THESIS

INTERCROPPING ALFALFA WITH SELECT GRASS SPECIES FOR INCREASED YIELD AND QUALITY UNDER DEFICIT IRRIGATION

Submitted by

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ABSTRACT

INTERCROPPING ALFALFA WITH SELECT GRASS SPECIES FOR INCREASED YIELD AND QUALITY UNDER DEFICIT IRRIGATION

Drought and water scarcity have plagued the Western US for decades. As these issues become more prevalent, we must explore possibilities to utilize available water more efficiently. The objective of this study was to:

> Evaluate the ability of mixed and stripped intercropping alfalfa with grasses to increase yield and quality of the forage produced under deficit irrigation.

Alfalfa (*Medicago sativa*) is the most common forage grown in the West and is known for its high-water use. Intercropping alfalfa with perennial grasses can potentially improve water use efficiency. Orchardgrass (*Dactylis glomerata*), meadow brome (*Bromus biebersteinii*), and tall fescue (*Festuca arundinacea*) were mixed on the same bed or strip intercropped on alternating beds with alfalfa under 100% and 60% ET irrigation regimes using subsurface drip irrigation. Three cuts occurred in 2021 and 2022, with deficit irrigation starting after cut one. Yield, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), neutral detergent fiber digestibility (NDFD), and relative feed value (RFV) were analyzed in this study. During year one, irrigation did not have a significant impact on yield due to high precipitation and the fact that alfalfa performs well under deficit irrigation. Quality was not affected by irrigation treatments throughout both years of this study. Planting treatments significantly impacted yield

and all quality parameters throughout this study. In 2021, mixed intercropping treatments averaged 14,210 kg ha^{-1}, stripped treatments averaged 12,285 kg ha^{-1}, and alfalfa averaged 13,406 kg ha^{-1}; significant differences were not present. All mixed treatments, tall fescue stripped, and meadow brome stripped yields were similar to alfalfa in 2021. In 2021, quality was generally only reduced in mixed intercropping treatments compared to alfalfa in the first cutting. The inclusion of grasses with alfalfa reduced crude protein content and increased neutral detergent fiber content during cutting one, overall reducing quality. In cuttings two and three, mixed intercropping did not generally reduce quality. Stripped treatments also reduced quality in cutting one but did not have a large effect on quality in subsequent cuttings. Relative feed value, a common parameter used among producers, was similar among all treatments for all cuttings in 2021. In 2022, deficit irrigation had a significant impact on yield in cuttings two and three. Yields due to deficit irrigation were reduced by 22% and 35% in cuttings two and three, respectively. Total yearly yields were reduced by 12.5% between irrigation treatments. Total yields in mixed intercropping treatments were significantly higher than the alfalfa monoculture, especially the tall fescue and orchardgrass. Meadow brome generally had a higher yield than alfalfa, though not always significant. Mixed treatments averaged 13,308 kg ha^{-1} and stripped treatments averaged 9,488 kg ha^{-1} compared to alfalfa at 10,758 kg ha^{-1}. Similar to 2021, quality was only reduced in intercropping treatments during the first cutting. Crude protein and RFV decreased while NDF and ADF increased in intercropping treatments compared to alfalfa alone, resulting in reduced quality. In subsequent cuttings, quality was generally similar among intercropping treatments and alfalfa alone. Mixed intercropping demonstrated to be more productive throughout both years of this study compared to stripped intercropping. Advantages from intercropping were reduced in stripped treatments due to independent cultivation and

limited species interactions. Grass species did not have as large of an effect on yield and quality compared to intercropping method. Tall fescue typically performed the best of the grasses, yet all grasses in mixed intercropping performed well compared to alfalfa. Mixed intercropping grass with alfalfa can lead to increased yields with minimal effects on forage quality compared to alfalfa alone. As severe drought continues in areas across the Western US, mixed intercropping could be an option for maintaining or improving yields while producing similar forage quality compared to alfalfa alone under deficit irrigation.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Forage

Forage refers to all parts of a plant, except for separated grain, which is utilized by animals for feed or is harvested for animals (Moore et al. 2020). Forage can be broken down into three main subcategories: herbage, browse, and mast. Herbage is defined as the leaves, roots, stems, and seeds of non-woody species (Moore et al. 2020). Browse and mast refer to forage from woody species. Forages are some of the most economically important crops grown in the US and around the World (Capstaff and Miller, 2018). These crops come in a variety of forms including pasture, hay, haylage, silage, greenchop, and others.

Globally, land used for forage production occupies 26% of the ice-free area or 3.5 billion hectares (ha) (Capstaff and Miller, 2018). Pasture and hay are the most common types of forage in the US, occupying an estimated 73 million ha (Nelson et al. 2012). Pastures are areas of land established with forages for grazing by animals (Nelson et al. 2012; Moore et al. 2020). Hay is forage that is cut and then field-dried to moisture levels low enough to prevent spoilage from microbial activity (Moore et al. 2020). Once dry, the cut forage is baled into various size and shaped hay bundles that can be directly fed to animals. Hay bales are ideal for storing forage and are essential in areas where forage production is not year-round.

Yield and quality are the two most important factors in evaluating forages. Forage yield is simply the amount of dry matter harvested in a given area, typically expressed as pounds per acre or kilograms per hectare. Forage quality is more complicated to measure and determine (Moore et al. 2020).

Forage Quality

Forage quality is defined in multiple ways. Moore et al. (2020) describes forage quality as the ability of a forage to meet the nutritional requirements of the animals consuming it. Forage quality can also be defined by a focus on nutritive value and intake to meet animal requirements (Ball et al. 2001; Moore et al. 2020; Putnam and Orloff 2014; Van Saun 2013). Knowing forage quality is essential for proper livestock management.

When forage quality is unknown, livestock producers may over or underestimate the amount of feed required, in turn wasting money (Hall and Ishler, 2013). If forage quality is under-estimated, producers will be providing more feed or supplemental nutrients than required. On the other side, a producer who over-estimates the quality of their feed will see decreased animal performance (Hall and Ishler, 2013). Taking the time to accurately measure forage quality can save money and maximize animal performance.

There are subjective and objective ways of determining forage quality (Ball et al. 2001; Van Saun 2013). Subjectively, characteristics such as color, odor, and relative leaf-stem ratio can be used to evaluate forages, however, these methods do not provide measurements of nutrient content (Van Saun 2013; Ball et al. 2001). The best approach when determining forage quality is to combine a subjective evaluation with quantitative results from laboratory analytical testing methods.

Wet chemistry has been the standard for forage quality analysis, consisting of proven laboratory methods to determine nutritional content (Van Saun 2013; Moore et al. 2020). Near infrared reflectance spectroscopy (NIRS) has become a more common method for forage analysis due to its rapid speed and low cost compared to wet chemistry. This method uses light reflectance to determine quality parameters (Van Saun, 2013). Near infrared reflectance spectroscopy equipment are calibrated based on wet chemistry standards to quickly produce accurate results (Moore et at. 2020).

In dry plant matter, there are two main fractions of the plant that differ based on structure (Adesogan et al. 2017; Ball et al. 2001). The first fraction is cell contents (CC) which are soluble and easily digestible (90 to 100% digestibility) while the other fraction is comprised of cell wall constituents (CWC), which are fiber components and only partially degradable (Adesogan et al. 2017; Ball et al. 2001). Cell contents are the highest quality and are the non-structural components of cells that are concentrated in the leaves. Cell wall constituents include cellulose, hemicellulose, and lignin which are the structural components of the cells, typically found in higher concentrations in the stems. Cellulose and hemicellulose are partially degradable while lignin is not degradable, and therefore the presence of these three compounds is associated with lower quality. Overall, there are a variety of measurements used to determine quality.

Crude protein (CP) is an estimate of protein content based on total nitrogen (N) in the forage (Adesogan et al. 2017; Ball et al. 2001; Rocateli and Zhang 2017). Higher CP values are associated with higher quality forages. Protein is essential for proper animal function. Too little protein causes digestion, intake, and overall animal performance to be reduced (Rocateli and Zhang, 2017). Proteins are in highest concentration in the cell contents and more abundant in the leaves (Adesogan et al. 2017; Ball et al. 2001). Crude protein is one of the most common quality parameters measured, along with fiber.

Fiber is another important parameter that is measured to determine forage quality. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) are the two main fiber measurements. Neutral detergent fiber is measured by boiling a forage sample in a neutral detergent solution and measuring the insoluble fraction. Acid detergent fiber is measured similarly to NDF however an acid detergent solution is used. Both ADF and NDF can have a major impact on animal performance.

Neutral detergent fiber is the entire fibrous fraction (%) of the forage, including cellulose, hemicellulose, lignin, and some minerals that make up cell walls (Rocateli and Zhang, 2017). This measurement contains the slowly digestible and indigestible proportions of the forage plant, and thus are less desirable in forages. As NDF increases, forage digestibility, intake, and overall quality decreases (Rocateli and Zhang, 2017). Neutral detergent fiber is bulky and there is a limited amount of NDF that can fit into an animal's stomach. Once the stomach is full, the animal will cease to consume more forage until a significant proportion has digested or passed to the lower parts of the digestive system. Neutral detergent fiber is used to estimate forage intake/consumption (Rocateli and Zhang 2017; Moore et al. 2020).

Acid detergent fiber is a fraction of NDF, mainly composed of lignin and cellulose (Adesogan et al. 2017; Ball et al. 2001; Rocateli and Zhang 2017). The ADF fractions are poorly or indigestible and therefore less desirable. The higher the proportion of ADF, the lower total digestibility and quality of a forage. Acid detergent fiber has been used historically to estimate forage digestibility/energy (Rocateli and Zhang 2017; Moore et al. 2020).

In recent years, neutral detergent fiber digestibility (NDFD), or the nutrient available proportion of fiber, has become an increasingly important parameter and is now commonly used in evaluating feed rations (Hoffman et al. 2001; Adesogan et al. 2017). Neutral detergent fiber digestibility is measured with in vitro or in situ methods that look at the amount of NDF that is digested over a period of time (typically 30 or 48 hours) with a maintained level of intake. NDF is made of slowly digestible and indigestible proportions. An increase in NDFD is an increase in the slowly digestible proportions of NDF. An increase in NDFD results in higher digestibility and quality (Mertens, 2009). However, this increase in quality can be negated if NDF also increases. The digestibility of NDF can vary among forage families and species.

Relative feed value (RFV) is a common method used to evaluate and compare the quality of different forages and provides a single value to price hay and predict animal performance (Jeranyama and Garcia, 2004). This value is unitless and compares feeds to full-bloom alfalfa (ALF) (*Medicago Sativa)*, which has an RFV of 100. Neutral detergent fiber and acid detergent fiber are used to calculate dry matter intake (DMI) and digestible dry matter (DDM), respectively, which are then used in the calculation of RFV with the following equations (Jeranyama and Garcia, 2004):

DDM (% of DM) = 88.9 – (0.779 * %ADF)

DMI (% of Body Weight) = 120/%NDF

RFV= (DDM*DMI)/1.29

While there are some disadvantages when using RFV compared to other quality measurements, the simplicity and low cost to analyze fiber make the RFV measurement widely used among forage and livestock producers.

There are many properties that affect the proportions of CC and CWC in forages, and in turn affect the quality, such as forage species, variety/cultivar, stage of maturity at harvest, soil fertility, harvest time of year, environmental factors, etc. (Ball et al. 2001; Putnam et al. 2014; Van Saun 2013). The main plant families used for forages are grasses (*Poaceae*) and legumes which generally vary in terms of quality (*Fabaceae*) (Capstaff and Miller, 2018). Legumes are typically higher quality, with higher CP and lower fiber than grasses (Ball et al. 2001). However, fibers in grasses can be more digestible than those in legumes, resulting in higher NDFD in grasses.

Maturity is another major factor impacting forage quality. As plants mature, yield increases, however, quality decreases making this a difficult factor to control (Figure 1) (Moore et al. 2020; Ball et al. 2001; Putnam et al. 2014). As plants mature, they become more fibrous, with elongating stems and a decrease in leaf:stem ratio. Due to less leaves compared to stems, quality is reduced since leaves are higher quality with more CC as compared to stems (Moore et al. 2020; Ball et al. 200 1; Putnam et al. 2014).

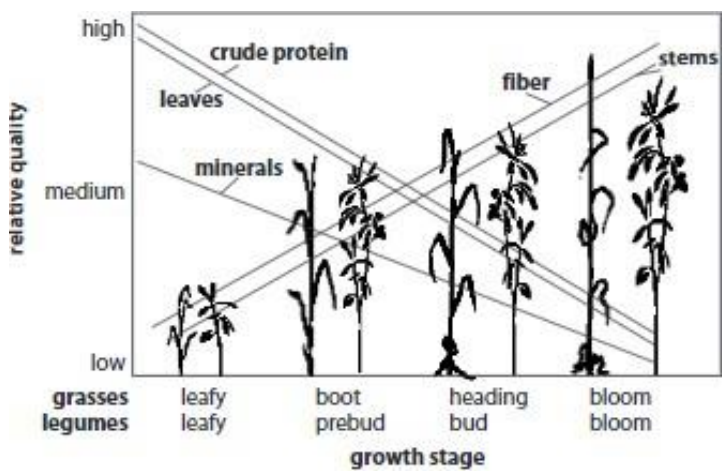

Figure 1. Relative quality vs growth stage for grasses and legumes. Source: Ball et al. 2001.

The timing of harvest is also an important factor affecting forage quality. Plant maturity at the time of harvest can have a major impact on quality. Furthermore, time of year can affect plant maturity and, therefore, different hay cuttings will have different quality. For example, non-jointing grasses will go to maturity during the first cutting, yet in subsequent cuttings, will only produce vegetative biomass resulting in lower quality earlier in the year (O'Reilly, 2020).

Forage species can have a major impact on yield and quality due to fundamental differences that naturally occur between species (morphology, anatomy, breeding traits, etc.) (Moore et al. 2020).

Forage Families

Grasses and legumes are the most common plant families grown as forages globally (Capstaff and Miller, 2018). These two families differ in their anatomy and classification. Each of these families contributes significantly to forage production globally and is unique in their forage quality, growth habits, and role they play in forage agriculture (Capstaff and Miller 2018; Moore et al. 2020).

Most legumes have a taproot system and exhibit broad leaves with netlike veins, unique flowers, and seeds contained in pods (Simpson 2010; Putnam et al. 2014). Flowers are irregular, with five petals that form a distinctive shape (i.e., zygomorphic). The shape includes the banner (one petal), wings (two petals), and keel (two petals, generally fused) (Simpson 2010). Legumes can be annuals which complete their lifecycle in one year, or perennials which live for multiple years and go dormant in winter. The quick growing nature of legumes can allow for high yields and multiple harvests per year, depending on the species, local environment, management factors, and water availability (Capstaff and Miller 2018; Moore et al. 2020). Forage legumes are generally higher quality when compared to grasses. The most popular forage legume in the US is alfalfa, with millions of hectares grown in the Western US alone.

Plants in the legume family are unique due to their ability to grow specialized nodules on their roots (Pandey 2020; Lindemann et al. 2015). These nodules contain nitrogen fixing bacteria known as rhizobia that form symbiotic relationships with the legume plants. These rhizobia can fix atmospheric nitrogen (N_2 gas) into the plant available form, ammonium (NH_4). In return, the plant provides carbohydrates that supply energy for the bacteria (Simpson 2010; Lindemann et al. 2015). This unique relationship allows legumes to thrive in N poor soils without the need for synthetic fertilizer. In some cases, soil conditions are improved with the addition of nitrogen fixed by legumes.

As nodules on legume roots die and decompose, there can be a release of N to the surrounding soil, which can then be utilized by other plants (Lindemann et al. 2015; Berdahl et al. 2001; Moore et al. 2020). The amount of N fixed and released into the soil varies greatly across legume species and associated rhizobia. Alfalfa is one of the best fixers of N, averaging about 200 lbs/acre/year (Moore et al. 2020).

There are a wide variety of grass types and species utilized as forages for hay and pasture. Forage grasses can be divided into a few distinct categories. There are annual and perennial grasses, warm-season and cool-season grasses, and jointing/non-jointing grasses. The cool- and warm-season grasses are determined by their photosynthetic pathway (C_3 or C_4, respectively) which determines which climate they thrive in. Depending on the region, cool-season or warm-season grasses may dominate forage crops in that area. Grasses used during this study were cool-season, non-jointing grasses.

Cool-season grasses are most productive during the spring, with an uptick in growth occurring during the fall as temperatures cool (Figure 2). Optimal air temperature for cool-season grass growth is 20°–25° C, with little growth occurring under 10° C (Moser et al. 1996). Air temperatures above 25° C cause reduced growth in these species and little to no growth occurs at temperatures above 30° C. These grasses exhibit the best growth during the spring and early summer when temperatures are ideal. During the hottest parts of the summer, these grasses experience a reduction in growth known as a “summer slump” (Putnam et al. 2014).

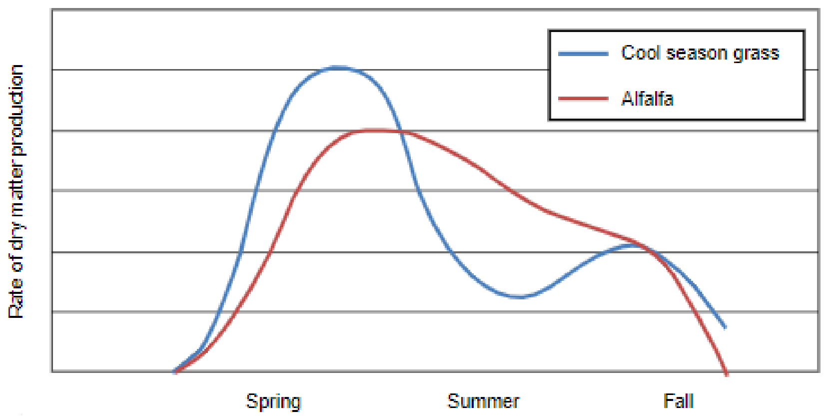

Figure 2. Relative dry matter production of cool-season grasses compared to alfalfa over the growing season. Source: Putnam et al. 2014.

Jointing and non-jointing grasses differ in the way that they regrow after the seedhead is removed (O'Reilly, 2020). Jointing refers to the process of stem elongation and is considered part of the transition phase from vegetative to reproductive growth (Moore et al. 2020). When grasses produce a seedhead and that seedhead is removed by harvesting or grazing, two types of regrowth can then occur. For jointed grasses, regrowth after initial seedhead defoliation will produce leaves and stems but no additional seedheads (Moore et al. 2020; O'Reilly 2020). When stem elongation occurs in jointed grasses, the growth point is raised and vulnerable to damage. If the growing point is removed during the stem elongation, new growth must come from energy reserves in the root, significantly stressing the plant. Non-jointing grasses do not attempt stem elongation after seedhead defoliation and only produce vegetative growth. Non-jointing grasses only go through the jointing process once per year after a period of winter dormancy (O'Reilly, 2020).

While there are a significant number of grasses cultivated for forage across the US, orchardgrass (*Dactylis glomerata*), tall fescue (*Festuca arundinacea*), and meadow brome (*Bromus biebersteinii*) are some of the dominant grasses grown in mixtures with alfalfa in the US (Crème et al. 2016; Malhi et al. 2002; Aponte et al. 2019). Furthermore, these three grasses are common in the area this study was conducted. For these reasons, these grasses were selected for use in this study. All of the grasses used are perennial, cool-season, non-jointing grasses.

Forage Species

Alfalfa

Alfalfa is a perennial forage legume crop commonly grown globally. It is the most common forage crop in the US, being the 4th most valuable crop behind soybean, corn, and wheat (USDA NASS; Capstaff and Miller, 2018). Originating in the Middle East, alfalfa is a cool-season plant with trifoliate leaves and a single crown at the soil surface that produces multiple stems (NRCS, 2002). The flowers of alfalfa are commonly light to dark purple but can also be white. The seeds of alfalfa are very small, and kidney shaped (1-2 mm), with an olive green to brown color. Alfalfa has a taproot that can reach up to 4.6 m underground. Other common names for alfalfa include lucerne, purple medic, and burgundy clover (Moore et al. 2020)

Referred to as the “Queen of Forages”, alfalfa is known for its high nutritional quality, which makes it a staple crop for livestock globally (Lacefield et al. 2009; Putnam 2001). According to the USDA NASS, there were 6,151,220 hectares of alfalfa grown in the US in 2020, with a value of 8.4 billion dollars (US, 1998). This does not include the value of animals and animal products produced from feeding this alfalfa. Table 1 compares the dollar value of alfalfa, other hay (excluding alfalfa), and other crops produced in the US over a four year period. Table 1 shows that alfalfa alone is consistently the 3rd or 4th most valuable crop in terms of total production in the US, with values similar to wheat. Total hay production in 2022 was valued at $21.2 Billion dollars in the US (US 1998).

Table 1. Alfalfa and other hay value (US$) in the US compared to other common crops between 2018 and 2021. Source: USDA National Agricultural Statistics Service (1998).

Crop	2018	2019	2020	2021
Alfalfa	8,583,806,000	9,098,728,000	8,415,852,000	9,693,580,000
Hay excl. alfalfa	8,704,409,000	8,941,067,000	8,912,675,000	9,583,761,000
Corn	52,102,404,000	48,940,622,000	61,039,005,000	82,578,637,000
Soybean	36,819,008,000	30,525,961,000	46,068,982,000	57,478,662,000
Wheat	9,661,916,000	8,919,117,000	9,324,496,000	11,896,243,000
Cotton	6,375,167,000	5,865,099,000	4,677,566,000	7,459,979,000
Sugar beats	1,183,562,000	1,697,944,000	1,697,944,000	1,935,249,000

Alfalfa typically grown for hay as grazing can be associated with animal health issues (NRCS, 2002). Use of alfalfa for pasture should be applied with caution as it (and certain other legumes) can cause frothy bloat in ruminants when grazed as fresh standing forage. Alfalfa (and legumes with high soluble protein) can create a film in the rumen that traps fermentation gases that results from slime formation when soluble proteins are digested. These gases are normally expelled from the animal, however, when they build up there is a decreased animal performance and function, with extreme cases resulting in death (Lehmkuhler et al. 2011; Capstaff and Miller 2018). Due to this risk, it is more common for alfalfa to be processed into hay versus grazing as there is no bloating risk.

Alfalfa is popular as a forage crop due to its long growing season, wide range of cultivars, adaptability to different environmental conditions, and its high-quality forage (Putnam et al. 2001; Moore 2020; Yost et al. 2020). Cuttings of alfalfa in the Western US range from one to ten per year, primarily related to length of the growing season in a given area (Putnam et al. 2001). Due to its long growing season, deep root system, dense canopy, high production, and other factors, alfalfa can use large amounts of water compared to other crops (Yost et al. 2020; Putnam et al. 2001). While alfalfa has a relatively high water use efficiency, it undeniably uses a significant amount of water in part to reasons listed above, but also simply due to the amount of alfalfa acreage (Putnam et al. 2001). Alfalfa is consistently in the top three in terms of acreage in the Western US (depending on the state), with irrigation amounts ranging from 24 to 100 inches per year, depending on the area (Yost et al. 2020; Putnam et al 2001).

Meadow Brome

Meadow Brome (MB) is a cool-season, non-jointing, perennial grass with short rhizomes (St. John et al. 2012). The leaves are flat, pubescent on both sides, with deep groves on the top and a prominent mid-nerve on the bottom that creates a folded appearance. It prefers soils from coarse gravelly to medium textured. Meadow brome was introduced from Turkey to the US in 1949 primarily to serve as forage for livestock and wildlife. It is highly palatable to all classes of livestock and is commonly used for hay and pasture (Hybner, 2013).

Due to its dense, fibrous root system and short rhizomes, this grass is good for soil erosion control. Meadow brome can thrive on the plains or at higher elevations in conifer and aspen forests. This grass is moderately tolerant to shade, has relatively strong winterhardiness, and has moderate salinity tolerance. Meadow brome performs better in alfalfa/grass mixtures compared to other species in the genus, such as smooth brome (Bromus *inermis*) (Hybner, 2013).

The summer slump effect is not as drastic in meadow brome compared to other cool-season grasses. Meadow brome has also been shown to grow well in mixtures with other legumes such as birdsfoot trefoil *(Lotus corniculatus)* and sainfoin *(Onobrychis viciifolia).*

Tall Fescue

Tall fescue (TF) is a cool-season, non-jointing, perennial grass (Moser, 1996). This grass can have short rhizomes, yet there is a wide range in rhizome variability among different varieties and it often exhibits a bunch-type growth habit. Forage varieties have leaves that are wide and feel smooth with a glossy coat and deep ribs on the top side. Tall fescue is native to Europe and was introduced to the US during the early 1800's. Tall fescue was predominantly a forage crop until the 1900's when certain tall fescue turf cultivars were developed and utilized for lawns.

Tall fescue has a large root system compared to other cool-season grasses with roots extending three plus feet downwards (Hensen, 2001). This large root system makes TF drought, shade, and heat tolerant compared to other grasses. It can grow at low soil temperatures showing a wide range of adaptation. Tall fescue is known as a disease resistant grass, with easy establishment and persistence. It is adapted to a wide range of environmental conditions, demonstrated by its tolerance to various stress factors (Hensen, 2001). Tall fescue is very productive, winter hardy, and persistent compared to many grasses which makes it a popular forage crop in the US.

While TF grows well in a wide range of conditions, it is considered a low palatability forage due to its tendency to produce poor animal gains and toxicosis symptoms (Bates, 2015). In the 1970's, it was discovered that TF has an endophyte, or a fungus living within the plant. This endophyte has been shown to increase TF persistence, competitive ability, and resistance to environmental stressors. However, this endophyte can cause toxicosis in grazing animals. This led to the development of endophyte-free and novel endophyte cultivars that do not affect animal performance.

Orchardgrass

Orchardgrass (OG) is a cool-season, non-jointing, perennial bunchgrass (Bush, 2006). It is native to central and western Europe but was introduced to the US in the 1750's. Orchardgrass grows between 50 to 120 cm tall at maturity. The leaves are V-shaped and narrow towards the tip with a blue-green appearance. This grass is highly palatable to all classes of livestock and is mainly utilized as a hay and grazing crop. In addition to early spring productivity, orchardgrass does not suffer as severely from summer slump (similar to MB) as other cool-season grasses, so it grows well during summer and into the fall.

Orchardgrass is moderately tolerant to infertile, acidic, and drought prone areas, and is grown expansively across the US (Moore et al. 2020; Moser et al. 1996). Compared to other grasses, OG typically reaches the reproductive stage earlier during the spring, which can result in lower quality. However, due to its non-jointing characteristics and quick regrowth, subsequent cuts of OG can produce high yield and quality (Moore et al. 2020). Orchardgrass has high shade tolerance, is extremely responsive to N applications, has rapid regrowth, and is a preferred species for alfalfa/grass mixtures (Moore et al. 2020; Moser et al. 1996).

Intercropping

Intercropping refers to the cultivation of two of more crops that coexist for part of their lifecycles on the same field or plot of land (Smith and Carter 1998; Brooker et al. 2015; Bi et al. 2019). Intercropping allows for increased productivity on the same area of land by maximizing resource utilization and exploitation that would not be possible from a single crop (Smith and

Carter 1998; Raza et al. 2019; Brooker et al. 2015; Bi et al. 2019). Although intercropping is an ancient practice, with the green revolution and mechanization of agriculture, monocultures (i.e., fields cultivated with single crop at a time) have become dominant in many regions across the globe (Brooker et al. 2015; Jansen 2012; Bi et al. 2019). While monocultures can be advantageous in many ways, issues arise such as pest pressure, high inputs, soil degradation, and moderate yields (Brooker et al. 2015; Bi et al. 2019). Intercropping is being explored as a solution to these issues.

Forms of intercropping include mixed, relay, row, and strip (Jansen 2012; Brooker et al. 2015). Mixed intercropping is when two or more crops are seeded and grown together with no distinctive arrangement (i.e., randomly mixed) in an effort to maximize resource exploration. Relay intercropping involves the planting of a second crop into an established crop (Raza et al. 2019; Brooker et al. 2015). Row intercropping is the cultivation of different crops in alternating rows (Jansen, 2012). Strip intercropping, similar to row intercropping, is the cultivation of multiple rows (strips) of one crop alternating with a strip of another crop (Smith and Carter, 1998). Strips of crops are wide enough for individual cultivation but narrow enough to allow for plant-plant interactions (Smith and Carter, 1998).

Intercropping can be more difficult to manage compared to monocultures. Managing nutrients and water for two species can be complex and can lead to lower yields and quality compared to monocultures if not done properly (Bi et al. 2019; Raza et al. 2019; Brooker et al. 2015). Understanding the mechanisms and processes that provide many of the benefits from intercropping are complex and require further research.

Alfalfa-grass Intercropping

Alfalfa-grass intercropping (or mixtures) has been shown to have many advantages over alfalfa or grass monocultures (Sleugh et al. 2000; Spandl and Hesterman 1997; Aponte et al. 2019; Martin-Guay et al. 2018). Advantages include increased yield, improved quality, reduced pest pressure, reduced weed pressure, increased stand persistence, and reduced fertilizer requirements compared to monocultures (Sleugh et al. 2000; Spandl and Hesterman 1997; Aponte et al. 2019; Roda et al. 1997; Berdahl et al. 2001; Martin-Guay et al. 2018; Degooyer et al. 1999). However, some trials demonstrated that these advantages can actually be negated, such as decreased quality and yield instead of increased (Tesar and Marble 1988; Aponte et al. 2019). Grass species and establishment success, site-specific factors, and an increase in difficulty of managing alfalfa-grass mixtures results in variable yield and quality compared to monocultures. (Spandl and Hesterman 1997; Tesar and Marble 1988; Aponte et al. 2019).

Yield

Alfalfa-grass intercropping for increased forage yield has been explored utilizing a variety of grass species and different seeding rates of alfalfa and grasses. Spandl and Hesterman (1997) conducted a trial at two sites in Michigan comparing alfalfa monocultures and alfalfa grown with smooth bromegrass and timothy (*Phleum pratense*) under dryland conditions. Three cuttings occurred for each of the two fields.

In cut one, Spandl and Hesterman (1997) found that total biomass was significantly greater in both alfalfa-grass intercropping treatments compared to the alfalfa monoculture. For the second cut, the grass-alfalfa mixtures yielded significantly lower than the alfalfa monoculture. There was no difference in total biomass in the third cut among treatments. Alfalfa biomass in the mixtures was lower than the alfalfa monoculture in the first and second cut, with grass more than compensating for the difference in yield during the first cutting. Total annual yields were not significantly different among the planting treatments.

In cut two, the grass was unable to compensate for suppressed alfalfa production, resulting in lower total biomass. Total annual production was not significantly different among the treatments. Spandl and Hesterman (1997) hypothesized that competition from the grasses is what suppressed alfalfa yield in the mixtures during cut one. Grass growth after the first cut is purely vegetative, reducing vigor and competition. The summer slump effect paired with vegetative growth in grasses could explain this decrease in grass yield. Furthermore, poorly established alfalfa in mixtures reduced overall mixture yields compared to alfalfa monocultures during the second cut.

Berdahl et al. (2001) explored dryland forage production of four grass monocultures compared to grass and alfalfa mixtures under two levels of N application over a five-year period in Mandan, ND. During 1997 and 1998 (two harvests per year), Berdahl et al. (2001) found the highest grass yields in all treatments during the first cutting (Mid-June), similar to Spandl and Hesterman (1997). Grass monocultures had significantly lower yields than any of the alfalfa-grass mixtures during the two years, especially in the second cut, demonstrating that alfalfa was the main contributor to yield. Nitrogen application significantly increased grass monoculture yield in both years but did not increase yield of alfalfa-grass mixtures. Nitrogen application significantly increased the grass component in the alfalfa-grass mixtures.

Aponte et al. (2019) performed a trial to study alfalfa-grass mixtures compared to grass and alfalfa monocultures under dryland conditions at three different sites in North Dakota. This trial studied alfalfa intercropped with 10 grass species, alfalfa in monoculture, and each grass species in monoculture. The grass species included MB, OG, TF, and a variety of other grasses.

For one site, no harvests occurred during the establishment year, but the other two sites had two harvests. For the three subsequent years, grass monocultures were harvested twice, and alfalfa and alfalfa-grass mixtures were harvested three to four times during the season. Grasses were harvested at the heading stage while the mixtures and alfalfa monoculture were harvested at the 10% alfalfa bloom stage.

In the first year of this trial, the average yield of mixtures was greater than the yield of alfalfa. In the second and third year, there was a decreased yield in mixtures compared to alfalfa. In the final year, an increase in yield was again seen in the mixtures compared to the alfalfa, demonstrating variability in the results. This trial used a wide range of grasses causing significant variation in yields, altering the mean yield of mixtures. Focusing on the TF mixture treatment, yield was higher for all but one year (year three) compared to the alfalfa monoculture. There were two OG mixture treatments using different OG cultivars. The OG cv. Potomac had similar yields to alfalfa in monoculture throughout each year except for the third. This study demonstrated that some grass-alfalfa mixtures can produce yields equal to or greater than alfalfa, while other grasses significantly decreased yields likely due to complex interactions between the species.

Sleugh et al. (2000) conducted a trial in Iowa exploring mixed intercropping of legumes and grasses on forage yield, quality, and seasonal distribution. Three legume species and three grass species were grown in monoculture and mixtures of each legume species mixed with each grass species. The legumes used for this experiment were alfalfa, Kura clover *(Trifolium ambiguum),* and birdsfoot trefoil. The three grasses used were SB, OG, and intermediate wheat grass *(Thinopyrum intermedium).* Four cuttings per year occurred over two years.

Total forage across both years was highest for the alfalfa monoculture. The highest yields for each treatment occurred during the first cutting due to favorable growth conditions during the spring. All mixtures and legume monocultures yielded at least 100% more than the grasses in monoculture, regardless of species. Grass mixtures with alfalfa had the highest yield compared to mixtures with Kura clover and birdsfoot trefoil. Inclusion of legumes with grasses significantly increased yield compared to grass monocultures regardless of species. Unlike Spandl and Hesterman (1997), intercropping treatment yields were not as high as the alfalfa monoculture.

Bi et al. (2019) conducted a trial assessing forage yield in mixed perennial legume and grass intercropping systems with different rates of phosphorus (P) fertilizer in a rainfed system in China. The planting treatments consisted of mixed intercropping four species together and monoculture controls. Species used include alfalfa, sainfoin, OG, and TF planted at different legume to grass ratios (3:7, 4:6, 5:5, 6:4, & 7:3) legume to grass, respectively). This trial occurred over three years, with two harvests during the first year, and four harvests in each subsequent year. Phosphorus was applied to these treatments at rates of 0, 40, 80, and 120 kg ha^{-1} of P_2O_5.

For the first year, the monocultures yielded significantly more forage compared to all the intercropping treatments at the same rate of *P* application. For the remaining two years, the mixtures were significantly higher yielding than the monocultures, likely due to the longer establishment time required for the intercropping treatments compared to monocultures. Total year over three years was higher in intercropping treatments compared to monocultures.

Nikolova et al. (2018) conducted a study focused on intercropping of orchardgrass with legumes on yield and pest damage compared to legumes in monoculture. Legumes utilized in this study were alfalfa, sainfoin, and birdsfoot trefoil. The authors found that yield and root biomass significantly increased in intercropping treatments compared to the legumes alone. During the three years of this study, the ALF intercropping treatment was significantly higher in yield and root biomass compared to the ALF monoculture, showing a clear benefit from intercropping with orchardgrass. During the third year, there was a larger difference in yield between the two treatments, suggesting that as the stand matures, the benefits of intercropping increase.

Damage from the weevil (*Sitona* genus) and the alfalfa snout beetle (*Otiorrhynchus ligustici)* were assessed in each treatment to determine if intercropping with OG can reduce pest damage. Compared to the ALF control, intercropping treatments had 55.6% less root nodule damage caused by the weevil. There was also a 59.5% reduction in alfalfa snout beetle damage when alfalfa was intercropped with OG. Nikolova et al. (2018) demonstrated the benefits of intercropping alfalfa with OG include reduced pest damage and increased yield compared to alfalfa monocultures.

Quality

Aponte et al. (2019) found that alfalfa-grass mixtures can have a similar CP content compared to alfalfa alone. The authors also found that mixtures were significantly higher in CP content compared to grasses alone. Aponte et al. (2019) found that NDFD of the mixtures was significantly greater than alfalfa NDFD, thus improving digestibility and quality. When compared to grass monocultures, the addition of alfalfa significantly improved nutritive value. The authors concluded that higher yields and nutritive value per unit area in mixtures could help reduce the amount of land needed for forage production in order to fulfill animal feeding requirements.

Sleugh et al. (2000) found that intercropping grasses with alfalfa produced a similar CP content as compared to the alfalfa alone in four cuttings across two years (except for the first cut in year one). In-vitro dry matter digestibility (IVDMD) is a calculation used to estimate overall digestibility of a feed or forage was similar among mixtures and alfalfa alone for all cuttings in both years of the study. In-vitro dry matter digestibility is total digestibility of a forage measured by placing a sample in rumen fluid for a period of time (30 or 48 hours) followed by the NDF procedure or the addition of acid and pepsin. Non-detergent fiber was higher in mixtures than alfalfa alone during the first year. In the second year, NDF of mixtures was similar to alfalfa. The authors determined that while including legumes with grasses can increase NDF which lowers quality, it can also increase IVDMD, CP, and seasonal distribution which raises quality. This demonstrates that while mixtures can increase quality in some parameters, they can also decrease quality in others.

Spandl and Hesterman (1997) looked at alfalfa quality when intercropped with bromegrass and timothy. They found that intercropping treatments had reduced CP and increased NDF during the first cutting, resulting in lower quality, compared to alfalfa alone. Acid detergent fiber was also lower during first cutting in the mixtures. During the second and third cutting, there was no decrease in quality when comparing the intercropping treatments and alfalfa alone, demonstrating that mixed intercropping mainly affects certain quality parameters in the first cutting.

Putnam et al. (2001) conducted an experiment involving overseeding of OG into existing stands of alfalfa to understand the effect on yield and quality. Over the three years of this study, only the first year saw a decrease in CP in the orchardgrass treatments compared to alfalfa alone. During the second year, CP was 4% higher in the mixed treatments compared to alfalfa alone.

During the third year, the CP values were similar. Acid detergent fiber was lower during all years of this study in OG plots compared to alfalfa alone. This demonstrated that OG could improve quality when overseeded into existing alfalfa stands.

Deficit Irrigation of Forages

Yield

In the Western US, there have been various drought conditions for decades (US Drought Monitoring Service, 2022) as shown in Figures 3 and 4. Figure 3 shows the overall drought at different levels throughout the Western US from 2000 to 2023, demonstrating the continuous drought issues in this area. Figure 4 shows the alfalfa hay acreage in varying degrees of drought from 2012 to 2022. While the numbers are extremely variable (normal fluxes for the water cycle), we can see that there is constantly some percentage of moderate to extreme drought occurring in the Western US which impacts alfalfa production fields.

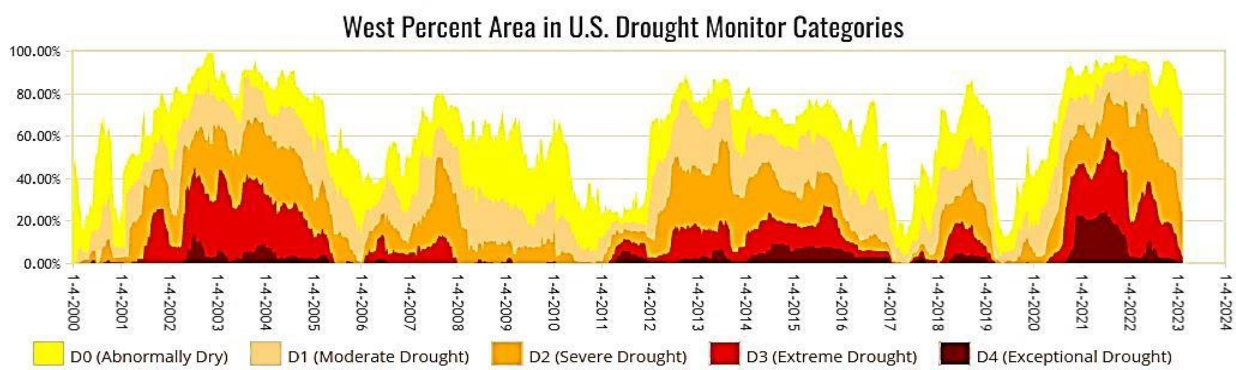

Figure 3. Graph of land in Western US that is experiencing various levels of drought from January 2000 to January 2023. Source: US Drought Monitor (2022)

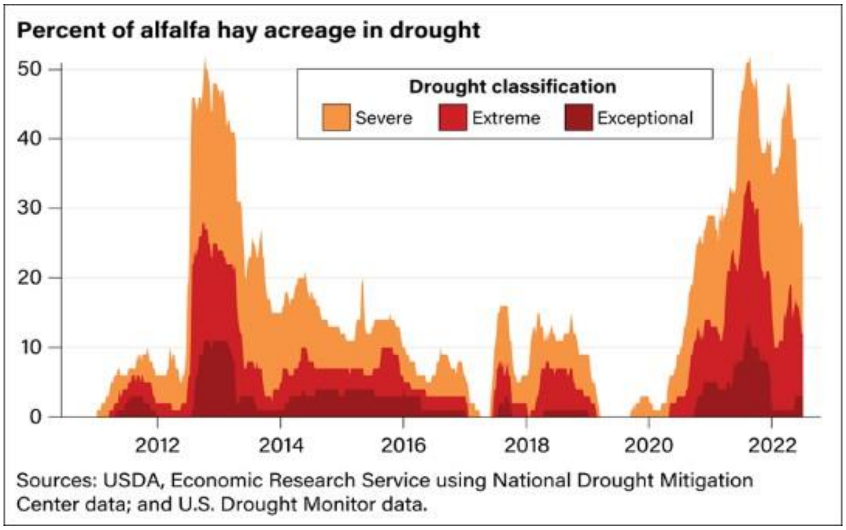

Figure 4. The percentage of cultivated alfalfa acreage that experienced various levels of drought from 2012 to 2022. Source: USDA Economic Research Service using National Drought Mitigation Center data; and US Drought Monitor data (2022).

About 40% of alfalfa hay production in the US occurs in the 11 western states (CO, CA, UT, AZ, WA, ID, WY, NV, MN, NM, and OR), highlighting the importance of this region to alfalfa production in the US. While alfalfa can be grown without irrigation in the Midwest, about 77% of all alfalfa is under irrigation in the West (Putnam et al. 2000). Utilizing the limited water resources available for maximum productivity is crucial for the Western agricultural industry.

As continued droughts occur and water resources become scarcer in the Western US, effectively utilizing available water is increasingly important. The use of deficit irrigation, or applying irrigation in amounts lower than evapotranspiration rates, is one of the main strategies utilized to combat water scarcity while still allowing for crop production (Fereres and Soriano, 2007). When facing dwindling water resources, farmers can choose to deficit irrigate. Deficit irrigation presents issues revolving around when is the most critical time to apply limited water.

Neal et al. (2009) conducted a trial that studied yield, water-use efficiency, and quality of 15 perennial forages under three irrigation regimes: optimum irrigation, 66% of optimum, and 33% of optimum. Optimum irrigation was calculated using a modified Penman-Monteith equation multiplied by the proper crop coefficient depending on species. Of the 15 species, alfalfa and tall fescue were both represented, sown at rates of 15 and 25 kg ha^{-1}, respectively. This trial occurred in Camden, New South Wales, Australia, utilizing sprinkler irrigation for a three-year period.

Both deficit irrigation treatments significantly reduced yields of all forage species, which was expected as water is the most limiting resource in many forage systems. Alfalfa yield was reduced by an average of 9% and 22% when irrigated at 66% and 33% of optimum, respectively, as compared to full irrigation. Tall fescue yield was reduced by an average of 19% and 50% when irrigated at 66% and 33% of optimum, respectively, as compared to full irrigation. Of the 15 forages tested, alfalfa had the smallest reduction in yield at 22% compared to white clover (*Trifolium repens)* which had a reduction of 70%. Neal et al. (2009) attributed these differences to root structure differences and drought adaptability. Alfalfa has a deep taproot that can extract water from depths of two meters. While white clover also has a taproot and can draw water from up to 1.25 meters in depth, the root system in the top 10 cm was the smallest for any species in this trial. This observation also explained the reduction in yield for tall fescue, which has a fibrous root system that does not allow uptake of water from depths as great as alfalfa.

The lower reduction in yield from deficit irrigation found in alfalfa demonstrates that alfalfa is a candidate for deficit irrigation management, as alfalfa can withstand a lack of water. For alfalfa, the yield reduction increased with each subsequent year of deficit irrigation. During the first year, there was a 16% reduction compared to 24% and 26% in years 2 and 3, respectively (Neal et al. 2009). When comparing the 11 harvests of alfalfa that occurred, only four had significant differences in yields between the 100% and 33% ET. Alfalfa had the largest decrease in yield with decreasing plant density, highlighting the importance of proper seeding rate and good establishment for a robust, long-lived alfalfa stand.

Li and Su (2017) conducted a similar deficit irrigation trial in China utilizing sprinkler systems. This trial studied alfalfa (15 kg ha^{-1}) under four different irrigation levels of 100% ET, 66% ET, 33% ET, and rainfed. ET was calculated using the Penman-Monteith energy balance equation. Four harvests occurred each year for two years.

Annual yield was significantly different between each irrigation treatment for both years. The highest yield was in the 100% ET, followed by the 66% ET, 33% ET, and rainfed treatments. In the first year, the 66% ET, 33% ET, and rainfed annual yields were reduced by 8%, 15%, and 26%, respectively, as compared to the 100% ET treatment. In the second year, the 66% ET, 33% ET, and rainfed annual yields were reduced by 16%, 33%, and 50%, respectively, as compared to the 100% ET treatment. The highest yield, regardless of irrigation treatment, occurred during the first harvest due to the longer growth period and optimum soil moisture from the winter.

A significant linear relationship was found between alfalfa yield and water applied to the field, except in the first harvest for both years (R^2>0.96; Li and Su 2007). While the greatest yield occurred in the 100% ET treatment, the lowest water use efficiency was found in that treatment while the highest WUE was found in the rainfed treatment. This study demonstrated that a reduction in irrigation amount can still result in adequate alfalfa yields. When reducing irrigation by 1/3, yield losses were less than 10% in the first year and 20% in the second year.

Hanson et al. (2007) conducted a study of deficit irrigation to alfalfa in California in order to provide water for other areas. There were three irrigation treatments, full irrigation, no irrigation in July and August (hottest months) with no fall irrigation, and no irrigation in July and

August followed by irrigation in September. This trial took place over a three-year period. Alfalfa yield and quality were measured during each harvest period.

In treatments with no fall irrigation, yields declined 12 to 22% in year one, 16 to 17% in year two, and 35 to 49% in year three during the deficit irrigation period compared to full irrigation. Yields of the deficit irrigation treatments recovered during subsequent years in the spring when irrigation was applied in full, indicating good recovery by alfalfa. Yields in deficit irrigation treatments rebounded compared to full irrigation when there was a September irrigation. Overall, yields decreased over time, with the largest reduction in yields occurring during the last year of the trial (Hanson et al. 2007).

Quality

Hanson et al. (2007) analyzed the effects of deficit irrigation on CP, ADF, and NDF of alfalfa (details stated above). The researchers only measured quality in the last two years of the study, once before deficit irrigation was applied during that year and once after the deficit irrigation period. There were no significant differences in any quality parameter before deficit irrigation was applied for both years. During the first year, there was no significant difference in any parameters after deficit irrigation was applied. During the second year, there was a significant decrease in NDF and ADF after deficit irrigation occurred, resulting in higher quality. Crude protein was not affected by deficit irrigation during either of the years in which quality was analyzed.

Holman et al. (2016) studied the effects of timing and amount of irrigation on alfalfa nutritive value. Irrigation treatments consisted of 680 mm of total irrigation under typical timing, 380 mm under typical timing, 380 mm with no irrigation between cut 2 and 3, 200 mm with no irrigation between cut 2 and 3, 200 mm with normal timing, and no irrigation at all. The authors analyzed CP, ADF, NDF, RFV, and total digestible nutrients (TDN). Results were gathered over four years.

Crude protein content decreased as the irrigation amount increased, with the 0 mm treatment having the highest CP concentration. This was due to an increased leaf:stem ratio and decreased maturity. In the final year, CP dropped in the 0 mm treatment due to weed competition and a reduced stand. There was no significant difference in CP based on timing of irrigation. There was a decrease in ADF content as irrigation amount decreased, in turn improving quality. Neutral detergent fiber followed a similar trend to ADF and decreased as irrigation amount increased, thus improving quality. Total digestible nutrients increased as the irrigation amount decreased. Overall, results showed that irrigation amount had an inverse relationship with relative quality (Holman et al. 2016).

Li and Su (2017) focused on CP content when deficit irrigation was used to grow alfalfa in China. The irrigation treatments consisted of 100% ET, 66% ET, 33% ET, and no irrigation. Similar to Holman et al. (2016), there was a decrease in CP with increased irrigation amount, demonstrating an increase in quality when deficit irrigation is applied. With dwindling water resources facing producers in many parts of the world, deficit irrigation is an option for producing higher quality forages with less water.

Summary

Alfalfa is one of the most important forage crops in the Western US, an area facing major issues with drought and water supply. Due to its large amount of acreage and productivity throughout the year, alfalfa uses a large amount of water. Deficit irrigation is one strategy used to reduce water use while still producing crops. Alfalfa-grass intercropping has been shown to produce yields similar to or higher than alfalfa in monoculture due to increased resource utilization and niche exploration (Nikolova 2018; Spandl and Hesterman, 1997; Aponte et al. 2019). Intercropping grasses with alfalfa has also been shown to produce similar quality compared to alfalfa alone. Alfalfa responds to deficit irrigation better than many other crops due to its root morphology containing a deep taproot (Putnam et al 2001; Kelly et al 2006). Alfalfa-grass intercropping under deficit irrigation is a potential strategy to increase yield and quality compared to monocultures when water resources are limited. The objective of this study is to evaluate the ability of mixed and stripped intercropping alfalfa with grasses to increase yield and quality of the forage produced under deficit irrigation.

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CHAPTER 2. MATERIALS AND METHODS

Experimental Site

This trial was conducted at the Colorado State University Grand Valley Research Station near Fruita, Colorado (39º 15' 00" N, 108º 71' 67" W) from 2020 to 2022. Fruita is at an elevation of 1402 m above sea level with 180 frost-free days a year. Monthly average (30 year) temperature and precipitation data are shown in Table 2. Yearly averages for temperature and precipitation for the past 30 years are 11.2 ℃ and 251.2 mm per year. This area is part of the high desert with a cold, semi-arid climate. The soil at the experimental site belongs to the Sagrlite loam series (Fine-silty, mixed, super active, calcareous, mesic Typic Torriorthents). The experimental field (Field L) was approximately 0.53 hectares in size.

Table 2. Monthly average (1991 – 2020) precipitation and temperature for Fruita, Colorado. Source: NOAA

Month	Mean temperature (℃)	Mean precipitation (mm)
Jan	-2.8	19.05
Feb	1.3	19.56
Mar	6.7	23.37
Apr	10.6	23.37
May	16.5	21.59
Jun	21.6	13.97
Jul	25.1	16.76
Aug	23.8	21.34
Sep	18.7	28.45
Oct	11.3	29.97
Nov	4.2	16.51
Dec	-2.1	17.27

The field was previously planted with orchardgrass. Prior to planting, all orchardgrass was terminated with glyphosate and then moldboard plowed. Before placing drip tape, the field was roller harrowed to create a flat surface. A subsurface drip tape system was installed in the field. Drip tape (Driptech) was placed 25.4 cm below the soil surface using a custom-made drip tape applicator on a John Deere 6140D. The drip tape used had 20 cm spacing between emitters and a drip rate of 0.95 liters an hour @ 10 PSI. Once drip tape was placed, the field was creased with a Mormon creaser into 76.2 cm beds with furrows. Tape lines were in the middle of the beds, with a single line per bed.

Planting Treatments

Planting treatments are shown in Table 3. Each plot was comprised of four 76.2cm wide by 7.62m long beds. Each bed was planted with three rows of crops. Treatment one was alfalfa monoculture and was considered a control. Treatments 11, 12, and 13 were grass monocultures/controls of meadow brome, tall fescue, and orchardgrass, respectively. Treatments 2-7 were mixed intercropping treatments with either 75% ALF and 25% grass or 50% ALF and 50% grass. The mixed treatments were seeded with both species combined in the same row (See figure 5). Treatments 8-10 were the stripped treatments and required two passes through the plots in order to plant the seed (See figure 6). The first pass planted the first and third beds of the plot with alfalfa. The second pass planted the second and fourth beds with grass. Grass species selection was based on grower preferences in the area. Treatments were planted with a cone planter attached to a John Deere 2155.

Figure 5. Photograph of mixed intercropping plot.

Figure 6. Photograph of stripped intercropping plot.

TRT 6 **205**	TRT 11 **210**	TRT 8 **215**	TRT 3 **220**	TRT 12 **225**	TRT 4 **230**	TRT 4 **405**	TRT 98 **410**	TRT 3 **415**	TRT 3 **420**	TRT 11 **425**	TRT 7 **430**
TRT 3 **204**	TRT 13 **209**	TRT 10 **214**	TRT 5 **219**	TRT 11 **224**	TRT 7 **229**	TRT 6 **404**	TRT 13 **409**	TRT 5 **414**	TRT 1 **419**	TRT 99 **424**	TRT 10 **429**
TRT 7 **203**	TRT 98 **208**	TRT 2 **213**	TRT 1 **218**	TRT 98 **223**	TRT 8 **228**	TRT 7 **403**	TRT 12 **408**	TRT 10 **413**	TRT 5 **418**	TRT 13 **423**	TRT 2 **428**
TRT 9 **202**	TRT 99 **207**	TRT 5 **212**	TRT 9 **217**	TRT 99 **222**	TRT 6 **227**	TRT 1 **402**	TRT 11 **407**	TRT 2 **412**	TRT 9 **417**	TRT 98 **422**	TRT 8 **427**
TRT 1 **201**	TRT 12 **206**	TRT 4 **211**	TRT 10 **216**	TRT 13 **221**	TRT 2 **226**	TRT 8 **401**	TRT 99 **406**	TRT 9 **411**	TRT 4 **416**	TRT 12 **421**	TRT 6 **426**
TRT 2 **105**	TRT 98 **110**	TRT 5 **115**	TRT 7 **120**	TRT 11 **125**	TRT 9 **130**	TRT 9 **305**	TRT 12 **310**	TRT 4 **315**	TRT 2 **320**	TRT 11 **325**	TRT 3 **330**
TRT 8 **104**	TRT 13 **109**	TRT 7 **114**	TRT 6 **119**	TRT 99 **124**	TRT 5 **129**	TRT 5 **304**	TRT 11 **309**	TRT 1 **314**	TRT 8 **319**	TRT 13 **324**	TRT 4 **329**
TRT 4 **103**	TRT 12 **108**	TRT 9 **113**	TRT 2 **118**	TRT 13 **123**	TRT 10 **128**	TRT 10 **303**	TRT 98 **308**	TRT 7 **313**	TRT 5 **318**	TRT 98 **323**	TRT 6 **328**
TRT 6 **102**	TRT 11 **107**	TRT 3 **112**	TRT 8 **117**	TRT 98 **122**	TRT 3 **127**	TRT 3 **302**	TRT 99 **307**	TRT 8 **312**	TRT 10 **317**	TRT 99 **322**	TRT 9 **327**
TRT 10 **101**	TRT 99 **106**	TRT 1 **111**	TRT 4 **116**	TRT 12 **121**	TRT 1 **126**	TRT 2 **301**	TRT 13 **306**	TRT 6 **311**	TRT 7 **316**	TRT 12 **321**	TRT 1 **326**
Zone 1: 100% ET 16 rows			Zone 2: 60% ET 16 rows			Zone 3: 100% ET 16 rows			Zone 4: 60% ET 16 rows		

Figure 7. Map of field with planting treatments (TRT) and Irrigation treatments (zones). Treatments 98 and 99 are filler treatments.

Table 3. Planting treatments and seeding rates.			
Treatment	Planting configuration	Alfalfa seeding kg ha^{-1}	Grass seeding kg ha^{-1}
1	Alfalfa Monoculture (ALF)	22.4	0
2	75:25 ALF:OG mix	16.8	2.8
3	75:25 ALF:TF mix	16.8	4.2
4	75:25 ALF:MB mix	16.8	4.2
5	50:50 ALF:OG mix	11.2	5.6
6	50:50 ALF:TF mix	11.2	8.4
7	50:50 ALF:MB mix	11.2	8.4
8	50:50 ALF:OG strip	11.2	5.6
9	50:50 ALF:TF strip	11.2	8.4
10	50:50 ALF:MB strip	11.2	8.4
11	Meadow Brome monoculture (MB)	0	16.8
12	Tall Fescue monoculture (TF)	0	16.8
13	Orchardgrass monoculture (OG)	0	11.2

Cultivars

The alfalfa cv. FSG (Farm Science Genetics®) 415BR was supplied by Allied Seed LLC based in Nampa, Idaho. The alfalfa seed was inoculated with rhizobia and a fungicide was applied to the seed before planting. This cultivar is highly resistant to Aphanomyces-Race 1 & 2, bacterial wilt, fusarium wilt, verticillium wilt, stem nematode, and others. This cultivar has wide adaptability from the Intermountain West to the Northeast US and has a very fast recovery after cutting (Allied Seed LLC). This cultivar has a fall dormancy of 4 (scale 1 to 11, 11 most hardy) and a winter hardiness of 2 (scale of 1 to 5, 1 most hardy).

The TF cultivar used for this trial was FSG 402TF supplied by Allied Seed LLC. This cultivar is described as a high yielding, endophyte-free TF adapted to a range of environments (Allied Seed LLC). FSG 402 TF showed significant resistance to stem rust and crown rust diseases when compared to other TF cultivars. This cultivar was also shown to have significant regrowth during the summer months compared to other TF cultivars such as Kentucky 31 and Fawn.

Orchardgrass cv. Pawnee was supplied by Allied Seed LLC. This cultivar was bred for wide adaptability, excellent regrowth, drought/grazing tolerance, and stem rust resistance (Allied seed LLC). This cultivar is widely adapted and grows well across the US. Pawnee has been shown to perform well under limited and full irrigation. This cultivar produces some of the highest yields among OG cultivars (Allied seed LLC).

For our trial, we used meadow brome cv. Cache which was supplied by Buffalo Brand Seed LLC located in Greeley, CO. This cultivar was released in 2004 by the USDA Agricultural Research Service in Logan, Utah. This cultivar was developed for increased seedling vigor/establishment and increased forage yields (Jensen, 2004). Cache is intended for use in high-elevation western states on irrigated or semi-irrigated pastures.

Establishment

Planting occurred on August 10, 2020, with the first irrigation on August 12, 2020. Subsequent irrigations were performed utilizing the drip system. Flow was measured with a FLOWMEC® Tm series flowmeter. The pump used to supply water to the drip system was a Munroe 3 HP centrifugal pump (LP series) that utilized a disc filter (100 micron) for filtration. Four manifolds were created, separating the field into four, 16-row irrigation zones that were used to apply irrigation treatments. Pressure was kept at >10 PSI to ensure proper flow from each emitter.

Irrigation Treatments

All planting treatments were irrigated at 100% evapotranspiration (ET) through the first cutting (Table 4). After the first cutting, irrigation treatments were adjusted to either 100% or 60% ET as shown in Table 4. Irrigation was based on reference ET using the ASCE Standardized Reference Equation (Walter et al. 2001). ET rates were based on alfalfa and calculated using data from the CSU CoAgMET website, for the CSU Fruita Experiment Station (FRT03), which houses the CoAgMET weather station onsite. Sub-surface drip irrigation is 95% efficient (Payero et al. 2005). Irrigation occurred when cumulative total ET from the last irrigation reached 35 to 43 mm.

Table 4. Irrigation treatments for each cutting.

Treatment	**1st cut**	**2nd cut**	**3rd cut**
Full Irrigation	100% ET	100% ET	100% ET
Deficit Irrigation	100% ET	60% ET	60% ET

Sample Processing

Three harvests occurred in both the 2021 and 2022 growing seasons (Table 5). Sample harvesting occurred by hand sickle when alfalfa plants were in the 10% bloom stage. Samples were taken from the middle two 76.2 cm beds to minimize border effects. Each sample area was 0.76 m^2 (76.2 cm by 1 m) and plants were cut to a stubble height of 10 cm. In monoculture (control) treatments, only one sample was taken from each plot per cutting. In the alternate row plots, one sample was taken from the grass and one from the alfalfa and processed separately. In the mixed plots, two samples were taken from each of the middle two beds. Once hand harvesting of samples occurred, the field was mechanically harvested with a swather to a stubble height of 10 cm and then baled.

Table 5. Sampling and swathing dates.

2021	Sampling Date	Swathing date
Cut 1	5/24 - 5/28/2021	6/4/2021
Cut 2	7/12 - 7/14/2021	8/7/2021
Cut 3	09/11 - 09/14/2021	9/20/2021
2022		
Cut 1	05/23 - 05/25/2022	6/11/2022
Cut 2	07/18 - 07/22/2022	7/25/2022
Cut 3	08/22 - 08/25/2022	9/3/2022

In the mixed plot samples, alfalfa and grasses were hand separated and processed separately. All samples were dried in a forced-air oven at 55°C for 72 hours. Samples were then weighed to determine biomass. The biomass of each sample was used to extrapolate dry matter yield (DMY) in kg ha^{-1}. Once dry, samples were prepared for quality analysis by grinding dried samples through a Wiley mill to pass a 2-mm screen. Therefore, samples were then ground through a cyclone mill with a 1-mm screen for uniform particle size. For mixed and stripped treatments, the previously separated alfalfa and grass were combined into one ground sample according to the biomass measurement ratios for each plot. This allowed for one set of quality data that represented the whole plot.

Quality analysis was performed using near infrared reflectance spectroscopy at Colorado State University. Parameters of interest included CP, ADF, NDF, NDFD, and RFV. Calibration equations for pure alfalfa, pure grass, and alfalfa-grass mixtures were used (NIRS Consortium). Samples were run in house at CSU using a Unity Scientific SpectraStar 2600XT (KPM Analytics, Westborough, MA).

Statistical Analysis

A split-plot analysis of variance (ANOVA) was used to analyze the yield and quality parameters by planting and irrigation treatments as well as interactions. Irrigation was the main plot while the plant was the split plot. Block, irrigation zone, and plot were random effects. Yield, cutting, and year were fixed effects. Pairwise comparisons using estimated marginal means with a Tukey adjustment was used to compare planting treatments with one another. All statistical analyses were performed using R 4.2.2. (R Core Team, Vienna Austria 2020). Significant differences were determined using a p-value < 0.05.

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CHAPTER 3. RESULTS AND DICUSSION

Each cutting and year were analyzed separately due to differences in growth/climatic conditions, degree of grass versus alfalfa establishment, and other factors impacting yield and quality. All of these factors caused a number of significant interactions between years and cuttings (Table 6).

Table 6. Significant interactions between and among variables.

Significant Interactions	*p*-value
Irrigation:Cutting	<.0001
Planting Treatment:Cutting	<.0001
Irrigation:Year	<.0001
Planting Treatment:Year	<.0001
Cutting:Year	<.0001
Irrigation:Cutting:Year	<.0001
Planting:Cutting:Year	<.0001

Dry Matter Yield (DMY)

2021

There were no interactions between planting and irrigation treatments during any of the cuts in 2021 ($p \geq 0.4738$). There were also no significant differences between irrigation treatments for any of the cuts ($p \geq 0.1513$). Large rain events reduced the effects of deficit irrigation resulting in no differences in yield between irrigation treatments during the 2021 season. Between cuttings 1 and 2 there was 10 mm of precipitation and between cutting 2 and 3 there was 71 mm of precipitation. Mean dry matter yield by cutting for the 2021 season is presented in Table 7.

Table 7. Dry matter yield for each cutting in 2021.

Treatment	Cut 1	Cut 2	Cut 3	Total
	yield (kg ha^{-1})			
Alfalfa (ALF)	5386 AB	4214A	3618 A	13406 AB
75:25 ALF-OG mix	5345 AB	4136 AB	3970 A	13451 AB
75:25 ALF-TF mix	6227 A	4554 A	3938 A	14719 A
75:25 ALF-MB mix	5987 A	4613 A	4150 A	14751 A
50:50 ALF-OG mix	5432 AB	4556 A	3913 A	13712 AB
50:50 ALF-TF mix	5804 A	4290 AB	4140 A	14234 A
50:50 ALF-MB mix	5949 A	4339 AB	4018 A	14306 A
50:50 ALF-OG strip	4269 BC	3413 B	3393 A	11075 C
50:50 ALF-TF strip	5604 AB	3928 AB	3717 A	13249 AB
50:50 ALF-MB strip	5568 AB	3628 AB	3335 A	12532 BC
Meadow Brome (MB)	5213 AB	962 C	1185 B	7361 E
Tall Fescue (TF)	5820 A	2027 C	1411 B	8718 D
Orchardgrass (OG)	3017 C	1042 C	1297 B	5356 F

Means followed by the same letter within a column are not significantly different ($p<0.05$).

For all cuts in 2021, there were significant differences among planting treatments ($p<0.0001$). The ALF monoculture, mixed treatments, TF stripped, and MB stripped were all similar in the first and second cutting (Table 7). Orchardgrass DMY during cutting one was the lowest compared to the other grasses, potentially due to poor establishment during the previous fall. Grass monocultures had the lowest yields and were significantly different from all other treatments. In the third cutting, there were no differences among the ALF monoculture, mixed intercropping, and stripped treatments. Similar to the second cutting, grass monocultures had the lowest yields and were significantly different from all other treatments in cutting three.

When looking at the 2021 total dry matter yield, there was no significant difference between irrigation treatments (p=0.2140) and no interaction between irrigation and planting treatments (p=0.9906). There was, however, a significant difference between planting treatments (p<0.0001). The alfalfa monoculture, all of the mixed treatments, and the TF strip treatment were all the same. Meadow brome and OG strip treatments were similar but lower than those previously described, followed by TF, OG, and MB monocultures in terms of overall yield. Grass monocultures were significantly lower than all intercropping treatments.

In the first cutting, differences between irrigation treatments were not expected as deficit irrigation was implemented after cut one. Yields during the first cut were the highest due to favorable spring growing conditions and grass stem production, as observed by others (Mahli et al. 2002; Aponte et al. 2019). Grass species were in the reproductive phase and developed seed heads in cut one, which also increased yields. Orchardgrass had an abnormally low yield potentially due to poor establishment.

Following the first cutting at the end of May, temperatures increased, and growing conditions became less favorable for both grasses and legumes, as noted by Aponte et al. (2019). The average temperature during May is 16.5°C compared to 21.6°C in June. The decrease in yield after the first cut was more drastic for the grasses than alfalfa. This was likely due to reduced growth caused by the summer slump (higher temperatures) that most cool-season grasses experience, along with grass growth being purely vegetative after the first cutting (Aponte et al. 2019; Sleugh et al. 2000). This results in the grasses being less competitive and having lower yields. Grasses in the intercropping treatments likely benefit from additional N in the soil provided by the rhizobia in the root nodules on the alfalfa (Berdahl et al. 2001; Moore et al. 2020), although intercropping yields still decreased from cutting one to two. Similarly, Malhi et al. (2002) observed a decline in alfalfa yields from cut one to cut two when alfalfa was mix intercropped with bromegrass, even when significant N fertilizer was applied (200 kg ha^{-1}).

Alfalfa dominated the mixed plots throughout 2021, especially in the 2nd and 3rd cuttings when grasses were not as competitive due to the summer slump and vegetative growth. The grasses used in this study were non-jointing and only produced reproductive growth during cut one. These plots were established during the prior late summer, so the grasses were not fully established in the mixed intercropping treatments due to competition with the alfalfa. This was likely the main reason for lack of significant yield increases in mixed intercropping treatments compared to the ALF monoculture during the first full growing season. Year one results can be variable for intercropping, with some studies demonstrating no increase in yield compared to monocultures and others with significant increases (e.g., Bi et al. 2019; Sleugh et al. 2000; Aponte et al. 2019; Spandl and Hesterman 1997).

Table 8 shows the percentage of grass present decreased for the intercropping treatments between the 1st, 2nd, and 3rd cuttings in 2021 and 2022. Similarly, Sleugh et al. (2000) and Aponte et al. (2019) noted an increase in the legume:grass ratio after the 2nd and 3rd cutting, illustrating the reduced competitiveness and productivity of grasses in later season cuttings. There was an average decrease of 47% and 52% in grass yield from cut one to cut two and three, respectively. Grass monoculture yields decreased the most over the 2021 season (Table 7), most likely due to non-ideal growing conditions for these cool season grasses during later cuttings, along with potential N deficiencies being present. Grasses require high N inputs, and without proper fertilization, N can become limiting (Moser et al. 1996). Compared to the grass monocultures, there was a significant increase in yield, regardless of intercropping method, when ALF was mixed with the grasses (Table 7).

Table 8. Grass percentages for intercropping treatments during each cutting in 2021 and 2022.

Treatment	Cut 1 2021	Cut 2 2021	Cut 3 2021	Cut 1 2022	Cut 2 2022	Cut 3 2022
	------------------ grasses present (%) ------------------					
75:25 ALF-OG mix	21%	16%	10%	46%	17%	11%
75:25 ALF-TF mix	22%	14%	13%	51%	19%	16%
75:25 ALF-MB mix	16%	6%	4%	34%	15%	9%
50:50 ALF-OG mix	25%	12%	11%	38%	20%	15%
50:50 ALF-TF mix	35%	21%	19%	64%	21%	21%
50:50 ALF-MB mix	35%	12%	9%	53%	19%	15%
50:50 ALF-OG strip	33%	19%	23%	46%	23%	19%
50:50 ALF-TF strip	51%	32%	33%	58%	27%	30%
50:50 ALF-MB strip	50%	19%	20%	43%	17%	17%

2022

Mean dry matter yields by cutting for the 2022 season are presented in Table 9. Irrigation treatments were significantly different from each other during the 2nd and 3rd cuttings. There was one significant interaction between irrigation and planting treatments during cut three.

Table 9. Dry matter yield for each cutting in 2022. There was a significant interaction between irrigation and planting treatments during cut 3 (p=0.00219).

Treatment	Cut 1	Cut 2	Cut 3 100% ET	Cut 3 60% ET	Total
	yield (kg ha^{-1})				
Alfalfa (ALF)	4348 C	3370 C	3850 B	2482 B	10758 BC
75:25 ALF-OG mix	5160 AB	4521 A	4456 A	3172 A	13494 A
75:25 ALF-TF mix	5279 AB	4457 A	4817 A	3146 A	13719 A
75:25 ALF-MB mix	4964 ABC	3974 B	4320 AB	2994 AB	12663 AB
50:50 ALF-OG mix	5145 AB	4281 AB	4544 A	3252 A	13323 A
50:50 ALF-TF mix	5399 A	4333 AB	4623 A	3464 A	13776 A
50:50 ALF-MB mix	5078 AB	4134 AB	4343 AB	2978 AB	12873 AB
50:50 ALF-OG strip	4219 C	2708 D	2961 C	1839 C	9327 C
50:50 ALF-TF strip	4653 BC	2708 D	3276 BC	1953 BC	9975 C
50:50 ALF-MB strip	4120 C	2667 D	2968 C	1783 C	9162 C
Meadow Brome (MB)	2920 D	784 E	1198 D	462 D	4533 D
Tall Fescue (TF)	3022 D	725 E	1340 D	496 D	4440 D
Orchardgrass (OG)	2251 D	704 E	1130 D	501 D	3903 D
Means followed by the same letter within a column are not significantly different (p<0.05).					

During cut one in 2022, there was no difference in yield between irrigation treatments (p=0.2657) and no interaction between planting and irrigation treatments (p=0.5093). There were significant differences among planting treatment dry matter yields (Table 9; p<0.0001). All mixed treatments were significantly higher than the ALF monoculture except for the 75:25 ALF:MB. All stripped treatments were similar to the ALF monoculture. The highest yielding stripped treatment was the ALF:TF which did not differ from most of the mixed treatments.

The lowest yields in 2022 for all cuttings were in the grass monocultures which were significantly different from the rest of the treatments (Table 9). No fertilization occurred on this field during the 2021 or 2022 seasons, likely reducing grass monoculture yields (Mahli et al. 2002). Grasses in intercropping treatments were not as limited by N, as the alfalfa supplied some

N through rhizobia N fixation, boosting yields and improving quality compared to the grasses grown in monoculture (Aponte et al. 2019; Mahli et al. 2002; Créme et al. 2016).

There was major alfalfa weevil *(Hypera postica)* pest pressure during the spring of 2022, which could have affected the alfalfa monoculture yield during cut one. The mixed intercropping treatments did not suffer as much of a decline in yield as the grasses compensated for some of the losses due to the weevil as well as reduced overall weevil damage to the alfalfa in those plots. Nikolova et al. (2018) and Roda et al. (1996) documented the ability of forage grasses to decrease pest damage when grown with alfalfa, including alfalfa weevil.

In the mixed treatments, the grasses filled in empty spaces between plants at the soil surface as well as within the alfalfa canopy. Grass seed heads were visible above the alfalfa canopy. The lack of response from 2021 in mixed treatments was likely due to slower grass establishment compared to alfalfa caused by greater competition from the alfalfa (Aponte et al. 2019). In 2022, the grasses likely had a larger, more established root system that allowed them to exploit the top layers of soil. At the same time, the alfalfa taproot was deeper in 2022, allowing the two species to thrive together due to exploitation of different soil niches (Ameri and Jafari 2016; Nikolova et al. 2018). Nikolova et al. (2018) demonstrated a 49% increase in root biomass when alfalfa was mix intercropped with OG compared to ALF alone, showing increased exploitation of the soil. As mixed stands mature, grasses become more dominant compared to alfalfa (Aponte et al. 2019; Sleugh et al. 2000).

When comparing the stripped intercropping treatments, the independent cultivation of each species on different beds provided some benefits for individual species. Due to independent cultivation, the alfalfa can receive greater sunlight with less competition from adjacent grasses. Grasses likely benefited in these plots due to some increased nitrogen fixed by the alfalfa and reduced competition due to separate cultivation. While the two species were spatially separate on the surface, they were close enough to allow interspecies interactions (Ameri and Jafari 2016; Glaze-Corcoran et al. 2020; Smith and Carter 2013). However, interactions were likely reduced in stripped plots compared to mixed plots. Mixed treatments tended to yield higher during cut one.

The deficit irrigation treatment was initiated after cut one. Dry matter yields during cut two were significantly different between irrigation (p=0.0196) and planting treatments (p<0.0001), but there was no interaction (p=0.3746). The mean DMY was 3398 and 2658 kg ha^{-1} for the 100% and 60% ET irrigation treatments, respectively, a 22% difference. After the first cutting, there was a lack of regrowth in all plots due to pest pressure, primarily alfalfa weevil. The field was sprayed with Cyfluthrin (44 g a.i. ha^{-1}) and regrowth began to occur shortly after.

During the second cutting, yields followed: all mixed intercropping treatments > ALF monoculture > all stripped treatments > all grass monocultures. The lowest yielding mixed treatment was the 75:25 MB mix, which was significantly lower than the 75:25 TF and OG mixtures. However, this treatment still significantly improved yields over ALF and MB grown alone. The 50:50 MB mixed treatment was similar to all other mixtures. The stripped treatments likely decreased in yield due to the inability of the grass to yield as much as the alfalfa. Furthermore, grasses and alfalfa in the stripped treatments had limited root interactions that likely reduced nitrogen transfer from alfalfa root nodules to grasses compared to mixed treatments. Pest damage likely affected regrowth of alfalfa following the first cut, reducing the ALF monoculture yield.

In the third cutting, there were significant differences between irrigation treatments (p=0.0229), planting treatments (p<0.0001), and an interaction was present between irrigation and planting treatments (p=0.0021). Cut 3 mean dry matter yields for the 100% and 60% ET irrigation treatments were 3371 and 2189 kg ha^{-1}, respectively, which equated to a 35% difference.

The interaction between planting and irrigation treatments was likely due to the larger percentage decrease in grass monoculture yields between irrigation treatments compared to other treatments. Grasses yields were reduced 60% on average between irrigation treatments compared to 29.9% and 39.4% for mixed and strip treatments, respectively. Deficit irrigation treatments decreased the grass monoculture yields more than other treatments since grass root systems are not as deep as alfalfa, and therefore are more affected by limited soil moisture in the upper soil depths.

Across both irrigation treatments for the third cutting, the OG and TF mixed treatments, regardless of seeding ratio, were significantly higher yielding than the ALF monoculture (Table 9). Meadow brome mixtures were similar to the ALF alone. There was no difference in yield among mixed treatments. In stripped treatments, TF was the only stripped treatment that was similar to the ALF monoculture, regardless of irrigation. All intercropping treatment yields were significantly higher than the grass monocultures, regardless of irrigation.

For yearly total DMY, there were significant differences between irrigation treatments (p=0.0287) and among planting treatments (p<0.0001), but no interaction between planting and irrigation treatments (p=0.9606). The mean DMY was 11,214 and 9,807 kg ha^{-1} for the 100% and 60% ET irrigation treatments, respectively, which equated to a seasonal reduction of 12.5% in the 60% as compared to the 100% ET treatment. Total differences among planting treatment DMY is presented in Table 9. Compared to 2021, the OG monoculture was similar to the other grass monocultures in 2022. Similarly, the OG stripped treatment was similar to the other stripped treatments in 2022, unlike 2021. The TF and OG mixed treatments had significantly higher total yields than the ALF monoculture. Stripped treatments had total yields similar to one another averaging 9,488 kg ha^{-1} which did not differ from the ALF monoculture (10,758 kg ha^{-1}).

Grass monocultures were significantly lower than all other treatments and similar to one another, averaging 4,292 kg ha^{-1} across the three species. Compared to the higher yielding mixed treatments, the stripped treatments and grass monocultures averaged 28.7% and 54.8% less in total yield, respectively. Intercropping with alfalfa significantly increased yields throughout both years, regardless of the grass species, compared to the grasses alone. This demonstrates a clear benefit to growing alfalfa with grass compared to grasses alone.

Alfalfa has a more consistent growth pattern throughout the year compared to cool-season grasses (Figure 2). This growth pattern results in more consistent yields throughout the year and allows for larger yields when the grasses enter the "summer slump." Also, these are non-jointing grasses, meaning there is no stem production following the first cutting, reducing productivity compared to alfalfa, which exhibits significant stem production all season. While both intercropping methods provided a yield advantage compared to the grasses, mixed intercropping clearly was more productive compared to stripped.

There was a 13.4% and 28.7% reduction in yield when comparing the average mixed yield to the average stripped yield in 2021 and 2022, respectively. Stripped treatments yearly DMY were significantly different from all mixed treatments in 2022 (Table 9). Li et al. (2021) demonstrated that greater root entanglement results in higher yields compared to when there is limited or no root entanglement. Stripped intercropping treatments likely had less root interactions compared to mixtures due to separate cultivation, though some still may have occurred near in-field bed edges. A lack of root interaction reduced the typical benefits of intercropping, and therefore there was a reduction in yield (Li et al. 2021). Overall, mixed intercropping had a more pronounced effect on yield compared to stripped intercropping, regardless of grass species.

Quality

Crude Protein- 2021

One of the most important nutritional forage parameters is crude protein. The mean crude protein percentage for each cutting during 2021 is presented in Table 10. There was an interaction between planting and irrigation treatments for cut 2 in 2021.

Table 10. Crude protein (%) for all cuts in 2021.

Treatment	Cut one	Cut 2 - 100% ET	Cut 2 - 60% ET	Cut three
	------------------ Crude Protein (%) ------------------			
Alfalfa (ALF)	19.0 A	22.1 AB	22.2 A	24.3 A
75:25 ALF-OG mix	17.8 B	22.1 AB	20.7 AB	23.1 AB
75:25 ALF-TF mix	18.4 A	22.7 A	21.6 A	22.8 AB
75:25 ALF-MB mix	17.5 B	21.8 ABC	22.4 A	23.6 A
50:50 ALF-OG mix	17.4 BC	20.4 ABC	21.3 A	23.3 AB
50:50 ALF-TF mix	17.8 B	21.5 ABC	21.0 AB	23.5 A
50:50 ALF-MB mix	16.4 BC	21.3 ABC	22.0 A	22.8 AB
50:50 ALF-OG strip	15.6 C	19.8 BC	21.4 AB	19.8 C
50:50 ALF-TF strip	13.2 D	16.5 D	18.4 B	20.4 BC
50:50 ALF-MB strip	13.2 D	19.2 C	21.1 AB	22.3 ABC
Meadow Brome (MB)	5.4 E	11.8 E	12.3 C	11.9 D
Tall Fescue (TF)	5.8 E	6.6 F	7.6 D	8.5 E
Orchardgrass (OG)	5.4 E	8.3 F	7.2 D	10.5 DE
Means followed by the same letter within a column are not significantly different (p<0.05).				

No differences were expected in cut one due since all plots received the same irrigation. There was a significant difference in CP among planting treatments (p<0.0001). The ALF monoculture and the 75:25 ALF:TF mix had the highest CP (Table 10). The ALF:TF 75:25 mix CP did not decrease significantly, as compared to ALF alone, likely due to the low proportion of grass and additional N fixed by the alfalfa being taken up by the TF in those plots. Créme et al. (2016) found that when intercropping grasses with alfalfa, there was a significantly higher rate of N fixation by the alfalfa compared to alfalfa grown in monocultures. Ameri and Jafari (2016) found that tall fescue responded the best to legume fixed N compared to other grasses, resulting in increased CP.

Due to reproductive growth and stem elongation in grasses during this cutting, CP was reduced in intercropping treatments. Mixed treatments typically had higher CP content compared to the stripped treatments. The TF and MB stripped treatments had a larger percentage of grass in the plots (~50%) compared to mixed treatments (Table 8), resulting in a reduction in CP content. The OG strip treatment had a lower grass percentage and thus a higher CP as compared to the TF and MB strip treatments. The grass monocultures had significantly lower CP content than all other treatments due to their maturity as well as the fact that grasses are typically lower in CP compared to legumes (Ball et al. 2001; Capstaff and Miller, 2018). Therefore, incorporating grasses with alfalfa will generally result in lower CP compared to pure alfalfa.

In cut two, there was no difference between irrigation treatments (p=0.6255), but there were differences among planting treatments (p<0.0001). In addition, there was an interaction between planting and irrigation treatments (Table 10, p=0.0286). Crude protein was not different between the alfalfa monoculture and any of the mixed intercropping treatments, regardless of irrigation treatment. In the 60% ET, there was a clear increase in CP content in stripped treatments compared to the 100% ET, likely resulting in the interaction during this cutting. Grasses in stripped treatments yielded 32% more in the 100% ET treatment, compared to the

60% ET treatment (Table 8). This increase in grass yield in the 100% ET treatment likely drove CP content down due to higher grass proportions. Furthermore, forages under water stress typical have higher quality due to the concentration of nutrients and therefore we would expect lower CP in the full irrigation compared to the deficit irrigation (Hanson et al. 2007; Holman et al. 2016).

In general, the stripped intercropping treatments were lower than the alfalfa monoculture in the 100% ET irrigation treatment. However, in the 60% ET, the stripped treatments generally had a CP content similar to the ALF monoculture. Lower grass yields would result in a larger proportion of alfalfa in those plots, in turn increasing CP in those treatments. This is compounded with the fact that stressed plants typically show an increase in CP content due to less dilution of nutrients (Hanson et al. 2007; Holman et al. 2016). The monoculture grasses all had the lowest CP contents out of all treatments; however, the TF and OG were significantly lower than MB, regardless of irrigation. Meadow brome had a larger decrease in yield (82%) from cut one to cut two compared to the other two grasses (65% for TF & OG), likely concentrating the CP, similar to that observed by Holman et al. (2016).

In cut three, there was no difference in CP between irrigation treatments (p=0.7869) and no interaction between planting and irrigation treatments (p=0.3388). There were significant differences in CP among planting treatments (p<0.0001). There was no difference in CP content between the ALF monoculture compared to all mixed treatments and the 50:50 ALF:MB stripped. The TF and OG stripped treatments had significantly lower CP content compared to the ALF monoculture. Grass monocultures had the lowest CP content of all treatments.

The vegetative regrowth of grasses results in a high leaf:stem ratio, increasing CP content. Also, additional N is available from alfalfa N-fixation in mixed treatments which likely increased CP content of the grasses (Ameri and Jafari 2016). The TF and OG stripped treatments were significantly lower in CP than the ALF monoculture due to the larger proportion of grass in those plots compared to mixed treatments (Table 8). Half of stripped plots are planted exclusively to grass, allowing the grass to express itself without competition, thus resulting in larger grass proportions compared to ALF and leading to lower CP. The MB stripped had the lowest proportion of grass as well as the most significant decrease in yield over time, resulting in higher CP due to a higher proportion of alfalfa. Segregation of the grasses and alfalfa in stripped plots could also reduce CP by minimizing root interactions (i.e., sharing of fixed N) between the two species. Grass monocultures had significantly lower CP content than all other treatments.

Lack of differences between mixed plots and pure alfalfa was likely due to increased N in the soil from N-fixation by the alfalfa rhizobia, resulting in elevated CP content in grasses grown with alfalfa plus the purely vegetative growth the grass exhibited in second and third cuttings. Ball et al. (2001) noted that grasses grown with substantial amounts of N can have comparable CP to legumes. Mixing grasses and alfalfa results in greater amounts of N-fixation by the alfalfa, reducing fertilizer inputs and improving soil fertility (Créme et al. 2016). Except for cut one, mixed intercropping of grasses with alfalfa does not significantly lower CP content, demonstrating that intercropping alfalfa with grasses is a viable practice as it does not compromise CP and decrease quality.

Crude Protein- 2022

Mean crude protein for each cut during 2022 is presented in Table 11. For all cuttings in 2022, there were no differences in CP between irrigation treatments ($p>0.2775$) and no interaction between planting and irrigation treatments ($p>0.2134$). There were significant differences among planting treatments ($p<0.0001$) in all cuttings.

Table 11. Crude protein for each cut in 2022.

Treatment	Cut one	Cut two	Cut three
	------------ Crude Protein (%) ------------		
Alfalfa (ALF)	22.1 A	23.6 A	26.3 A
75:25 ALF-OG mix	17.9 BC	22.3 A	25.1 AB
75:25 ALF-TF mix	18.6 BC	23.0 A	25.9 A
75:25 ALF-MB mix	19.9 B	22.0 A	25.1 AB
50:50 ALF-OG mix	18.8 BC	22.2 A	24.4 AB
50:50 ALF-TF mix	17.9 BC	22.2 A	25.1 AB
50:50 ALF-MB mix	18.0 BC	22.8 A	24.8 AB
50:50 ALF-OG strip	17.7 C	21.9 A	23.6 AB
50:50 ALF-TF strip	17.3 C	21.5 A	22.6 B
50:50 ALF-MB strip	18.1 BC	21.7 A	24.0 A
Meadow Brome (MB)	7.4 D	11.9 B	14.6 C
Tall Fescue (TF)	6.3 D	7.8 C	10.0 D
Orchardgrass (OG)	7.1 D	11.3 B	12.4 CD

Means followed by the same letter within a column are not significantly different (p<0.05).

During the first cut in 2022, the alfalfa monoculture had the highest CP content as compared to all other treatments. For most comparisons, mixed and stripped treatments were not significantly different in terms of CP. The grass monocultures had the lowest CP compared to all other treatments. These results were similar to the first cutting in 2021. As cool-season grasses mature, the stems begin to elongate. Elongated stems require thick cell walls, composed of low-quality fiber, to support them. Elongation decreases the leaf-to-stem ratio, decreasing the CP content in the plant, and CP content is diluted due to stem production (Moore et al. 2020; Ball et al. 2001; Putnam et al 2014). This explains the slight reduction in CP throughout the intercropping treatments and the lowest CP values in the grass monocultures during cut one.

In the second cutting, the ALF monoculture CP content was similar to all mixed and stripped intercropping treatments. The grass monocultures had the lowest CP content. The difference in CP in third cutting, across treatments, was similar to cutting two, even though CP increased in cutting three as compared to cutting two (and cutting one). The vegetative grass morphology characteristics of non-jointing grass regrowth is higher quality due to the increased leaf:stem ratio compared to grasses during cutting one, similar to that described by Adesogan et al. (2017) and Ball et al. (2001). Furthermore, when alfalfa is grown with grasses, there is an increase in rhizobial N fixation compared to alfalfa alone (Créme et al. 2016). Since CP is directly related to N content, elevated N levels allow for increased CP content (Ameri and Jafari 2016; Ball et al. 2001). This allowed for higher yield and quality of the grasses in intercropping plots in cuttings two and three. Due to this, there was not a significant reduction in CP content due to intercropping.

Similar to 2021, there was no significant decrease in CP for mixed treatments in 2022 compared to the alfalfa monoculture, except for cut 1. This demonstrates that mixed intercropping grass with alfalfa does not generally compromise quality, especially in later cuttings when non-jointing grass regrowth is all vegetative.

Neutral Detergent Fiber-2021

Mean NDF values for each cut in 2021 are presented in Table 12. There was no significant difference in NDF percentages between irrigation treatments ($p \geq 0.2348$) and no interaction between planting and irrigation treatments ($p \geq 0.1496$) for all cuttings in 2021. There were significant differences among planting treatments ($p<0.0001$) for all cuttings. Throughout all three cuttings, the grass monocultures had the highest NDF contents as compared to all other treatments.

Table 12. Neutral detergent fiber (NDF) for all cuts in 2021.

Treatment	Cut one	Cut two	Cut three
		NDF (%)	
Alfalfa (ALF)	40.5 F	40.4 DE	36.5 CD
75:25 Alfalfa-OG mix	42.3 DEF	39.8 E	36.6CD
75:25 Alfalfa-TF mix	41.8 EF	38.2 E	36.9 CD
75:25 Alfalfa-MB mix	43.0 DEF	39.2 E	36.6 CD
50:50 Alfalfa-OG mix	43.1 DEF	41.6 DE	37.3 CD
50:50 Alfalfa-TF mix	43.9 DEF	40.5 DE	36.1 CD
50:50 Alfalfa-MB mix	46.7 DE	40.3 DE	35.8 D
50:50 Alfalfa-OG strip	47.6 D	43.5 CD	45.6 B
50:50 Alfalfa-TF strip	50.7 CD	46.9 C	43.9 B
50:50 Alfalfa-MB strip	54.9 C	43.7 CD	41.0 BC
Meadow Brome (MB)	69.7 A	57.2 B	58.6 A
Tall Fescue (TF)	61.0 B	59.7 AB	58.8 A
Orchardgrass (OG)	59.6 B	62.8 A	62.2 A
Means followed by the same letter within a column are not significantly different (*p*<0.05).			

In cut one, the lowest NDF contents were in the ALF monoculture and most of the mixed treatments. Due to lower proportions of grass in most of the mixed treatments, there was not a significant increase in NDF content and, therefore, no impact on quality. The larger proportion of grasses in the stripped intercropping treatments increased NDF significantly, reducing quality. Since all the grasses went to maturity in the first cutting, one would expect higher NDF values with more grass (Adesogan et al 2017). The same NDF pattern for all treatments was observed in the second and third cutting. These results demonstrate that mixed intercropping of grasses with alfalfa does not necessarily decrease quality in terms of NDF content.

Neutral Detergent Fiber-2022

Mean NDF values for each cut and planting treatment for 2022 are presented in Table 13. There was no significant difference in NDF percentages between irrigation treatments ($p \geq 0.2033$) and no interaction ($p \geq 0.5346$) for all cuttings in 2022. There were significant differences among planting treatments ($p<0.0001$) for all cuttings. Similar to 2021, the grass monocultures had significantly greater NDF contents throughout all cuttings as compared to all other treatments.

Table 13. Neutral detergent fiber (NDF) for each cut in 2022.

Treatment	Cut one	Cut two	Cut three
	--------------- NDF (%) ---------------		
Alfalfa (ALF)	34.8 C	38.4 B	33.6 C
75:25 ALF-OG mix	44.6 B	39.4 B	34.4 BC
75:25 ALF-TF mix	42.7 B	37.8 B	34.1 C
75:25 ALF-MB mix	40.3 B	39.7 B	34.6 BC
50:50 ALF-OG mix	42.5 B	40.5 B	36.0 BC
50:50 ALF-TF mix	44.2 B	39.1 B	35.1 BC
50:50 ALF-MB mix	44.5 B	38.7 B	35.1 BC
50:50 ALF-OG strip	43.5 B	40.1 B	37.6 BC
50:50 ALF-TF strip	43.7 B	40.3 B	39.1 B
50:50 ALF-MB strip	42.3 B	39.1 B	36.1 BC
Meadow Brome (MB)	60.6 A	55.6 A	56.4 A
Tall Fescue (TF)	55.7 A	58.0 A	60.2 A
Orchardgrass (OG)	60.3 A	60.0 A	60.9 A
Means followed by the same letter within a column are not significantly different (*p*<0.05).			

In the first cutting of 2022, the ALF monoculture had significantly lower NDF as compared to all other treatments. All mixed and stripped intercropping treatments were similar. In the second cutting, the ALF monoculture was not significantly different from all mixed and stripped intercropping treatments. In the third cutting, the ALF monoculture was not significantly different from almost all mixed and stripped intercropping treatments. Except for cutting one, intercropping grass with alfalfa did not increase NDF content, regardless of grass species or intercropping arrangement, in 2022.

The elevated NDF in intercropping treatments during the first cutting can be attributed to the maturity level of the grasses. First growth of cool-season, non-jointing grasses goes through the transition phase in the spring where stems elongate, resulting in the elevated NDF content observed during the first cutting (O'Reilly 2020; Adesogan et al. 2017). However, when grass growth is purely vegetative in subsequent cuttings, there is not an elevation in NDF and, therefore, no decrease in quality.

Acid Detergent Fiber-2021

Mean ADF values for each cut and planting treatment for 2021 are presented in Table 14. There was no significant difference in ADF content between irrigation treatments ($p \geq 0.1754$) and no interaction for any of the cuttings ($p \geq 0.3902$). There were significant differences among planting treatments ($p<0.0001$).

Table 14. Acid detergent fiber (ADF) for all cuts in 2021.

Treatment	Cut one	Cut two	Cut three
	--------------- ADF (%) ---------------		
Alfalfa (ALF)	35.1 C	36.1 A	33.3 B
75:25 Alfalfa-OG mix	31.2 D	29.8 B	30.1 BC
75:25 Alfalfa-TF mix	31.4 D	30.1 B	30.6 BC
75:25 Alfalfa-MB mix	31.0 D	31.3 B	31.7 BC
50:50 Alfalfa-OG mix	31.3 D	31.2 B	31.0 BC
50:50 Alfalfa-TF mix	31.5 D	30.4 B	28.8 C
50:50 Alfalfa-MB mix	32.1 D	30.3 B	28.7 C
50:50 Alfalfa-OG strip	35.8 BC	36.2 A	35.1 AB
50:50 Alfalfa-TF strip	35.9 BC	36.9 A	34.1 AB
50:50 Alfalfa-MB strip	37.8 B	36.6 A	34.1 AB
Meadow Brome (MB)	41.9 A	38.3 A	37.5 A
Tall Fescue (TF)	37.4 B	38.2 A	35.5 AB
Orchardgrass (OG)	36.4 BC	38.0 A	36.3 AB
Means followed by the same letter within a column are not significantly different ($p<0.05$).			

In the first cutting, the ALF monoculture ADF content was greater than all mixed intercropping treatments. In fact, the ALF monoculture was 3.7 percentage points greater than the average ADF of all mixed intercropping treatments. The ADF of all stripped treatments were significantly higher than all mixed treatments and similar to the ALF, TF, and OG monocultures.

During the first cutting, there was significant alfalfa weevil damage which defoliated the alfalfa plants. These weevils do not attack grasses. Reduction in foliage can reduce CP and increase fiber, resulting in lower quality (Ball et al. 2009). Weevil damage could explain the higher ADF content in the ALF monoculture due to extensive defoliation. Grass presence could have reduced weevil impact (Roda et al. 1996; Putnam et al. 2001), resulting in the lower ADF values found in mixed treatments. However, this trend continues into cuts two and three, suggesting another mechanism is responsible for the reduction in ADF content in mixed treatments.

In cut two, the ADF content of stripped treatments was similar to the ALF monoculture and all grass monocultures. The mixed treatments had significantly lower ADF compared to all other treatments. In cut three, the ADF content followed the trend of mixed treatments ≤ ALF monoculture ≤ stripped treatments = grass monocultures. This demonstrates relatively similar ADF content across most treatments.

In cuttings 1 and 2, the significant reduction in ADF content demonstrates the grasses' ability to reduce ADF content when mix intercropped with alfalfa, overall improving quality. Grasses typically have higher ADF values than legumes, leading one to think that the inclusion of grasses with alfalfa would increase ADF. However, this was not the case.

Acid detergent fiber is a measure of cellulose and lignin within a plant. This suggests that the presence of grass with alfalfa reduces one or both components in the cell wall, possibly by impacting the leaf:stem ratio of one or both species as they compete with one another. Spandl and Hesterman (1997) found similar results when mix intercropping ALF with timothy and bromegrass. They found no significant difference in ADF content between ALF alone compared to mixtures with grasses in cut one and cut three of their study. In the second cutting, these researchers found that mix intercropping significantly reduced ADF content compared to the ALF monoculture, agreeing with my results. Hesterman (1997) suggested that competition between alfalfa and grass reduced alfalfa development compared to alfalfa alone and subsequently lowered ADF content.

Acid Detergent Fiber-2022

Mean ADF values for each cut and planting treatment in 2022 are presented in Table 15. There was no significant difference in ADF content between irrigation treatments ($p \geq 0.6689$) and no interaction for any of the cuttings ($p \geq 0.2824$). There were significant differences among planting treatments ($p < 0.0001$).

Table 15. Acid detergent fiber (ADF) for each cut in 2022.

Treatment	Cut one	Cut two	Cut three
	ADF (%)		
Alfalfa (ALF)	30.0 D	32.9 C	30.3 BC
75:25 ALF-OG mix	33.5 C	34.5 BC	31.4 BC
75:25 ALF-TF mix	32.9 C	32.7 C	29.8 C
75:25 ALF-MB mix	32.5 C	34.8 BC	31.5 BC
50:50 ALF-OG mix	33.2 C	34.5 BC	31.1 BC
50:50 ALF-TF mix	33.3 C	34.0 BC	30.2 BC
50:50 ALF-MB mix	33.4 C	33.2 C	31.0 BC
50:50 ALF-OG strip	33.3 C	34.1 BC	32.6 B
50:50 ALF-TF strip	33.2 C	33.9 BC	32.3 BC
50:50 ALF-MB strip	33.4 C	33.7 BC	32.2 BC
Meadow Brome (MB)	37.2 A	37.2 AB	35.0 AB
Tall Fescue (TF)	35.2 B	38.9 A	38.7 A
Orchardgrass (OG)	35.9 AB	37.1 AB	38.3 A
Means followed by the same letter within a column are not significantly different (*p*<0.05).			

Acid detergent fiber values followed a different trend in 2022 compared to 2021. During the first cutting, the alfalfa monoculture was significantly lower than all other treatments, indicating higher quality. This again was likely due to the maturity of the grass during the first cutting. As the grasses continued to mature, more stem production occurred, resulting in higher fiber proportions in the crop, and thus a decrease in quality.

While the first cutting showed lower quality in intercropping plots, during the second and third cuttings, there was no decrease in quality. All intercropping treatments were similar to the alfalfa monoculture ADF content in cutting two and three. Grasses in these cuttings exhibited purely vegetative growth, resulting in higher quality and comparable ADF values to the alfalfa monoculture.

While the addition of grasses lowered quality in the first cutting, this trend did not continue for subsequent cuttings, similar to NDF. The addition of grasses did not lower forage quality when grass growth was vegetative. Compared to the first season, root systems were likely more established, and less competition was occurring between species in mixed treatments. This would result in more typical growth for both grass and alfalfa. Grasses generally have higher ADF content compared to alfalfa and, therefore, mixtures would be expected to have higher ADF compared to the ALF monoculture (Adesogan et al. 2017). Spandl and Hesterman (1997) noted that quality was compromised in alfalfa grass mixtures in cut one but not subsequent cuts, similar to my results.

Neutral Detergent Fiber Digestibility-2021

Mean NDFD values for 2021 are shown in Table 16. There was no significant difference in NDFD between irrigation treatments ($p \geq 0.3752$) and no interaction between planting and irrigation treatments ($p \geq 0.4408$) for any of the cuttings in 2021, but there were significant differences among planting treatments ($p<0.0001$).

Table 16. Neutral detergent fiber digestibility (NDFD) for all cuts in 2021.

Treatment	Cut one	Cut two	Cut three
	--------------- NDFD (%) -----------------------		
Alfalfa (ALF)	18.3 D	18.5 E	17.9 D
75:25 Alfalfa-OG mix	25.3 C	26.1 B	23.8 BC
75:25 Alfalfa-TF mix	24.7 C	24.7 BC	24.7 BC
75:25 Alfalfa-MB mix	25.8 C	24.4 BC	21.1 CD
50:50 Alfalfa-OG mix	26.2 C	26.7 B	22.9 BC
50:50 Alfalfa-TF mix	27.3 BC	27.7 B	25.6 B
50:50 Alfalfa-MB mix	28.4 BC	26.9 B	24.6 BC
50:50 Alfalfa-OG strip	26.0 C	21.5 DE	25.1 BC
50:50 Alfalfa-TF strip	28.3 BC	24.8 BC	25.0 BC
50:50 Alfalfa-MB strip	29.4 B	22.4 CD	22.8 BC
Meadow Brome (MB)	38.3 A	39.2 A	39.1 A
Tall Fescue (TF)	39.8 A	38.1 A	37.9 A
Orchardgrass (OG)	39.9 A	39.4 A	39.0 A
Means followed by the same letter within a column are not significantly different ($p<0.05$).			

In cutting one, all mixed and stripped intercropping treatments were significantly higher in NDFD than the ALF monoculture. A similar trend followed in cut two, where all intercropping treatments, except the OG stripped, were significantly higher in NDFD than the ALF monoculture. In the third cutting, a similar trend again was followed. Regardless of cutting, the addition of grasses with alfalfa significantly increased the NDFD of the forage, with few exceptions. For all cuttings in 2021, grass monocultures had significantly higher NDFD than all other treatments. ALF monoculture had the lowest NDFD.

While the addition of grasses increases NDFD, which is desirable. However, grasses also increased the NDF content in many situations, which is undesirable. In mixed treatments, there was an average of 8, 7.6, and 5.9 percentage points more NDFD compared to the ALF monoculture in cuttings 1, 2, and 3, respectively. In mixed treatments, there was an average of 3 and 4.6 percentage points more NDF compared to the ALF monoculture for cuttings 1 and 3, respectively; in cutting two, there was an average of 0.5 percentage points less NDF in mixed treatments as compared to the ALF monoculture (see Table 12).

In stripped treatments, there was an average of 9.6, 4.4, and 6.4 percentage points more NDFD compared to the ALF monoculture in cuttings 1, 2, and 3, respectively. With respect to NDF in the stripped treatments, there was an average of 10.6, 4.3, and 7 percentage points more NDF compared to the ALF monoculture for cuttings 1, 2, and 3, respectively (see Table 12).

In mixed plots, there was a larger increase in NDFD versus NDF compared to ALF monoculture. Neutral detergent fiber digestibility has been correlated with higher total digestible nutrients and intake (Mertens 2009; Combs 2004). However, NDF is 2 to 3 times as important in regard to intake and productivity compared to NDFD and should be considered to a greater degree when creating feed rations (Mertens 2009). Therefore, the larger increase in NDFD compared to NDF is less significant in terms of overall quality.

Neutral Detergent Fiber Digestibility-2022

Mean NDFD values for 2022 are presented in Table 17. There was no significant difference in NDFD between irrigation treatments ($p \geq 0.1551$) and no interaction between planting and irrigation treatments ($p \geq 0.3789$) for any of the cuttings in 2021, but there were significant differences among planting treatments ($p<0.0001$). Similar to 2021, the highest NDFD values were found in the grass monocultures while the lowest were in the ALF monoculture.

Table 17. Neutral detergent fiber digestibility (NDFD) for all cuts in 2022.

Treatment	Cut one	Cut two	Cut three
	--------------- NDFD (%) ---------------------- -		
Alfalfa (ALF)	16.2 D	18.3 C	16.3 D
75:25 ALF-OG mix	32.0 BC	28.7 B	26.3 B
75:25 ALF-TF mix	30.8 C	28.7 B	26.6 BC
75:25 ALF-MB mix	28.6 C	28.9 B	26.2 B
50:50 ALF-OG mix	30.4 C	29.6 B	28.5 BC
50:50 ALF-TF mix	32.0 BC	28.8 B	27.6 BC
50:50 ALF-MB mix	31.5 C	27.3 B	27.1 BC
50:50 ALF-OG strip	31.3 C	29.9 B	28.0 BC
50:50 ALF-TF strip	31.3 C	30.4 B	29.9 B
50:50 ALF-MB strip	30.1 C	28.9 B	27.0 BC
Meadow Brome (MB)	37.8 A	36.5 A	36.8 A
Tall Fescue (TF)	35.6 AB	37.5 A	36.6 A
Orchardgrass (OG)	38.4 A	37.2 A	37.1 A

Means followed by the same letter within a column are not significantly different ($p<0.05$).

In 2022, all three cuttings showed similar trends in NDFD to the 2021 season. There was no difference between mixed and stripped intercropping treatments across all cuttings. In mixed treatments, there was an average of 8.3, 0.8, and 1.3 percentage points more NDF compared to the ALF monoculture for cuttings 1, 2, and 3, respectively (see Table 13). In the mixed treatments, there was an average of 14.7, 10.4, and 10.8 percentage points more NDFD compared to the ALF monoculture in cuttings 1, 2, and 3, respectively.

In stripped treatments, there was an average of 8.4, 1.4, and 4 percentage points more NDF compared to the ALF monoculture for cuttings 1, 2, and 3, respectively (see Table 13). However, in stripped treatments, there was an average of 14.7, 11.4, and 12 percentage points more NDFD compared to the ALF monoculture in cuttings 1, 2, and 3, respectively.

Neutral detergent fiber digestibility, similar to ADF, is an indicator of forage digestion and intake (Hoffman et al. 2001; Adesogan et al. 2017). The significant increase in NDFD in intercropping treatments can be attributed to the presence of grasses, which typically have higher NDFD compared to legumes. While both mixed and stripped treatments increased NDFD more than they increased NDF compared to alfalfa, NDF is a more critical factor in animal feeds. It is difficult for increased NDFD to compensate for an increase in NDF (Mertens 2009). Therefore, the increase in NDF likely negates or lessens the importance of the increase in NDFD in intercropping treatments.

Relative Feed Value-2021

Mean RFV values for 2021 are presented in Table 18. There was no significant difference in RFV between irrigation treatments ($p \geq 0.1997$) and no interaction between planting and irrigation treatments ($p \geq 0.1938$) for any of the cuttings in 2021, but there were significant differences among planting treatments ($p<0.0001$).

Table 18. Relative feed value (RFV) for all cuts in 2021.

Treatment	Cut 1	Cut 2	Cut 3
	---------------- RFV ----------------		
Alfalfa (ALF)	142 A	141 AB	162 A
75:25 ALF-OG mix	142 A	154 A	168 A
75:25 ALF-TF mix	144 A	160 A	165 A
75:25 ALF-MB mix	141 A	154 A	165 A
50:50 ALF-OG mix	140 A	146 A	162 A
50:50 ALF-TF mix	137 AB	150 A	172 A
50:50 ALF-MB mix	129 ABC	152 A	174 A
50:50 ALF-OG strip	120 BCD	131 BC	127 B
50:50 ALF-TF strip	113 CD	120 C	134 B
50:50 ALF-MB strip	101 DE	129 BC	142 B
Meadow Brome (MB)	75 F	96 D	95 C
Tall Fescue (TF)	92 EF	92 D	97 C
Orchardgrass (OG)	95 EF	88 D	91 C

Means followed by the same letter within a column are not significantly different ($p<0.05$).

All cuttings during the 2021 season followed a similar trend. The alfalfa monoculture was similar to all mixed treatments throughout all cuttings. Stripped intercropping treatments typically had lower RFV values compared to alfalfa alone and the mixtures. The lowest RFV values were found in the grass monocultures across all cuttings, reflecting their high amounts of NDF and ADF.

These results demonstrate that mixed intercropping does not affect RFV compared to alfalfa alone, regardless of grass species. All stripped intercropping treatments significantly reduced the RFV compared to the ALF monoculture, demonstrating that stripped intercropping had a more profound effect on quality. Lower grass proportions paired with relatively high ADF values for ALF lead to similar RFV values among mixed treatments and ALF alone. High grass proportions in the stripped treatments resulted in increased ADF and NDF and, therefore, reduced RFV. Grasses typically have lower RFV compared to legumes due to their higher fiber content (Ball et al. 2001; Adesogan et al. 2017).

Relative Feed Value-2022

RFV values for 2022 are shown in Table 19. There was no significant difference in RFV between irrigation treatments ($p \geq 0.1305$) and no interaction between planting and irrigation treatments ($p \geq 0.4930$) for any of the cuttings in 2022, but there were significant differences among planting treatments ($p<0.0001$). Similar to 2021, the lowest RFV values were found in the grass monocultures which were significantly lower than all other treatments.

Table 19. Relative feed values (RFV) for all cuts in 2022.

Treatment	Cut 1	Cut 2	Cut 3
	----------------	RFV	----------------
Alfalfa (ALF)	176 A	154 A	181 A
75:25 ALF-OG mix	133 B	147 A	176 AB
75:25 ALF-TF mix	138 B	157 A	179 AB
75:25 ALF-MB mix	148 B	146 A	174 ABC
50:50 ALF-OG mix	139 B	143 A	171 ABC
50:50 ALF-TF mix	134 B	149 A	174 ABC
50:50 ALF-MB mix	133 B	153 A	173 ABC
50:50 ALF-OG strip	135 B	147 A	158 BC
50:50 ALF-TF strip	135 B	145 A	153 C
50:50 ALF-MB strip	139 B	149 A	165 ABC
Meadow Brome (MB)	92 C	100 B	102 D
Tall Fescue (TF)	103 C	94 B	91 D
Orchardgrass (OG)	94 C	93 B	90 D

Means followed by the same letter within a column are not significantly different ($p<0.05$).

During the first cutting, the ALF monoculture RFV was significantly higher than all other treatments. There was no difference between mixed and stripped intercropping treatments, which had average RFVs of 138 and 136, respectively. All intercropping treatments were 22% lower than the ALF monoculture, on average. This clear decline in RFV and quality during cut one in intercropping treatments was likely due to mature grasses (reproductive phase) and higher proportions of grasses, resulting in elevated NDF and ADF contents (Ball et al. 2001; Adesogan et al. 2017).

In the second cutting, there was a reduction in RFV across all treatments, except for the grasses which were relatively the same. There was no significant difference between the ALF monoculture and mixed and stripped treatments. Purely vegetative growth reduced the fiber components of grasses in mixed plots and resulted in higher RFVs. Compared to 2021, grass percentages were more similar between stripped and mixed plots, resulting in similar RFVs.

The highest RFV values for ALF monoculture, stripped, and mixed intercropping treatments were during the 3rd cutting. There was no difference between ALF alone and all mixed treatments. Stripped treatments were significantly lower than ALF alone except for the MB treatment. While typically similar, stripped treatments had an average RFV of 159 compared to mixed treatments which averaged 175.

Except for the first cutting, mixed intercropping did not lower RFV values compared to the ALF monoculture. Stripped treatments only produced similar RFV to ALF during the 2nd cutting. Stripped treatments also produced RFV values similar to mixed treatments during the 3rd cutting. Grass species did not have any profound effect on RFV. Reduced RFV values in intercropping treatments during cut one were likely attributed to high grass proportions and advanced grass maturity (reproductive phase) which drove up ADF and NDF, and subsequently reduced RFV compared to alfalfa alone (Ball et al. 2001; Adesogan et al. 2017). These results demonstrate that the intercropping method was more impactful on RFV compared to grass species alone.

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CHAPTER 4. CONCLUSION

Deficit irrigation, paired with alfalfa-grass intercropping, can be a potential strategy to increase productivity for producers in the West facing dwindling water resources. Mixed intercropping produced similar or higher yields compared to alfalfa alone, regardless of grass species. Increases in yield were clearer in 2022 as compared to 2021. Quality was only lowered in mixed intercropping treatments during the first cutting. In subsequent cuttings, quality was similar to alfalfa monoculture. Mixed intercropping significantly improved yield and quality compared to all grass monocultures.

Alfalfa-grass mixed intercropping can provide increased yields and similar forage quality compared to alfalfa alone. Two species can explore soil more efficiently and exploit different niches to increase productivity (Aponte et al. 2019). Although not as important in years where natural precipitation is above average, as in 2021, this planting concept is highly important when below average precipitation occurs, as in 2022. When deficit irrigation was applied during a drought year (i.e., 2022), water was used more efficiently by mixtures as evidenced by the increase in yields compared to monoculture alfalfa. Although grasses typically have lower quality compared to legumes, the addition of grasses did not negatively affect quality parameters in cuts two and three when non-jointing grass regrowth was vegetative (Ball et al. 2001). These two crop families grow well together due to their differing root architecture and addition of soil nitrogen by the legume that grasses can utilize (Lindemann 2015; Berdahl et al. 2001).

Stripped intercropping did well in terms of yield in 2021, however in 2022, yields were significantly lower than mixed treatments and the alfalfa monoculture. Quality was generally lower in stripped plots than mixed and alfalfa alone in 2021 but was similar in 2022. Stripped treatments had larger proportions of grass during 2021 which lowered quality. Overall, mixed intercropping proved to be more advantageous compared to stripped throughout this study. However, stripped intercropping did improve yields and quality compared to the grass monocultures.

Limited interaction between species reduced the benefits of stripped intercropping compared to mixed. Furthermore, since the grass was occupying two of the four planting beds exclusively, it was not as productive throughout the year, especially in later cuttings, compared to treatments with alfalfa alone on all four beds. Mixed was more advantageous in terms of yield and, in some cases, quality versus stripped when compared to alfalfa alone, regardless of grass species or level of irrigation. Mixed intercropping could be an option for maintaining or improving yields while producing similar forage quality compared to alfalfa under deficit irrigation.

APPENDICES

Table 20. Yield for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	Yield (kg ha^{-1})					
Alfalfa (ALF)	5589	5223	4877	3685	3857	3379
75:25 Alfalfa-OG mix	5763	4927	4822	3450	3987	3952
75:25 Alfalfa-TF mix	6100	6354	4651	4457	4104	3772
75:25 Alfalfa-MB mix	6071	5904	4935	4292	4102	4199
50:50 Alfalfa-OG mix	5409	5456	4494	4619	4078	3748
50:50 Alfalfa-TF mix	6024	5584	4805	3776	3960	4319
50:50 Alfalfa-MB mix	6458	5440	4698	3981	4075	3961
50:50 Alfalfa-OG strip	4150	4389	3739	3088	3049	3737
50:50 Alfalfa-TF strip	5331	5877	4308	3549	3400	4035
50:50 Alfalfa-MB strip	5824	5313	4300	2956	3194	3477
Meadow Brome (MB)	5458	4969	1151	773	1414	958
Tall Fescue (TF)	6018	5355	2204	1717	1622	1199
Orchardgrass (OG)	3085	2948	1450	1061	1472	1123

Table 21. Yield for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	Yield (kg ha^{-1})					
Alfalfa (ALF)	4220	4276	3716	3024	3850	2029
75:25 Alfalfa-OG mix	5352	4968	4899	4142	4455	3172
75:25 Alfalfa-TF mix	5379	5179	4901	4013	4817	3146
75:25 Alfalfa-MB mix	5090	4972	4344	3604	4320	2994
50:50 Alfalfa-OG mix	5299	4991	4711	3851	4544	3252
50:50 Alfalfa-TF mix	5606	5191	4825	3841	4623	3465
50:50 Alfalfa-MB mix	5497	4659	4646	3623	4343	2978
50:50 Alfalfa-OG strip	4000	4437	3046	2369	2961	1839
50:50 Alfalfa-TF strip	4746	4561	3069	2347	3276	1953
50:50 Alfalfa-MB strip	4307	5042	3141	2193	2968	1783
Meadow Brome (MB)	3107	2733	1035	534	1198	462
Tall Fescue (TF)	2955	3109	876	574	1340	517
Orchardgrass (OG)	2212	2283	967	441	1130	496

Table 22. CP for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	CP (%)					
Alfalfa (ALF)	19.8	17.2	22.1	18.7	25.1	23.5
75:25 Alfalfa-OG mix	18.0	17.6	22.1	20.7	22.7	23.5
75:25 Alfalfa-TF mix	18.8	18.1	22.7	21.4	22.7	22.8
75:25 Alfalfa-MB mix	17.8	17.2	21.8	22.4	24.2	22.9
50:50 Alfalfa-OG mix	17.8	16.9	20.4	21.3	22.9	23.6
50:50 Alfalfa-TF mix	17.6	16.0	21.5	21.0	24.1	22.9
50:50 Alfalfa-MB mix	16.1	16.6	21.3	22.0	23.7	21.9
50:50 Alfalfa-OG strip	15.7	15.4	19.8	21.4	20.1	19.5
50:50 Alfalfa-TF strip	13.7	12.7	16.5	18.4	19.8	21.1
50:50 Alfalfa-MB strip	13.4	12.9	19.2	21.1	22.3	22.2
Meadow Brome (MB)	5.4	5.3	11.8	12.3	10.8	12.9
Tall Fescue (TF)	6.1	5.5	6.6	8.5	8.3	8.6
Orchardgrass (OG)	6.1	5.0	8.3	7.2	9.6	11.3

Table 23. CP for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	CP (%)					
Alfalfa (ALF)	21.9	22.2	23.0	23.3	23.1	23.1
75:25 Alfalfa-OG mix	17.7	18.1	22.9	21.7	26.2	26.2
75:25 Alfalfa-TF mix	18.3	18.9	23.1	22.9	26.2	26.2
75:25 Alfalfa-MB mix	19.9	19.8	21.8	22.2	25.5	25.5
50:50 Alfalfa-OG mix	19.1	18.5	22.2	22.1	23.2	23.2
50:50 Alfalfa-TF mix	17.2	18.6	22.5	21.9	25.8	25.8
50:50 Alfalfa-MB mix	17.6	18.3	22.5	23.2	25.4	25.4
50:50 Alfalfa-OG strip	17.7	17.7	21.2	22.5	24.0	24.0
50:50 Alfalfa-TF strip	17.6	16.9	21.6	21.5	22.1	22.1
50:50 Alfalfa-MB strip	18.1	18.1	21.6	21.9	23.6	23.6
Meadow Brome (MB)	7.1	7.6	11.7	12.1	15.2	15.2
Tall Fescue (TF)	6.3	6.2	7.2	8.4	9.9	9.9
Orchardgrass (OG)	7.4	7.0	11.7	10.8	13.1	13.1

Table 24. NDF for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	NDF (%)					
Alfalfa (ALF)	40.7	44.4	40.8	44.0	35.6	37.3
75:25 Alfalfa-OG mix	42.3	42.3	40.2	39.4	36.5	36.8
75:25 Alfalfa-TF mix	41.1	42.4	37.2	39.2	36.7	37.0
75:25 Alfalfa-MB mix	42.5	43.5	40.4	37.9	36.4	36.8
50:50 Alfalfa-OG mix	42.2	44.0	43.1	40.2	38.0	36.6
50:50 Alfalfa-TF mix	42.6	45.2	40.2	40.8	36.0	36.3
50:50 Alfalfa-MB mix	47.3	46.0	41.3	39.3	33.6	38.0
50:50 Alfalfa-OG strip	47.5	47.6	45.1	41.9	45.6	45.5
50:50 Alfalfa-TF strip	49.9	51.4	48.6	45.3	46.1	41.8
50:50 Alfalfa-MB strip	55.4	54.3	45.8	41.7	41.5	40.4
Meadow Brome (MB)	69.5	69.9	56.9	57.4	60.1	57.1
Tall Fescue (TF)	61.9	59.9	60.8	58.3	58.3	59.3
Orchardgrass (OG)	59.7	59.6	62.4	63.1	62.9	61.6

Table 25. NDF for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	NDF (%)					
Alfalfa (ALF)	35.0	34.5	39.0	37.8	33.8	38.8
75:25 Alfalfa-OG mix	44.8	44.5	38.8	40.0	36.1	32.6
75:25 Alfalfa-TF mix	43.7	41.6	37.6	38.0	34.7	33.6
75:25 Alfalfa-MB mix	39.6	41.0	40.6	38.8	36.4	32.8
50:50 Alfalfa-OG mix	41.5	43.6	40.2	40.8	34.3	37.6
50:50 Alfalfa-TF mix	46.1	42.3	39.3	39.0	36.9	33.3
50:50 Alfalfa-MB mix	45.1	43.8	39.7	37.7	35.7	34.4
50:50 Alfalfa-OG strip	43.7	43.3	42.5	37.8	38.9	36.4
50:50 Alfalfa-TF strip	43.2	44.1	40.6	40.1	38.6	39.6
50:50 Alfalfa-MB strip	42.4	42.2	39.3	38.9	36.3	36.0
Meadow Brome (MB)	61.3	59.8	56.1	55.1	52.3	50.4
Tall Fescue (TF)	55.3	56.4	57.5	58.4	54.6	51.3
Orchardgrass (OG)	61.0	59.5	60.5	59.4	55.2	54.0

Table 26. ADF for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	ADF (%)					
Alfalfa (ALF)	35.2	35.3	36.3	36.3	32.7	33.9
75:25 Alfalfa-OG mix	31.3	31.1	30.2	29.4	29.7	30.6
75:25 Alfalfa-TF mix	30.7	32.2	30.0	30.2	30.2	30.9
75:25 Alfalfa-MB mix	31.3	30.7	32.5	30.2	32.2	31.1
50:50 Alfalfa-OG mix	30.9	31.7	32.3	30.0	32.1	29.9
50:50 Alfalfa-TF mix	31.4	31.6	30.0	30.8	29.0	28.6
50:50 Alfalfa-MB mix	32.6	31.6	31.0	29.5	27.2	30.2
50:50 Alfalfa-OG strip	35.9	35.7	36.9	35.6	35.8	34.4
50:50 Alfalfa-TF strip	35.7	36.2	37.5	36.3	36.1	32.1
50:50 Alfalfa-MB strip	38.1	37.4	38.0	35.1	34.1	34.2
Meadow Brome (MB)	41.9	41.9	38.8	37.9	37.9	37.0
Tall Fescue (TF)	37.2	37.9	39.2	37.2	35.1	36.0
Orchardgrass (OG)	36.6	36.1	37.6	38.3	36.6	35.9

Table 27. ADF for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	ADF (%)					
Alfalfa (ALF)	29.9	30.0	33.3	32.5	30.1	31.9
75:25 Alfalfa-OG mix	33.2	33.8	34.1	35.0	32.8	29.9
75:25 Alfalfa-TF mix	33.0	32.7	32.4	33.0	30.6	29.0
75:25 Alfalfa-MB mix	32.4	32.6	35.4	34.2	32.7	30.3
50:50 Alfalfa-OG mix	33.1	33.3	34.2	34.9	31.0	31.3
50:50 Alfalfa-TF mix	33.5	33.1	33.9	34.1	31.1	29.4
50:50 Alfalfa-MB mix	33.3	33.5	34.2	32.3	31.9	30.2
50:50 Alfalfa-OG strip	33.4	33.3	35.5	32.7	33.4	31.9
50:50 Alfalfa-TF strip	32.8	33.6	33.7	34.1	32.0	32.6
50:50 Alfalfa-MB strip	33.7	33.2	34.4	33.0	32.3	32.2
Meadow Brome (MB)	37.6	36.9	37.5	36.8	27.6	25.5
Tall Fescue (TF)	35.0	35.5	39.2	38.5	29.7	25.5
Orchardgrass (OG)	36.1	35.6	36.2	38.0	29.7	28.1

Table 28. NDFD for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	NDFD (%)					
Alfalfa (ALF)	18.4	22.2	18.6	22.0	17.9	17.9
75:25 Alfalfa-OG mix	25.4	25.2	27.0	25.2	25.2	22.3
75:25 Alfalfa-TF mix	25.0	24.4	23.7	25.8	26.0	23.4
75:25 Alfalfa-MB mix	25.3	26.3	23.8	25.1	19.6	22.5
50:50 Alfalfa-OG mix	25.9	26.5	27.0	26.4	22.2	23.7
50:50 Alfalfa-TF mix	26.6	27.9	27.9	27.4	24.9	26.3
50:50 Alfalfa-MB mix	28.6	28.3	27.8	26.0	24.0	25.2
50:50 Alfalfa-OG strip	25.8	26.3	22.5	20.5	24.5	25.8
50:50 Alfalfa-TF strip	27.4	29.1	25.9	23.7	25.8	24.2
50:50 Alfalfa-MB strip	29.2	29.6	23.0	21.9	23.3	22.3
Meadow Brome (MB)	39.6	39.7	40.3	38.2	40.1	38.1
Tall Fescue (TF)	38.5	38.1	39.1	37.4	38.4	37.4
Orchardgrass (OG)	40.0	39.6	40.3	38.5	39.1	38.9

Table 29. NDFD for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	NDFD (%)					
Alfalfa (ALF)	17	16	19	18	17	20
75:25 Alfalfa-OG mix	32	32	29	29	27	26
75:25 Alfalfa-TF mix	31	30	29	29	26	27
75:25 Alfalfa-MB mix	28	29	29	28	27	26
50:50 Alfalfa-OG mix	30	31	30	30	27	30
50:50 Alfalfa-TF mix	33	31	29	29	28	27
50:50 Alfalfa-MB mix	32	31	29	26	27	27
50:50 Alfalfa-OG strip	31	31	30	29	29	27
50:50 Alfalfa-TF strip	31	31	31	30	30	30
50:50 Alfalfa-MB strip	30	30	29	29	27	27
Meadow Brome (MB)	38	38	38	35	29	28
Tall Fescue (TF)	36	36	38	37	28	25
Orchardgrass (OG)	39	38	39	36	29	28

Table 30. RFV for all planting treatments separated by cutting and irrigation for 2021.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	RFV					
Alfalfa (ALF)	141	143	139	143	168	157
75:25 Alfalfa-OG mix	142	142	151	156	168	168
75:25 Alfalfa-TF mix	147	141	164	155	167	163
75:25 Alfalfa-MB mix	142	140	147	161	164	165
50:50 Alfalfa-OG mix	143	136	138	152	157	168
50:50 Alfalfa-TF mix	141	132	152	149	173	172
50:50 Alfalfa-MB mix	126	131	147	157	188	161
50:50 Alfalfa-OG strip	120	120	125	137	125	128
50:50 Alfalfa-TF strip	115	110	114	125	124	144
50:50 Alfalfa-MB strip	100	102	120	138	141	144
Meadow Brome (MB)	76	75	96	96	92	98
Tall Fescue (TF)	90	93	90	95	98	96
Orchardgrass (OG)	94	95	89	87	89	92

Table 31. RFV for all planting treatments separated by cutting and irrigation for 2022.

Treatment	Cut one 100%	Cut one 60%	Cut two 100%	Cut two 60%	Cut three 100%	Cut three 60%
	RFV					
Alfalfa (ALF)	175	177	151	158	181	182
75:25 Alfalfa-OG mix	134	132	152	143	164	189
75:25 Alfalfa-TF mix	135	142	159	155	175	184
75:25 Alfalfa-MB mix	151	145	141	150	163	186
50:50 Alfalfa-OG mix	142	136	145	141	176	167
50:50 Alfalfa-TF mix	127	140	149	149	164	185
50:50 Alfalfa-MB mix	130	135	147	159	168	179
50:50 Alfalfa-OG strip	135	135	136	159	151	165
50:50 Alfalfa-TF strip	137	133	145	145	155	152
50:50 Alfalfa-MB strip	139	139	147	151	164	166
Meadow Brome (MB)	91	94	99	102	99	105
Tall Fescue (TF)	104	101	95	94	89	93
Orchardgrass (OG)	93	96	93	93	88	93

Table 33. Irrigation dates and amounts in liters for 2021. First irrigation applied with gated pipe due to issues with drip system at beginning of season. Deficit irrigation began on 06/10/2021.

Date (2021)	Method	Irrigation treatment	Irrigation Amount
20-Apr	gated pipe	all	0.4 acre inches
7-May	drip	100% ET	86,115
8-May	drip	60% ET	85,970
17-May	drip	100% ET	107,057
18-May	drip	60% ET	107,795
10-Jun	drip	100% ET	64,112
11-Jun	drip	60% ET	43,369
16-Jun	drip	100% ET	103,768
17-Jun	drip	60% ET	63,241
22-Jun	drip	100% ET	141,650
23-Jun	drip	60% ET	71,801
28-Jun	drip	100% ET	91,441
29-Jun	drip	60% ET	54,032
2-Jul	drip	100% ET	57,358
2-Jul	drip	60% ET	35,011
6-Jul	drip	100% ET	82,893
7-Jul	drip	60% ET	60,520
15-Jul	drip	100% ET	150,938
16-Jul	drip	60% ET	103,722
22-Jul	drip	100% ET	101,257
21-Jul	drip	60% ET	60,186
17-Aug	drip	100% ET	174,129
18-Aug	drip	60% ET	105,991
23-Aug	drip	100% ET	73,971
24-Aug	drip	60% ET	43,708
7-Sep	drip	100% ET	93,319
8-Sep	drip	60% ET	60,657

Table 33. Irrigation dates and amounts in liters for 2022. Deficit irrigation began on 06/16/2022. Drip irrigation used entire year.		
Date (2022)	Irrigation treatment	Irrigation Amount
25-Apr	100% ET	387,459
26-Apr	60% ET	391,972
10-May	100% ET	152,401
10-May	60% ET	152,018
17-May	100% ET	130,695
18-May	60% ET	130,298
26-May	100% ET	102,797
27-May	60% ET	102,528
2-Jun	100% ET	85,705
3-Jun	60% ET	85,157
8-Jun	100% ET	80,463
9-Jun	60% ET	80,652
24-Jun	100% ET	89,192
25-Jun	60% ET	53,768
5-Jul	100% ET	156,231
6-Jul	60% ET	93,901
12-Jul	100% ET	117,927
13-Jul	60% ET	72,309
17-Jul	100% ET	85,425
18-Jul	60% ET	52,186
2-Aug	100% ET	197,791
3-Aug	60% ET	108,478
10-Aug	100% ET	100,469
11-Aug	60% ET	57,712
17-Aug	100% ET	92,315
18-Aug	60% ET	51,334