FUNCTIONAL DIVERSITY IN SUMMER ANNUAL GRASS AND LEGUME FORAGE INTERCROPS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

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February 2016

ABSTRACT

Reintroducing crop diversity and reducing external inputs are important initial steps to a more sustainable agriculture. The role of functional diversity was explored in an annual forage intercropping system. Four warm-season, drought-tolerant annual forage crops were evaluated for use in the Northeast United States. The species had two different functional traits, stature and nitrogen acquisition traits: 1) cowpea (*Vigna unguiculata* L., legume, short); 2) sunn hemp (*Crotolaria juncea* L., legume, tall); 3) pearl millet (*Pennisetum glaucum* L., grass, short); and 4) sorghum sudangrass (*Sorghum bicolor* L. Moench x *S. sudanense* P., grass, tall) and were seeded in monocultures and in three and four species intercrops. Crop and weed biomass were sampled twice by clipping vegetation in 0.5 m^2 area at approximately 45 and 90 days after planting (DAP). When averaged across site-years, crop biomass and crop growth rate of legume monocultures were lower than other treatments at both sampling times. Biomass for the monocultures at the second sampling date ranged from 2,500 kg ha^{-1} (cowpea) to 9,300 kg ha^{-1} (pearl millet). No biomass differences were found between the intercrops and grass monocultures, which ranged from 7,800 to 9,600 kg ha^{-1}. Although the intercrop treatments did not produce more biomass than the two grass monoculture treatments, all intercrops had land equivalent ratios (LER) greater than 1. Grasses and intercrop treatments were similarly weed suppressive. The pearl millet-sorghum sudangrass-sunn hemp intercrop consistently produced the most biomass, but not significantly more than the pearl millet monoculture, which had a much lower seed cost. Therefore other potential benefits of summer annual forage intercrops (e.g. improved forage quality and increased soil health) must be considered to justify the increased seed costs.

BIOGRAPHICAL SKETCH

K. Ann Bybee-Finley was raised in Hurricane, West Virginia by her loving parents, Howard and Kris Finley, with her younger sister Karen. She attended West Virginia University after being awarded the Foundation Scholarship. During her four years in college, she worked in a Liberian Refugee Camp and became interested in food security. She became conversational in Arabic and spent a semester at Al Akhawayn University in Ifrane, Morocco, as well as a semester at the University of Natural Resources and Life Sciences in Vienna, Austria where she studied agricultural extension methods. She was briefly a research assistant at Imperial College London where she contributed to a paper documenting community networks involved in nursery plant epidemics. In 2011, she graduated with a Bachelor of Science in biochemistry from Davis College of Agriculture and a Bachelor of Arts in international studies with an emphasis in development from Eberly College of Arts and Sciences. She was awarded the Order of Augusta, the University's most prestigious student honor. Bybee-Finley then began a 10-month internship with the Maize Pathology Lab at the International Maize and Wheat Improvement Center in Texcoco, Mexico. There she became fluent in Spanish and characterized endophytes in corn lines, hoping the work would contribute to improved tolerance to drought stress. After her internship, she started her graduate work with Matt Ryan, and the Sustainable Cropping Systems Lab was formed. At Cornell, Bybee-Finley has been active in various graduate student organizations to improve the welfare and sense of community for students. In 2013, she worked as an agricultural consultant in Bangladesh through the Student Multidisciplinary Applied Research Team Program. That winter, she was awarded the MacDonald & Musgrave award for Graduate Recognition. Her current work has mostly focused on summer annual forage mixtures but her interests lie in integrating ecology into agricultural policy.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my advisor Matt Ryan. He has shown tremendous kindness and patience that it so rarely found in today's world. His attentive nature and quiet intelligence all but assures his success at Cornell University. I have learned so much from him. I trust him and am so grateful for his guidance. He has driven me to become the best scientist I can be. In all, he has been a delight to work for and I am looking forward to working with him for years to come.

I would also like to express my gratitude to the other professors on my committee, Laurie Drinkwater and Harold van Es. Laurie has given me access to the tools I needed to perform my work. Through her, I have been able to form a strong network of researchers studying similar intercrops. Harold has been pragmatic and direct giving helpful advice. He balanced out ever-expanding ideas with his wisdom and experience.

Additionally, I would like to thank Dave Wilson from King's Agriseed who helped select the crop species used in my research. He has been a wealth of knowledge on forage species, plant physiologies, forage management, and producer preferences.

I would also like to acknowledge Steven Mirsky my collaborator in Beltsville, MD at the USDA. His inputs in the design stage and advice throughout have been kind and useful. I very much appreciate the efforts he and his team made to carry out the field experiment at the Beltsville site.

A hearty thank you to Paul Stachowski for his assistance and advice on the Musgrave Research Farm in Aurora. He always made time to explain how a piece of equipment worked, the history of the land, or why things were done the way they were.

A very kind thank you to Mike Davis at the Willsboro Research Farm for his assistance and enthusiasm for research. I truly appreciate the work he and his crew put in for setting up the research plots and sampling at the Willsboro site.

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PROLOGUE

Across the world, various cultures have practiced intercropping from the dawn of agriculture to the present day. Peas and barley covered olive groves of ancient Greece to retain the arid soil, prevent the loss of soil moisture, and provide nitrogen. On the other side of the world a millennium later, the Iroquois in North America intercropped corn, beans, and squash (termed "three-sisters"), so that the bean climbed the corn and fixed nitrogen, while the squash provided ground cover (Lithourgidis et al., 2011). Without the use of GPS-directed combines or market analysts, women and men hedged their bets against the weather and protected themselves from the whims of traders by planting two or more crops together in one piece of land. They attempted to maximize the hard-earned space they had carved out from the wild. It was not romantic. It was a struggle for life.

Over the next centuries, the ability to produce food was honed, eventually becoming increasingly more productive and more artificial. Tillage instruments changed from handheld wood to animal-powered metal to intricate machines. The crops past generations chose co-evolved with human communities. The 20^{th} century brought agro-industry giants, manufactured chemical inputs, a globalized market, and further removed industrialized countries from a holistic food system. Although many have benefited from industrialized agriculture, most of the world's farmers, and the majority of agricultural-related scientists, are aware of the toll it takes on the environment (Barnosky et al., 2012; Vandermeer et al., 1998; Lin, 2011). These impacts range from soil erosion to nonpoint source pollution to massive reduction of biodiversity, largely in exchange for short-term economic gain (Vandermeer et al., 1998). Reintegrating polycultures in cropping systems is one solution to many of the current challenges facing agriculture.

Theoretical Framework

Several ideological discourses exist that can frame our approaches to abate destructive agricultural practices. One construct is a continuation of the current trajectory, hoping technology will temper our current actions in such a way that we are no longer damaging nature (Dryzek, 2013). An alternative construct is to embrace nature because it is an unconquerable force that should be considered in our moral sphere at least with the same equality we give humans (Smith, 2001; Cordova, 2004). It would be advantageous for us to continue to learn from it, learn to be more like it because we could better adapt to the environment. This is inherently a more complicated approach because it requires us to understand the interactions of plants and their environs, and apply this systems knowledge, leading to individualized recommendations for farmers based on their specific circumstances (geography, species present, farming capabilities) (Vandermeer, 1989).

Many who work in the realm of sustainable agriculture are concerned about the future, referencing record droughts, the formation of mega-cities, the patenting of seeds, and other important issues that threaten food security and the environment (Hansen et al., 2012; Patel, 2007). It is difficult to convey a sense of urgency to the public when agricultural problems are so massive in scale, engrained in culture, and systemic in policy. Approximately 40% of the Earth's land surface is being used for agricultural and animal production with an estimated 40% of that land experiencing degradation through erosion, reduced fertility, and overgrazing (Foley et al., 2005). Since the rise of industrialized agriculture, there has been a seven-fold increase in global fertilizer use where synthetic chemicals substituted for functional ecological processes (Foley et al., 2005; Lin et al., 2008). Soil erosion resulting from reduced agroecosystem complexity and overuse of synthetic inputs in industrialized agriculture has been estimated to cost \$44 billion yr^{-1}

in public and environmental health problems (Pimentel et al., 1995). Industrialized agriculture is fragile because it requires an enormous amount of nonrenewable fossil fuels, fails to regard the importance of nutrient cycling, and is vulnerable to geopolitical pressures. Current agriculture policy has led to an increasing farm size and an ever decreasing number of farms, further increasing the fragility. Additionally, large industrialized agriculture results in a very small interface between food production and food consumption.

Statement of Purpose

How can progress be made in creating a more regenerative agricultural system where synthetic fertilizer is replaced with local animal manure, disease and pests are managed with crop rotations, and weeds are managed by competitive crops? One approach is to increase crop diversity in agroecosystems. Many management practices already exist to reach this goal: perennial forage crops, cover crops, and annual forage crop intercrops are a few examples. Here, I report on field experiments conducted in 2013 and 2014 that were designed to quantify the effects of diversity in summer annual forage crops. This research contributes to a growing body of literature that examines the potential benefits of crop diversity on cropping system performance and overall agroecosystem resilience.

Summer annual forage crops are often called “emergency forages” because they are commonly planted after corn or soybean crops fail to establish, drought-ridden summer stalls perennial forage crop growth (e.g. summer slump), or harsh winters impair perennial forage stands (Kramer and Johnson, 1998). Climate change is already affecting continues to affect agricultural production in the Northeast with a 70 % increase in extreme precipitation events coupled with heat stress from warmer temperatures in the summer months (The Earth Institute, 2014). Lin (2008) suggests that more contrived agroecosystems with greater dependence on synthetic inputs will be more negatively affected than agroecosystems that resemble natural systems in their ecological complexity. Functionally diverse forage intercrops can also increase resource efficiency and provide additional ecosystem services compared to monocultures. In addition to being better buffered against extreme weather, the potential reduction in external inputs makes intercropping with emergency forage crops ecologically sound and economically feasible.

Benefits of Functional Diversity

Numerous experiments in natural systems have shown that species diversity increases tolerance (i.e. the ability to cope with stress) and resilience (i.e. the ability to recovery after a stress) of ecosystems (Folke et al., 2004). Hooper et al. (2005), expressed confidence that functional diversity of species that respond to environmental perturbations differently can stabilize ecosystem processes in response to disturbances. For example, decreasing diversity of the Great Plains in the United States due to an increasing conversion of grasslands to monoculture cropping systems has shown to dramatically alter the capacity of the environment to provide ecosystem services such as soil carbon sequestration (Lin et al., 2011). By mimicking a more natural environment and increasing species spatial and temporal diversity (i.e. increasing diversity in the same space over time), agriculture can be multifunctional and provide greater ecosystem services (Lin et al., 2011).

Crop diversity can be managed using different approaches including crop rotations, alley cropping, and intercropping. Four sub-categories of intercropping include: 1) strip intercropping, where two or more species are planted adjacently but in wide enough swaths to be independently cultivated; 2) row intercropping, where two or more species are grown in adjacent rows; 3) relay intercropping, where two or more species are grown within the same space and some parts of their life cycle overlap; and 4) mixed intercropping, where two or more species are grown together with no distinct row arrangement (Andrews and Kassam, 1976). Mixed intercropping was used in this experiment and heretofore is referred to simply as intercropping.

Functional diversity, a community-level phenomenon in which different species affect a variety of biological processes, occurs in intercropping when crop species occupy different niches. Niche differentiation is the ability to utilize different resources across a spatial and temporal scale (Tilman et al., 1997; Silvertown, 2004). Examples of functional diversity within the same temporal scale include, plant stature, biological nitrogen fixation, rooting depth, and microbial mediation (Silvertown, 2004). Through resource partitioning, intercrops can then be more efficient at accessing nutrients than species grown in monoculture. Cardinale et al. (2011) performed a meta-analysis using data from experiments in which species richness (i.e. number of different species) was manipulated. They found evidence that the net effect of species loss reduced biomass production and efficiency to assimilate inorganic resources. Increasing plant diversity allows for interactions between different species and can reduce intraspecific competition (Vandermeer, 1989). For example Hille Ris Lambers et al (2004) quantified the productivity of 14 grassland species and found that the most productive species were C4 grasses and legumes, which were adept at acquiring the limiting resource, nitrogen. In this case, grassland communities with greater functional diversity were better able to access resources (Hille Ris Lambers et al., 2004).

Increased resource use efficiency often leads to a yield advantage (i.e., overyielding), which occurs when two or more intercropped species create more biomass when grown together than if each were grown in monoculture (Vandermeer, 1989). Considerable evidence states that legume-grass intercropping can result in yield advantages of the intercrop over their respective monocultures (Tilman et al., 2006; Lin et al., 2011; Tofinga et al., 1993). Part of this increase in efficiency is due to changing the competition for resources through altering the light, and nutrient access, as well as an increased ability to outcompete weeds (Picasso et al., 2008). Gardiner and Craker (1981) reported that a bean (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) intercrop increased interception of photosynthetically active radiation (PAR) and had greater yields per unit of land area than of each species grown in monoculture. Hauggaard-Nielsen et al. (2001) observed that when barley (*Hordeum vulgare* L.) was intercropped with pea (*Pisum sativum* L.), the barley root system grew deeper than the pea root system. In a separate experiment, *Crotalaria ochroleuca* G. Don was intercropped with bean and corn in Uganda, and increased corn yield by 23% with an increased nitrogen supply and more favorable soil properties (Fischler et al., 1999). Szumigalski and Van Acker (2005) found that an intercrop of spring wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.) reduced weed biomass by almost 50 % compared to a monoculture of either species. All of these examples describe the greater ability of the intercrops to access light, water, and soil resources, and can lead to a decrease in weed biomass. Fewer resources are available for weeds when crops are grown together as intercrops because resources are more completely used by crops.

Crop Mixture Species Selection

In order to explore the potential benefits of intercropping, four warm-season annual crops were selected based on two functional traits that have demonstrated relevance in plant-plant competition research: plant architecture (tall vs. short) and biological nitrogen fixation (grass vs.

legume). The four forage crop species chosen for this research were: 1) cowpea (*Vigna unguiculata* L., legume, short); 2) sunn hemp (*Crotolaria juncea* L., legume, tall); 3) sorghum sudangrass (*Sorghum bicolor* L. Moench x *S. sudanense* P., grass, tall); and 4) pearl millet (*Pennisetum glaucum* L., grass, short). These crops were strategically selected because of their: 1) potential as high-quality forage with low input requirements, 2) lack of previous research in the Northeast, and 3) tolerance to extreme heat and short-term drought conditions, which is projected to increase in the coming years.

Cowpea

Cowpea serves as an important food crop for both human and animal consumption in many parts of the world, and originated in West Africa. The introduction of cowpea to North America occurred with the influx of West Africans brought to America through the slave trade (Perrino et al., 1993). In the past fifty years, global cowpea production has increased, whereas production in the United States has declined tenfold (Davis et al., 1991).

Cowpea is an herbaceous legume that grows best in warm, moist climates when soil temperatures are warmer than 18◦C (SARE, 2012). It can tolerate highly acidic soils but fares poorly in alkaline soils. Like the other crops mentioned, cowpea does not do well in poorly drained soils (SARE, 2012). After establishment, cowpea can withstand drought by growing deep taproots and delaying leaf senescence (Davis et al., 1991).

Cowpeas have two distinct growth habits, vining types and indeterminate bush types. The vining type typically serves as a better intercrop since it can use the taller grasses as a trellis, better enabling it to access light. The recommended seeding rate is between 35 and 100 kg ha^{-1} (SARE, 2012) with yields ranging from 3,400 to 5,000 kg ha^{-1}, which produce 100 to 170 kg ha^{-1}

of nitrogen (SARE, 2012). The physiology of cowpea is such that it attracts beneficial insects because of additional nectar-release sites on petioles and leaflets. It also serves as an excellent protein source for cows, hence the name (McGiffen et al., 2012).

Sunn Hemp

Sunn hemp is a legume that has been used for forage or fiber production for millennia in India. It was introduced to the United States in the 19th century, and the first research conducted on it in the United States was in the 1930's (Cook and White, 1996). Grown extensively as a green manure, it fixes nitrogen, increases soil organic matter, and suppresses weeds (FAO, 2014). Although uncommon to the United States, recent research has focused on using sunn hemp for weed suppression (SARE, 2012). Garie et al. (2013) reported that sunn hemp grown as a green manure before rice increased soil organic matter and rice yields by 80 %, while serving as a biological form of weed control.

Sunn hemp grows best in well-drained soil but has been adapted to grow on marginal land (Cook and White, 1996). It can reach three to nine feet tall with alternating leaves and is resistant to nematodes (NRCS, 1999). Sunn hemp has moderate drought tolerance, but is not frost tolerant (SARE, 2012). The recommended seeding rate is 45 to 55 kg ha^{-1} (NRCS, 1999). Sunn hemp grown in the southern United States has been reported to yield up to 5,600 kg ha^{-1} within 90 days, and can produce more than 100 kg $ha^{-1}$of nitrogen (SARE, 2012). It is important to note that most sunn hemp seed in United States is imported from tropical locations since the species will not readily produce viable seed north of 23◦ latitude, which excludes most of the United States (NRCS, 1999).

Most cultivars of sunn hemp contain toxic levels of alkaloids, which limit their use as a forage crops. A variety trial with the University of Hawaii and the NRCS produced a popular non-toxic variety ‘Tropic Sun’ (Rotar and Joy, 1983). Other researchers have examined growing sunn hemp in temperate locations to be used for dairy feed. Riday and Albrecht (2008) intercropped sunn hemp with corn in Wisconsin to determine potential intercrops for silage in dairy rations. Sunn hemp was found to be one of the more successful species for intercropping with corn because of its ability to compete for light and maintain total dry matter accumulation (Ridday and Albrecht, 2008).

Sorghum Sudangrass

Sorghum sudangrass is a cross between sorghum and sudangrass providing the yield advantage of sorghum with a finer stem from the sudangrass. Both sorghum and sudangrass are native to northeastern Africa (FAO, 2000) and all three grasses are drought and heat tolerant. Sorghum was first cultivated for sugar in North America the mid-19th century and became popular because of its drought tolerance. By the 1950’s, the majority of sorghum was grown as a forage crop in the central and Great Plains area of the United States (Undersander et al., 1990). Sorghum was crossed with sudangrass during the 1930’s. It has seen a revival of interest in the Northeast United States in recent years as the National Resource Conservation Service (NRCS) has begun to promote cover crops.

Sorghum sudangrass can reach between 1.2 m to 4 m tall and can produce 4,500 to 5,600 kg ha^{-1} of biomass. The yield potential of sorghum sudangrass is not damaged by severe drought because the plant goes dormant until the drought ends and then it resumes normal growth rates (Kilcer et al., 2005). It can also tolerate alkaline soils up to a pH of 9. The recommended seeding rate for sorghum sudangrass is 40 to 45 kg ha^{-1} and it requires approximately 80 to 100 kg ha^{-1} of nitrogen. Sorghum sudangrass is sensitive to temperature and best establishment results are seen when the soil is at least 18◦C (SARE, 2012).

The sorghum-sudangrass cross has been further improved as a forage crop through the introduction of brown-midrib (BMR) varieties (Wright et al., 1998; Ketterings et al., 2007). BMR mutations reduce lignin content in plants, increasing the digestibility of the plant and therefore the forage quality, resulting in long-term milk production similar to corn silage (Kilcer et al., 2005; Miller and Stroup, 2003). Sorghum sudangrass for forage production can be managed as a short-season single cut system or it can be cut multiple times, but young plants may not be safe to graze due to toxic prussic acid (HCN) content (Undersander and Lane, 2001).

Sorghum sudangrass can produce more biomass and at a lower seed cost than most other species grown as a cover crop (SARE, 2012). Its great biomass production adds considerable organic matter to the soil. Because of its more rapid growth and uniform ground cover, soil loss potential with sorghum sudangrass is less than half of conventionally-tilled corn (Kilcer et al., 2005). The roots also secrete allelochemicals that suppress annual weeds and nematicides that suppress nematodes (Weston et al., 1989).

<u>Pearl millet</u>

Pearl millet is the sixth widely grown cereal in the world (Obeng et al., 2012). It is considered an important forage crop with an estimated 607,300 ha grown in the United States grown more than a decade ago(Jefferson Institute, 2002). Domesticated south of the Sahara and along the Nile, pearl millet is used mainly as a food crop in Africa and India with production close to 30 million ha in 1980 (Andrews et al.,1993). This fast growing forage crop was introduced to the United States in the 19th century (Andrews et al., 1993) and is thought to be one of the most drought resistant grains (Lee et al., 2012). It grows rapidly and can perform well under unfavorable growing conditions like high heat, drought, and poor soil (Newman et al., 2010). It is more drought tolerant and matures earlier than sorghum, with approximately 50% reproductive maturity at approximately 60 days after planting (Jefferson Institute, 2002).

Pearl millet is a deep-rooted, tillering cereal grain crop (Lee et al., 2012). Because of its high tillering ability, a precise seeding rate is not considered critical (Jefferson Institute, 2002). It has a relatively low recommended seeding rate of 13 to 17 kg ha^{-1} (Newman et al., 2010) and requires 35 to 75 kg ha^{-1} of nitrogen, although Muchow reported (1988) that the nitrogen use efficiency of pearl millet is higher than many other crops.

Pearl millet varieties have a range of architectures from 1 m in dwarf varieties to 2.5 m (Sheahan, 2014). Certain varieties have been bred for grain production with an elongated inflorescence, whereas others have been bred for forage production. Breeding has also created short-season cultivars that can flourish in temperate conditions and short growing seasons (Andrews and Kumar, 1992). Forage yields reported for pearl millet in the United States range from 6,000 to 11,200 kg ha^{-1} (Sheahan, 2014; Obeng, et al. 2012). Pearl millet is considered a high-quality forage because it is high in protein and low in fiber (Newman et al., 2010).

When grown as a cover crop, pearl millet has been shown to suppress soil-borne diseases, root-lesion nematodes and increase soil organic matter (Ball-Coelho et al., 2001; Sheahan, 2014). While no significant pest issues have been reported, birds can damage grain heads (Sheahan, 2014). Rust can be a major disease issue, prevented by planting crops one to two weeks later than recommended when soils are warmer (Lee et al., 2012).

Experiment Summary

Intercrops mimic natural environments and are able to increase the resilience and stability of the agroecosystems they are a part of, decreasing the risks of crop failure because of their abilities to access different resources. However, the use of intercropping in modern agriculture suffers from its complexity. The choices of intercropping are complicated from the start: from the number of species, to the type of the species, to the cultivars of the species, to the seeding rate of each species, to the seeding rate ratios with the other species, to the type of fertilizer, to the fertility rate. Fortunately, knowledge is cumulative and everyday researchers and producers alike build upon the experiences of others. I have chosen to devote my years at Cornell University attempting to understand the four described annual forage crops grown in monoculture and in three and four species intercrops. My research examined the effects of seeding rates in monoculture versus intercrops on biomass production and weed suppression at the middle and at the end of the growing season in order to better understand the relationship between functional diversity, resource use, and productivity. Additional performance metrics were used to discern effects between the different intercrops and the species in monoculture. An economic assessment was performed to compare seed costs and cost of production for the four species grown separately and together. High yields matched with reasonable costs will make alternative forage species and functionally diverse intercrops more acceptable by dairy and other livestock producers.

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INTRODUCTION

Although highly productive, conventional agriculture in the United States undermines ecological processes and has now reached a saturation point for external inputs and yield increases (Cassman et al., 2010). Large scale monocultures are vulnerable through low natural resilience to disease, noxious or invasive weeds, and abiotic stressors like drought or above average temperatures (Lin et al., 2008). Diminishing returns from investments focused narrowly on increasing crop yields suggests that researchers, policymakers, and farmers should focus on creating semi-closed, regenerative systems that minimize external inputs and impacts of agricultural practices on the environment (Pearson, 2007). Goals for closing yield gaps should aim at restoring ecosystem system services through ecosystem enhancement and replacement (Bommarco et al., 2013). One approach to both minimizing external input requirements and reducing agricultural impacts is to draw on ecological theory to optimize agricultural systems.

Crop diversity has been linked to a more efficient use of resources as explained by diversity-productivity theory (Trenbath 1974; Tilman 1999). Ecological studies have shown that biodiversity increases tolerance (i.e. the ability to cope with stress) and resilience (i.e. the ability to recovery after a stress) of ecosystems (Foley 2005). By increasing species spatial and temporal diversity (i.e. increasing diversity in space and over time), agricultural systems can provide greater ecosystem services such as biological control of pests by mimicking a more natural environment (Lin et al., 2011).

Polycultures, two or more species grown in the same space at the same time, are a way to introduce diversity into agroecosystems. Mixed intercropping is a type of polyculture system in which two or more crop species are planted with no distinct row arrangement at the same time (Vandermeer, 1989). Perennial forages, particularly alfalfa (*Medicago sativa* L.) and timothy

(*Phleum pratense* L.) grass, are the most common intercropped system in the United States (Hall and Cherney, 2014). Previous work has indicated that summer annual forage intercrops have potential to be more widely used due to the benefits of diversity and their short season (Lithourgidis et al., 2011). Because many forage crops are often grown as cover crops, intercropping with summer annuals has also gained traction with farmers who grow grains and vegetables.

Increased resource use efficiency often leads to a yield advantage (i.e. overyielding), which occurs when two or more intercropped species create more biomass when grown together than if they were each grown in monoculture. Grass-legume combinations often have yield advantages over their respective monocultures due to the different functional traits for accessing nitrogen (Tilman et al., 2006). For example, in North Carolina, USA Creamer found that sorghum-sudangrass and cowpea produced 9,000 and 4,000 kg ha^{-1}, respectively in monoculture and 8,000 kg ha^{-1} in an intercrop (2000). In the same experiment, Japanese millet (*Echinochloa frumentacea* Roxb.) and soybean (*Glycine max* L.) each produced 4,000 kg ha^{-1} in monoculture and 3,000 kg ha^{-1}in intercrop (Creamer et al., 2000). Because diverse species can access resources in different ways, an intercrop can alter the competition dynamics for nutrient access, water, and light, either overcoming yield loss caused by weeds or suppressing weeds (Picasso et al. 2008).

Grass forages tend to be more weed suppressive than legume forages because they produce more biomass and are more competitive for nutrients (Creamer and Baldwin, 2000; Brainard et al., 2011). Weed suppression can therefore increase in grass-legume intercrops compared to legume monocultures, as seen by an increase in the number of plants m^{-2} from 2 to 14 in pure pea stands (Akemo et al., 2000). However, low-input systems that utilize grass-legume intercrops have been shown to result in less nitrogen immobilization and yields equivalent to high-input monoculture systems (Brainard et al., 2011).

Most intercropping experiments have been performed between two species using additive or replacement designs to understand yield differences at various seeding rates (Loreau and Hector, 2001). Because of this, it has been difficult to draw conclusions about biodiversity effects in more complex agroecosystems that include three and four crop species growing together. This research examined the efficiency and biodiversity effects of four forage crop species with two defined functional traits: plant architecture and biological nitrogen fixation, under low-input growing conditions. These species were selected based on their heat and drought tolerance and multifunctionality. Under various management regimes, these species can be considered cover crops or used as animal feed via grazing, hay, or silage. We hypothesized that 1) intercrop treatments would outperform monoculture treatments in terms of biomass production, and 2) weed suppression would increase with crop species richness.

MATERIALS AND METHODS

Research Sites

The experiment was conducted in 2013 and 2014 at: 1) the Cornell Musgrave Research Farm in Aurora, NY on a Honeyoye and Lima silt loam; 2) the Cornell Willsboro Research Farm in Willsboro, NY on a Stafford fine sandy loam; and 3) the USDA-ARS Beltsville Agricultural Research Center (BARC) in Beltsville, MD on an Elkton silt loam. The experiment was repeated a total of nine times with slight modifications to management practices and plot sizes across sites and years (Table 1).

Table 1: Planting and sampling dates for years and field sites.

Year	Site-ID	Location	Blocks	Planting date	Plot size (m^2)	1st sampling (DAP) †	2nd sampling (DAP)
2013	13 Aur	Aurora, NY	5	15-Jul	23	45	77
	13 Bel-E	Beltsville, MD	4	9-Jul	23	51	78
	13 Bel-L	Beltsville, MD	4	24-Jul	23	43	89
	13 Wil	Willsboro, NY	4	24-Jul	9	53	--‡
2014	14 Aur-E	Aurora, NY	4	20-Jun	37	46	91
	14 Aur-L	Aurora, NY	4	10-Jul	37	50	96
	14 Bel	Beltsville, MD	4	23-Jul	37	47	89
	14 Wil-E	Willsboro, NY	6	17-Jun	14	48	90
	14 Wil-L	Willsboro, NY	6	15-Jul	14	45	90

† DAP, days after planting.
‡ Plots were not sampled a second time at 13 Wil.

In 2013, the Beltsville site included two experiments, an early planting date and a late planting date. In 2014, the Aurora and Willsboro sites each included two experiments: an early planting date in mid-June and a later planting date in mid-July, after winter wheat (*Triticum aestivum* L.) was harvested (Table 1). The Beltsville site in 2014 (14 Bel) only included one experiment, which was established after wheat harvest.

Experimental Design

A randomized complete block design with 4 to 6 replications was used to compare four monoculture treatments and five intercrops treatments representing all combinations of three and four species intercrops. A complete randomized design was used at 13 Bel-L due to logistical challenges. The four summer annual forage species tested in monoculture and intercrops were cowpea (*Vigna unguiculata* L. cv. 'Iron Clay'), sunn hemp (*Crotolaria juncea* L. variety not stated, VNS) pearl millet (*Pennisetum glaucum* L. cv. 'Wonderleaf'), and sorghum sudangrass (*Sorghum bicolor* L. *x Sorghum sudanese* Stapf cv. 'AS6401'). Iron Clay is a mixture of a semi-bush and a vining cultivars and is nematode resistant. Although the sunn hemp was VNS, it was thought to be Tropic Sun, which is a forage variety developed for low alkaloid content and is one of the most commonly used sunn hemp varieties in the United States. Wonderleaf pearl millet is a bushy forage variety with a high-tillering ability. The sorghum sudangrass variety had brown mid-rib (BMR) trait, for improved forage quality. Both of the grass crops should be harvested at approximately 90 cm when grown for forage; however, the sorghum sudangrass will grow taller than the pearl millet if allowed to grow longer (King's Agriseeds, 2012).

Pearl millet, sorghum sudangrass, and cowpea seeds originated from Texas, whereas sunn hemp seed originated from Tanzania. Germination rates for pearl millet, sunn hemp, and cowpea were 80% and 85% for sorghum sudangrass. To compensate for incomplete germination, the recommended monoculture seeding rates were increased accordingly. Seeding rates [kg ha^{-1}] in intercrops were based on a replacement series design, such that each species included in a polyculture was seeded at the monoculture rate divided by the number of species in the polyculture (Table 2). Pearl millet had the lowest seeding rate (weight) due to its relatively small seed size.

Table 2: Seeding rates used in the nine forage species treatments.

Forage species	Cowpear(C)	Sunn Hemp (H)	S. sudangrass (S)	Pearl millet (M)
	Seeding rate (kg ha^{-1})			
M				21.00
S			66.00	
H		56.00		
C	70.00			
MSH		18.75	22.00	7.00
MSC	23.25		22.00	7.00
MHC	23.25	18.75		7.00
SHC	23.25	18.75	22.00	
MSHC	17.50	14.00	16.50	5.25

Field Operations

In general, fields were chisel plowed, disked, and cultipacked prior to seeding forage crops, but field preparation varied slightly across sites. Prior to seeding crops, 35 kg ha^{-1} of total nitrogen was broadcast in the form of poultry litter (5-4-3); however, in the 13Aur site, nitrogen was applied as mineral fertilizer (10-20-20) instead of poultry litter. Although this is more nitrogen than would typically be applied prior to legume crops, it represents less than half of the recommended rate for sorghum sudangrass (Ketterings et al. 2007). The legumes were inoculated with a rhizobium mixture suitable for cowpea and sunn hemp prior to seeding. Crops were seeded to a depth of 4 cm using a 1590 drill (John Deere, Moline, IL) at Aurora and BARC, and a Great Plains drill (Great Plains, Salina, KS) at Willsboro in 60 cm rows.

Sampling

In 2013, forage crop density was measured shortly after crop emergence and prior to biomass sampling; however, crop density measurements and biomass sampling occurred simultaneously in 2014. Crop density and biomass were measured separately for each species in the intercropped treatments. Crop density was measured and biomass samples were collected from 0.5 m^2 quadrats. The first biomass samples were collected halfway through the growing season (43-53 DAP), and the second biomass samples were collected prior to seed maturation (77-90 DAP). Plants were clipped 10 cm above the soil surface to mimic a forage cutting. Vegetation samples were separated by forage species and weeds (pooled across species), dried at 60°C for up to one week, and then weighed. Weeds data were not collected in 13 Bel-E at either sampling date in 2013. Temperature and precipitation data were collected daily using the on-farm weather stations.

Land Equivalent Ratio

Land equivalent ratio (LER) was used as a competition index to compare yield differences between monocultures and mixtures. LER is the sum of the ratios of an intercropped yield of a species to the yield of that species in monoculture (Equation 1).

$$LER = \frac{Intercrop\ Yield_A}{Monoculture\ Yield_A} + \frac{Intercrop\ Yield_B}{Monoculture\ Yield_B} + \cdots + \frac{Intercrop\ Yield_N}{Monoculture\ Yield_N} \qquad \text{(Eq. 1)}$$

When an LER is greater than 1, the intercrop uses less space to grown an equivalent amount of biomass than in monoculture (Vandermeer, 1992).

Crop Growth Rate

Crop growth rate (CGR) was used to compare biomass production over time for each species in monoculture and in each mixture (Equation 2).

$$CGR = \frac{BiomassT2 - BiomassT1}{Time2 - Time1} \qquad \text{(Eq. 2)}$$

The difference of the biomass of each species for each treatment was measured between the initial planting (i.e. seed weight) and the first sampling date (0 to approximately 45 DAP) and also between the first and second sampling date (approximately 45 to approximately 90 DAP).

Species Evenness

Species evenness by biomass was used to assess the relative production of each species in the intercropped treatments and species dominance (Equation 3).

$$\text{Species evenness} = -\,\frac{\sum[\mathrm{P(i)} * \ln \mathrm{P(i)}]}{\ln(S)} \qquad \text{(Eq. 3)}$$

The numerator is Shannon's diversity index, the sum of the proportions of the amount of biomass of a species in an intercrop divided by the total biomass of the intercrop multiplied by the natural log (ln) of that proportion for every species in the intercrop. The denominator is the natural log of the number of species in the intercrop (*S*). Species evenness is bounded between 0 and 1, with 1 meaning equal amount of biomass for each species in the intercrop.

Statistical analysis

Data from all sites and years were analyzed using JMP Pro 10 (SAS Institute Inc., Cary, NC, 1989-2007). Data from the different sampling dates were analyzed separately. A mixed effect analysis of variance (ANOVA) was used to test for treatment differences for the response variables of crop biomass, weed biomass, land equivalent ratio, crop growth rate, and species evenness. The response variables were transformed for the ANOVA using natural log, except for weed biomass in the second sampling, which used a square root transformation. The data shown are untransformed means. Treatment, site-year, and their interaction were considered fixed effects. At first, site-year and block, nested within site-year, were considered random effects, but after seeing a significant interaction between forage species treatment and site-year, each site-year was analyzed individually. Forage species treatment was then considered the only fixed effect and block was maintained as the random effect. A Tukey Honest Significance Difference (HSD) test was performed to compare treatment means at $\alpha = 0.05$.

RESULTS

Environmental Conditions

In 2013, spring in the Northeastern United States was dryer than normal until mid-June when six consecutive weeks of frequent rainfall events began, which led to higher than normal precipitation in June for all three sites (Table 3). Overall, 2013 had more precipitation than the 30-year mean, largely due to rainfall in June. The first half of the field season was marked by warmer than average temperatures and cooler than average temperatures in the second half of the season at all sites.

Table 3: Monthly precipitation and temperature at the Aurora, NY; Beltsville, MD; and Willsboro, NY field stations in 2013 and 2014 growing seasons, as well as 30-year normal.

	Aurora			Beltsville			Willsboro		
Month	Normal†	2013	2014	Normal	2013	2014	Normal	2013	2014
	Total monthly precipitation (mm)								
Apr.	82.8	56.4	89.9	85.1	50.8	132.1	59.4	54.6	93.0
May	80.3	74.2	99.3	109.7	93.2	225.8	70.1	130.0	100.1
June	95.5	146.1	69.6	94	193.0	72.9	89.4	252.2	110.5
July	89.4	82.3	110.0	100.1	74.9	78.5	87.4	73.4	140.7
Aug.	80.3	93.5	108.0	83.1	79.8	80.8	97.8	84.1	52.1
Sept.	101.9	100.1	54.4	103.6	49.3	81.0	64.8	120.4	41.4
Oct.	86.9	85.9	51.4	93.2	158.8	39.6	76.5	65.8	105.9
Total	617	638.3	582.5	668.8	699.8	710.7	545.3	609.1	643.6
	Average monthly temperature (◦C)								
Apr.	7.9	7.7	7.8	12.1	12.8	11.8	6.8	7.0	6.9
May	14.2	16.1	15.2	17.4	17.2	18.0	13.2	14.6	14.1
June	19.4	18.8	20.0	22.7	23.2	22.8	18.6	17.8	19.1
July	21.7	22.2	20.4	25.2	25.7	24.1	21.5	21.9	20.7
Aug.	20.9	19.6	19.3	24.3	23.1	23.0	20.3	19.6	19.2
Sept.	16.9	15.6	16.4	20.2	19.6	20.5	16.1	15.1	15.8
Oct.	10.5	12.0	11.9	13.6	11.6	18.4	9.1	10.3	11.0
Avg.	20.9	16.0	15.9	19.4	19.0	19.8	15.1	15.2	15.2

† Normal precipitation and temperatures are based on 30-yr means (1981-2010).

The Aurora and Willsboro field sites were seeded in late July. The 13 Wil site-year was sampled only once, due to the later planting date (24 July) and cooler climate of northeastern New York. The second sampling in 13 Bel-L site-year was delayed because the government furlough shut down the field site. During this time, a severe windstorm caused lodging in many plots at this site.

Total precipitation in 2014 in Aurora was lower than the 30-year normal, but above the normal in Beltsville and Willsboro. July had more precipitation than average for Aurora and Willsboro and September was drier than average for Aurora and Beltsville. Aurora had a cooler than normal year in 2014. The 14 Aur-L and 14 Bel site-years were planted after wheat was harvested.

Crop Production

Crop biomass varied by year and was nearly double in 2013 compared to 2014, which was likely due to the warmer temperatures in the first year (Table 3). The ANOVA results for crop biomass showed an interaction between the forage crop treatment and site-year at both sampling dates (Table 4); for this reason, site-years were analyzed separately (Table 5).

Table 4: Results from the Analysis of Variance (ANOVA) testing the effect of forage crop treatment (monoculture, 3-species, and 4-species intercrop), year, and their interaction on crop and weed biomass, land equivalent ratio (LER), and species evenness data.

	Crop biomass		Weed biomass		LER		Species evenness	
1st sampling	DF[†]	*P*	DF	*P*	DF	*P*	DF	*P*
Site-year	8	<0.001	8	<0.001	4	0.568	4	0.001
Treatment	8	<0.001	7	<0.001	7	0.038	8	<0.001
Treatment*Site-year	64	<0.001	56	0.406	28	0.320	32	0.001
2nd sampling	DF	*P*	DF	*P*	DF	*P*	DF	*P*
Site-year	8	<0.001	8	0.001	4	0.039	4	<0.001
Treatment	7	<0.001	6	<0.001	6	0.168	7	<0.001
Treatment*Site-year	56	<0.001	48	0.353	24	0.543	28	0.019

† DF, degrees of freedom

Table 5: Results from the Analysis of Variance (ANOVA) testing the effect of forage crop treatment (monoculture, 3-species, and 4-species intercrop) on crop and weed biomass, land equivalent ratio (LER), and species evenness data separately by site-year (Table 1).

Sampling Period	Location	Crop biomass		Weed biomass		LER		Species evenness	
		DF[†]	*P*	DF	*P*	DF	*P*	DF	*P*
1st sampling	13 Bel-E	8	0.001	--	--	4	0.073	4	0.378
	13 Bel-L	8	0.007	8	0.006	--	--	4	0.013
	14 Bel	8	<0.001	8	0.002	4	0.382	4	0.049
	13 Aur	8	<0.001	8	0.402	4	0.920	4	0.007
	14 Aur-E	8	0.054	8	0.039	4	0.855	4	0.335
	14 Aur-L	8	0.001	8	0.039	4	0.698	4	0.093
	13 Wil	8	<0.001	8	0.404	4	0.817	4	0.068
	14 Wil-E	8	<0.001	8	<0.001	4	0.308	4	0.275
	14 Wil-L	8	<0.001	8	0.211	4	0.646	4	0.001
		DF	*P*	DF	*P*	DF	*P*	DF	*P*
2nd sampling	13 Bel-E	8	<0.001	--	--	4	0.050	4	0.771
	13 Bel-L	8	<0.001	8	0.046	--	--	4	0.220
	14 Bel	8	0.001	8	0.005	4	0.315	4	0.002
	13 Aur	8	<0.001	8	0.912	4	0.752	4	0.001
	14 Aur-E	8	<0.001	8	0.006	4	0.686	4	0.120
	14 Aur-L	8	0.000	8	<0.001	4	0.171	4	0.110
	14 Wil-E	8	<0.001	8	0.001	4	0.487	4	0.040
	14 Wil-L	8	<0.001	8	0.317	4	0.023	4	<0.001

† DF, degrees of freedom

In general, the grass monocultures and all intercrops produced similar amounts of biomass in both sampling dates (Figure 1 and Figure 2). Legumes in monoculture produced the least amount of biomass of all forage species, but mixtures containing two legumes did not produce less than mixtures containing two grasses. Grasses produced more biomass in mixtures than either of the legumes. Sorghum sudangrass produced more biomass than pearl millet in mixtures containing both grasses. In 2013, pearl millet produced more biomass than sorghum sudangrass. Biomass production was greatest at the 13 Bel-E site-year with 8,000 and 16,000 kg ha^{-1} in the first and second sampling date, respectively. The short growing season for the 14 Wil-L site-year led to lower biomass. The field used in 14 Aur-L was seeded after wheat harvest in late July and suffered from poor field conditions and competition from wheat volunteers. The early seeding dates and more southern locations were more conducive to biomass production. In general, the mixtures that performed well in the first sampling, performed well in the second sampling in relation to other mixtures.

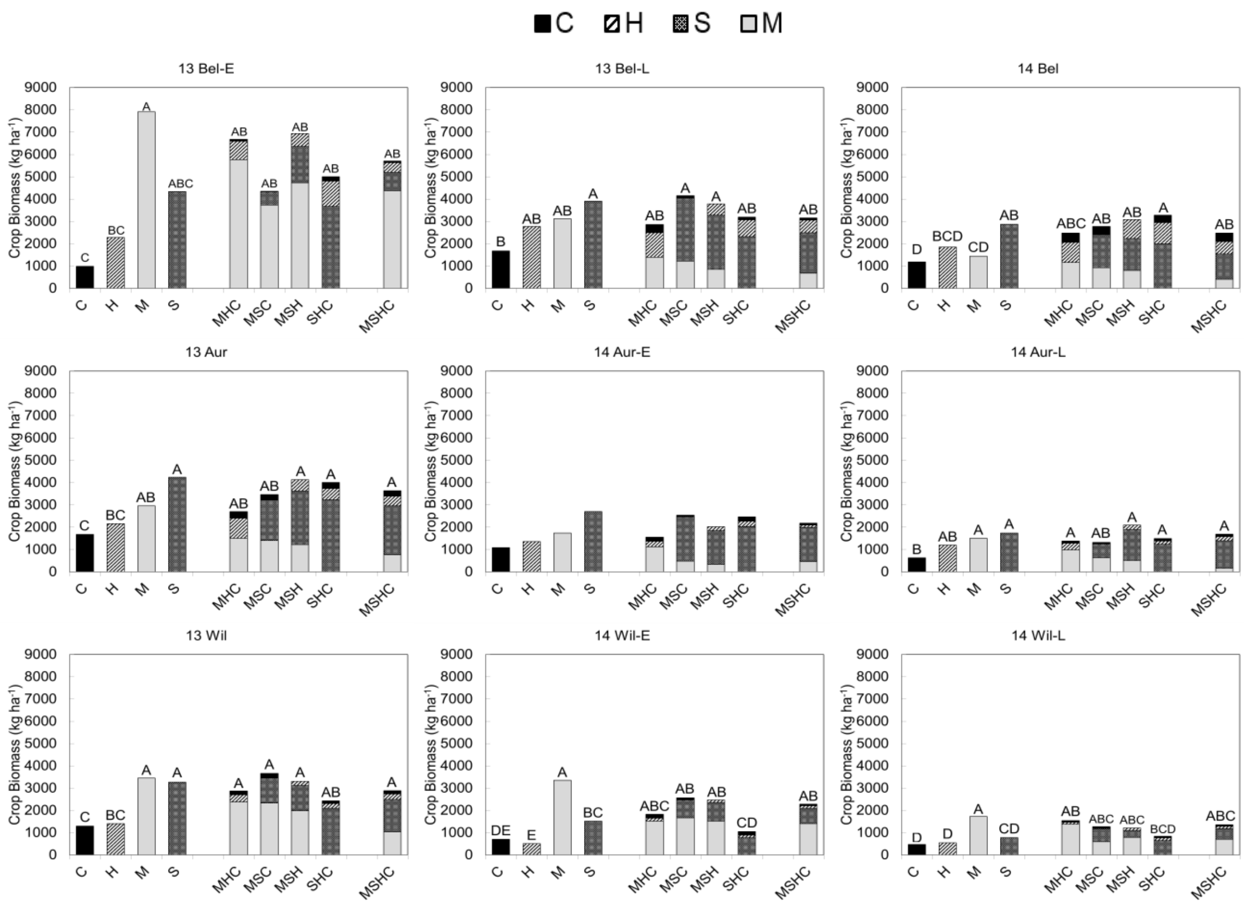

Figure 1: Crop biomass by species composition for the first sampling across site-years (Table 1). Same letters above bars indicate no significant differences in total crop biomass at $P < 0.05$. Lack of letters above bars indicate no significant differences between treatments. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

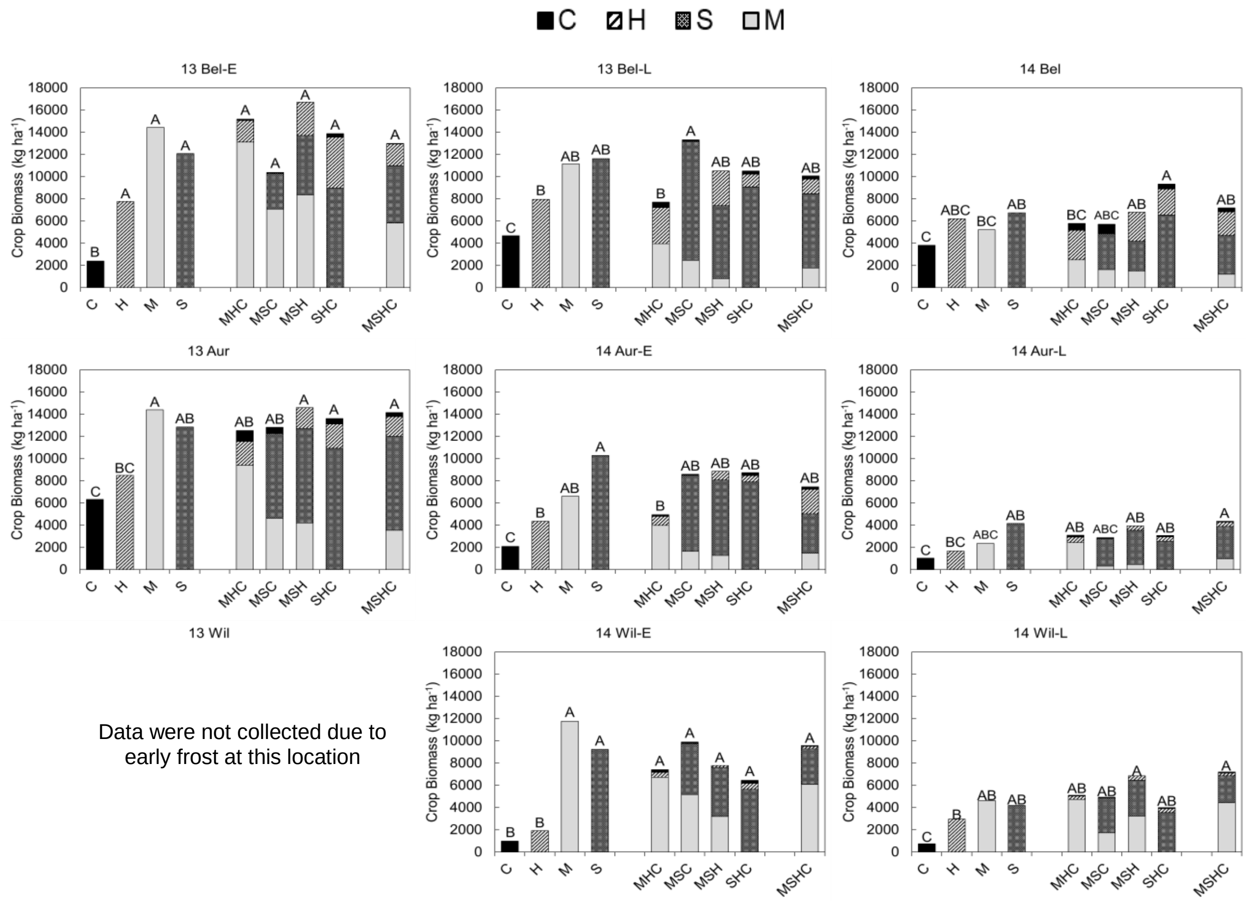

Figure 2: Crop biomass by species composition for the second sampling across site-year (Table 1). A second sampling was not done at 13 Wil. Same letters above bars indicate no significant differences in total crop biomass at $P < 0.05$. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Land Equivalent Ratio (LER)

The LER for intercrops was calculated within each block for each site-year and then the index was analyzed using the same mixed models used for crop biomass (Table 5). Land equivalent ratios were not analyzed for the 13 Bel-L site-year because the sampling method was completely randomized, and not blocked. Almost all LER values were above 1 indicating that the intercrop treatments were more efficient at biomass accumulation than monocultures (Table 6). Some LER values were close to 2 indicating that the intercrop was close to twice as efficient at producing biomass as monocultures, values like this or higher are mostly likely due to poor production of the monoculture treatments in that site-year. At the second sampling date, LER values were more variable and the 4-species intercrop had on average the greatest LER. However intercrop LER values were not significantly different between treatments at either sampling date for any site-year (Table 5). The 13 Bel-E site-year had the most variable LER values, particularly in the first sampling date, most likely due to the variability of the field site. Whereas 14 Wil-L had lower biomass production than other locations, mixtures outperformed monocultures in terms of land use efficiency with LER values consistently well above 1.

Table 5: Land equivalent ratio (LER) and standard error (SE) for the mixtures at each site-year (Table 1) for the two sampling dates. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

		MHC		MSC		MSH		SHC		MSHC	
Sampling Period	Location	LER	SE	LER	SE	LER	SE	LER	SE	LER	SE
First	13 Bel-E	1.33	0.13	0.78	0.11	1.69	0.29	3.60	1.01	1.07	0.21
	14 Bel	1.68	0.09	1.48	0.08	1.51	0.06	1.52	0.06	1.35	0.07
	13 Aur	1.18	0.07	1.22	0.07	1.30	0.09	1.13	0.06	1.29	0.08
	14 Aur-E	1.05	0.20	1.03	0.12	1.09	0.09	1.14	0.05	0.99	0.22
	14 Aur-L	1.10	0.10	1.13	0.19	1.38	0.10	1.14	0.13	1.19	0.02
	13 Wil	1.13	0.10	1.23	0.09	1.15	0.07	0.96	0.10	1.06	0.09
	14 Wil-E	1.18	0.06	1.43	0.11	1.45	0.13	1.04	0.08	1.52	0.19
	14 Wil-L	1.19	0.04	1.30	0.06	1.22	0.10	1.31	0.06	1.46	0.04
Second	13 Bel-E	1.26	0.12	0.68	0.07	1.26	0.18	1.44	0.08	1.04	0.15
	14 Bel	1.11	0.10	1.06	0.06	1.16	0.05	1.47	0.09	1.21	0.03
	13 Aur	1.11	0.06	1.08	0.09	1.23	0.03	1.29	0.08	1.22	0.04
	14 Aur-E	1.01	0.21	1.04	0.09	1.09	0.05	1.07	0.01	1.36	0.18
	14 Aur-L	1.65	0.17	0.81	0.06	1.17	0.05	1.18	0.11	1.66	0.12
	14 Wil-E	1.41	0.08	1.18	0.10	1.01	0.10	1.44	0.10	1.19	0.06
	14 Wil-L	1.48	0.12	1.29	0.07	1.81	0.10	1.26	0.09	2.01	0.16

Crop Growth Rate (CGR)

Generally, all species had higher CGRs in monoculture than when intercropped (Table 6). Average growth rates for the grasses were at least twice as high as the legumes in monoculture (Table 7). The differences of the CGR between grasses and legumes were even more evident when the species were intercropped. Between seeding and the first sampling, the CGRs for pearl millet and sorghum sudangrass were lower in MSH and MSC, intercrops that contained both grasses. The CGRs were greater at the end of the growing season (between the first and second sampling) than the CGR for the first half of the season (between planting and the first sampling). Sorghum sudangrass CGR appears to be less affected by competition during the first sampling period with one-third of the nine site-years not showing differences between monoculture and mixtures. Unlike sorghum sudangrass, cowpea showed a large difference in CGR between monoculture and mixtures but not between mixtures.

The CGRs in 13 Bel-E and 13 Aur site-years were very high during the second sampling period suggesting the location and weather were ideal at that time for the forage species. On the other hand, very small growth rates were seen for cowpea in 14 Wil-E and 14 Wil-L during the second sampling period, indicating that the Willsboro field site was too cold for ideal growth. In some cases, CGR was negative; while plant death is possible, this was more likely an artifact of sampling methodology. Pearl millet in the second sampling period showed the greatest growth rate when in monoculture. One factor contributing to a high growth rate for pearl millet and a low one for cowpea during the first sampling period is the small seed size of pearl millet and large size for cowpea.

Table 6: Results from the Analysis of Variance (ANOVA) testing the crop growth rate of each forage crop species on forage mixtures for each site-year (Table 1). C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

	Location	CGR							
		M		S		H		C	
		DF	*P*	DF	*P*	DF	*P*	DF	*P*
1st sampling	13 Bel-E	4	0.237	4	0.203	4	<0.001	4	0.068
	13 Bel-L	4	0.004	4	0.052	4	<0.001	4	<0.001
	14 Bel	4	<0.001	4	0.007	4	0.012	4	<0.001
	13 Aur	4	0.004	4	0.014	4	<0.001	4	<0.001
	14 Aur-E	4	0.003	4	0.302	4	<0.001	4	<0.001
	14 Aur-L	4	0.001	4	0.046	4	<0.001	4	<0.001
	13 Wil	4	0.041	4	0.009	4	<0.001	4	<0.001
	14 Wil-E	4	0.010	4	0.334	4	<0.001	4	0.002
	14 Wil-L	4	<0.001	4	<0.001	4	0.001	4	0.002
		DF	*P*	DF	*P*	DF	*P*	DF	*P*
2nd sampling	13 Bel-E	4	0.584	4	0.343	4	0.255	4	0.203
	13 Bel-L	4	0.034	4	0.315	4	0.204	4	<0.001
	14 Bel	4	0.008	4	0.028	4	0.206	4	0.001
	13 Aur	4	0.001	4	0.381	4	<0.001	4	<0.001
	14 Aur-E	4	0.028	4	0.013	4	0.086	4	0.002
	14 Aur-L	4	0.182	4	0.713	4	0.142	4	0.038
	14 Wil-E	4	0.098	4	0.018	4	0.002	4	0.588
	14 Wil-L	4	0.084	4	0.357	4	<0.001	4	0.258

Table 7: Crop growth rate (CGR) for each forage species between planting and the first sampling and between the first and second samplings by site-year (Table 1). A second sampling was not done at 13 Wil. The "—" symbol indicates a species absence in the mixture. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet; Mono, monoculture.

		Crop growth rate (kg $ha^{-1}day^{-1}$)															
		Planting to 1st sampling date								1st to 2nd sampling date							
Location	Forage species	M		S		H		C		M		S		H		C	
13 Bel-E	Mono	15.5†		4.3		4.4	A	1.3		24.1		33.6		20.3		3.9	
	MHC	11.3		—		1.6	BC	0.1		27.2		—		4.3		0.1	
	MSC	7.3		1.2		—		<0.1		9.9		7.7		—		0.1	
	MSH	9.3		3.2		1.1	BC	—		13.4		13.7		6.2		—	
	SHC	—		7.2		2.2	B	0.3		—		19.6		12.8		0.5	
	MSHC	8.6		1.6		0.8	C	0.1		6.3		14.2		5.5		-0.2	
13 Bel-L	Mono	7.3	A	8.9	A	6.3	A	3.7	A	18.4	a	16.7		11.2		6.5	a
	MHC	3.2	AB	—		2.5	B	0.8	B	6.0	ab	—		4.8		0.4	b
	MSC	2.8	AB	6.5	AB	—		0.2	B	2.6	ab	17.2		—		0.1	b
	MSH	2.0	B	5.6	AB	1.1	C	—		-0.2	b	9.2		5.7		—	
	SHC	—		5.3	AB	1.7	BC	0.2	B	—		14.1		0.7		0.4	b
	MSHC	1.6	B	4.2	B	1.3	BC	0.2	B	2.4	ab	11.0		1.6		0.5	b
14 Bel	Mono	3.0	A	6.0	A	3.8	A	2.4	A	9.0	a	9.2	a	10.4		6.3	a
	MHC	2.4	AB	—		1.9	AB	0.8	B	3.2	ab	—		4.2		0.4	b
	MSC	1.9	AB	3.1	B	—		0.7	B	1.7	b	4.1	ab	—		1.2	ab
	MSH	1.7	BC	3.0	B	1.7	AB	—		1.7	b	3.0	b	4.2		—	
	SHC	—		4.2	AB	2.0	AB	0.7	B	—		10.8	a	3.3		0.3	b
	MSHC	0.9	C	2.4	B	1.1	B	0.8	B	1.9	b	5.6	ab	3.7		<0.1	b
13 Aur	Mono	6.6	A	9.3	A	4.7	A	3.6	A	35.7	a	26.9		19.8	a	14.5	a
	MHC	3.3	AB	—		2.0	B	0.6	B	24.7	ab	—		3.8	b	2.2	b
	MSC	3.1	AB	4.0	B	—		0.5	B	10.1	bc	18.2		—		1.0	b
	MSH	2.7	B	5.3	AB	1.1	C	—		9.2	bc	18.8		4.2	b	—	
	SHC	—		7.2	AB	1.1	C	0.5	B	—		24.1		5.2	b	0.7	b
	MSHC	1.7	B	4.8	B	0.9	C	0.5	B	7.5	c	19.9		4.1	b	0.6	b
14 Aur-E	Mono	3.7	A	5.7		2.8	A	2.2	A	11.8	a	16.9	a	6.7		2.2	a
	MHC	2.4	AB	—		0.5	B	0.3	B	6.4	ab	—		1.3		-0.1	b
	MSC	1.0	B	4.3		—		0.1	B	2.6	ab	10.8	ab	—		0.1	b
	MSH	0.7	B	3.2		0.3	B	—		2.1	ab	11.7	ab	1.4		—	
	SHC	—		4.4		0.5	B	0.4	B	—		13.0	a	0.8		0.1	b
	MSHC	1.0	B	3.3		0.2	B	0.2	B	2.3	b	4.4	b	4.7		0.3	b

14 Aur-L	Mono	2.5	A	2.8	A	1.9	A	0.9	A	5.1		14.3		2.7		2.3	a
	MHC	1.6	AB	—		0.5	B	0.1	B	8.6		—		1.1		0.5	ab
	MSC	0.8	BC	0.7	B	—		0.1	B	-0.9		11.8		—		0.2	ab
	MSH	0.8	BC	2.3	AB	0.3	B			-0.3		10.0		1.1		—	
	SHC	—		2.0	AB	0.2	B	0.1	B	—		7.8		1.4		<0.1	ab
	MSHC	0.3	C	2.0	AB	0.3	B	0.2	B	4.8		9.9		1.2		-0.2	b
13 Wil	Mono	6.5	A	6.0	A	2.5	A	2.3	A								
	MHC	4.5	AB	—		0.6	B	0.3	B								
	MSC	3.3	AB	1.6	B	—		0.3	B								
	MSH	3.7	AB	2.1	B	0.3	B	—									
	SHC	—		3.9	AB	0.4	B	0.2	B								
	MSHC	2.0	B	2.7	AB	0.4	B	0.3	B								
14 Wil-E	Mono	6.9	A	3.0		0.9	A	1.3	A	20.0		18.4	a	2.8	a	0.6	
	MHC	3.9	B	—		0.3	B	0.4	B	11.5		—		0.6	b	0.1	
	MSC	4.3	AB	2.0		—		0.2	B	7.4		8.6	ab	—		0.0	
	MSH	3.9	B	2.1		0.3	B	—		3.1		8.0	ab	0.1	b	—	
	SHC	—		2.0		0.3	B	0.3	B	—		11.1	ab	1.0	b	0.2	
	MSHC	3.7	B	1.8		0.2	B	0.2	B	10.3		5.6	b	0.2	b	-0.1	
14 Wil-L	Mono	17.0	A	7.0	A	1.1	A	0.9	A	6.5		7.6		5.4	a	0.6	
	MHC	3.0	C	—		0.2	C	0.1	B	7.5		—		0.4	b	<0.1	
	MSC	1.3	C	1.3	C	—		0.1	B	2.5		5.6		—		<0.1	
	MSH	7.9	B	2.9	BC	0.9	ABC	—		5.4		6.5		0.6	b	—	
	SHC	—		1.4	C	0.2	BC	0.1	B	—		6.4		0.5	b	0.1	
	MSHC	6.9	B	4.7	AB	0.8	AB	0.5	AB	8.3		4.2		0.3	b	0.1	

† Within columns for each species, means followed by same letters indicate no significant differences at $P < 0.05$ within site-year and sampling date. Lack of letters next to means indicate no significant differences between treatments. Uppercase letters are designated for the first sampling date and lowercase for the second sampling date.

Species Evenness

Significant differences in species evenness occurred in approximately half of the site-years. At the first sampling date, MSH was typically the most even treatment, meaning all species in the intercrop contributed similar amounts of biomass (Figure 3). The other two intercrops that contained both grasses also tended to have more even mixtures. Species evenness decreased for all mixtures between the first and second sampling indicating a shift toward asymmetric competition, particularly for the three species mixtures containing two legumes. The MSH intercrop was an exception, maintaining evenness in one-third of the site-years. Generally, SHC had the lowest evenness of all the intercrops for both sampling dates, which is a result of very low cowpea biomass produced in this treatment. The lowest species evenness of any overall site-year was in13 Bel-E site-year with treatments having around 0.5 evenness due to the prolific biomass production of pearl millet. The two legume mixtures in the14 Wil-L site-year had particularly low evenness with MHC evenness dipping to 0.25 in the second sampling. This is most likely due to pearl millet succeeding in colder climates compared to the two tropical legumes. Very high evenness for both sampling dates occurred in the 14 Bel site-year, which can be seen by the even biomass composition (Figures 1 and 2).

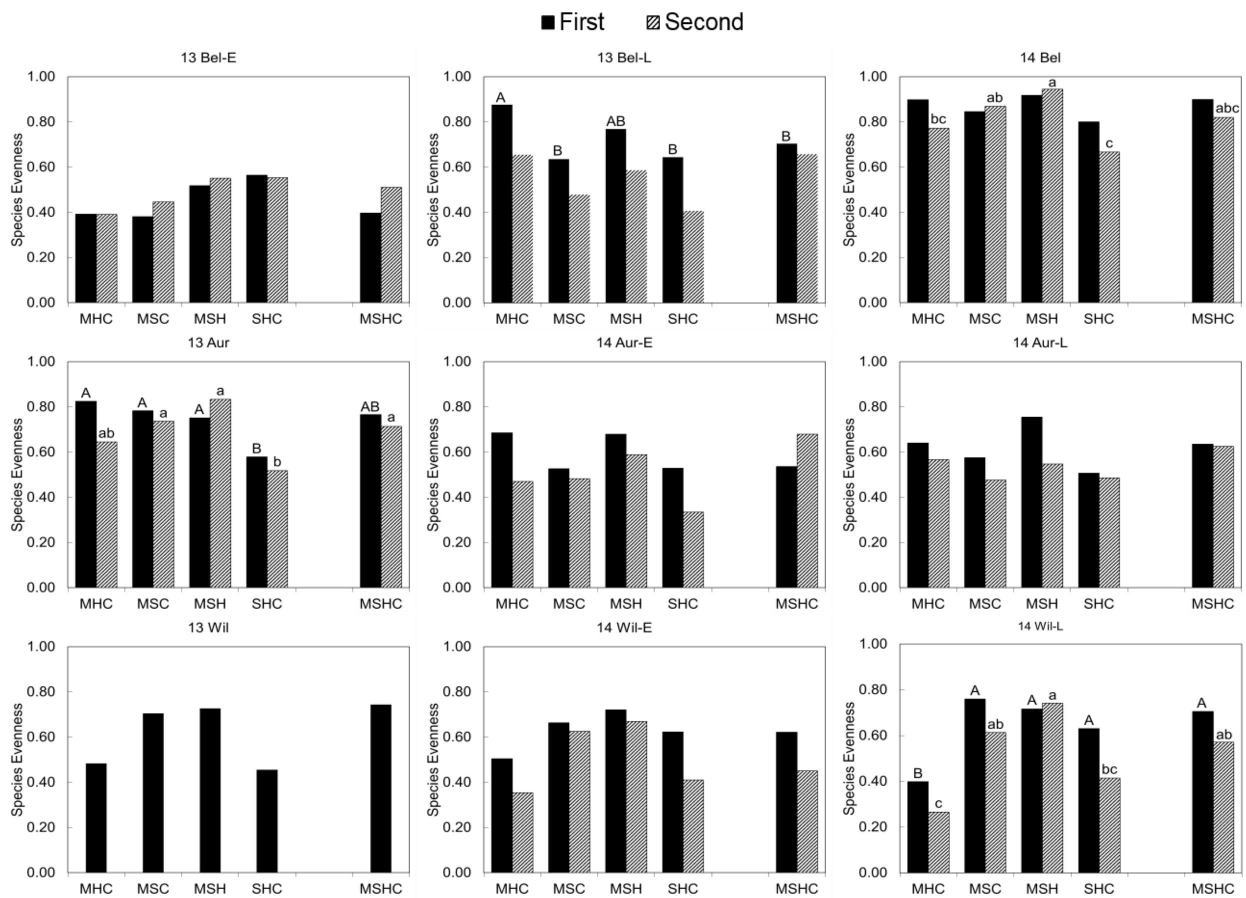

Figure 3: Species evenness for each site-year at the first (black bars) and second sampling (grey bars) for each site-year (Table 1). Same letters above bars indicate no significant differences in species evenness for the intercrops at *P* < 0.05. Lack of letters above bars indicate no significant differences between treatments. A second sampling was not done at 13 Wil. Uppercase letters are designated for the first sampling date and lowercase for the second sampling date. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Weed Biomass

Most weeds observed were summer annuals including common ragweed (*Ambrosia artemisiifolia* L.), pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), witchgrass (*Panicum capillare* L.), yellow mustard (*Brassica rapa* L.), foxtails (*Setaria* spp), venice mallow (*Hibiscus trionum* L.), and yellow nutsedge (*Cyperus esculentus* L.). Common ragweed, pigweed, and common lambquarters contributed the most biomass across site-years based on coarse visual estimates. In addition to these weeds, yellow mustard was the most abundant weed observed in the 14Aur-E site-year. Volunteer canola (*Brassica oleracea* L.) and wheat affected some experimental units, particularly the legumes in monoculture at 13Wil and 14Aur-L site-years, respectively.

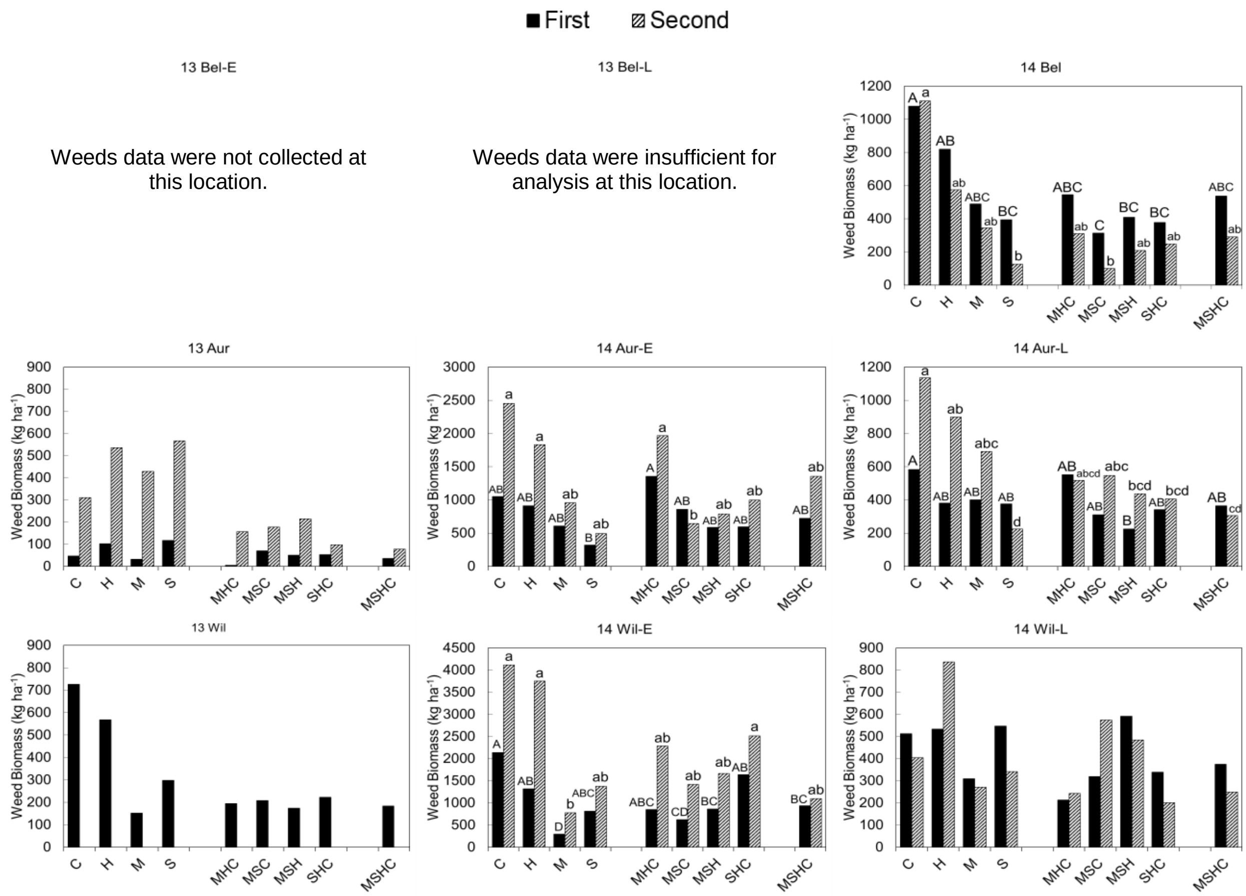

Figure 4: Weed biomass by forage species treatment for the first (black bars) and second sampling (grey bars) for each site-year (Table 1). The second sampling used a square root transformation instead of a log transformation on weed biomass. Weeds data were not collected for 14 Bel-E and insufficient for 14 Bel-L. A second sampling was not done at 13 Wil. Same letters above bars indicate no significant differences in weed biomass at $P < 0.05$. Lack of letters above bars indicate no significant differences between treatments. Uppercase letters are designated for the first sampling date and lowercase for the second sampling date. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

The two legume monoculture treatments had the greatest weed biomass in all site-years, particularly in 14 Wil-E (Figure 4). In general, grass monoculture and intercrops treatments produced similarly low weed biomass. Across site-years, MSHC had the lowest weed biomass at the second sampling date, suggesting that resources were more fully utilized by crops in this treatment. Most experimental plots in 13 Bel-L did not have weed biomass, for this reason there was not enough data to perform ANOVA. Interestingly, the early biomass sampling at 14 Bel produced more weeds than a later sampling date, while this could be a sampling artifact, it is consistent across treatments. One potential explanation is that early maturing weeds (e.g. *Barbarea vulgaris* L.) gained biomass quickly and then senesced prior to the second sampling date. Weed biomass ranged widely within locations (10 to 600 kg ha^{-1}), as well as between them (600 to 4,000 kg ha^{-1}). It appears that planting at a later date in mid-July rather than mid-June results in lower weed biomass, which is consistent with other research on weed emergence periodicity.

Weed biomass tended to decrease as crop biomass increased (Figures 5 and 6). The 13 Aur site-year in the first sampling does not fit the downward trend of points, but had the lowest weed biomass of any site-year. The 13 Wil site-year definitively illustrates the differences between the high weed and low crop biomass of legume monocultures and the high crop and low weed biomass of treatments containing grasses. The MSH intercrop appears to have the highest crop and lowest weed production of all mixtures across most locations. In the second sampling period, the downward trend appears more resolute with the grass monocultures located at the bottom right. The 14 Wil-L site-year does not fit this trend probably because conditions were less than ideal for crop growth and that the weed species present were better conditioned for the northern climate.

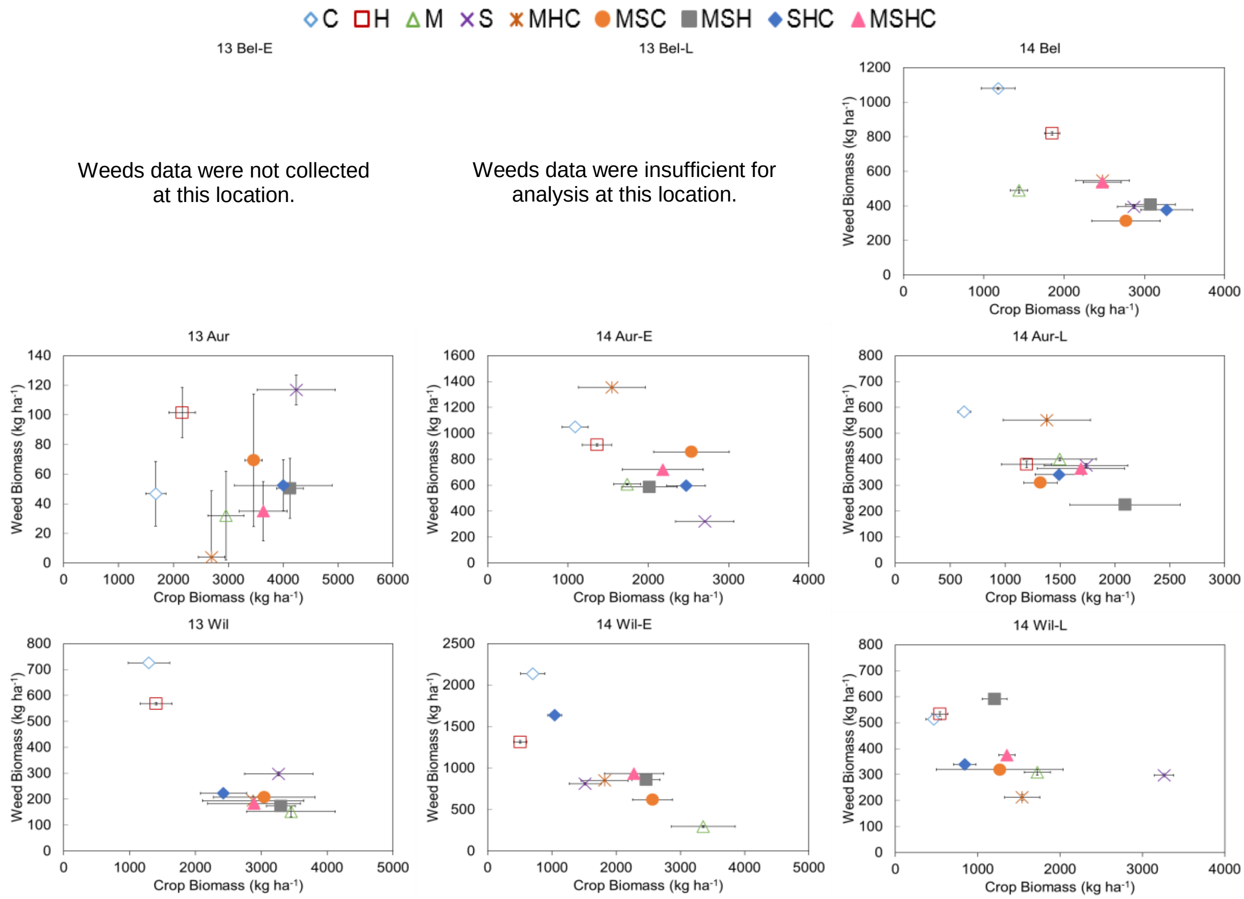

Figure 5: Mean crop biomass plotted with mean weed biomass for each forage species treatment for the first sampling at each site-year (Table 1). Horizontal error bars represent the standard error for crop biomass, whereas vertical error bars represent the standard error for weed biomass. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

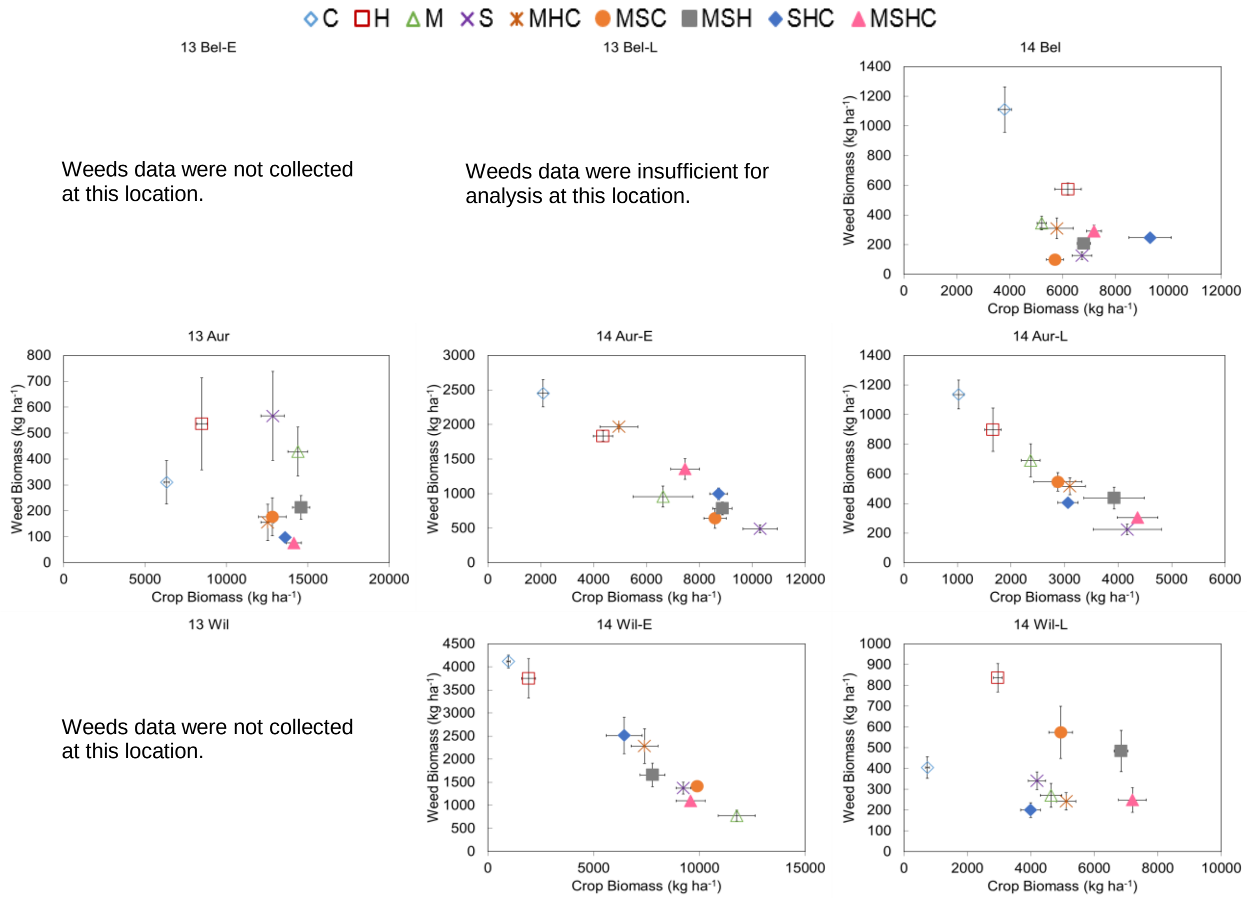

Figure 6: Mean crop biomass plotted with mean weed biomass for each forage species treatment for the second sampling at each site-year (Table 1). Horizontal error bars represent the standard error for crop biomass, whereas vertical error bars represent the standard error for weed biomass. A second sampling was not done at 13 Wil. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Species Richness

Species richness plotted with weed biomass for each location illustrates the range of weed biomass in monocultures compared to three or four species mixtures for the first and second sampling dates (Figures 7 and 8). A regression was fit to the data and a negative relationship between species richness and weed biomass was seen across most locations but it was not a strong linear relationship with many locations having correlations close to zero.

A more defined negative relationship is seen during the second sampling period with half of the available site-years showing significant linear regressions. In these second sampling the four species mixture in site-years 14 Bel, 13 Aur, and 14 Aur-L had the smallest range in weed biomass.

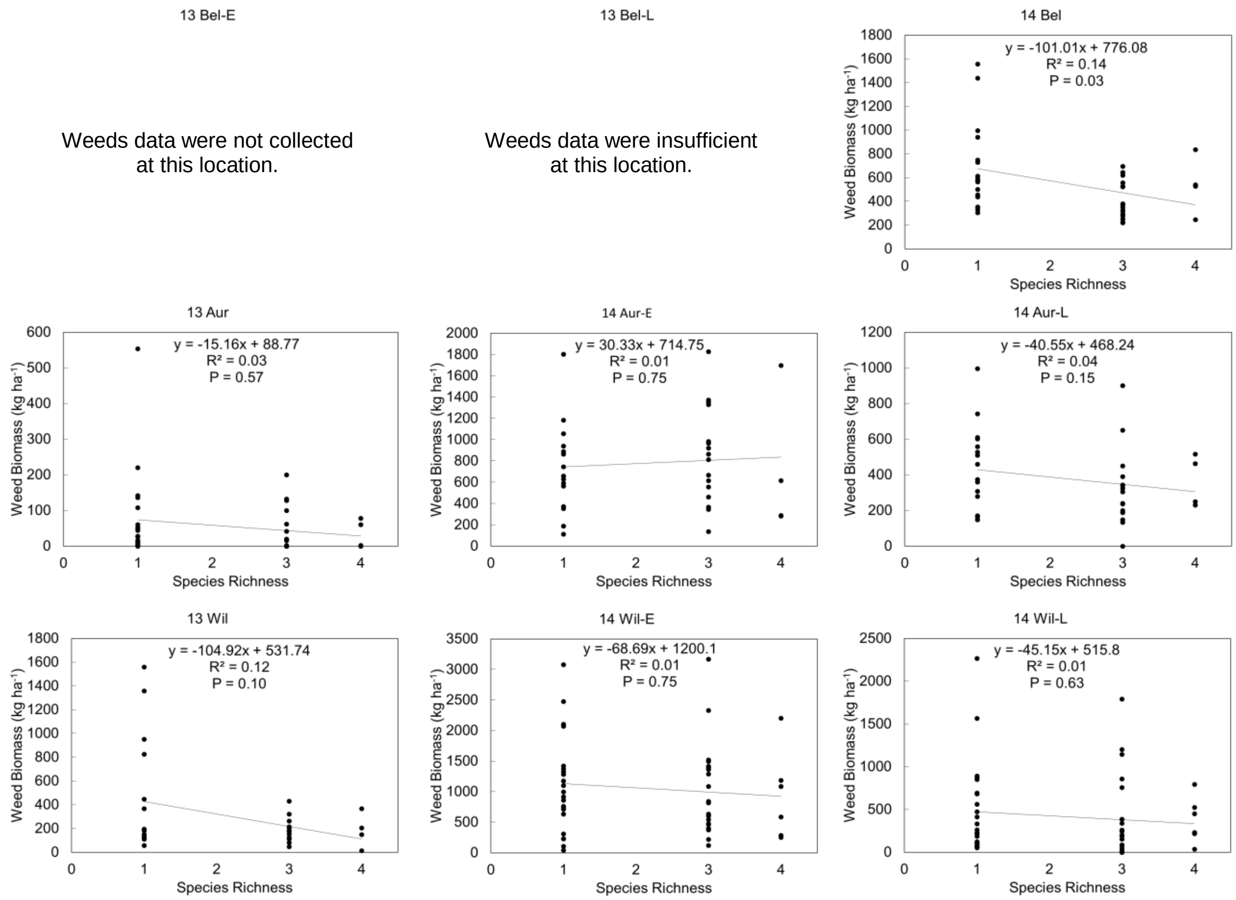

Figure 7: Species richness of treatments plotted with weed biomass for each forage species at each site-year (Table 1) at the first sampling. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

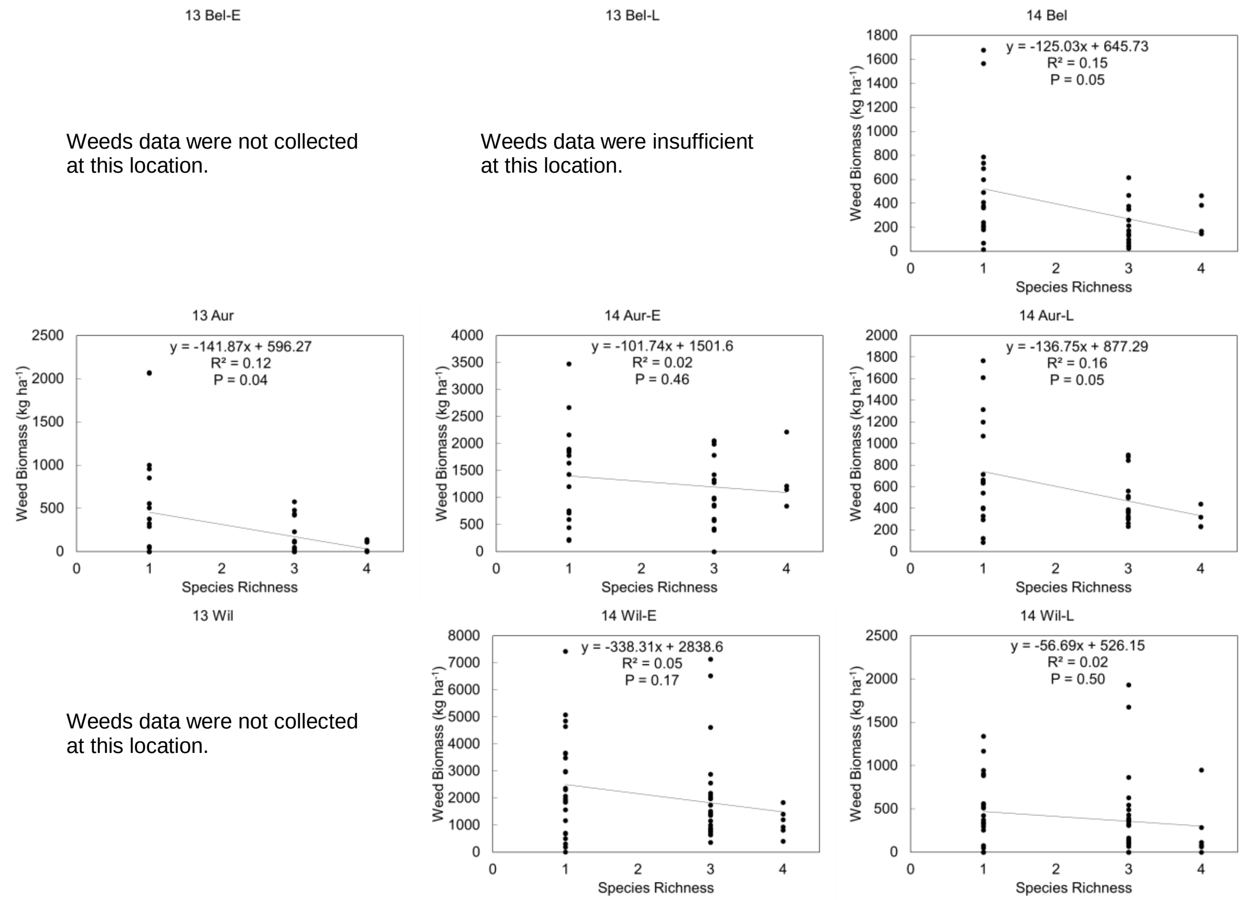

Figure 8: Species richness of treatments plotted with weed biomass for each forage species at each site-year (Table 1) at the second sampling date. A second sampling was not done at 13 Wil. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Economic Assessment

Pearl millet was the least expensive and most productive forage crop species, resulting in the greatest cost of production (Table 8). As biomass production increased between the sampling dates, the cost of production also increased (Table 9). Cost of production increased by a greater rate for the grasses than the legumes. The SHC intercrop was the most expensive mixture.

Crop biomass was relatively low in the SHC, making this intercrop the most expensive and least productive treatment. Site-years with later planting dates in 2014 generally had lower cost of production, highlighting the less than ideal growing conditions. 2013 generally had higher production per cost, particularly the more southern Beltsville locations.

Table 8: Calculated seeding cost per hectare. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Species	Cost per ha ($)
C	253.28
H	255.01
M	52.63
S	205.10
MHC	186.98
MSC	170.34
MSH	170.91
SHC	237.80
MSHC	191.51

Table 9: Calculated cost of biomass production for the first and second sampling dates for each site-year (Table 1). A second sampling was not done at 13 Wil. C, cowpea; H, sunn hemp; S, sorghum sudangrass; M, pearl millet.

Sampling Date	Species	Production per cost (kg dollar^{-1})								
		13 Bel-E	13 Bel-L	14 Bel	13 Aur	14 Aur-E	14 Aur-L	13 Wil	14 Wil-E	14 Wil-L
1st sampling	C	3.91	6.60	4.65	6.62	4.30	2.48	5.11	2.78	1.83
	H	8.96	10.90	7.26	8.46	5.34	4.69	5.50	1.99	2.12
	M	150.31	59.23	27.35	56.15	33.00	28.45	65.58	63.76	32.76
	S	21.18	19.06	13.99	20.65	13.18	8.47	15.91	7.39	3.76
	MHC	35.71	15.30	13.26	14.41	8.28	7.37	15.38	9.74	8.24
	MSC	25.55	24.32	16.27	20.31	14.89	7.76	21.46	15.06	7.44
	MSH	40.60	22.13	17.99	24.12	11.79	12.24	19.29	14.43	7.06
	SHC	21.05	13.44	13.78	16.83	10.39	6.27	10.20	4.38	3.54
	MSHC	29.81	16.45	12.92	18.98	11.39	8.83	15.08	11.90	7.08
2nd Sampling	C	9.47	18.47	15.05	24.96	8.26	4.04		3.84	2.92
	H	30.42	31.15	24.33	33.29	17.08	6.52		7.57	11.60
	M	274.14	211.84	99.06	273.39	125.82	44.95		223.51	88.11
	S	58.91	56.59	32.85	62.63	50.20	20.34		45.05	20.45
	MHC	81.24	36.55	30.93	67.02	26.49	16.58		39.61	27.34
	MSC	60.96	78.19	33.55	75.28	50.44	16.88		58.07	29.01
	MSH	93.32	61.48	39.81	85.35	51.89	22.97		45.54	40.04
	SHC	58.34	44.17	39.18	57.22	36.69	12.89		27.10	16.79
	MSHC	67.79	52.52	37.55	73.83	38.94	22.79		50.04	37.60

DISCUSSION

I tested the effects of intercropping on crop performance and weed suppression using four warm-season alternative summer annual forage crops grown in monoculture and three and four species combinations. The field experiment was conducted in 2013 and 2014 in Beltsville, MD, Aurora, NY, and Willsboro, NY for a total of nine site-years.

Crop Production

Overall, the two grasses produced greater biomass than the two legumes, both in monoculture and when intercropped. No yield benefit was observed when intercrop diversity increased from three to four species, but a smaller range of weed biomass production was seen. Other potential benefits, such as increased soil health and decreased insect pest populations, went unmeasured. We did not find support for the hypothesis that intercrops would produce more biomass than monocultures. The grasses in the intercrop treatments produced comparable biomass levels to the grasses grown in monoculture, despite being seeded at ⅓ or ¼ of the monoculture rate.

Legume crop biomass was within the range of yields reported in the literature, although the cooler climate of the Northeast likely limited their growth. This is particularly true for the Willsboro site, which was the northern most location. The cool temperatures in the summer of 2014 also contributed to lower crop production compared to the previous year. However, pearl millet yields from this experiment were greater than previous experiments. Sunn hemp is not commonly grown in the Northeast, thus this experiment provided a benchmark for future research. Sunn hemp monoculture yields at the second sampling (1,700 kg ha^{-1} in the 14 Aur-L site-year to 8,500 kg ha^{-1} in the 13 Aur site-year) were lower than sunn hemp yields (9,300 kg ha^{-1}) collected at 68 DAP in a green manure experiment in Vicosa, Brazil. On the other hand, pearl millet monoculture yields at the second sampling (2,400 kg ha^{-1} in the 14 Aur-L site-year to 14,400 kg ha^{-1} in site-years 13 Bel-E and 13 Aur) were on average higher than pearl millet yields (7,100 kg ha^{-1}) reported in the same experiment (Perin et al. 2006). In the Philippines, Lales and Mabbayad (1983) observed that sunn hemp seeded at 60 kg ha^{-1} produced 770 kg ha^{-1} of biomass when harvested at 30 DAP, approximately half the biomass of our findings of an average of 1,500 kg ha^{-1} at the first sampling. Creamer and Baldwin (2000) reported yields for cowpea, pearl millet, and sorghum sudangrass of 8,000, 4,000, and 6,700 kg ha^{-1} when seeded in monoculture at 78, 34, and 39 kg seed ha^{-1}, respectively, and harvested approximately 70 DAP in South Carolina. The cowpea biomass was much greater when seeded at a higher rate than this experiment in a warmer climate, whereas the pearl millet biomass was lower, despite being seeded at a higher rate than this experiment. Sorghum sudangrass biomass was similar for both experiments, suggesting the species adaptability to different climates.

Biomass production from this experiment was within the yield ranges of forages commonly grown in the Northeast. Monoculture average yields ranged from 2,500 (cowpea) to 9,300 (pearl millet) kg ha^{-1} with a low of 740 kg ha^{-1} (cowpea in the 14 Wil-L site-year) and a high of 14,400 kg ha^{-1} (pearl millet in site-years 13 Bel-E and 13 Aur). The intercropped forage species produced less biomass than corn silage but more biomass than alfalfa mixtures. The average biomass produced in intercrops ranged from 7,800 (MHC) to 9,600 (MSH) kg ha^{-1} with more biomass produced during warmer site-years and earlier planting dates. The average corn silage yield for 2011-2013 was 37,300 kg ha^{-1} in New York (NASS, 2014). Cox and Cherney (2001) fertilized corn for silage at reduced rate of 50 kg ha^{-1} of urea (46-0-0), compared with the 40 kg ha^{-1} of N used in this experiment, and reported silage yields of 18,800 kg ha^{-1}. Average alfalfa and alfalfa-grass intercrop yields for 2013 and 2014 were 5,300 kg ha^{-1} in New York (NASS 2014b). The intercropped forage species produced less biomass than corn silage but more biomass than alfalfa, all within a 90 day growing period.

Land Equivalent Ratio (LER)

Intercrops were more efficient in terms of biomass production per area than monocultures as shown by almost all LERs being above 1. Some LERs were unusually high indicating poor monoculture stands and thereby emphasizing the resilience and redundancy benefits of mixtures that are less likely to result in complete crop failure. The LERs had a mean of 1.29 and 1.27 for the first and second sampling date, respectively, indicating that each intercrop produced more than a quarter more biomass than if each species of the intercrop were planted in monoculture on the same amount of space. Since there was no significant difference between intercrop treatments, no one intercrop was superior in this regard, although MSC had the most LERs below 1.00. Similar results have been found in grass-legume experiments that have included some of the species tested here. Corn and cowpea intercrops in a dry region of eastern Kenya had a LER of 1.42 (Miriti et al. 2012) and 1.96 in an experiment in central Mozambique that had alternate rows of corn and cowpea (Rusinamhodzi et al. 2012). Pearl millet and groundnut (*Arachis hypogaea* L.) intercrop planted in a 1:3 ratio in Andhra Pradesh, India also had a similar mean LER of 1.28 (Marshall and Willey, 1983).

Crop Growth Rate (CGR)

Both grasses grew at a faster rate than legumes, although the grasses did have smaller seed sizes. Although previous research has shown that species with larger seed reserves, like cowpea, are better enabled at establishment (Liebman, Mohler, and Staver 2001), the grasses emerged faster (data not shown). Cowpea was a poor competitor overall, whereas sunn hemp was better able to compete with the grasses for light. Rapid and vigorous grass growth could be partially attributed to the added fertilizer. Low soil fertility would likely increase the competitive ability of the legumes (Vandermeer 1989). Bedoussac and Justes (2011) examined the effects of nitrogen availability in durum wheat-winter pea intercrops and reported that intercropping is more suitable in low nitrogen environments. Alternatively, other grass-legume experiments that describe stronger legume competition had greater legume-grass seeding rate ratios. For example, the intercrops Creamer and Baldwin (2000) tested were based on 60% of the monoculture seeding rate for legumes and 40% of monoculture seeding rate for grasses. Brainard et al. (2011) used a 50-50% seeding rate for the intercrops, but had a monoculture seeding rate of 168 kg ha^{-1} for cowpea and 56 kg ha^{-1} for sorghum-sudangrass. Clark and Myers (1994) used a seeding rate of 66% of the monoculture rate for cowpea and 44% of the monoculture rate for pearl millet in an intercrop. The greater growth rate of the grasses when intercropped could be due to the legume seeding rate being too low relative to the grasses.

Species Evenness

Competition and dominance was further explored by using crop biomass data to calculate species evenness. In the first sampling, fewer differences in evenness were detected among the forage mixtures; this can be attributed to less light competition affecting growth. The decrease in evenness over time suggests that as the growing season progressed, the grasses when intercropped asserted a greater dominance in biomass production. The MSH treatment was the most even intercrop because sunn hemp was the more competitive legume, decreasing the dominance of the grasses. Riday and Albrecht (2008) made similar observations, noting that the sunn hemp was better able to compete with corn for light compared to the other legumes tested. The MSHC treatment had the smallest difference in evenness between the first and second sampling date suggesting that the additional species prevented any one from dominating.

Weed Suppression

The results in this experiment show that intercrops were more weed suppressive than monocultures of legumes and had similar weed suppressive abilities to grass monocultures. However, only at the end of the growing season was there enough evidence to support the hypothesis that weed biomass decreased with increased species richness. Historically, forage legumes like cowpea and soybean were recommended for weed suppression (Muenscher, 1935). Variability in weed biomass at the second sampling differed greatly among experimental units, but did tend to decrease with increasing species richness. The 13 Aur and 14 Bel site-years are excellent examples of the tight clustering of weed biomass in mixtures (Figure 8), thereby strengthening the argument that mixtures tend to have lower weed biomass as well as lower variability of weed biomass. The MSHC treatment had better and more persistent weed suppression than other intercrops, which is consistent with other research. Species in intercropped treatments can complement each other using resources, like light, water, and soil that would otherwise be used by weeds. Creamer and Baldwin (2000) found that intercrops of sorghum sudangrass and cowpea produced consistent, high biomass and little weed growth. Picasso et al. (2008) reported that weed biomass decreased exponentially with an increasing number of forage species. Liebman and Dyck (1993) reviewed studies regarding intercropping as a tool for weed management and found that intercrops composed of two or more main crops suppressed more weeds than all the species in monoculture approximately half the time, while the other half the time intercrops suppressed more weeds than half of the species in monocultures.

Weeds suppression depends on field conditions and seed bank composition, as well as weather and agronomic practices. This led to interesting weed biomass responses in the separate site-years. In 13 Aur, 13 Wil, and 14 Wil-L, site-years with low weed biomass, there was no difference in weed biomass production between forage crop species treatments. On the other hand, the 14 Wil-E site-year had very high weed biomass, particularly in the legume monocultures and two legume mixtures, but the differences diminished as the growing season progressed. Planting these summer annual forages after wheat in mid-July did have some drawbacks. The later planting date reduced overall weed biomass but there were issues with wheat volunteers in the plots and lower crop biomass, which was likely due to nitrogen immobilization from wheat residue.

Economics

Pearl millet was the least expensive seed (\$3.70 kg^{-1}) and had the lowest seeding rate, resulting in a very low seeding cost. Because cowpea or sunn hemp are not widely grown in the United States, economies of scale have not been achieved to deliver this seed to farmers at a reasonable price. The sunn hemp seed used in this experiment was relatively expensive (\$5.70 kg^{-1}) and was imported from Tanzania. More common forage crops are less expensive but part of the purpose of this experiment was to explore alternative species, expanding the body of research available to those selecting seeds.

Conventional alfalfa seed costs for 2014 were \$9.00 kg^{-1}, approximately \$160 to \$200 ha^{-1} when seeded at the recommended amount of 20 to 25 kg ha^{-1}. Corn grown for silage when seeded between 60,000 and 90,000 plants ha^{-1} cost between \$163 and \$215 (Hancock Seed Company 2014). Although intercrops were more costly than pearl millet in monoculture, they were less costly than the other species in monoculture. All of the intercrops, apart from SHC, fall within the seed costs for alfalfa and corn silage.

Forage Quality

An important aspect of this research not included in this thesis is the analysis of forage quality for the selected forage species treatments. It is understood that as forage crops mature the ratio of digestible, nutritious fibers to indigestible, structural fibers becomes smaller. For this reason, we believe that the inverse relationship of biomass production and forage quality will mean higher forage quality for the first sampling date than the second sampling date (Titlow et al. 2012). Differences in forage quality between treatments likely exist with legumes contributing more crude protein. Sunn hemp, used regularly as a fiber crop, is predicted to have a lower digestibility, but we expect this characteristic to be offset when combined with other species (Rotar and Joy 1983). Although pearl millet produced the greatest biomass at the lowest cost, forage species mixtures likely had greater forage quality. In addition to yield and seed costs, farmers need to consider forage quality and effects of different forage crops on milk production or weight gain when deciding which crops to grow and whether or not to use intercropping.

Limitations

Aboveground plant material was collected twice to better understand the differences in crop growth rate and competition within a growing season. In order to maximize the forage quality of all species in an intercrop, some species were harvested before their optimal maturation date (data not shown). Because pearl millet is likely the most sensitive to a decrease in quality upon maturation and also the fastest maturating species chosen, its growth was used as the benchmark for sampling periods (Cherney personal communication, 2013). The results may have been affected by limiting the growth of later maturing species in favor of the pearl millet. The experimental design also limited our ability to make assumptions regarding functional traits or other mechanisms found in intercropping because each intercrop treatment contained at least one grass or one legume. Additional treatments of biculture intercrops of the four species would allow for better understanding of the effects of plant architecture and biological nitrogen fixation. Various seeding rate ratios of biculture treatments would assist in understanding the effects of seeding rates on productivity and efficiency. In addition to crop and weed production and forage quality, intercrops have other expected benefits that were not examined, these include but are not limited to increased soil health, increased diversity of soil microbes, pest suppression, disease suppression, and climate change mitigation (Lin, 2011; Walter Zegada-Lizarazu et al., 2006).

CONCLUSION

Results from this nine site-year experiment illustrate some of the benefits and challenges of using functional diversity to support the shift toward semi-closed nutrient cycling and regenerative agriculture. Intercropping with warm season annual forage crops can complement, and in some cases be a viable alternative to, corn silage and perennial forage crop production in the Northeast, although more work is needed in selecting more appropriate warm season summer annual legumes. The rapid growth of the warm season annual forage crops that were tested enables them to be established after failed corn silage. These crops can also be seeded early and harvested with ample time for a winter grain or cover crop, like barley or triticale, to be established. Thus in addition to increasing spatial diversity, mixed intercropping with warm season annul forage crops can facilitate increased temporal diversity and lead to greater cropping system flexibility, buffering against extreme weather events, and lower risk associated with crop failure.

Forage crop mixtures produced the same amount of biomass as pearl millet and sorghum sudangrass monocultures but had lower variability in weed biomass and used space more efficiently. The biomass production, land use efficiency, and weed suppressive abilities demonstrate a pathway to a more diverse cropping system. However, seed costs are important to consider if farmers are expected to adopt functionally diverse annual forage intercropping. Mixtures likely had higher forage quality than grass monocultures and seed costs for the mixtures were within the range of those for corn silage and alfalfa. Although intercropping grain crops presents logistical challenges with harvesting, our research shows that intercropping with functionally diverse forage crops can provide advantages. Future research should focus on identifying optimum mixtures that minimize costs while maximizing production and forage quality.

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