frequency of occurrence (19 June 2017) for alfalfa, oat, and sorghum-sudangrass in treatments of early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), sorghum-sudangrass companion crop at 1.37 kg PLS ha^{-1} (1.37kg PLS/ha), sorghum-sudangrass companion crop at 2.73 kg PLS ha^{-1} (2.73 kg PLS/ha), sorghum-sudangrass companion crop at 5.46 kg PLS ha^{-1} (5.46 kg PLS/ha), and sorghum-sudangrass companion crop at 10.92 kg PLS ha^{-1} (10.92 kg PLS/ha).

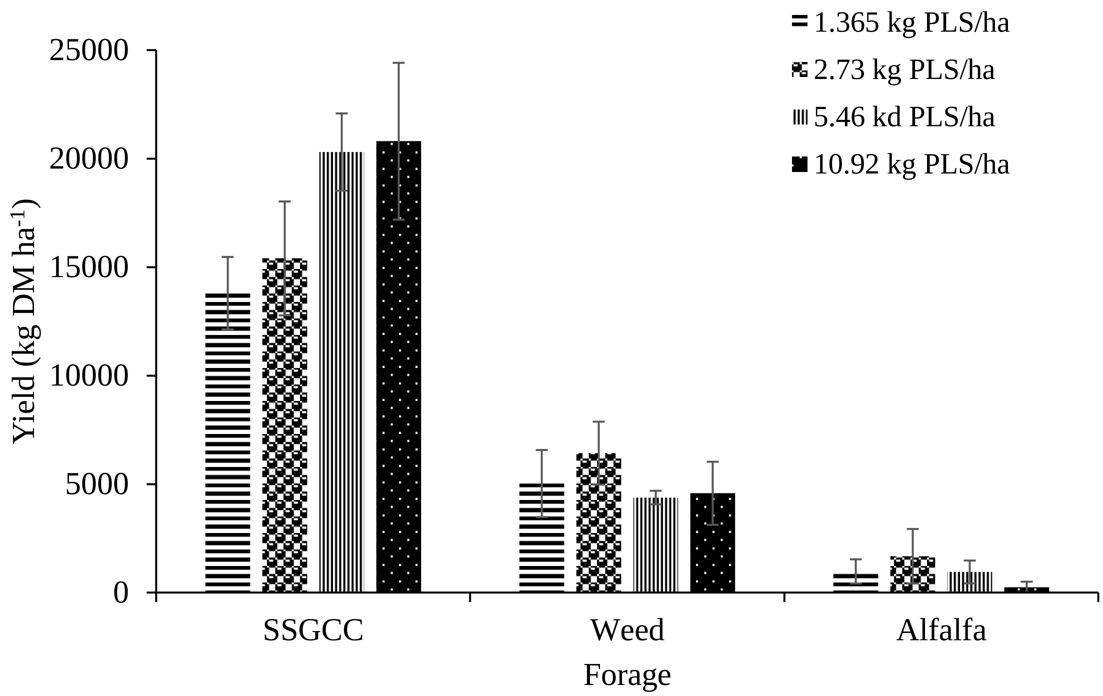

Figure 3-5: Mean yield (kg DM ha^{-1}) of sorghum-sudangrass (SSGCC), weeds (Weed), and alfalfa for treatments where sorghum-sudangrass was seeded at a rate of 1.37, 2.73, 5.46, or 10.92 kg PLS ha^{-1}.

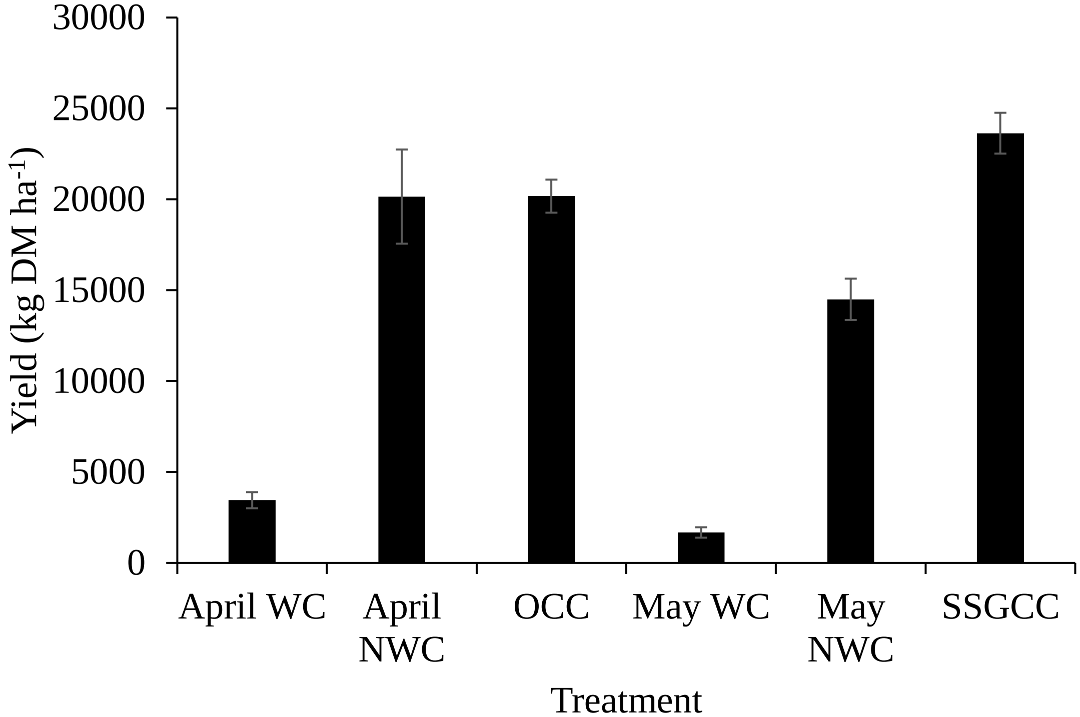

Figure 3-6: Mean total dry matter yield (kg DM ha^{-1}) for the early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments during 2017. Total dry matter yield equated to the sum of alfalfa, weed, and companion crop production.

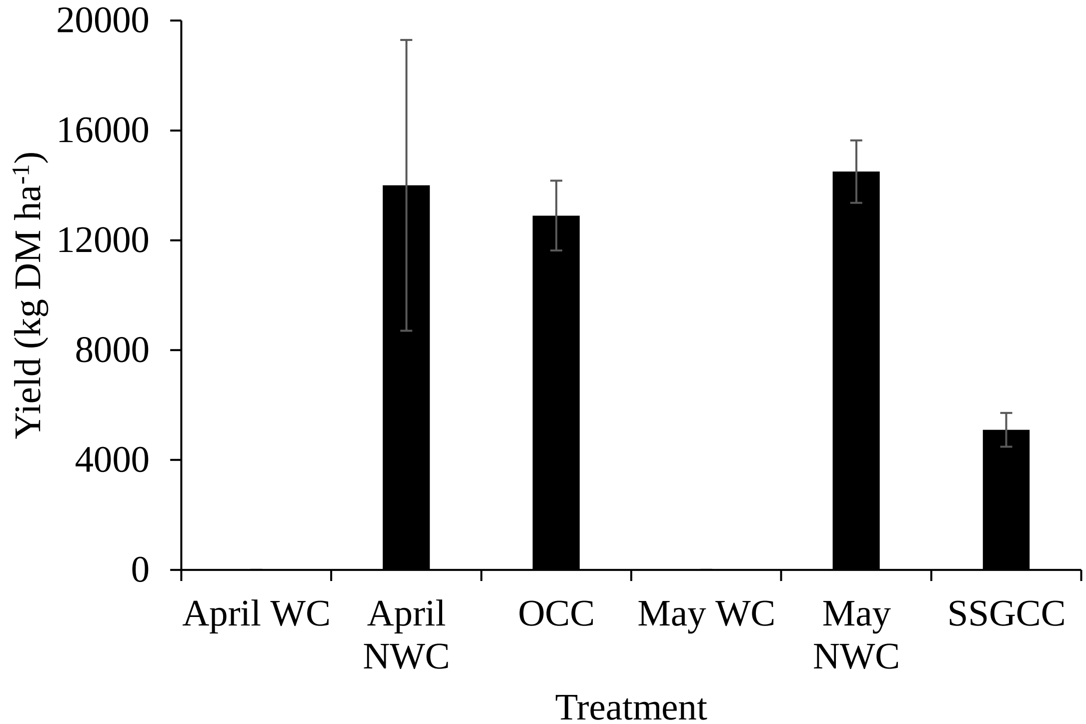

Figure 3-7: Mean weed biomass production (kg DM ha^{-1}) for the early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments during 2017.

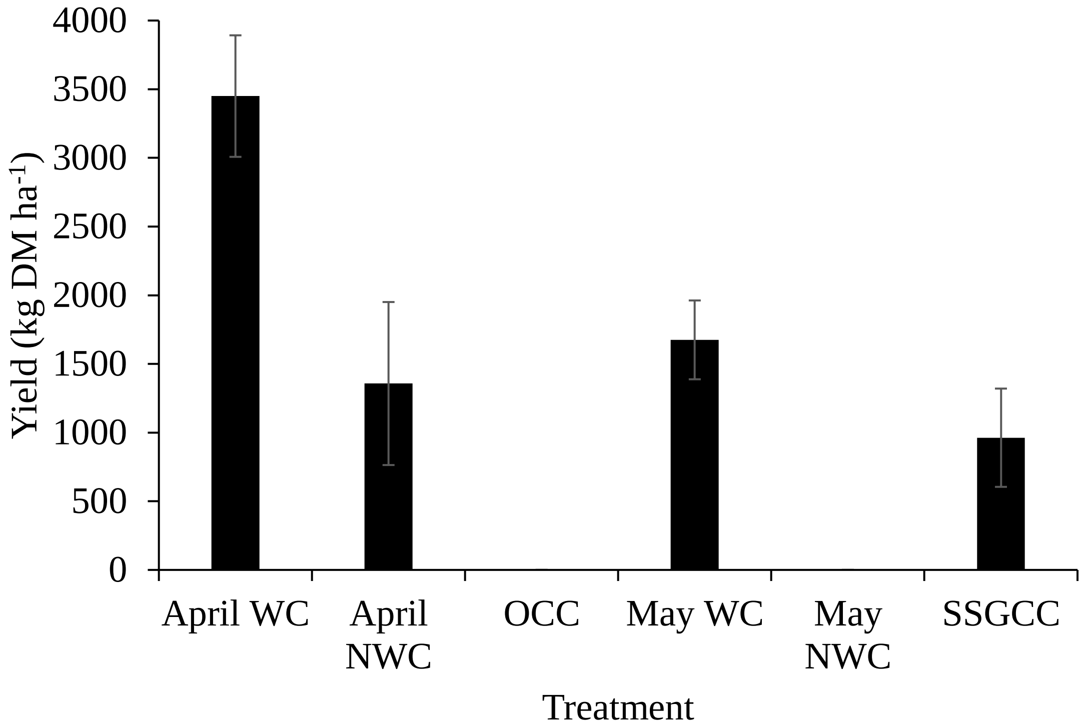

Figure 3-8: Mean alfalfa biomass production (kg DM ha^{-1}) for the early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments during 2017.

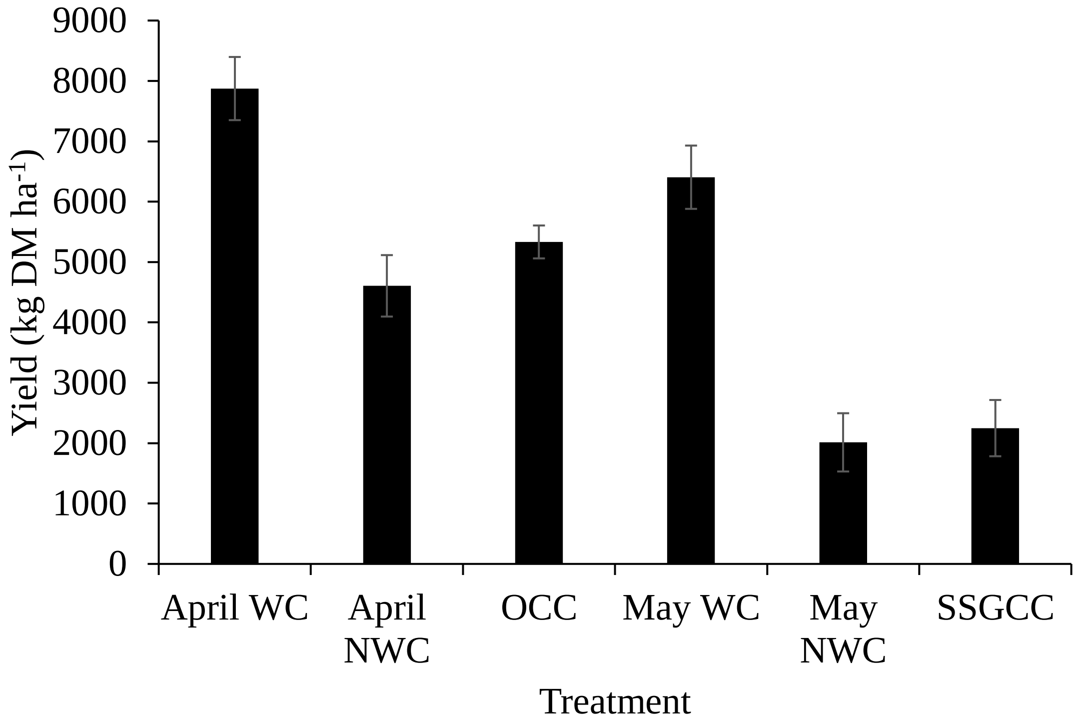

Figure 3-9: The mean alfalfa production (kg DM ha^{-1}) for the first cutting (17 May 2018) during the second year of growth for the early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments.

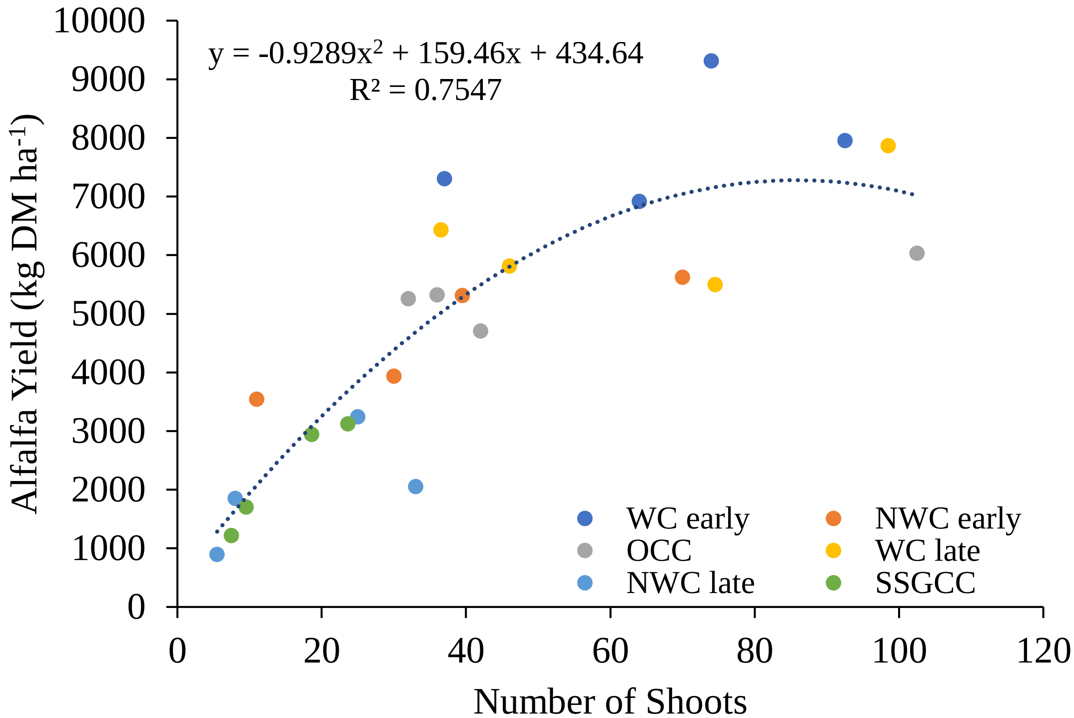

Figure 3-10: Scatter plot with a best fit regression line indication the correlation between the first cutting (17 May 2018) alfalfa yield and number of shoots present (R^2=0.7547) for the early-planted weeded control (WC early), early-planted non-weeded control (NWC early), oat companion crop (OCC), late-planted weeded control (WC late), late-planted non-weeded control (NWC late), and sorghum-sudangrass companion crop (SSGCC) treatments.

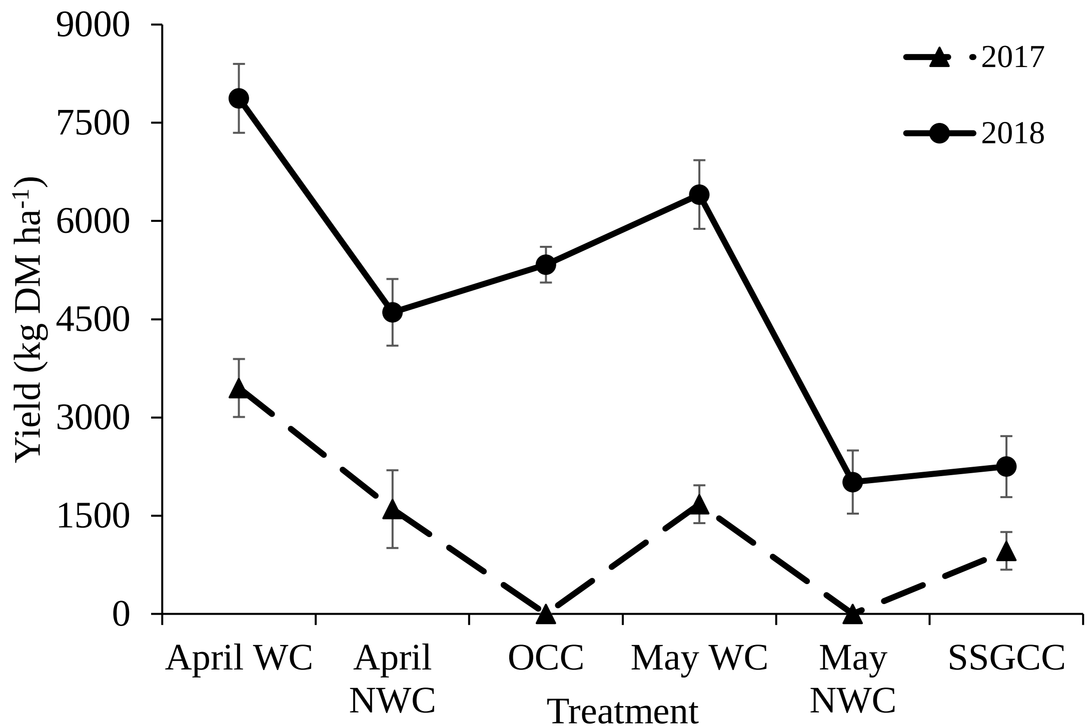

Figure 3-11: Mean alfalfa production (kg DM ha^{-1}) from treatments of early-planted weeded control (April WC), early-planted non-weeded control (April NWC), oat companion crop (OCC), late-planted weeded control (May WC), late-planted non-weeded control (May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments for two years (2017 and 2018).

Table 3-1: Mean yield (kg DM ha^{-1}) for total dry matter yield (Total Yield), sorghum-sudangrass (SSG Yield), weed (Weed Yield), alfalfa (Alfalfa Yield), and oat (Oat Yield) by companion crop treatment of an early-planted weeded control (11 April WC), early-planted non-weeded control (11 April NWC), an oat companion crop (OCC), a late-planted weeded control (16 May WC), a late-planted non-weeded control (16 May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments during 2017.

Treatment	Total Yield	SSG Yield	Weed Yield	Alfalfa Yield	Oat Yield	Total SE	SSG SE	Weed SE	Alfalfa SE	Oat SE
	kg DM ha^{-1}									
11 April WC	3450a†	0a	0a	3450a	0a	442.53	0	0	442.53	0
11 April NWC	20150b	0a	18550b	1600b	0a	2590.21		2619.64	443.47	0
OCC	18177b	0a	12900c	0c	5277b	909.56	0	1270.83	0	1787.06
16 May WC	1675a	0a	0a	1675b	0a	286.87	0	0	286.87	0
16 May NWC	14500c	0a	14500c	0c	0a	1136.52	0	1136.52	0	0
SSGCC	23638b	17575b	5100d	963b	0a	1123.17	1316.68	528.85	287.68	0

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Table 3-2: Mean yield (kg DM ha^{-1}) and count of shoots for the first cutting of alfalfa (17 May 2018) during its second year of growth for the early-planted weeded control (11 April WC), early-planted non-weeded control (11 April NWC), oat companion crop (OCC), late-planted weeded control (16 May WC), late-planted non-weeded control (16 May NWC), and sorghum-sudangrass companion crop (SSGCC) treatments.

Treatment	Alfalfa Yield	Alfalfa SE	Shoot #	Shoot SE
	– kg DM ha^{-1} –			
11 April WC	7873a†	523.08	67a	11.58
11 April NWC	4606b	508.93	38ab	12.31
OCC	5333b	272.59	53abc	16.59
16 May WC	6405a	524.31	64abc	14.09
16 May NWC	2014c	482.34	18bd	6.65
SSGCC	2249c	465.89	15bd	3.81

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

CHAPTER 4: ESTABLISHMENT AND EARLY FORAGE PRODUCTION OF ALFALFA WITH SORGHUM-SUDANGRASS AS A COMPANION CROP

Introduction

The production of forage is a vital component of the agricultural industry in raising livestock. One of the most prominent sources of forage across the Midwest and particularly in the state of Nebraska is the perennial legume, alfalfa (*Medicago sativa* L.). In the state of Nebraska, alfalfa production accounts for 30% (315,654 ha) of the total forage production hectares within the state (United States Department of Agriculture, 2015). Alfalfa has many desirable characteristics as a forage option, including high protein content, high yield potential, and good nutritional value (Li *et al*., 2007). When these characteristics are considered alongside the longevity of alfalfa that allows it to produce high yields for 4-6 seasons, it is no wonder alfalfa is a highly sought-after forage option among producers (Frame, 2005).

However, the establishment period of alfalfa growth can be a challenging time of the plant's lifecycle for a forage producer. As a perennial legume, alfalfa has a very small seed size making it highly prone to drought before emergence (Ćupina et al., 2011) and a slow germination period leaving the plant at a competitive disadvantage to neighboring weeds with quicker germination periods. The competition from neighboring weed seeds is more prominent in a spring sown alfalfa crop, often leading to lower yields during the establishment year when compared to a late-summer sown alfalfa crop (Ćupina *et al*., 2000, 2004).

Producers have a few options to overcome and combat the challenges presented with a spring planting of alfalfa. Popular choices in battling weeds and ensuring successful establishment and good yields of alfalfa include the use of herbicides, tillage practices or an annual companion crop. Due to recent societal shifts and increased ecological knowledge, many consumers and producers are searching for more sustainable practices to decrease the use of herbicides and tillage. Companion crops offer a more sustainable option in achieving a successful stand establishment while still providing weed control. When choosing a companion crop, the species used is often selected based on a variety of benefits they may provide including soil erosion prevention, weed suppression, pest management, and increased plant utilization (Simmons *et al*., 1995; Anil *et al*., 1998). Additionally, companion crops will provide a beneficial boost in total forage yield during the establishment year of a perennial legume by providing additional plant material (Pappa *et al*., 2012; Dane and Laugale, 2014).

When establishing an alfalfa stand, oat (*Avena sativa* L.) and other annual small grain cereal crops are traditionally the primary selection as they have been found to be highly competitive against weed growth but favorable for the growth of a perennial legume (Meiss *et al*., 2010; Sheaffer *et al*., 2014). As cool-season crops, small grain cereals provide a boost in forage production during the early summer months, but a lull in the production cycle occurs during the peak summer months of July and August, often referred to as the summer slump. An alternative to overcome this summer slump would be the substitution of the traditional cool-season crop with a warm-season crop. As a warm-season annual, sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. sudanses*) could become an alternative companion crop option to oat during the establishment period that would help boost the summer slump in forage production (Frame *et al*., 2005). However, the use of sorghum-sudangrass as a companion crop is relatively unexplored.

To examine the compatibility of sorghum-sudangrass as a companion crop during establishment of an alfalfa stand, we analyzed the total production of a weeded control (WC), non-weeded control (NWC) and sorghum-sudangrass companion crop

(SGG) treatments along with the production of sorghum-sudangrass, alfalfa, and weeds during the establishment year and the first spring of the year after seeding. These treatments were pulled and analyzed from Chapter 2 and Chapter 3 of the study by La Vallie *et al.* (unpublished). This study will help to address the use of sorghum-sudangrass as a companion crop option to not only assist in the establishment of a perennial legume and suppression of weeds, but also as companion crop option to help fill the summer slump in forage production.

Materials and Methods

Research Location

This study was carried out in conjunction with studies by La Vallie *et al.* (unpublished) at the University of Nebraska-Lincoln's Horticulture Research Garden in Lincoln, NE (40°49'40" N 96°39'26" W, 358 m ASL) during the years of 2016-2018. Details regarding the research location, including the 30-year average in both annual precipitation (Figure 4-1) and summer temperatures (Figure 4-2), and specification for the experimental plots that were established in 2016 and 2017 can be found in La Vallie *et al.* (unpublished).

Experimental Design

We conducted our experiment as a randomized complete block design with three blocks and a split-plot arrangement as specified in La Vallie et al. (unpblished Chp. 2). Our study differs in that only the plots consisting of alfalfa cv. Ranger legume will be. Our subplot factor was companion crop treatment consisting of four treatments, specifically an alfalfa plot that was hand-weeded (WC), an alfalfa plot that was non-weeded (NWC), and two plots where alfalfa was seeded with (SSG) as a companion crop. Of the two treatments receiving SSG, one had the sorghum-sudangrass harvested three times (SSG3), and the other treatment had the sorghum-sudangrass harvested four times throughout the growing season (SSG4). For the case of this study the two SSG treatments were averaged together for a sorghum-sudangrass companion crop treatment (SSGCC). Treatments were seeded on 19 May 2016 with sorghum-sudangrass cv. Super Sugar at a pure live seed (PLS) rate of 10.92 kg PLS ha^{-1}, and alfalfa at 10.8 kg PLS ha^{-1} with 36% labeled hard seed. Alfalfa legume seed was purchased from Stock Seed Farms (Murdock, NE) and inoculated with appropriate rhizobium before planting.

In 2017, we conducted our experiment as a randomized complete block design with four blocks, each receiving nine treatments as specified in La Vallie *et al.* (unpublished). Our study differs in that only the plots consisting of the May-WC, May-NWC, and the average of the four SSG treatments (SSG seeded at rates of 1.37, 2.73, 5.46, and 10.92 kg PLS ha^{-1} with alfalfa to comprise the four SSG treatments) to create a sorghum-sudangrass companion crop treatment (SSGCC) and will be analyzed. Treatments were seeded on 16 May 2017 with sorghum-sudangrass cv. Super sugar, and alfalfa at 10.8 kg PLS ha^{-1} with 36% labeled hard seed. Alfalfa legume seed was purchased from Stock Seed Farms (Murdock, NE) and inoculated with appropriate rhizobium before planting.

Planting

Plot establishment follows procedures detailed in La Vallie et al. (unpublished). Specifically, these authors outline methods for the 2015 preparation, the spring 2016 planting, and the spring 2017 planting of forage establishment plots from which data were gathered for this study.

Stand Establishment

Early establishment data were gathered from all treatments on 10 June 2016 and on 20 June 2017. We followed established protocol using a frequency-frame method for data collection (Vogel and Masters, 2001; La Vallie et al. unpublished). Briefly, this method consists of counting stems from a total of 100 cells (25 cells/frame; 4 frames/plot) and converting these counts into a frequency of occurrence (divide by 100). From these data, a conservative estimate of plant density for each species can be computed by multiplying frequency of occurrence by a factor of 4 (Vogel and Masters, 2001).

Harvesting and Clipping

On 27 June 2016, 4 August 2016, and 20 September 2016, we followed protocol for SSG harvest (La Vallie *et al.* unpublished Chp. 2). Protocol was followed for the harvest of SSG, alfalfa, and weeds on 25 October 2016 as well. Harvesting of the SSG in the second year followed protocol of La Vallie *et al.* (unpublished Chp. 3). A harvest of SSG occurred on 20 July 2017, and a harvest of SSG, alfalfa, and weeds occurred on 7 September 2017. Briefly, the methods consisted of collecting a total plot weight, a subsample to calculate dry weight via the drying process; and for the 25 October 2016 and 7 September 2017 harvests clippings of each plot were taken, sorted, and labeled into bags for SSG, alfalfa, and weeds were collected to provide kg DM ha^{-1} per treatment.

Year Two Harvest

The season following the year of establishment 2016 and 2017, the first cutting of alfalfa was collected on 24 May 2017 and 17 May 2018, respectively, following established protocol by La Vallie *et al.* (unpublished Chp. 2 and Chp. 3). Briefly, a total plot weight and a subsample to calculate dry weight via the drying process were collected to provide kg DM ha^{-1} of alfalfa per treatment.

Analysis

The gathered establishment, harvest, clipping, and return-year forage data were analyzed for significance between treatments in common between the 2016 and 2017 experiments using the SAS 9.4 statistical software (SAS Institute, Cary, NC). An ANOVA was used to determine significance (p-value <0.05) of main effects and interactions and proc mixed tests that included contrasts statements and least square means were used to determine if there were significant differences (p-value <0.05) between treatments. The fixed effects for these analyses were year and companion crop treatment. Random variables of the study consisted of the yields for total dry matter yield, and yields of sorghum-sudangrass, alfalfa, and weeds and block.

To evaluate initial establishment frequency of occurrence data for alfalfa and sorghum-sudangrass were collected on 10 June 2016, and 19 June 2017. To determine if the addition of sorghum-sudangrass as a companion crop allows for the successful establishment of alfalfa, the yield of alfalfa at the end of the first season of growth was collected from all treatments. To determine if the inclusion of sorghum-sudangrass decreased weed production during the establishment year of alfalfa, weed production yields were measured from the weeded, non-weeded, and sorghum-sudangrass companion crop treatments. To determine if sorghum-sudangrass when used as a companion crop increased forage yield during the first year of growth, the total dry matter yield from the weeded, non-weeded, and sorghum-sudangrass companion crop treatments were analyzed. To establish if the addition of sorghum-sudangrass as a companion crop had any carry-over effect on the growth of alfalfa into the second year, the first cutting of alfalfa was gathered from all treatments in the spring following the establishment year. To determine the effect of sorghum-sudangrass as a companion crop on the success of alfalfa establishment across years the yield of alfalfa at the end of first season of growth and the yield of alfalfa from the first cutting of the second season of growth were gathered.

Results

Early Establishment

Alfalfa and SSG established in 2016 were successfully established in all treatments (Figure 4-3). Alfalfa had establishment frequencies of 83, 83, and 78% for the NWC, SSGCC, and WC treatments, respectively, and sorghum-sudangrass had a frequency of 58%; these frequencies correlate with plant densities of greater than 20 plants/m^2 (Vogel and Masters, 2001). In 2017 alfalfa and SSG were only found to have adequate establishment (Figure 4-3). Sorghum-sudangrass was found to have a frequency of 24%, while alfalfa had a frequency of 38, 47, and 46% in NWC, WC, and SSGC treatments, respectively; these frequencies correlate with plant densities of 10-20 plants per m^2 (Vogel and Masters, 2001).

Dry Matter Production

It was discovered that the yield of alfalfa during the first season of growth was significantly influenced by the treatment, but the year and year x treatment interaction did not have a significant effect on the yield of alfalfa (Table 4-1). The inclusion of sorghum-sudangrass with an establishing alfalfa stand produced an alfalfa yield similar to the alfalfa yield of a non-weeded stand. These yields were 25% of the alfalfa production from the weeded control (Figure 4-4).

We found that the production of weeds was influenced by the main effects of treatment and year, as well as by a year x treatment interaction (Table 4-1). Weed production was 2.5 times greater during 2017 than 2016. The production of weeds in the weeded treatment and the sorghum-sudangrass companion crop treatments were not different. The non-weeded treatment produced a significantly greater amount of weeds than the other two treatments (Figure 4-5).

The yield of sorghum-sudangrass was found to have significant year and treatment effects as well as a significant year x treatment interaction during the first season of growth (Table 4-1). Sorghum-sudangrass yielded 3,967 kg DM ha^{-1} more during 2016 than 2017 (Figure 4-6).

We found that total dry matter yield was greatest in the sorghum-sudangrass companion crop treatment, followed by the non-weeded and then weeded treatments for 2016 and 2017 (Figure 4-7). A year x treatment interaction affected the total production of forage (Table 4-1). The total dry matter yield was greatest in SSGCC, followed by NWC, and then the WC treatments for both establishment years. However, the total dry matter yield is greater in 2016 for the SSGCC and WC treatments, with the total dry matter yield of NWC greater during 2017.

Year Two Production

The yield of alfalfa production during the second season of growth was significantly influenced by the treatment and year effect, but not by the year x treatment interaction (Table 4-2). It was found that even into the second season of growth, treatments that received a sorghum-sudangrass companion crop produced yields of alfalfa significantly similar to the yields produced in NWC treatments and 50% of the yield produced from the WC treatments (Figure 4-8). Year was also found to have a significant effect on the yield of alfalfa during its second year of growth, with the 2016 established alfalfa yielding twice as much alfalfa as the 2017 established alfalfa (Figure 4-9).

Year One / Year Two Production

It was discovered that the yield of alfalfa was significantly influenced by the season, establishment year, and treatment effect, as well as by the establishment year x season of growth, establishment year x treatment, and season of growth x treatment interactions (Table 4-3). These interactions indicate that the differences in alfalfa yield were in part due to the year in which the alfalfa was established, the season of growth it was in, and the companion crop treatment applied (Figures 4-10, 4-11, 4-12).

Discussion

The application of sorghum-sudangrass as a warm-season annual companion crop reduced the production of alfalfa during the first season of growth to comparable yields of those found in non-weeded alfalfa stands. However, alfalfa was able to successfully emerge during the second season of growth and have moderate-good production. While sorghum-sudangrass did decrease the yield of weeds during the first season of growth, it also inhibited the yield of alfalfa during that season. These findings do not support the hypothesis that sorghum-sudangrass is an effective option as a warm-season annual companion crop for successfully establishing alfalfa.

The addition of sorghum-sudangrass increased the overall forage production between the three treatments (Figure 4-7). Total dry matter yield of SSGCC treatments ranged from 1.8-25 times that of the NWC and WC during the first season of growth for both establishment years (2016 and 2017). The increase of total dry matter yield in the treatments must be considered carefully, as this total is composed of the growth of sorghum-sudangrass, alfalfa, and weeds. Therefore, it is important to analyze the yields of sorghum-sudangrass, alfalfa, and weeds to fully understand the total dry matter yield seen in treatments during the first season of growth.

The high production of sorghum-sudangrass during both establishment years is the greatest influence on the increase in total dry matter yield seen during the first season of growth for both years of the study, although this yield of sorghum-sudangrass did decrease in the 2017 establishment year. While it was not found to be significant, the yield of alfalfa simultaneously decreased in the first season of growth from 2016 to the 2017 establishment year. Notably, the yield of weeds increased from the first season of growth for 2016 to the first season of growth for 2017. These differences in yield for each component of the total dry matter yield, explain the decrease in total dry matter yield seen in the SSGCC and WC treatments for the first season of growth in 2017 establishment year and 2016 establishment year, and the increase seen in total dry matter yield for NWC.

The increase of weed production seen from 2016 to 2017 could be partially explained by weather conditions. The 2017 establishment year had monthly precipitation totals much higher than the 30-year average in the months of May through July, and the continuously wet conditions may have created an unfavorable environment for the establishment of alfalfa and sorghum-sudangrass that both favor well drained soils (Stubbendieck & Conrad, 1989), especially sorghum-sudangrass as it prefers hot and dry areas and is highly tolerable of low moisture levels (Cothren *et al.,* 2000; Fribourg, 1995). With decreased establishment of alfalfa and sorghum-sudangrass (Figure 4-3) during 2017 due to high moisture levels, weeds were allowed an opportunity to establish within the area. The decreased crop competition and ample resources during 2017 explain the increase in weed yields found during this establishment year (Figure 4-6). The prior condition of the study sites also contributed to the increased weed presence in the 2017 site. Prior to the study, the 2016 site was managed as a grass sod with minimal weed presence. Whereas the 2017 study followed behind a poorly managed soybean crop with a very heavy weed presence that contributed many weed seeds to the soil bed, that then established during 2017.

Our findings reveal that sorghum-sudangrass significantly reduced weed competition when compared to the NWC treatment during the establishment year (Figure 4-6). The success found in weed suppression by sorghum-sudangrass aligns with previous studies that have identified other grass-legume pairings to have greater weed suppression than that of a legume monoculture (Akemo *et al*., 2010; Brainard *et al*., 2011; Creamer and Baldwin, 2000; Mohler and Liebman, 1987). This capability is aided by the faster growth rates and ability of grasses to tiller, which allows the plant to be more suppressive of weeds than legumes (Pederson & Rooney, 2004; Bybee-Finley *et al*., 2016). However, while weed suppression is one of the goals when using sorghum-sudangrass as a companion crop, producers prefer that the growth of the alfalfa not be sacrificed for weed control. We found that use of sorghum-sudangrass as a companion crop caused the yield of alfalfa to suffer significantly in the establishment year (Figure 4-4).

Going into the second season of growth, it was found that the yield of alfalfa was also lower in the 2017 established stand than the 2016 established stand (Figure 4-9). This is again believed to be due to the differences in weather conditions and weed production noted during the establishment years of the alfalfa stands. The companion crop treatment applied to alfalfa also showed to have a carry-over effect into the second season of growth (Figure 4-8).

Yields of the alfalfa were able to recover moderately in the second season of growth, but the negative effects of sorghum-sudangrass were still significant and indicate that sorghum-sudangrass may not be an ideal companion crop option. This suggests that while alfalfa will recover from a competitive establishment year, it is not able to make a full recovery and match the production of a weed-free environment. A producer may have other options to compensate for the yield decrease suffered by the established alfalfa from the sorghum-sudangrass companion crop. Since alfalfa was able to produce an adequate stand during the spring of the second-year growth, a producer could look at broadcasting a perennial grass over the alfalfa stand to create a mixed grass-alfalfa stand. Overseeding of perennial grasses and other forages has previously been suggested to improve thin, aging alfalfa stands and could be fitting given the results of this study as well (Canevari et al., 2000).

Overall, the yield of alfalfa was found to be dependent on the year of establishment, season of growth, and companion crop treatment, and their interactions. Yields of alfalfa seen from season one of growth to season two of growth demonstrate that if alfalfa can at least adequately establish during the first year, regardless of the treatment applied or the year of establishment, that the yields will significantly increase into the second year of growth. Previous studies have found similar results where a perennial legume, red clover (*Trifolium pratense* L.), was found to have a yield increase in the spring following the year of establishment with a companion crop (Tan *et al*., 2004; Ćupina *et al*., 2010). And similar to the findings of total dry matter yield during the first year of growth, the yield of alfalfa was found to be influenced by the year of its establishment and the treatment applied when averaged across both seasons of growth. Thus, proper establishment conditions have a significant role on the success of alfalfa in regard to weather and plant competition.

There were some factors that may have contributed to the suppressed growth of the alfalfa seen in the first and the second seasons of growth when paired with sorghum-sudangrass. A major factor is the possibility of competition between the sorghum-sudangrass and the alfalfa for resources. The Classical Competition Theory identified by Smith *et al*. (2015) highlights that when pairing species for intercropping there must be favorable timing between the needs for each resource between the crops. If the intercropped species are demanding of the same resources simultaneously, one is likely to out-compete the other. While this study did not address the issue of resource competition, sunlight may be a limiting resource negatively affecting alfalfa growth. Ghosh *et al*. (2006) intercropped sorghum with soybeans and found the shading effect of the tall sorghum crop adversely affected soybean biomass, nitrogen uptake, chlorophyll, and photosynthesis.

Another unanticipated factor that also may have led to suppressed alfalfa yield was lodging and residue of sorghum-sudangrass left behind after each harvest. Lodging has previously been cited as the cause of suppressed growth for undersown species when planted with full-leafed pea (*Pisum sativum* L.) cultivar companion crops (Faulkner, 1985; Gilliland and Johnston, 1992). Furthermore, when sorghum-sudangrass residue is left behind, the allelopathic compounds found in the plant begin to release during decomposition, negatively affecting the establishing alfalfa crop (Marchi *et al*., 2008; Weston 1989). These aspects were not a focus within this study and require further investigation to better understand the competitive nature and interactions present between the pairing of sorghum-sudangrass and alfalfa.

Conclusion

The application of sorghum-sudangrass as a companion crop with alfalfa was found to be moderately successful, as the sorghum-sudangrass effectively suppressed weeds and allowed for a successful establishment and continued growth of alfalfa. However, while the establishment of alfalfa was successful and grew with sorghum-sudangrass, companion crop treatment along with the year of establishment and season of growth influenced the ultimate success of alfalfa stand establishment. Given the increased production provided by sorghum-sudangrass in the first season of growth, and the reasonably good alfalfa production in the second season of growth, potential exists for the seeding of perennial grasses into alfalfa for a mixed stand from the second season on that meet forage production goals and produce well-rounded nutritious forage. However, this direction will require further studies and the use of sorghum-sudangrass as a companion crop may be better understood through adjustments to planting and harvesting techniques. In conclusion, the findings of our study ultimately did not support our hypothesis of sorghum-sudangrass as a compatible companion crop to establish a highly productive pure alfalfa stand for the years following establishment. This study highlights the need for discussion and research regarding the successful pairing of the establishing alfalfa crop with a warm-season annual grass.

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Figures and Tables

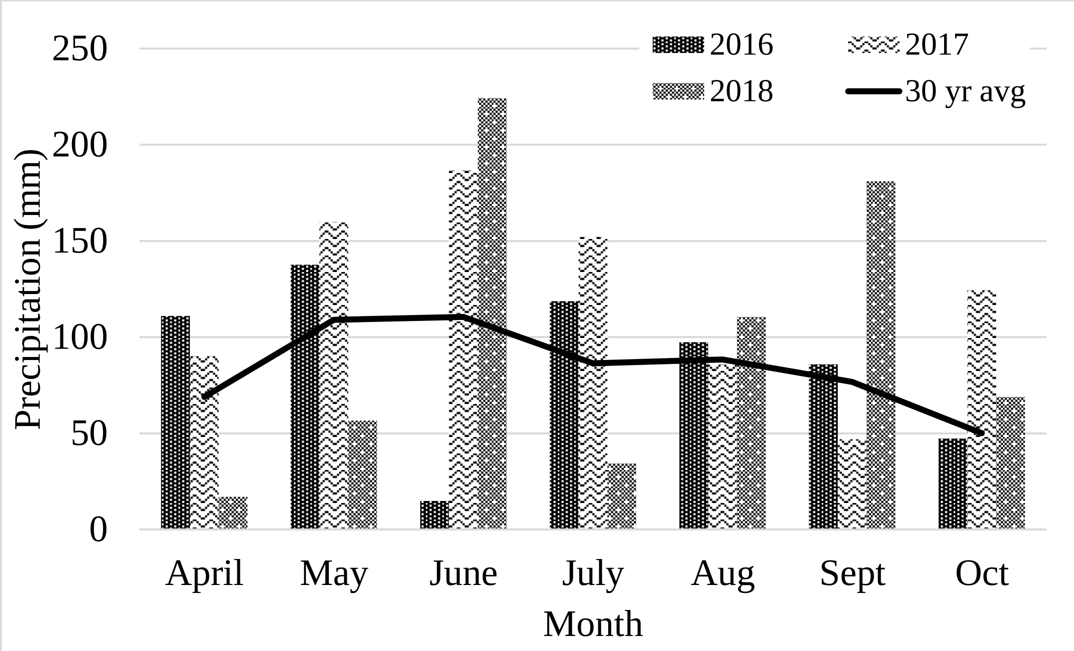

Figure 4-1: Monthly precipitation (mm) from April through October for 2016-2018, and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska

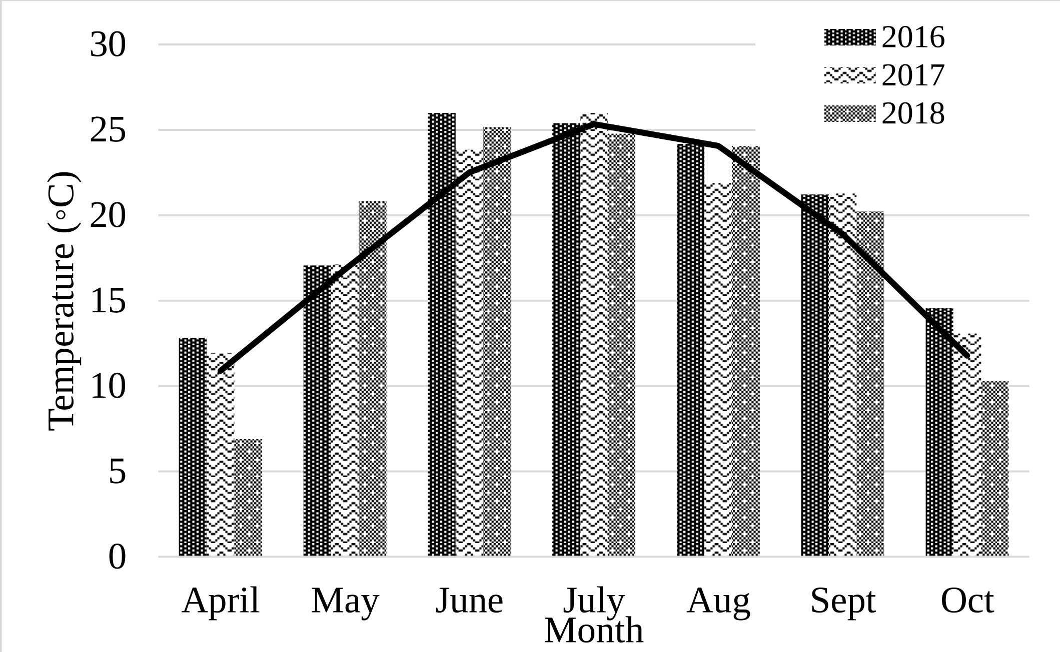

Figure 4-2: Monthly average temperature (degrees Celsius) from April through October for 2016-2018, and the 30-year average (1981-2010) at the High Plains Regional Climate Center station at the Lincoln Airport in Lincoln, Nebraska.

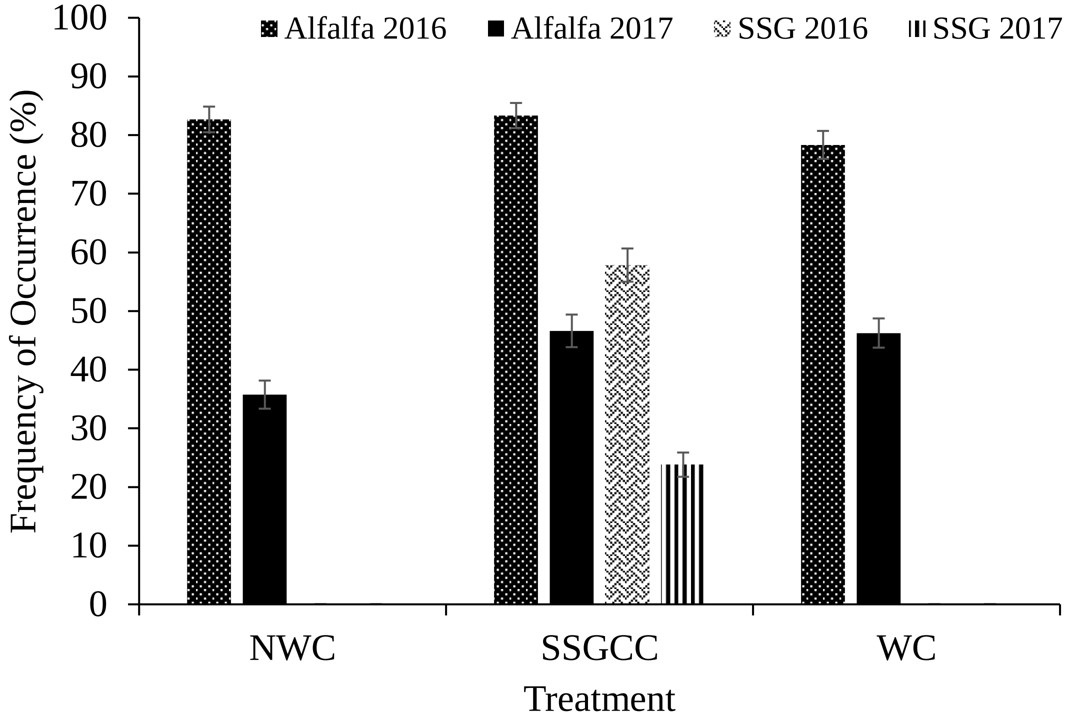

Figure 4-3: Frequency of occurrence of alfalfa and sorghum-sudangrass (SSG) in non-weeded control (NWC), sorghum-sudangrass companion crop (SSGCC), and weeded control (WC) alfalfa seeding treatments during the summers of 2016 and 2017.

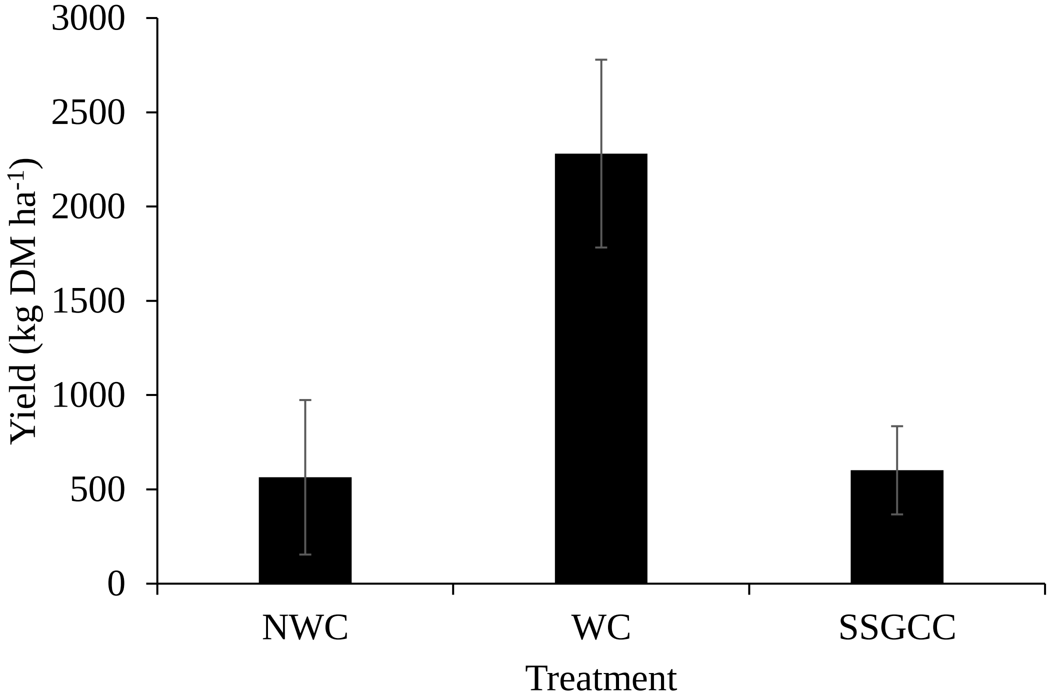

Figure 4-4: Mean alfalfa yield (kg DM ha^{-1}) in non-weeded control (NWC), weeded control (WC), and the sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments during the first season of growth, averaged across two years (2016 and 2017).

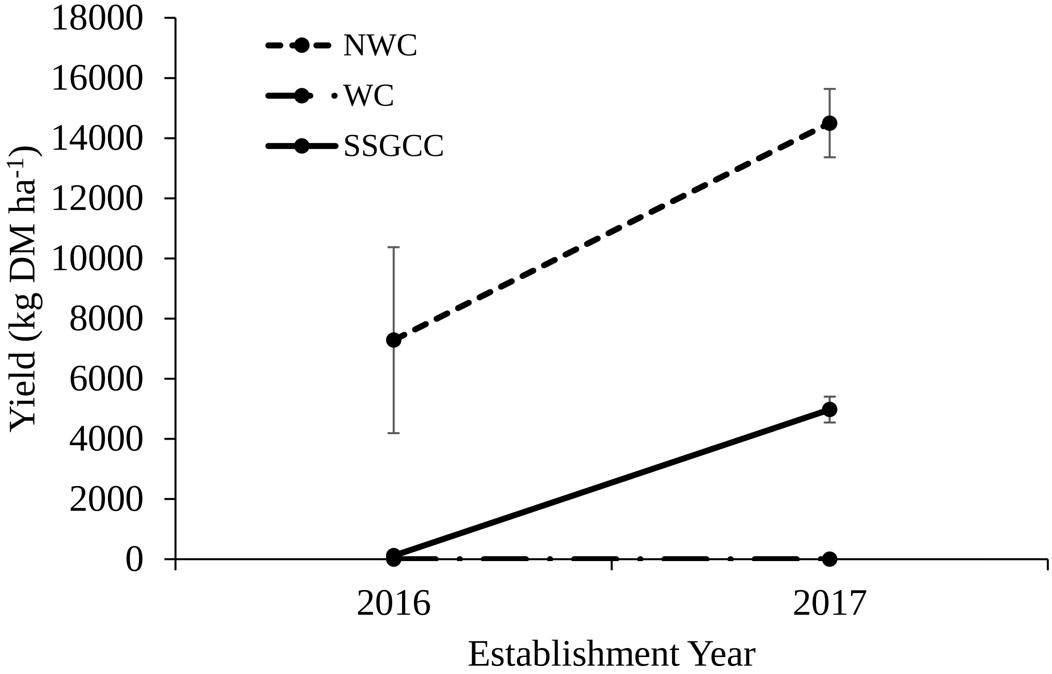

Figure 4-5: Mean weed production (kg DM ha^{-1}) in non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments during each establishment year.

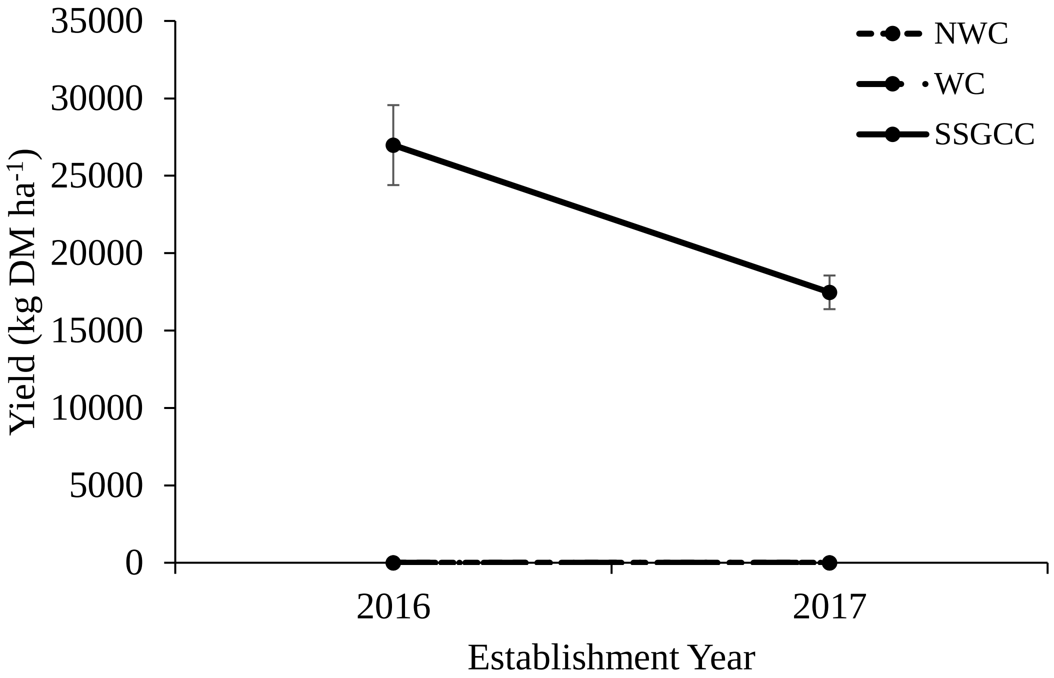

Figure 4-6: Mean sorghum-sudangrass production (kg DM ha^{-1}) in non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments during the establishment year.

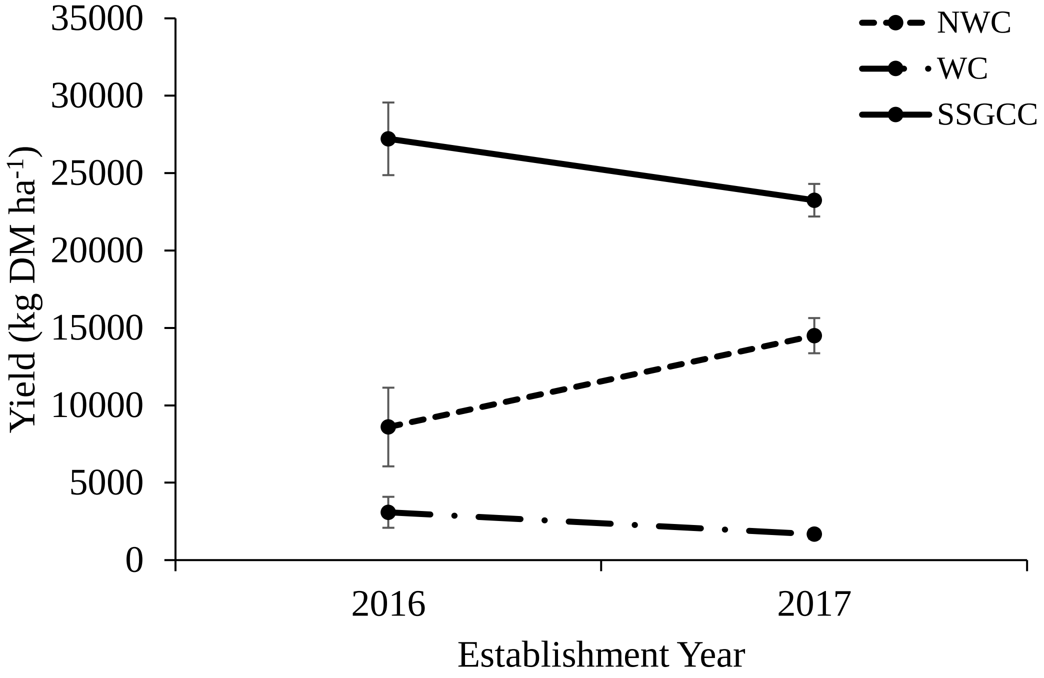

Figure 4-7: Mean total dry matter yield (kg DM ha^{-1}) in non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments during establishment year.

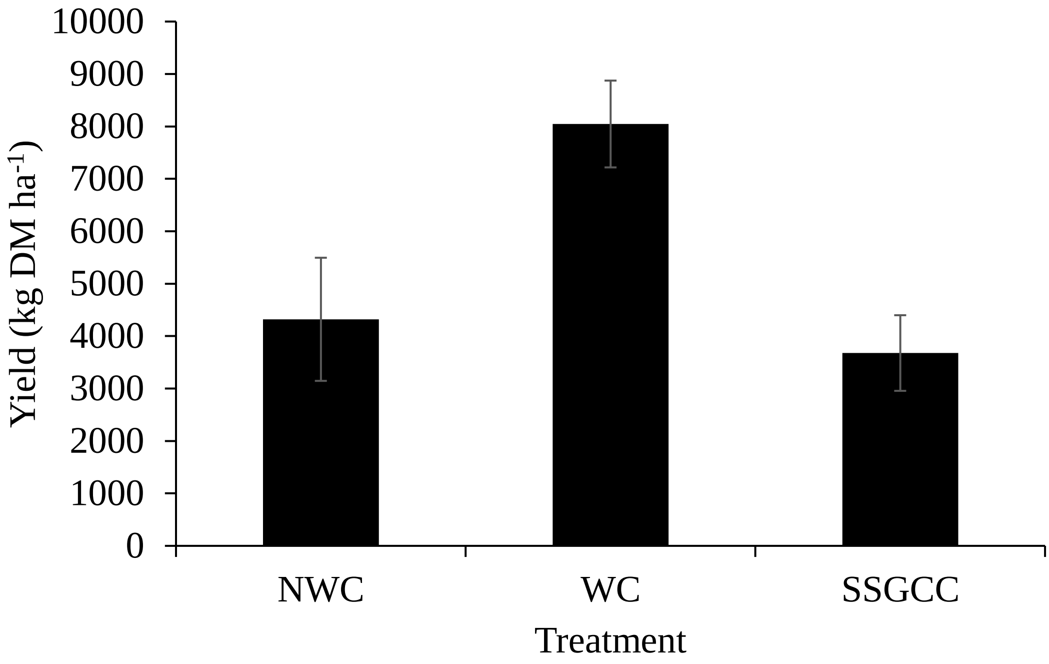

Figure 4-8: Mean alfalfa yield (kg DM ha^{-1}) in the non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa treatments in the first cut of the second season of growth, averaged across both years (2017 and 2018).

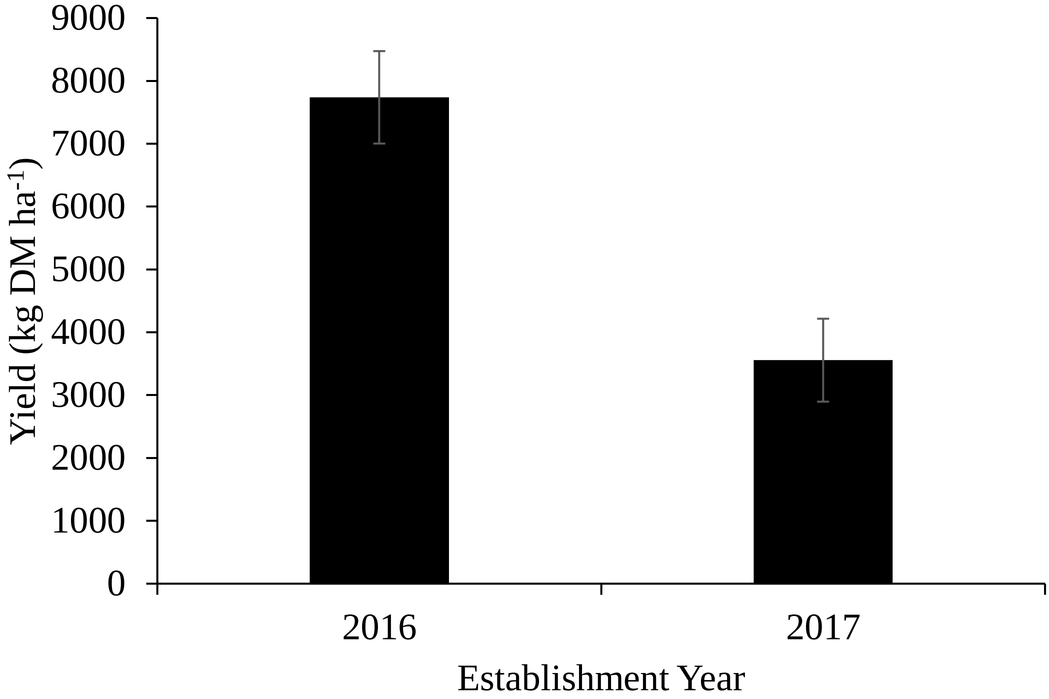

Figure 4-9: Mean alfalfa yield (kg DM ha^{-1}) in the first cut of the second season of growth (2017 and 2018) shown by establishment year (2016/2017), averaged seeding across treatments.

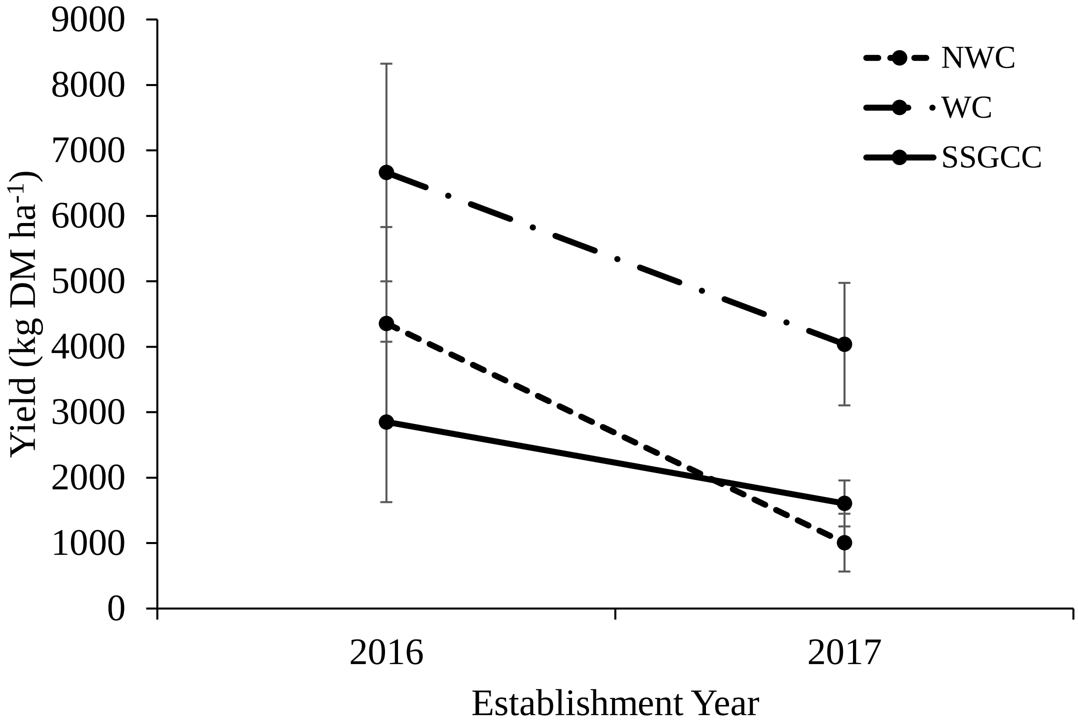

Figure 4-10: Mean alfalfa production (kg DM ha^{-1}) for non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments for the first season of growth of each establishment year.

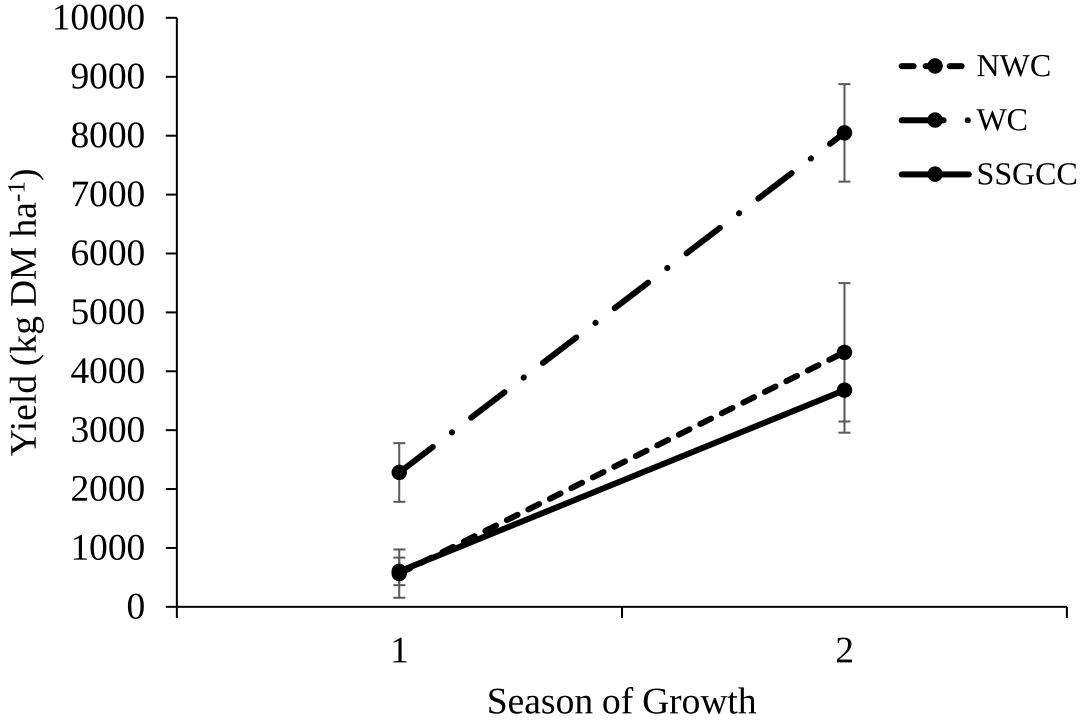

Figure 4-11: Mean alfalfa production (kg DM ha^{-1}) for non-weeded control (NWC), weeded control (WC), and sorghum-sudangrass companion crop (SSGCC) alfalfa seeding treatments in the first season of growth (2016 and 2017) and first cut of the second season of growth (2017 and 2018).

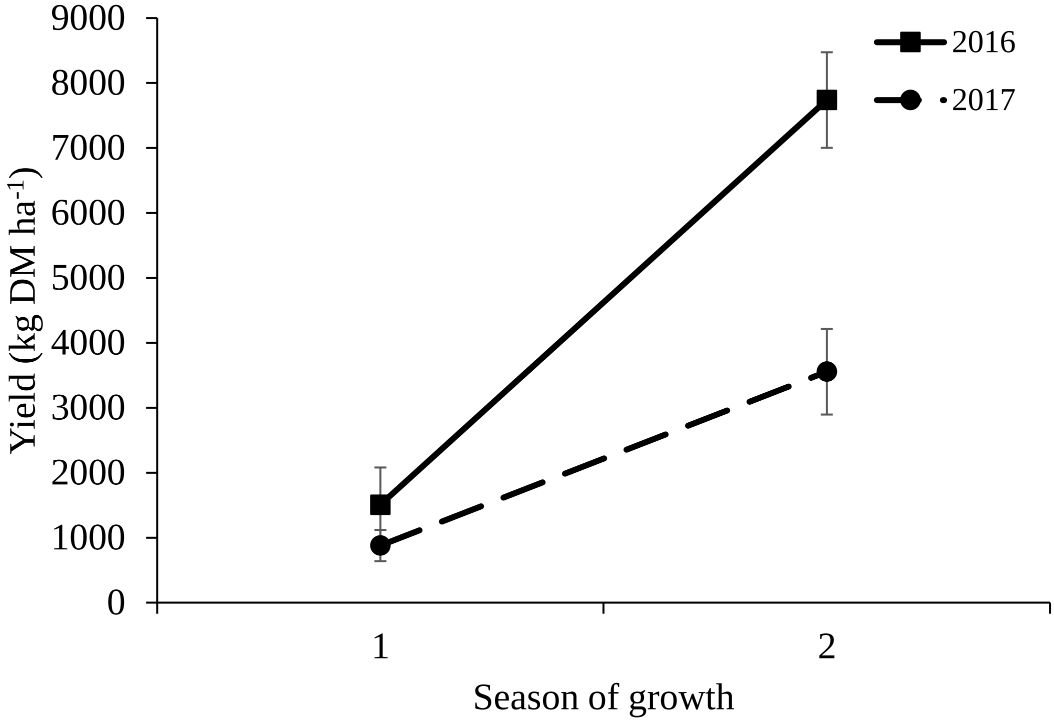

Figure 4-12: Mean alfalfa production (kg DM ha^{-1}) in the first season of growth and first cut of the second season of growth as averaged across seeding treatments for the 2016 and 2017 establishment years.

Table 4-1: Analysis of variance of alfalfa, weed, sorghum-sudangrass (SSG), and total dry matter yield during the establishment year (2016 and 2017) of alfalfa as related to year, alfalfa seeding treatment, and year by treatment interactions. P-values <0.05 denote significance.

Fixed Effect on Yield in the Establishment Year				
Effect	**Alfalfa**	**Weed**	**SSG**	**Total**
Year	0.1352	0.0011	0.0007	0.928
Treatment	0.0031	<.0001	<.0001	<.0001
Year*Treatment	0.0608	0.0285	0.0002	0.008

Table 4-2: Analysis of variance of alfalfa yield during the first cut of the second season of growth (2017 and 2018) based on the effect of year, treatment, and a year by treatment interaction. P-values <0.05 denote significance.

Fixed Effects on Yield in the Second Season of Growth	
Effect	**Alfalfa**
Year	<.0001
Treatment	<.0001
Year*Treatment	0.1223

Table 4-3: Analysis of variance of alfalfa yield across the first season of growth and first cut during the second season of growth (2016 and 2017, 2017 and 2018) based on the effect of season, year, treatment, season by year, season by treatment, year by treatment, and season by year by treatment interaction. P-values <0.05 denote significance.

Fixed Effects on Yield in First and Second Year of Growth	
Effect	**Alfalfa**
Season	<.0001
Year	<.0001
Treatment	<.0001
Season*Year	<.0001
Season*Treatment	0.0029
Year*Treatment	0.0177
Season*Year*Treatment	0.384