Assessing yield, quality, water use efficiency and profitability of forage crops in rainfed agricultural management systems

by

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AN ABSTRACT OF A DISSERTATION

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Abstract

Forage production is an integral part of the livestock industry as it significantly impacts animal performance, including body weight gain, reproduction, and milk production. Moreover, it is one of the key contributors to the agricultural economy of the United States. However, despite its high demand and economic value, the yield and production of forage crops have not improved in the last two decades. Unpredictable weather events such as erratic rainfall and periodic drought, reliance on traditional wheat-based cropping systems, and failures in various management aspects including crop and variety selection, irrigation management, and delays in planting and harvesting are the primary factors that influence forage dry matter yield (DMY) and forage nutritive value (FNV).

Considering these factors, the first chapter of this dissertation estimated the yield gap in major alfalfa-producing states of the United States. County-level yield and weather data were collected from 393 counties in 12 major rainfed alfalfa-producing states and estimated attainable yield (Ya) using frontier function analysis, water-limited potential yield (Yw) and water use efficiency (WUE) using boundary function analysis, and major yield-limiting factors using conditional inference tree. This study estimated the Ya of 9.6+1.5 Mg ha^{-1}, resulting in a mean yield gap of 34%, and Yw of 15.3+3 Mg ha^{-1}, resulting in a mean yield gap of 58%. The potential WUE was 30 kg ha^{-1} mm^{-1}. The CIT analysis revealed that the rainfall and minimum temperature during the growing season were the primary weather variables influencing rainfed alfalfa production. This study provides a better understanding of the difference in yield levels observed in rainfed alfalfa production across major alfalfa-producing states, suggesting potential for further improvement through better management practices. The methodologies used in this study could be useful for many other countries that don't have research-based data to estimate crop yield and yield gaps.

The second chapter explored alternative summer forage crops for wheat-based rainfed cropping systems in Kansas. A three-year field experiment was conducted, comparing seven different crop sequences and intensities. The results showed the variability in DMY, WUE, FNV and profitability across crops, growth stages, and planting times. Crops planted at optimum planting dates demonstrated higher DMY, while those planted late exhibited higher FNV. Forage soybean had the highest DMY (13.9 Mg ha^{-1}) followed by soybean and alfalfa. Soybean, alfalfa and forage soybean had an excellent FNV, with crude protein (CP) above 18% and relative feed value (RFV) exceeding 150. The WUE varied among crops, with cowpea demonstrating the highest efficiency (26.8 kg mm^{-1}). Forage soybean and cowpea were recommended as potential summer annual forage crops, considering their DMY, WUE, FNV and net farm income. The findings of this study provide valuable insights into appropriate crop selection, efficient management of planting and harvesting times, and strategies to enhance yield, quality, and profitability within forage production systems.

The third chapter evaluated the impact of water regimes, maturity stages, and subsequent cuttings on DMY and FNV in alfalfa production. Different varieties were planted under drought, rainfed, and irrigation conditions, and DMY and FNV were evaluated at different growth stages. The results indicated that DMY and FNV were influenced by soil water availability, production year, and maturity stages. Drought-stressed alfalfa showed lower DMY but higher FNV. The delayed harvesting resulted in lower DMY but higher RFQ under drought conditions and higher DMY but lower RFQ under irrigation. Early harvesting led to lower yields but higher protein content and digestibility. Both conventional and lower-lignin varieties performed equally in terms of yield and forage quality. The financial analysis indicated that alfalfa is a highly profitable crop, with an estimated profit margin ranging from 52 to 64% per hectare under different soil moisture conditions. The study provides valuable information for alfalfa producers to make informed decisions about harvesting time and irrigation investments.

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The second chapter explored alternative summer forage crops for wheat-based rainfed cropping systems in Kansas. A three-year field experiment was conducted, comparing seven different crop sequences and intensities. The results showed the variability in DMY, WUE, FNV and profitability across crops, growth stages, and planting times. Crops planted at optimum planting dates demonstrated higher DMY, while those planted late exhibited higher FNV. Forage soybean had the highest DMY (13.9 Mg ha^{-1}) followed by soybean and alfalfa. Soybean, alfalfa and forage soybean had an excellent FNV, with crude protein (CP) above 18% and relative feed value (RFV) exceeding 150. The WUE varied among crops, with cowpea demonstrating the highest efficiency (26.8 kg mm^{-1}). Forage soybean and cowpea were recommended as potential summer annual forage crops, considering their DMY, WUE, FNV and net farm income. The findings of this study provide valuable insights into appropriate crop selection, efficient management of planting and harvesting times, and strategies to enhance yield, quality, and profitability within forage production systems.

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Dedication

I devotedly dedicate this dissertation to my respected father and mother Baudhaman Baral and Hira Kumari Baral, my beloved wife Sangita Bhandari, my precious daughter Aisha Baral, my little son Ayaan Baral and all my cherished family members who hold a special place in my heart. Their boundless love, unwavering patience, countless sacrifices, relentless encouragement, guidance, support, care, presence and understanding have been the driving force behind my success at every step of my journey. I am forever indebted to my wife, daughter, and son for bringing boundless joy and happiness into my life.

Chapter 1 - Yield gap analysis of rainfed alfalfa in the United States

Abstract

The United States (U.S.) is the largest alfalfa (*Medicago sativa* L.) producer in the world; however, there have only been limited attempts to understand the alfalfa forage yield gap. Considering that yield and production of rainfed alfalfa have been relatively stagnant in the country for decades, there is a need to better understand the magnitude of the yield gap in this region. Thus, the main objective of this study was to estimate the current yield gap in respect to water availability in major US rainfed alfalfa producing states. We collected 10-yr (2009 - 2018) county-level government-reported yield and weather data from 393 counties within 12 major U.S. rainfed alfalfa producing states and delineated alfalfa growing season using probabilistic approaches based on temperature thresholds for crop development. We then calculated county-level growing season rainfall (GSR), which was plotted against county-level yield to determine attainable yield (Ya) using frontier function analysis, and water-limited potential yield (Yw) using boundary function analysis. Average and potential water use efficiencies (WUE) were estimated, and associated yield gaps referring to attainable (YGa) or water-limited yields (YGw) were calculated. Finally, we used conditional inference trees (CIT) to identify major weather-related yield-limiting factors to alfalfa forage yield. The frontier model predicted a mean Ya of 9.6±1.5 Mg ha^{-1} and an associated optimum GSR of 670 mm, resulting in a mean YGa of 34%. The boundary function suggested a mean Yw of 15.3±3 Mg ha^{-1} at the mean GSR of 672±153 mm, resulting in a mean yield gap of 58%. The potential alfalfa WUE was 30 kg ha^{-1} mm^{-1} with

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associated minimum water losses of 163 mm (or 24% of mean GSR), which was three times greater than the mean WUE of 10 kg ha^{-1} mm^{-1}. The CIT suggested that GSR and minimum temperature in the season were the weather variables most associated with alfalfa in rainfed alfalfa production in the US. Given that alfalfa was only limited by water availability in 21% of the environments, future research on management practices to narrow yield gaps at current levels of water supply is warranted.

1.1 Introduction

Alfalfa (*Medicago sativa* L.) is the fourth largest crop in terms of area harvested and production, and the third-largest crop in terms of economic value, in the U.S. (USDA-NASS, 2022a). The country is also the world's largest alfalfa producer in the globe, with an annual hay production of above 50 million tons from about 7 million hectares which has a current market value of over 9 billion U.S. dollars (Gardner & Putnam, 2018; USDA-NASS, 2022b). Alfalfa is commercially cultivated in 42 states and several reasons justify such a widespread production, including its high nutritive value, high yield, long stand persistence, wide adaptation, being a perennial legume with biological nitrogen fixation, and soil benefits (Adhikari & Missaoui, 2017; Putnam et al., 2007).

The U.S. domestic livestock production has increased by 19% over the past 10 years (USDA-NASS, 2022b). Simultaneously, the export of livestock and meat products has increased by 21%, and of dairy products by 36%. Likewise, alfalfa production acreage has declined by 18% and total production by 23%. Consequently, livestock feed and forage imports have increased by 25% (USDA-FAS, 2021). Although increased alfalfa production could help alleviate the need for hay importation, it is challenging to expand production acreage due to limited cropland, water scarcity, low yield in many states, subsidized competing crops (e.g.,

wheat, *Triticum aestivum* L.; maize, *Zea may*s L.; soybean, *Glycine max* L.), lack of alfalfa insurance program, and expansion of maize acreage for ethanol production (Creech & Foster, 2013; Putnam et al., 2000). In this context, quantifying potential forage yield, current forage yield gap, and its causes, can help to meet the growing forage demand in existing cropland, potentially counteracting the production reduction due to fewer acres, and can also help guide research and development investments in the region with larger gaps (Edreira et al., 2017).

Water is the main limiting factor limiting the yield of rainfed crops, including alfalfa (Holzman & Rivas, 2016; Tadesse et al., 2015). Alfalfa requires a relatively high amount of water as compared to major cereal crops and vegetables because it has a long growing season, deep root system, and a dense vegetation canopy (Schneekloth & Andales, 2017; Shewmaker et al., 2011; Takele & Kallenbach, 2001). Thus, growing season rainfall (GSR) and the water holding capacity of the soil are important modulators of rainfed alfalfa forage yield (Grimes et al., 1992; Jia et al., 2006; Jun et al., 2014). The dry matter yield (DMY) of alfalfa is positively correlated with the amount of water used (Bauder et al., 1978; Rogers et al., 2016; Shewmaker et al., 2011), with a mean water-use efficiency (WUE, the ratio of crop biomass to evapotranspiration) of 16 kg ha^{-1} mm^{-1} (Lindenmayer et al., 2011). Jensen and Miller (1988) documented 155 to 213 mm of water is required to produce one metric ton of alfalfa forage whereas Shewmaker et al. (2011) reported 508 to 1168 mm per season, depending on climate, elevation, growing season, number of cuttings, latitude, and alfalfa fall dormancy.

In the U.S., 24 states including the Midwest and some states of the South and Northeast regions, cultivate alfalfa mostly under rainfed conditions which accounts for over 44% of the U.S. total area harvested (USDA-NASS, 2022b). The mean annual alfalfa yield of those states ranges from 2.9 to 7.6 Mg ha^{-1} whereas previous research conducted in some of these rainfed

states found that yields over 13 Mg ha^{-1} are attainable (**Table 1.1**). Correspondingly, Russelle (2013) quantified the alfalfa yield gap in the U.S. using several approaches ranging from 58 to 70 % for non-irrigated regions, suggesting a large room for improvement in current yields. Beyond managerial factors, these rainfed U.S. states have been experiencing moderate to exceptional drought for decades during the alfalfa growing season (April-October; **Supplemental Figure 1.1**). Takele and Kallenbach (2001) reported that moderate to severe drought can decline alfalfa yield up to 72%. Hence, quantifying the level of water limitation to alfalfa yield grown under rainfed conditions in the U.S. can help define regions where greater yield improvements are possible.

Similarly, temperature is another major abiotic factor affecting plant growth and yield. The growing season of summer and winter crops have been delineated as determined by the occurrence of minimum temperature (Tmin) thresholds (Lollato et al., 2020; Purcell et al., 2003; Torres et al., 2013; Van Ittersum et al., 2013); however, to our knowledge, there have been no attempts to objectively define the growing season for alfalfa across large growing regions. The available literature determines alfalfa growing season using very loose and arbitrary definitions, such as (i) a fixed day of the year (Raun et al., 1999), (ii) the occurrence of at least five days when the mean temperature is above 5°C (Sanderson et al., 1994), (iii) a flexible growing season definition based on a combination of the approaches above (Sulc et al., 1999), or (iv) the occurrence of Tmin below -2.8°C, a temperature threshold below which substantial damage to vegetative tissue occur in alfalfa (McKenzie & McLean, 1982; Nath & Fisher, 1971; Sprague, 1955). Despite the discrepancies above, there is a consensus that the base temperature for alfalfa is 5^{o}C (Confalonieri & Bechini, 2004; Fick et al., 1988; Onstad & Fick, 1983; Sharratt et al., 1989; Wolf & Blaser, 1972), as seed germination and seedling growth are restricted below this

threshold (Ahmed et al., 2019; Andrews, 1987; Leep et al., 2001; Townsend & McGinnies, 1972; Vough & Marten, 1971). Because determination of the length of the growing period is important to estimate crop potential yield (Lobell et al., 2009; Purcell et al., 2003; Torres et al., 2013), there is a need to objectively determine the growing season for alfalfa using daily weather data.

Several papers on yield gap analysis of major field crops are available such as wheat (Anderson, 2010; Hatfield & Beres, 2019; Lollato et al., 2019; Neumann et al., 2010; Patrignani et al., 2014), maize (Balboa et al., 2019; Egli & Hatfield, 2014; Grassini et al., 2011; Liu et al., 2017; Neumann et al., 2010), and soybean (Balboa et al., 2019; Grassini, Torrion, et al., 2015; Zhang et al., 2016). However, to the best of our knowledge, the yield gap analysis of rainfed alfalfa in the U.S. has not been studied and the magnitude of yield gap for these rainfed states is still unknown. Therefore, the overarching objective of this study was to estimate the yield losses of alfalfa grown under rainfed conditions in the major U.S. rainfed alfalfa-growing regions. To do so, our specific objectives were to systematically (i) delineate county-specific alfalfa growing season using long-term weather data; (ii) calculate the cumulative growing season rainfall and optimum amount of rainfall required to obtain maximum yield; (iii) estimate minimum water losses (percolation, evaporation, runoff) and maximum WUE during the alfalfa growing season; (iv) compare maximum and attainable yields with the current yield at the state level, and (v) assess the possible weather determinants of alfalfa yield.

1.2 Materials and Methods

1.2.1 Study area

Twenty-four states produce alfalfa mostly under rainfed conditions in the U.S. (USDA-NASS, 2022b) (**Supplemental Table 1.1**). Out of those, 12 states (i.e., Illinois, Indiana, Iowa, Kentucky, Minnesota, Missouri, New York, North Dakota, Ohio, Pennsylvania, South Dakota,

and Wisconsin) were selected for analyses based on their rainfed alfalfa production area and total production. In those states, more than 95 % of the alfalfa is cultivated under rainfed conditions, thus, the selection of these states avoided the inclusion of irrigated alfalfa fields in the database, as those are not reported separately. Those states represent different U.S. growing regions, including the Southeast (Kentucky), Northeast (New York and Pennsylvania), upper Midwest (Iowa, Minnesota, North Dakota, South Dakota, Wisconsin), and lower Midwest states (Illinois, Indiana, Missouri, Ohio) (**Figure 1.1**). We excluded the other 12 rainfed states because 11 states produce less than 1% of the U.S. total rainfed production and one state (i.e., Michigan) does not have recorded county-level yield data. For the 12 states above, county-level alfalfa yield was retrieved from the United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS, 2022b) for the 2009-2018 period. The selected 393 counties from those 12 selected rainfed states accounted for more than 70 % of the total rainfed alfalfa production in the U.S. (**Figure 1.1**), which is sufficient to reliably estimate yield gaps and the 10-yr period avoids major technological trends (Van Ittersum et al., 2013). The soils in the study area are mainly Alfisols, Mollisols, and Entisols (Clark et al., 2019).

1.2.2 Delineation of the growing season, weather variables, and weather yield drivers

We developed code in Python 3.7.6 (Python Language Reference, version 3.7.6 available at http://www.python.org) using information from Applied Climate Information System (ACIS) web services of National Oceanic and Atmospheric Administration-Regional Climate Centers (NOAA-RCCs) to obtain daily weather data of all stations located in each selected state for the 10-yr period (2009-2018) (ACIS, 2020). Then, we sorted the data by county using federal information processing system (FIPS) code, the number of digits that identify U.S. state and

county area (NOAA-NWS, 2022) and station name. For each of the 393 counties from 12 states (i.e., Illinois, Indiana, Iowa, Kentucky, Minnesota, Missouri, New York, North Dakota, Ohio, Pennsylvania, South Dakota and Wisconsin) included in the study, daily weather data for maximum (Tmax) and minimum (Tmin) temperatures, as well as rainfall, was selected from one weather station centrally located in the respective county. Counties with more than 10% missing weather data were interpolated from nearby ground stations. The days with missing values were replaced with the value of the nearest station located in the same county or adjacent county.

The growing season of alfalfa is defined as the number of days in a year when the mean temperature is equal to or above the alfalfa's base temperature, which is 5^{o}C (Confalonieri & Bechini, 2004; Fick et al., 1988; Onstad & Fick, 1983; Sharratt et al., 1989; Wolf & Blaser, 1972). The selection of this temperature threshold is justified because alfalfa plants stop or significantly reduce their growth and development below it. To delineate the alfalfa growing season, we used a method similar to that described for summer crops by Torres et al. (2013) and Purcell et al. (2003). Here, the temperature-limited alfalfa growing season for each county was estimated as the mean number of days between the last day in spring (called as growing season start day) and the first day in fall (called as growing season end day) when the probability of occurrence of growing degree days (GDD) <0°C for each day of the year (DOY) for last 10 years was 0.2 (P = 0.2) (**Figure 1.2**). The 20% probability threshold is justified as there is a minimum effect on yield if exposed up to 2 days of Tmin < 5^{o}C out of 10 days. February 29 was ignored in leap years. The probabilities of GDD < 0°C were plotted against DOY and regressed separately against the decreasing probability values (between last day of P = 0 and first day of P = 100%) in the spring and the increasing P values (between last day of P = 100 and first day of P = 0%) in the fall as suggested by Torres et al. (2013). The resulting linear equations developed for each

county were then used to calculate the respective DOY when P = 0.2. The mean of the county-level growing season length was considered as state-level growing season length.

After delineating the growing season length, we calculated growing season minimum and maximum temperature (Tmax), and cumulative GDD and rainfall. To understand the major weather drivers of alfalfa yield in the dataset, we created a conditional inference tree (CIT), which is a machine learning algorithm based on a regression model, to analyze the most significant weather variables contributing to alfalfa yield. The CIT described the conditional distribution of alfalfa yield predicted by multiple weather variables through tree-structured recursive partitioning (Hothorn et al., 2006). To avoid variable selection bias and overfitting, we performed (1) global null hypothesis test between any of the randomly selected weather variables and alfalfa yield and then selected the best predicting weather variable which had the lowest root mean square error (RMSE) and highest R^2 values, (2) binary split on the selected predicting variables, and (3) recursively repeated step 1 and 2. We started with a CIT that allowed a minimum of 5% of the observations to be included in intermediate nodes and of 1% of observations to be included in the terminal nodes. We then increased these bucket sizes to allow for the inclusion of minimums of 40 and 10%. The model fit exercise selected the most parsimonious CIT that resulted in changes of less than 5% in R^2 from the initial CIT. The CIT was built in R using the package partykit (Hothorn et al., 2015).

1.2.3 Yield estimation and yield gap calculation

We used recorded alfalfa hay yield data combined with weather records of 393 counties from 2009 to 2018 for the estimation of three types of yield: i) current yield (Yc), ii) attainable yield (Ya), and iii) water-limited potential yield (Yw). The yield gap (Yg) was then calculated as

the difference between Yw and Yc or Ya and Yc. The WUE was assessed using linear boundary function approach used by French and Schultz (1984).

The Yc was calculated as the weighted mean yield of the last 10 years at a county level, assumedly using adapted alfalfa cultivars grown under the existing production environment and management practices.

$$\boldsymbol{Y_c = \sum_{i=1}^{n} \frac{Y_{wt}}{N}} \qquad \textbf{(1)}$$

Where, Y_c is the state-level current yield, Y_{wt} is the weighted yield of alfalfa of county i and N is the number of year.

We used Cobb-Douglas stochastic frontier yield function to estimate Ya (Neumann et al., 2010) (**Figure 1.3**). In this approach, the Ya was calculated as the maximum yield of alfalfa hay that was ever achieved within a county in the last 10 years at a given level of GSR. The entire range in GSR was divided into equally spaced bins, and the maximum yield from each bin was selected. Then those selected values were plotted against corresponding GSR and regressed using non-linear regression (Neumann et al., 2010; Patrignani et al., 2014).

$$lnY_a = \beta_0 + \beta_1 lnX_i + \beta_2 (lnX_i^2), \text{ where } X_i > 0 \qquad (2)$$

Where, Y_a is the attainable yield which represents the maximum yield ever achieved by county i within last 10 years at each rainfall bin, X_i represents the corresponding GSR of county i, β_0 is the intercept when yield is zero, and β_1 and β_2 are the slope of parameters of GSR. The maximum yield value found on the frontier line is referred as the Ya and the corresponding rainfall as optimum rainfall to achieve maximum yield for the given county. The optimum GSR at which the yield is maximized was determined by equating derivative of frontier yield with respect to GSR to zero, and solving the equation for this particular rainfall amount returns the maximum yield value. The quadratic nature of this function is justified as Ya is expected to

decline at lower or greater rainfall amounts due to insufficient or excessive water supply or harvesting losses due to continuous or heavy rainfall during harvesting time.

Water-limited potential yield was estimated using linear boundary function (**Figure 1.4**) following French and Schultz (1984) approach. Here, county-level yield data were plotted against corresponding GSR, dividing the GSR range in which yield is responsive to increases in water supply into equally spaced bins, selecting the maximum yield within each rainfall bin, and regressing both variables. The resulting linear equations developed from this model are used to estimate state-level Yw.

$$Y_w = WUE\ (GSR\text{-}WL) \quad (3)$$

Where, Y_w represents theoretical water-limited potential yield, the slope of the linear regression is WUE, and WL is the minimum non-productive water losses. The difference between GSR and WL is the amount of water used by the crop during the entire growing season to obtain maximum potential yield. To ensure the robustness of the linear function and to increase the range in yields for linear function development, we added variety trial data of each state similar to the approach by Patrignani et al. (2014). Variety trials data of the study period were obtained from the respective state's extension reports and published research papers (**Figure 1.5; Table 1.1**).

1.3 Results

1.3.1 Growing season delineation

The length of the alfalfa growing season for the selected rainfed states ranged from 169 days in Minnesota to 241 days in Kentucky, with a mean of 204 growing days in a year (**Table 1.2**). The growing season was found longer in the lower Midwest and Southeast regions (206 to 241 days), where it started from mid-March (73 DOY in Kentucky) to early April (100 DOY in

Iowa) and ended in the second week of November (316 DOY in Missouri). This compared with 169-192 days of growing season duration in the upper Midwest and Northeast regions, where it started from the second to the third week of April (107 DOY in Wisconsin to 113 DOY in Minnesota) through the second to last week of October (282 DOY in Minnesota to 300 DOY in Wisconsin).

1.3.2 Growing season temperature

Mean growing season temperature increased from the north (16.7±0.4°C) to the south (18.1±0.5°C). The maximum mean temperature during the growing season was 23±0.7°C in upper Midwest and Northeast states and 24.1±0.5°C in lower Midwest and Southeast states, whereas the minimum mean temperature was 10.4±0.4°C in upper Midwest and Northeast states and 12.1±0.4°C in lower Midwest and Southeast states (**Figure 1.6 and 1.7; Table 1.2**). Similarly, to thermal gradients, our study identified increasing GSR from the Northeast to the Southeast. The accumulated GDD during the growing season was 2096±126°C-day for the upper Midwest and Northeast regions and was 2840±249°C-day for the lower Midwest and Southeast regions, with North Dakota showing the lowest (1964°C-day) and Kentucky showing the highest accumulated GDD (3278°C-day) (**Figure 1.8; Table 1.2**).

1.3.3 Growing season rainfall and potential water use efficiency

Over the 2009-2018 period, the mean annual rainfall within the study area ranged from 285 mm in Sioux County (ND) to 1143 mm in Hardin County (KY), with a mean of 672 mm (ACIS, 2020). The mean GSR in the upper Midwest and Northeast was estimated as 525±101 mm. The GSR in Wisconsin has slightly higher (648±66 mm) than those in other upper Midwest states. Similarly, the GSR in the lower Midwest, Southeast, and Northeast states was estimated at 778±77 mm. North Dakota was the driest state, followed by South Dakota, and Minnesota

whereas the highest rainfall was recorded in Kentucky, followed by Missouri and Illinois (**Figure 1.9; Table 1.3**). Moreover, the optimum GSR required to produce the maximum possible yield in the study region was estimated 670±113 mm. Our linear model resulted in alfalfa WUE of 30+4 kg ha^{-1} mm^{-1}, with minimum water loss (x-intercept in **Figure 1.4**) of 163 mm (or 24% of mean GSR). Meanwhile, mean WUE was 10 kg ha^{-1} mm^{-1}, representing a significant WUE gap. Mean GSR was below the optimum requirement in around 20% of the environments, suggesting that water availability does not limit alfalfa yields in this region in 80% of the cases.

1.3.4 Alfalfa yield and yield gap

The current alfalfa hay yield at the state level ranged from 4.8 to 7.8 Mg ha^{-1} and averaged 6.4±1 Mg ha^{-1} (**Table 1.4**), though at the county level Yc ranged from 2.7 Mg ha^{-1} in Perkins County of South Dakota to 10.8 Mg ha^{-1} in Clinton County of Illinois (**Figure 1.1**). The state of Iowa had the highest Yc of 7.8±1 Mg ha^{-1} with a mean GSR of 698 mm. Meanwhile, New York and North Dakota had the lowest Yc (4.8±1 Mg ha^{-1}) which might be partially due to a concomitant lowest mean GSR at least in North Dakota (366 mm). Our frontier yield model predicted an alfalfa Ya of 9.6 Mg ha^{-1} at an optimum GSR of 670 mm, which is almost 51% greater than the Yc and originated a mean attainable yield gap of 34%. The highest alfalfa Ya was 11.9 Mg ha^{-1} and occurred in Indiana, with an optimum GSR of 768 mm. The linear boundary function estimated a mean alfalfa Yw of 15.3 Mg ha^{-1} at the mean GSR of 672 mm, which is 140% greater than the Yc and originated a mean yield gap of 58%. The highest estimated Yw was 19.4 Mg ha^{-1} at a mean GSR of 880 mm in Kentucky whereas the lowest Yw was 7.8 Mg ha^{-1} at a mean GSR of 366 mm in North Dakota.

1.3.5 Weather variables driving alfalfa yield

The most parsimonious CIT explaining alfalfa yield as determined by weather variables resulted in an R^2 of 0.16 and a *RMSE* of 1.94 Mg ha^{-1} and suggested that GSR and Tmin were the largest drivers of alfalfa yield (**Figure 1.10**). We found higher Ya, Ya and Yw in the lower Midwest and Southeast compared to the upper Midwest and Northeast as these regions have warmer summer, longer GS and higher rainfall (**Figure 1.9, Table 1.2**). The highest yields (~7 Mg ha^{-1}) occurred in seasons and areas with GSR > 478 mm and Tmin >10.6ºC. In cooler seasons (Tmin <10.6ºC), alfalfa yields ranged from 5.3 to 6.6 Mg ha^{-1} depending on temperature and rainfall regimes. For growing seasons receiving between 309 and 478 mm, alfalfa yields depended on Tmin with cooler season (<9.3ºC) yielding less than warmer seasons (4.9 vs. 5.9 Mg ha^{-1}). The lowest yields (3.9 Mg ha^{-1}) were associated with GSR <309 mm.

1.4 Discussion

We used a systematic approach previously used for summer crops (Purcell et al., 2003; Torres et al., 2013) to delineate the duration of alfalfa growing season representing over 70% of the total rainfed alfalfa area in the US. Subsequently, we calculated weather variables for the growing season that allowed for calculating attainable yield and water-limited yield based on GSR, benchmarking WUE for the calculation of yield gaps. Lastly, we identified major weather drivers of rainfed alfalfa yield in this large geography.

An original contribution of this research is that, to our knowledge, this is the first systematic delineation of growing season duration using a probabilistic approach for a perennial crop such as alfalfa, which to date has been performed arbitrarily and inconsistently (Raun et al., 1999); (Sanderson et al., 1994); (Sulc et al., 1999); (McKenzie & McLean, 1982; Nath & Fisher, 1971; Sprague, 1955). The duration of the growing seasons using the current method aligned

well with the alfalfa growing season recommended by respective states' forage agronomists for the lower Midwest and Southeast regions (Henning & Nelson, 1993; Lacefield et al., 1997; Rocateli et al., 2017; Stachler, 2016), as well as for the upper Midwest and Northeast regions (Wells et al., 2018). From a practical standpoint, the estimated start DOY in spring and end DOY in the fall could be considered as the cropping calendar for optimum planting and last cutting dates for the respective states. More broadly, this is an important contribution to perennial crop systems in general as we showed that the method here presented could potentially be used to delineate the growing season for other perennial crops in other regions.

We used ten years of weather and yield data to estimate Yc, Ya and Yw, which is sufficient for relevant representation of the system and avoids possible effects of changes in production factors such as advancement of production technology, expansion of irrigation program, breeding improvement or climate change effect on crop yield which can happen with longer weather series (Grassini, van Bussel, et al., 2015; Undersander et al., 2015; Van Wart et al., 2013). We also note in passing that in the case of alfalfa grown in the U.S., government-reported county-level yield data is only available after 2009; thus, considering the need for a minimum of 10-yr of yield data, this is the first time when such analysis is possible at a country level.

Several methods have been used to estimate crop yield gaps, such as remote sensing (Dehkordi et al., 2020; Wang et al., 2020), crop model simulation (Jaenisch et al., 2021; Jáuregui et al., 2022; Jones et al., 2003; Lobell & Ortiz-Monasterio, 2006; Lollato et al., 2017; Soltani et al., 2020; Van Wart et al., 2013; Yang et al., 2004), upper percentile of farmer's yield (Affholder et al., 2013; Laborte et al., 2012; Van Ittersum et al., 2013), field experiment or yield contest (Lobell et al., 2009; Lollato et al., 2019; Van Ittersum et al., 2013), maximum farmers yield

(Lobell et al., 2009; Lobell et al., 2005; Van Ittersum et al., 2013), boundary-function analysis (Affholder et al., 2013; Lobell et al., 2009; Patrignani et al., 2014; Sadras et al., 2015; Van Ittersum et al., 2013), linear boundary function (French & Schultz, 1984; Milne et al., 2006; Patrignani et al., 2014; Sadras et al., 2015; Sadras & Angus, 2006) and frontier yield function model (Affholder et al., 2013; French & Schultz, 1984; Lobell et al., 2009; Patrignani et al., 2014; Soltani & Sinclair, 2012; Van Ittersum et al., 2013). Here, we used two approaches (i.e., frontier yield and linear boundary functions) that consider the biophysical boundaries of crop yield potential determination in rainfed systems based on GSR. These methods allow for the respective estimation of attainable yield and water-limited potential yield, which are reasonable approaches to estimate Yg in rainfed systems (Van Ittersum et al., 2013).

Our study revealed that there is a large Yg in rainfed alfalfa in the U.S. as current yields are only 66% of the attainable yield and 42% of the water-limited potential yield. Our results are consistent with many previous studies. For example, Russelle (2013) reported up to 70% Yg in non-irrigated alfalfa regions in the U.S. Similarly, Soltani et al. (2020) estimated 69% Yg in Iran and Jáuregui et al. (2022) estimated 53% in Argentina under rainfed condition. Our estimated Yw seems to be similar to the yield obtained from the variety trials or research experiments conducted in the study area and nearby locations (**Table 1.1**). Thus, the estimated region-specific Yw based on the WUE benchmark we developed in this manuscript can be used as a benchmark alfalfa yield under rainfed conditions (Sadras et al., 2015; Van Ittersum et al., 2013). Meanwhile, the decrease in Ya below and above the estimated optimum GSR **(Figure 1.3)** is likely due to water deficit stress in the low end (Djaman et al., 2020; Qiu et al., 2021; Takele & Kallenbach, 2001), and either excessive water regarding the crop requirements during the growing season (Graven et al., 1965; Thompson & Fick, 1981), waterlogging issues that may decrease biological

N fixation (Andrés et al., 2012; Havelka et al., 1982), or increase harvest losses due to continuous or heavy rainfall during harvesting and drying time.

The large yield gap found for rainfed alfalfa in the US using the current approaches suggests that water availability is usually not a limiting factor to alfalfa yield in the region. Correspondingly, only 21% of the environments had total GSR less than the optimum GSR required for maximum forage yield, and the resulting WUE was about three times less than the potential WUE (**Table 1.3**). This suggests that, at least in c.a., 80% of the environments, alfalfa yields are limited by factors other than water availability e.g., crop management factors. While the goal of the current manuscript was not to determine best management practices for reduced alfalfa yield gaps, we highlighted the opportunity to improve alfalfa yields at current levels of water supply. Future research should focus on strategies to minimize the current gap at the farm level.

In rainfed production systems, evapotranspiration and WUE have linear relationship with alfalfa forage yield (Li & Su, 2017; Lindenmayer et al., 2011; Undersander et al., 2015). Our model predicted that the most efficient use of growing season rainfall by alfalfa resulted in about 24% minimum water losses with the remaining 76% mostly being used by plants through transpiration with a 30 kg ha^{-1} mm^{-1} efficiency (**Table 1.3**). While the fractions of seasonal water available and lost were within the range reported by previous studies (Berg & Sheffield, 2019; Kool et al., 2014; Li et al., 2017; Wagle et al., 2021), the WUE (27-36 kg ha^{-1} mm^{-1}) was greater than it the majority of the other studies – as expected due to the nature of the boundary function. Still, careful evaluation of the data reported by Lindenmayer et al. (2008) suggests a few maximum WUE values in the same range, validating our linear model. Furthermore, we found higher WUE and lower dry matter yield in the upper Midwest and Northeast states as these states

have dryer and cooler summer (**Table 1.2 and 1.3**). These results correspond well with previous studies conducted by Ismail and Almarshadi (2013); Lindenmayer et al. (2008), and Li et al. (2017) who also reported greater WUE and lower dry matter yield under water-stressed conditions. The reason behind higher WUE could be the ability of alfalfa to extract moisture from deeper soil layers and to remain dormant during moisture-stressed conditions. Meanwhile, the lower yield could be the result of insufficient GSR, well below the values required to produce maximum attainable yield (**Table 1.3**).

While we found a wide range of yield variability across the rainfed states which were associated with the variability in weather conditions, we note that weather conditions only explained about 16% of yield variability of alfalfa. This low explanatory power could be function of the coarse scale of this study, evaluating a single reference weather station centered at the county – which may not be representative of weather conditions occurring in other parts of the county. Likewise, we note that the current approach does not consider rainfall distribution, thus, while total amount may not be limiting, distribution may be. Nonetheless, within the limitations of our analysis, data suggested that GSR and Tmin were the main drivers of alfalfa productivity at the county level. These results are supported by numerous previous studies (Boyer, 1982; Hamidi & Safarnejad, 2010; Lafitte et al., 2007; Takele & Kallenbach, 2001; Zeid & Shedeed, 2006) suggesting that water stress can adversely affect plant growth, reproductive capacity, yield, quality, and alfalfa survival. Similarly, a recent study by Pourshirazi et al. (2022) estimated up to 33% alfalfa yield loss due to cold temperatures in Iran. In alfalfa, the production of interest is predominantly biomass. Biomass accumulation is driven by solar radiation but modulated by moisture and temperature regimes (Soltani and Sinclair, 2012); therefore, the effect of GSR and Tmin on alfalfa forage yield is straightforward. Furthermore, lower Tmin

could lead to slow regrowth (Evenson, 1979; Körner, 2015), resulting in fewer cuttings per season, which associate negatively with alfalfa annual yield (Fink, 2021).

1.5 Conclusion

Our study estimated the current yield gap of 34% when compared to attainable yield, and of 58% when compared to the water-limited yield from the evaluation of about 70% of the rainfed alfalfa production area in the US. These results revealed that in most of the environments evaluated, on average 21% GSR was found below the optimum requirements indicating that alfalfa yield is only limited by suboptimal water availability in 21% of the cases. Our results suggested that GSR and Tmin were two key weather factors associated with alfalfa forage yield. We found higher attainable yield and water-limited potential yield in lower Midwest and Southeast regions as these states have warmer summer, longer growing season, and higher growing season rainfall than those in the upper Midwest and Northeast regions.

The findings of this study are particularly useful for alfalfa forage growers to realize that their production is mostly not limited by water availability and thus indicating that they could manage their production resources (i.e., labor, capital, technology, and irrigation) for higher yield levels for the given amount of water supply. Likewise, these results should be considered by government officials and policymakers to develop research and development programs that can address the current alfalfa forage yield gap. Of interest to other major perennial crops, this study also provides a reliable method to calculate the growing season based on probabilities of growing degree day accumulation, which allows for estimates of growing season weather variables needed to estimate yield gaps.

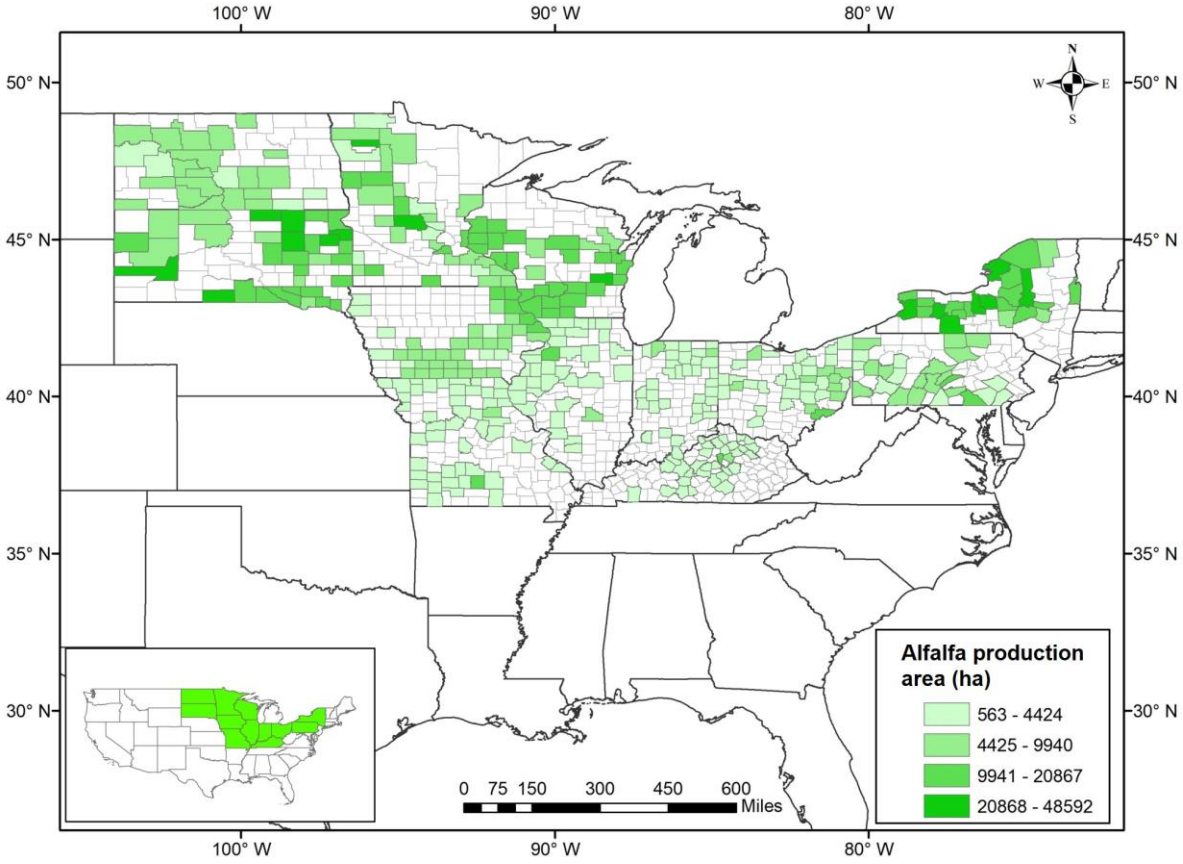


Figure 1.1. Map of the U.S. showing selected rainfed alfalfa producing counties.

The green color represents harvested area. Inset shows selected states as rainfed states within the continental U.S. for this study.

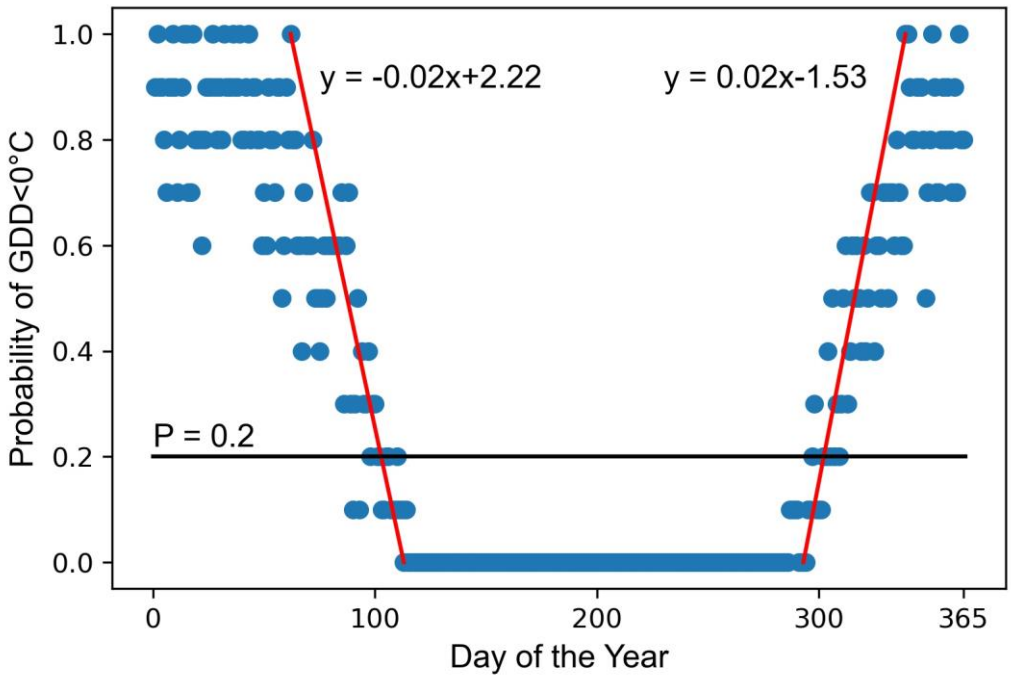


Figure 1.2. Methodology for estimating growing season duration for alfalfa.

This is an example of Noble County, Indiana, where solid black line represents 0.2 probability of occurrence of growing degree days (GDD) <0°C using a base temperature of 5°C for each day of the year for the last 10 years. Solid red lines are the linear regression for decreasing (spring) and increasing (fall) probabilities of days where no GDD were accumulated.

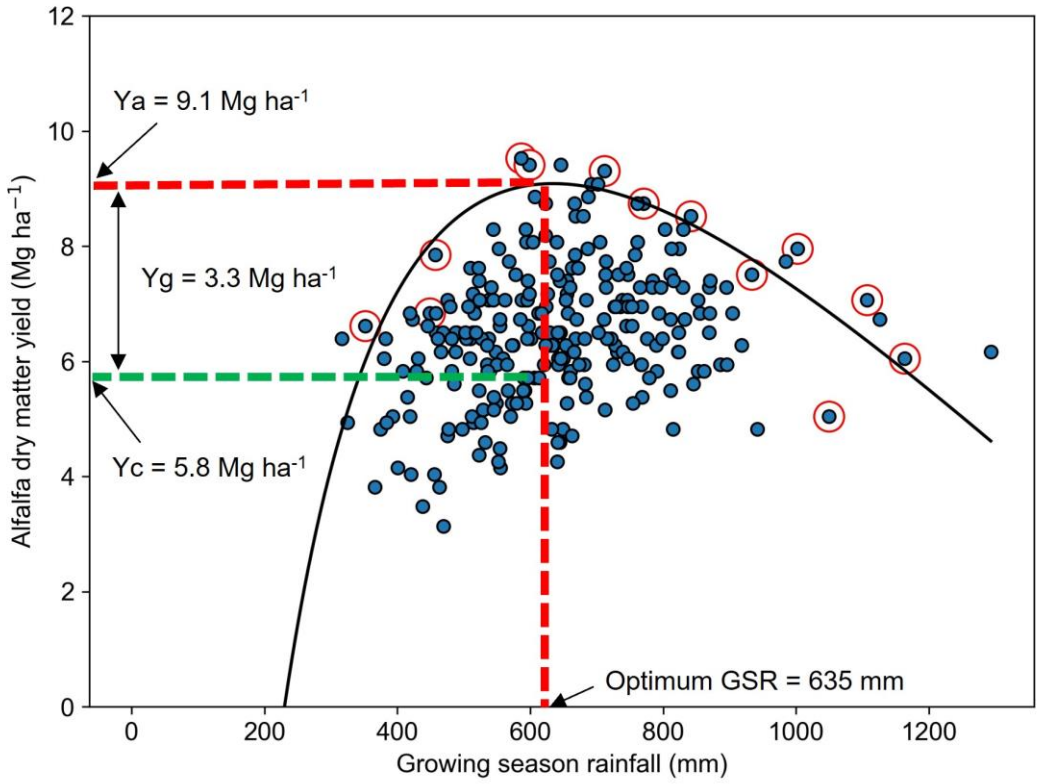


Figure 1.3. Example of estimating attainable yield for Wisconsin using frontier yield function.

The value in the peak of the non-linear line represents maximum attainable yield (the red dotted line intersecting Y-axis) at an optimum growing season rainfall of 635 mm (the red dotted line intersecting in X-axis). The blue dotted markers represent annual yield for a 10-yr period (2009-2018) of selected counties within WI (n=29) obtained from USDA-NASS. The red circled dotted markers represent maximum yield achieved in a county within a certain rainfall range.

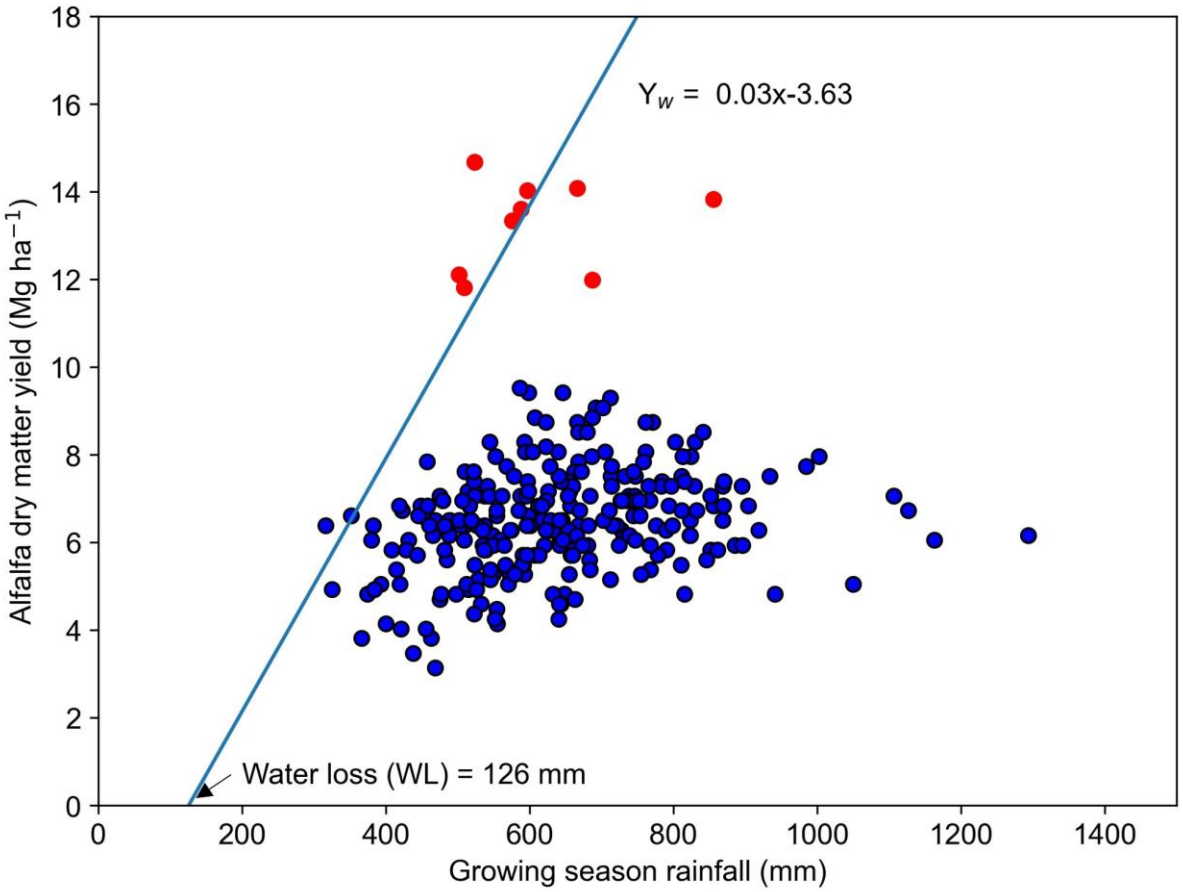


Figure 1.4. Example of estimating water-limited potential yield for Wisconsin using linear boundary function.

The slope of a linear line represents the water-limited potential yield (Yw) obtained from growing season rainfall, after allowing for a minimum loss of 126 mm during the entire growing season. The blue dotted markers represent annual yield for a 10-yr period (2009-2018) of selected counties within WI (n=29) obtained from USDA-NASS. The red dotted points represent data from variety trials conducted at Outagamie County of WI during the study period.

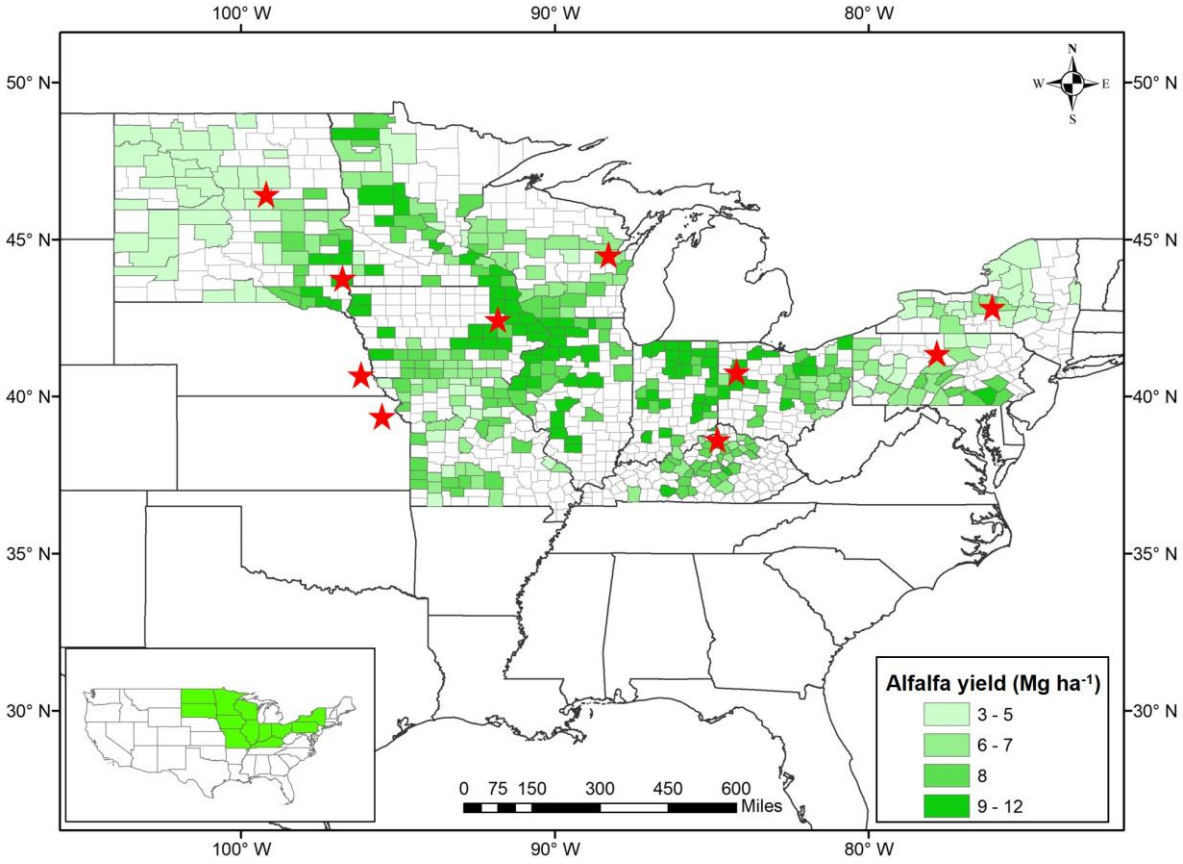


Figure 1.5. Map of the U.S. showing selected rainfed alfalfa producing counties (n = 393).

The green color represents forage yield. The red stars represent the locations (n=10) from where alfalfa yield data obtained from research experiments were used for this study. Inset shows selected states as rainfed states within the continental U.S. for this study.

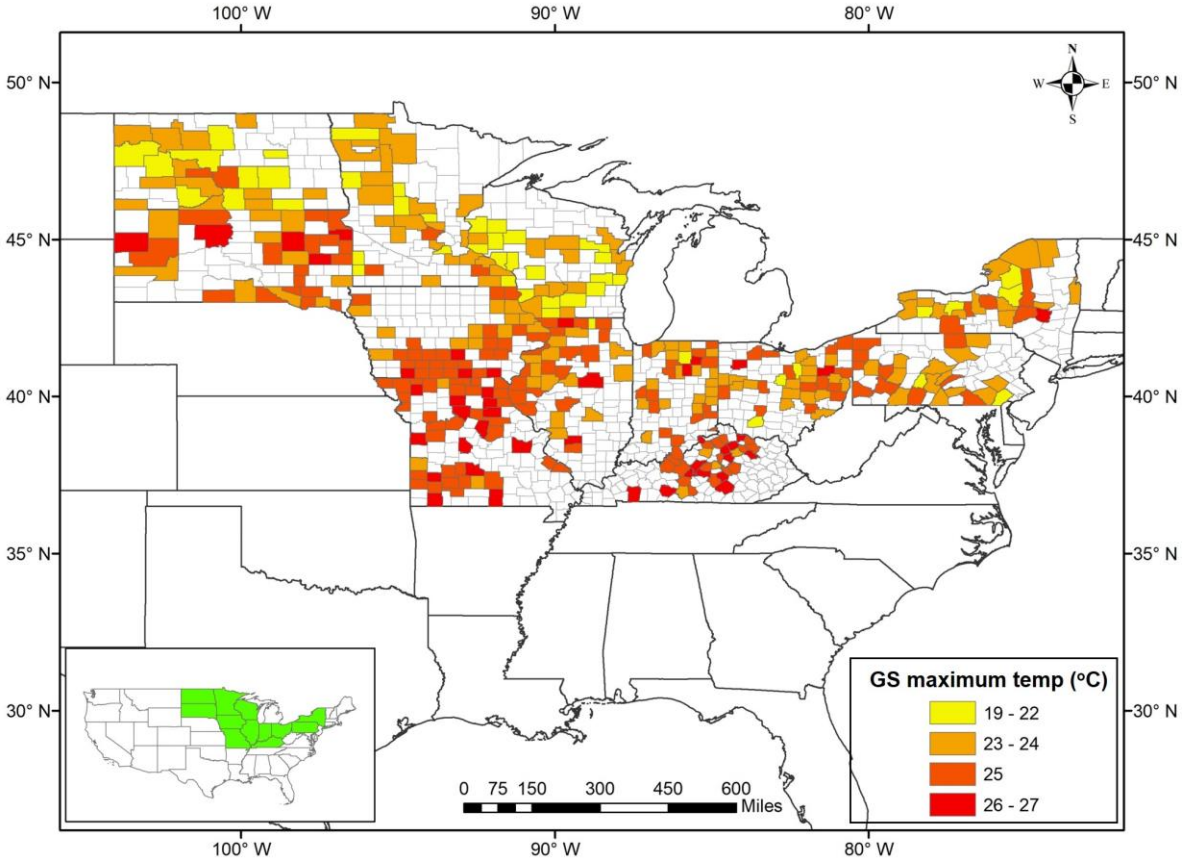


Figure 1.6. Mean growing season maximum temperature in the study area during the 2009-2018 period.

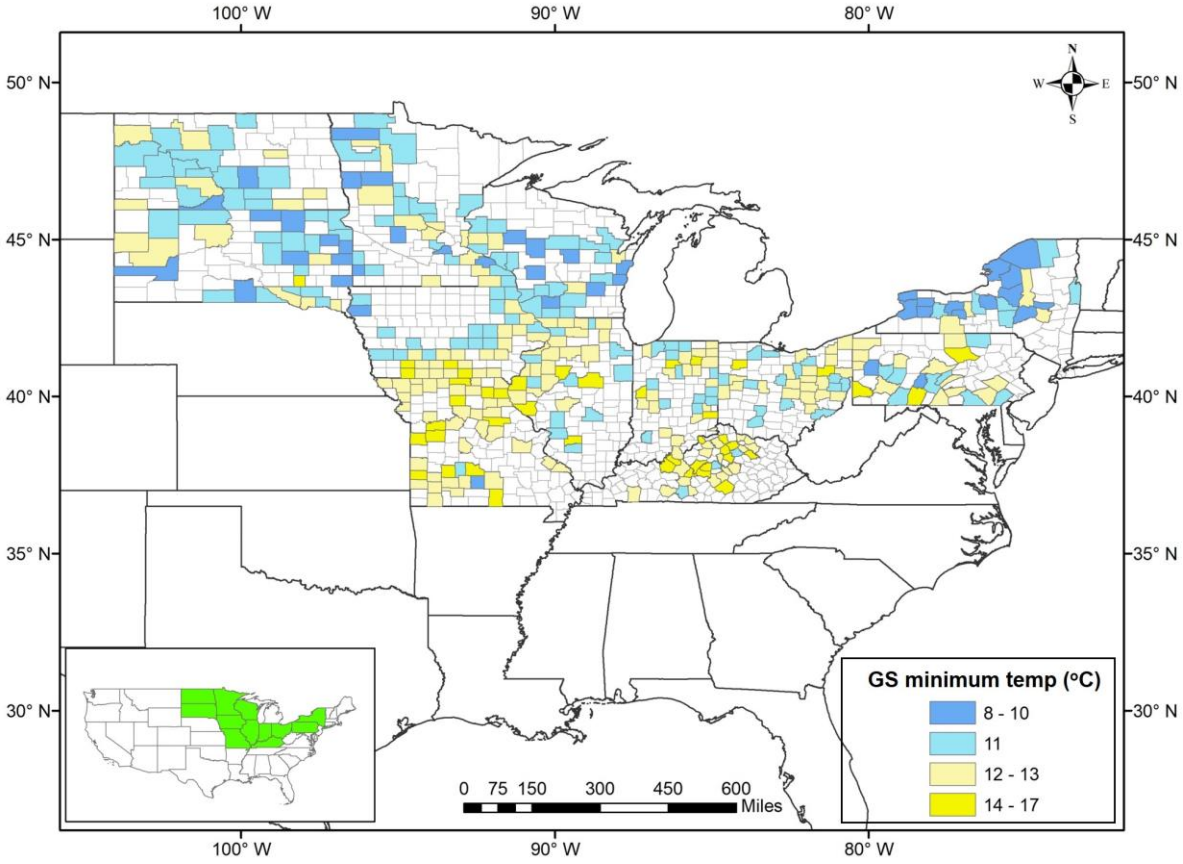


Figure 1.7. Mean growing season minimum temperature in the study area during the 2009-2018 period.

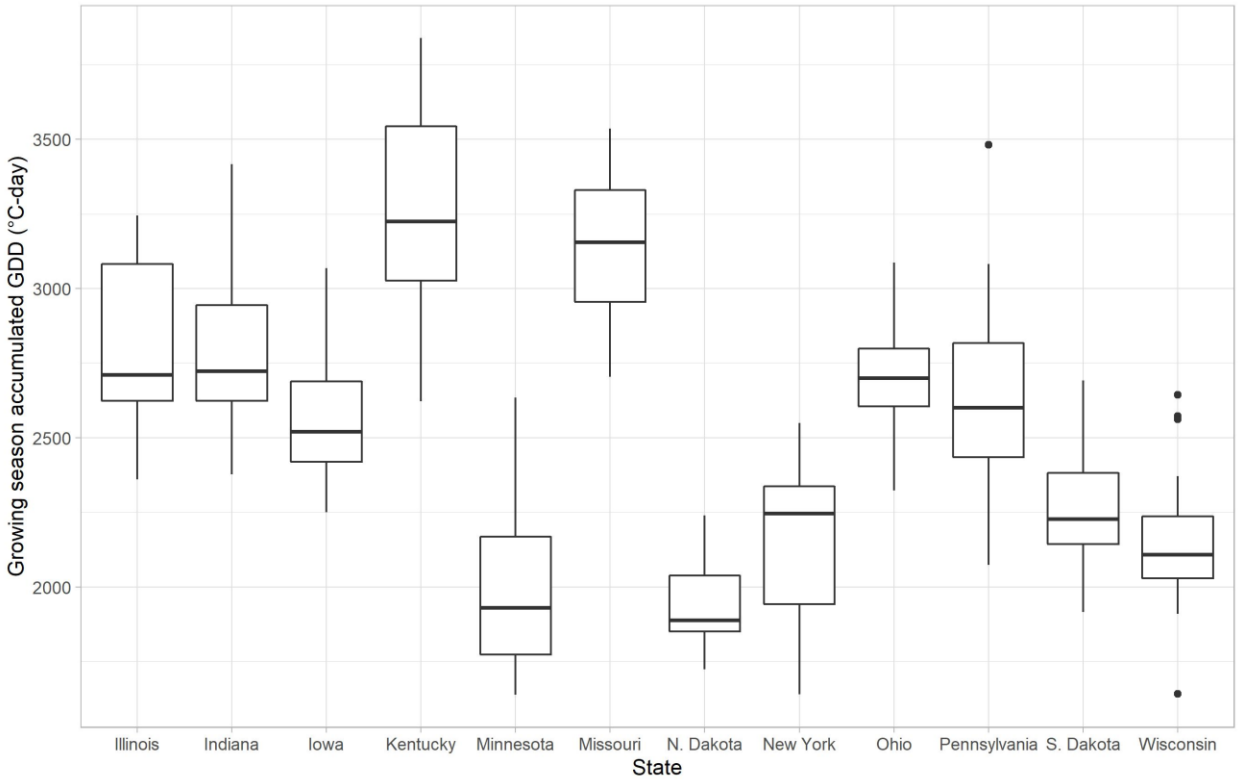


Figure 1.8. Mean growing season accumulated growing degree days (GDD) in the study area during the 2009-2018 period.

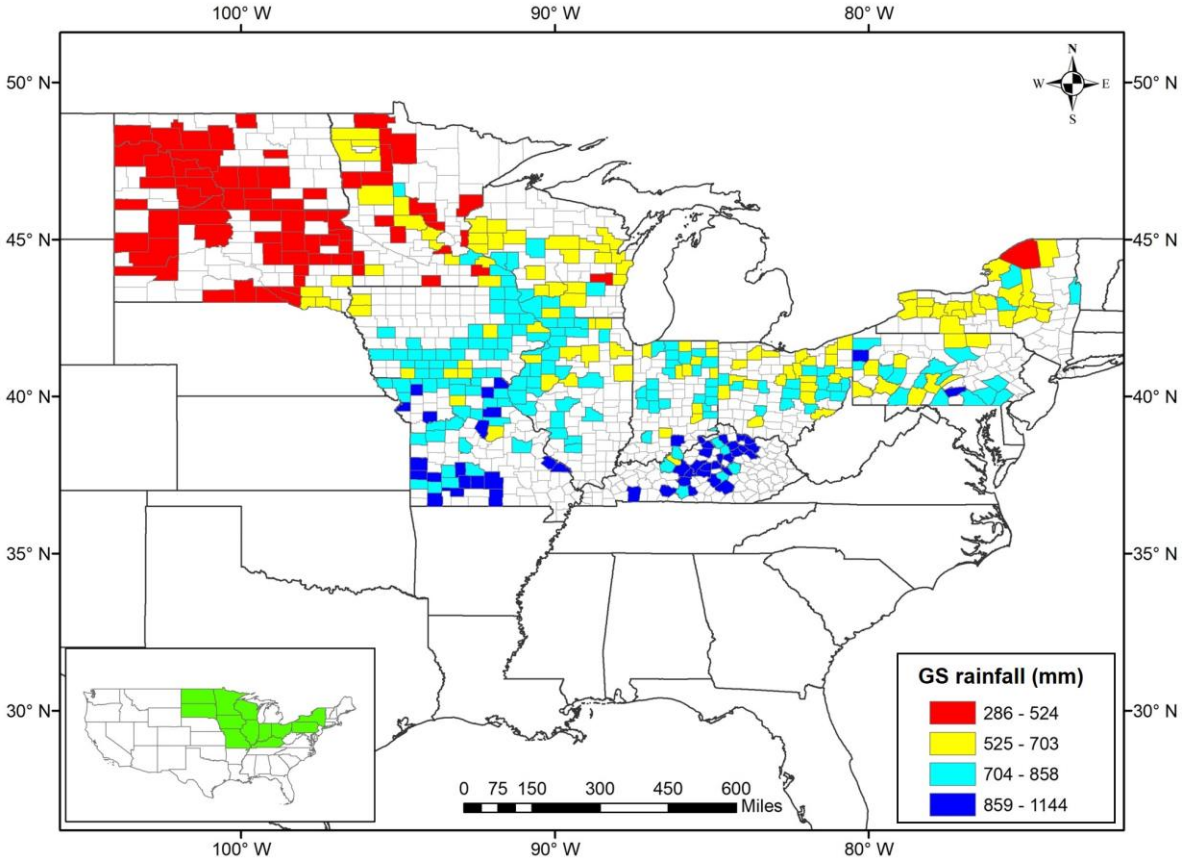


Figure 1.9. Mean growing season cumulative growing season rainfall (GSR) in the study area during the 2009-2018 period.

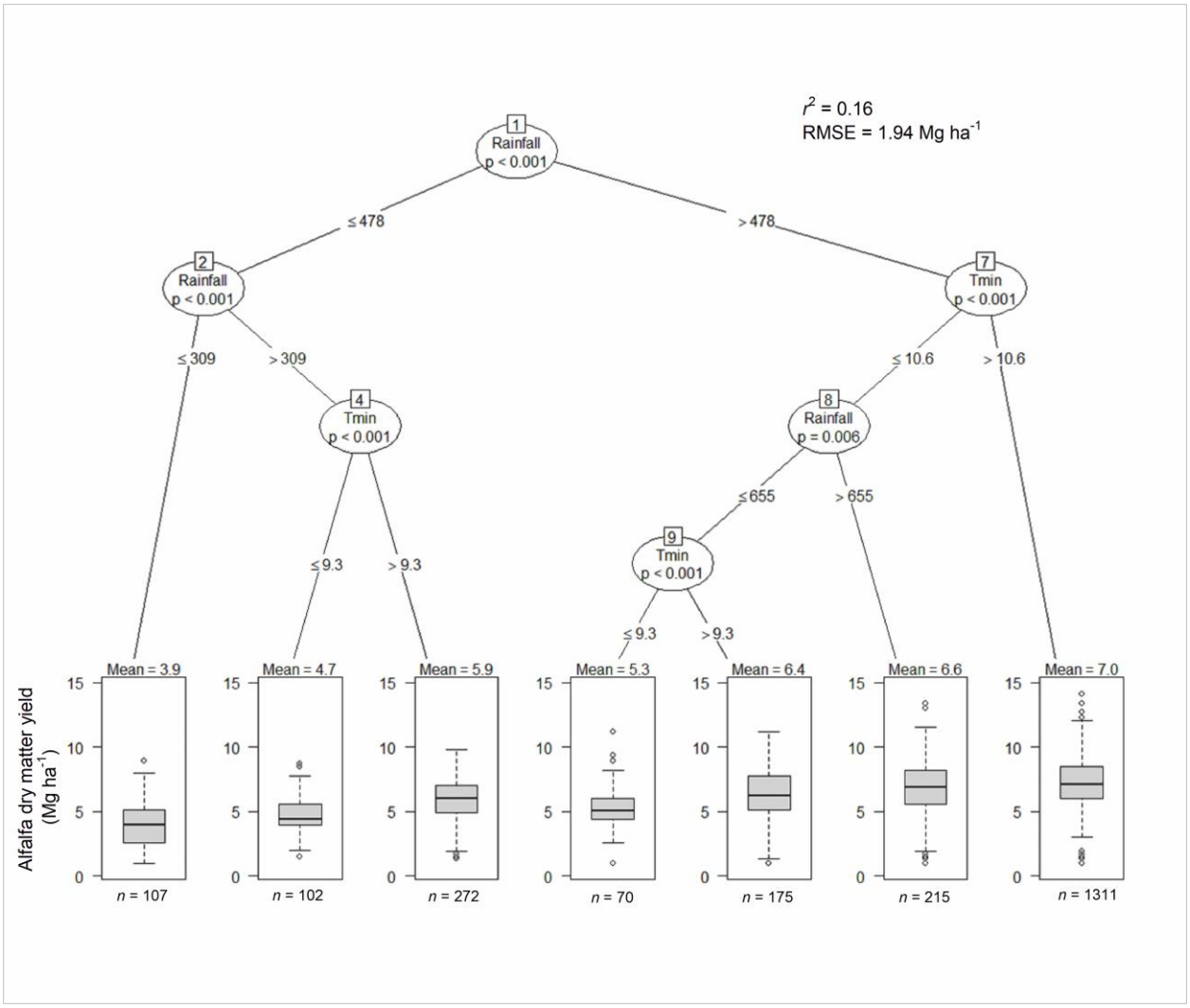


Figure 1.10. Conditional inference tree for alfalfa forage yield as affected by growing season weather variables.

The yield as a function of the interaction between growing season weather variables (cumulative rainfall and growing degree days, and mean Tmax and Tmin) for 393 counties over 10 years period. The oval-shaped circle contains a specific predictor that affects yield, the branches represent binary partition of the variables based on the shown threshold of predictor. Each boxplot inside the terminal nodes represents the interquartile range (gray box), median (solid line inside the gray box), upper and lower extreme (whiskers), and outliers (black circles) of alfalfa yield in Mg ha^{-1}. The value of *n* on the bottom of the terminal node represents the total number of observations in each terminal node. The GSR is expressed in mm and Tmin in ^{o}C.

Table 1.1. Mean and range in alfalfa forage yield as reported by various field experiments during the study period (2009-2018).

State	Location	Yield (mean, range; Mg ha^{-1})	*n*	Source
Kansas	Manhattan, Topeka, Garden city	19.0 (21.3 –16.1)	7	Kansas State University (2013); McDonald et al. (2021b)
Kentucky	Lexington	13.7 (19.8-8.5)	10	University of Kentucky (2021)
Minnesota	Dakota	15.6 (18.8-11.7)	10	University of Minnesota (2021)
Nebraska	Havelock	19.1 (21.3-17.2)	8	University of Nebraska Lincoln (2016)
New York	Ithaca	14.0 (15.4-12.5)	10	Cornell University (2021)
North Dakota	Carrington	8.3 (12.6-5.1)	8	Aponte et al. (2019); North Dakota State University (2018); Wang et al. (2014)
Ohio	South Charleston	14.2 (18.3-10.2)	10	Ohio State University (2019)
Pennsylvania	Rock Spring	18.3 (24.6-13.8)	10	PennState Extension (2021)
South Dakota	Beresford	15.4 (18.3-13.3)	5	Owens et al. (2017); Sara et al. (2019)
Wisconsin	Outagamie	13.3 (14.7-12)	9	University of Wisconsin Madison (2016)

Note: n = Number of published field-based research paper.

Table 1.2. Estimated alfalfa growing season for 12 rainfed states including start and end day in day of year (DOY), and key weather variables.

State	Growing season						
	Start DOY	End DOY	Total GDD	Tmax (°C)	Tmin (°C)	Tav (°C)	Accumulated GDD (°C-day)
Illinois	91 (31-Mar)	309 (4-Nov)	218±16	23.9±0.7	12±0.9	18±0.7	2783±274
Indiana	94 (3-Apr)	311 (6-Nov)	217±11	23.8±0.8	11.9±1.2	17.9±0.9	2779±251
Iowa	100 (8-Apr)	306 (31-Oct)	206±10	24.1±0.8	11.9±1.0	18.0±0.8	2574±216
Kentucky	73 (12-Mar)	314 (9-Nov)	241±24	24.9±1	12.8±1.1	18.8±1	3278±313
Minnesota	113 (22-Apr)	282 (8-Oct)	169±20	22.8±0.7	10.7±1.1	16.8±0.8	1964±244
Missouri	82 (22-Mar)	316 (10-Nov)	234±19	24.8±0.7	12.6±0.8	18.7±0.7	3152±242
New York	109 (17-Apr)	298 (23-Oct)	189±12	22.5±0.9	10.6±1	16.6±0.7	2156±253
North Dakota	115 (23-Apr)	284 (10-Oct)	170±19	23.4±0.9	9.8±1.2	16.6±1	1935±142
Ohio	92 (31-Mar)	307 (1-Nov)	21±10	23.8±0.8	11.7±0.8	17.8±0.7	2692191
Pennsylvania	94 (3-Apr)	306 (31-Oct)	212±13	23.6±0.7	11.5±1.4	17.6±0.9	2624±314
South Dakota	109 (17-Apr)	294 (19-Oct)	185±21	24.2±0.8	10.7±1.2	17.5±0.8	2268±211
Wisconsin	107 (16-Apr)	300 (25-Oct)	193±14	22.1±1.1	10.5±1.1	16.3±0.8	2155±210
Mean	98 (7-Apr)	302 (28-Oct)	204±22	24±0.8	110±.9	18±0.8	2530±422

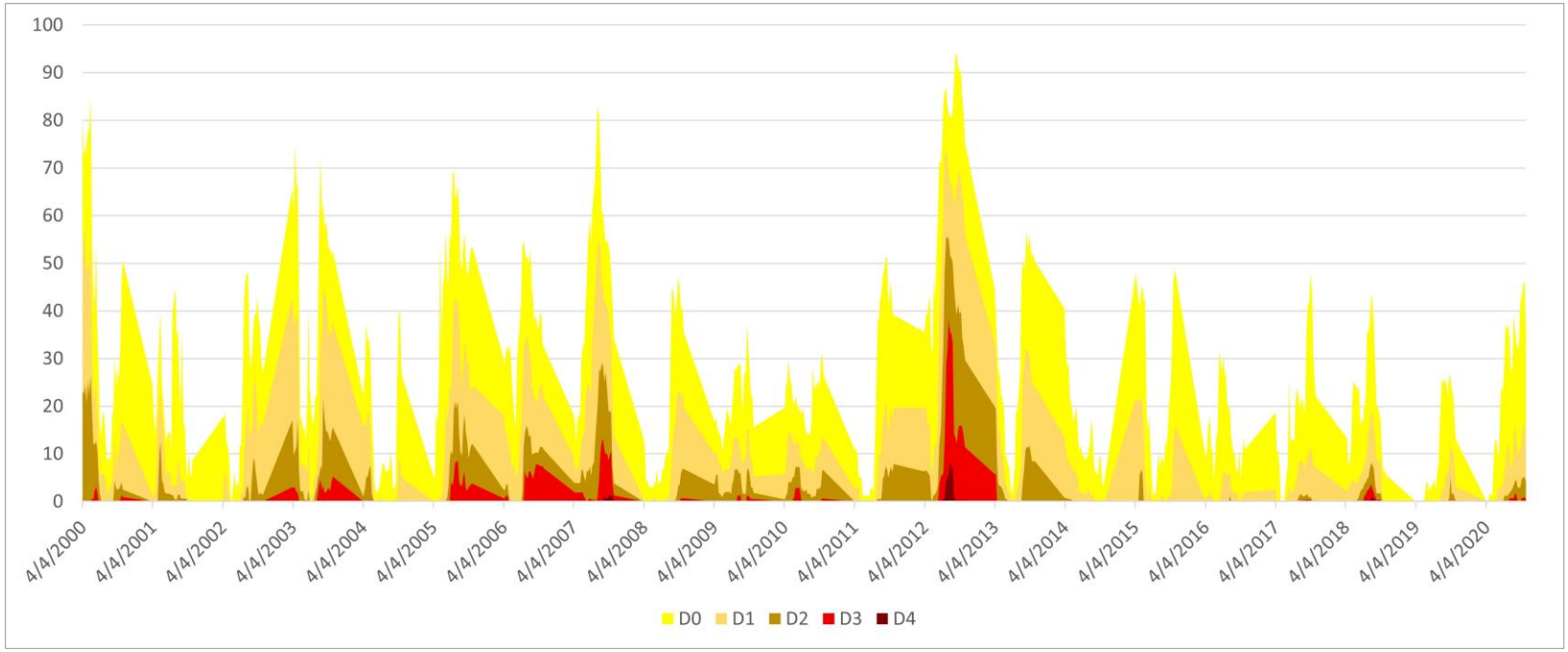
Note: Weather variables are 10 year's mean maximum and minimum temperature and accumulated GDD during the alfalfa growing season across the selected counties.

Table 1.3. State-level GSR optimum GSR, minimum water loss, mean WUE, potential WUE and percentage of GSR below the optimum requirement.

State	Mean GSR (mm)	Optimum GSR (mm)	Minimum water loss	Minimum water loss (%)	Mean WUE (kg $ha^{-1}mm^{-1}$)	Potential WUE (kg $ha^{-1}mm^{-1}$)	% of GSR below the optimum
Illinois	746±56	759	190	25	10	27	27
Indiana	740±69	768	171	23	10	27	26
Iowa	745±45	698	176	24	10	31	17
Kentucky	936±92	880	214	23	8	27	21
Minnesota	542±119	630	77	14	13	34	22
Missouri	827±87	719	195	24	7	27	12
New York	632±59	587	154	24	8	34	14
North Dakota	366±40	391	75	21	12	27	13
Ohio	693±56	645	215	31	11	38	22
Pennsylvania	743±67	636	253	34	8	31	19
South Dakota	441±77	688	109	25	13	34	47
Wisconsin	648±66	635	126	19	10	27	15
Mean	672±153	670+113	163+54	24+5	10+2	30+4	21+9

Table 1.4. State-level current yield (Yc), attainable yield (Ya), water-limited potential yield (Yw) and yield gap in comparison to attainable (YGa) and water-limited yield (YGw).

State	Yc (Mg ha^{-1})	Ya (Mg ha^{-1})	Yw (Mg ha^{-1})	YGa (Mg ha^{-1})	YGw (Mg ha^{-1})	YGa (% of Ya)	YGw (% of Yw)
Illinois	7.6	11.5	15.5	3.9	7.8	34	51
Indiana	7.5	11.9	15.0	4.4	7.4	37	50
Iowa	7.8	11.0	17.9	3.2	10.1	29	57
Kentucky	6.7	9.2	19.4	2.5	12.8	28	66
Minnesota	7.0	10.5	15.6	3.5	8.6	33	55
Missouri	5.6	8.7	17.0	3.1	11.4	36	67
New York	4.8	6.9	16.1	2.1	11.3	31	70
North Dakota	4.8	7.4	7.8	2.6	3.0	35	39
Ohio	7.2	10.1	18.2	2.9	11.1	29	61
Pennsylvania	5.9	8.5	15.4	2.7	9.5	31	62
South Dakota	5.8	10.9	11.2	5.1	5.4	47	48
Wisconsin	5.8	9.1	14.1	3.3	8.3	36	59
Mean	6.4±1.0	9.6±1.5	15.3±3	3.3±0.8	8.9±2.6	34±5	58±9



Supplemental Figure 1.1. Percent area of the Midwest region of the US affected by drought from 2000 to 2020 during alfalfa-growing period (April to October).

The severity of the drought is categorized as D0: Abnormally dry, D1: Moderate drought, D2: Severe drought, D3: Extreme drought, and D4: Exceptional drought (NDMC, 2021).

Supplemental Table 1.1. Selection of States based on alfalfa production and rainfed production area.

State	Irrigated area (ha)	Irrigated %	Rainfed %	Total harvested area (ha)	% US harvested area	Production (tons)	% of US total production	% of US total rainfed production
South Dakota	32175	4.4	95.6	729374	9.0	2877067	4.5	6.5
North Dakota	111	1.0	99.0	5943	8.1	2089778	3.3	4.7
Wisconsin	6218	0.8	99.2	335459	5.2	3071064	4.8	7.0
Minnesota	3524	1.9	98.1	233267	4.1	2345020	3.6	5.3
Iowa	140	0.1	99.9	11716	3.5	2385316	3.7	5.4
Michigan	1051	1.5	98.5	91997	2.9	1351628	2.1	3.1
Ohio	6396	0.2	99.8	659201	2.1	1217582	1.9	2.8
Pennsylvania	3325	0.2	99.8	421689	2.0	1161432	1.8	2.6
New York	214	0.2	99.8	91233	1.8	836233	1.3	1.9
Illinois	346	0.1	99.9	148154	1.2	845430	1.3	1.9
Indiana	362	1.1	98.9	166859	1.1	696575	1.1	1.6
Missouri	298	0.2	99.8	166015	1.1	554878	0.9	1.3
Kentucky	142	0.0	100.0	100430	1.0	587809	0.9	1.3
Virginia	269	0.0	100.0	285409	0.4	209188	0.3	0.5
Maryland	0	1.2	98.8	3190	0.1	96179	0.1	0.2
Vermont	0	0.0	100.0	77903	0.1	46278	0.1	0.1
New Jersey	0	1.9	98.1	3547	0.1	40604	0.1	0.1
West Virginia	0	0.0	100.0	3545	0.1	34818	0.1	0.1

North Carolina	0	0.0	100.0	1088	0.1	29842	0.0	0.1
Tennessee	0	0.0	100.0	5505	0.1	28473	0.0	0.1
Maine	0	0.0	100.0	4560	0.0	14576	0.0	0.0
Massachusetts	0	0.0	100.0	10416	0.0	20973	0.0	0.0
Connecticut	0	0.0	100.0	32243	0.0	13542	0.0	0.0
New Hampshire	0	0.0	100.0	5912	0.0	5241	0.0	0.0

Note: The top 12 states are selected for this study. Because of the unavailability of county-level alfalfa yield data, we excluded Michigan State for this study.

Chapter 2 - Exploring alternative summer forage crops for wheat-based rainfed cropping systems in Kansas

Abstract

This study explored alternative summer forage crops for wheat-based rainfed cropping systems in Kansas. A three-year field study was conducted with seven different crop sequences and intensities. Various summer crops including soybean, forage soybean, cowpea, moth bean, tepary bean, and alfalfa. Biomass was sampled at different growth stages. Analysis included forage yield, forage nutritive value, water use efficiency, and net farm income. Forage soybean had the highest dry matter yield (13.9 Mg ha^{-1}) when planted at the optimal time and harvested at reproductive (R3) growth stage. Soybean and alfalfa also had relatively high yields (~13 Mg h^{-1}). Soybean, alfalfa and forage soybean had higher crude protein and relative feed value. All the crops met the recommended hay quality standard, with a relative feed value greater than 150. Water use efficiency varied among the crops, with cowpea demonstrating the highest efficiency (26.8 kg mm^{-1}). In terms of net farm income, forage soybean and alfalfa were the most profitable crops, yielding a net profit of $322 and $877 per hectare, respectively. Conversely, soybean, moth bean, and tepary bean showed negative net profits. Based on the findings, forage soybean is recommended as a potential summer forage crop in wheat-based rainfed cropping systems in Kansas, considering its water use efficiency, prolonged vegetative growth, forage yield, nutritional benefits for livestock, and profitability. Cowpea was also identified as an efficient water user and economically viable crop. This study provided valuable insights for farmers and researchers in crop selection, planting and harvesting time management, and maximizing yield, quality and profitability in forage production systems.

2.1 Introduction

Rainfed farming systems heavily rely on rainfall to meet the water requirements for different crops. The potential match between crop water demand and precipitation distribution, thus, dictates which specific crops can be grown in rainfed regions. Moreover, this dependency on rainfall poses a significant challenge and is considered one of the most limiting factors in crop production across the globe (Araya et al., 2017; Holzman & Rivas, 2016; Nielsen et al., 2005).

Kansas, located in the US Great Plains, is an important agricultural region where crops are predominantly grown under rainfed conditions. Here, approximately 7.3 M ha are grown to major grain crops [i.e. wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), sorghum (*Sorghum bicolor* L.) and maize(*Zea mays* L.)], about 1 M ha to hay and haylage including alfalfa (*Medicago sativa* L.), 1.2 M ha are currently under native grasslands, and roughly 1.7 million hectares are cultivated with tame pasture excluding alfalfa and small grains (USDA-NASS, 2023). The rainfall pattern in Kansas and surrounding states is characterized by limited and erratic distribution, both spatially and temporally (Lollato et al., 2020; Patrignani et al., 2014). The amount of rainfall varies across the state, ranging from over 1100 mm per year in southeast Kansas to less than 500 mm per year in the southwestern region (Kansas Mesonet, 2023). This variation in rainfall causes significant constraints on crop production and requires farmers to carefully manage water resources and adopt strategies to mitigate the impact of such unpredictable and limited rainfall.

Due to the geographical variability in rainfall amount and distribution, the traditional wheat-based cropping systems most commonly used by growers depend on the region within the state. In the western third of the state, where the climate is semi-arid (Sciarresi et al., 2019), the predominant crop rotation consists of a two-year rotation of wheat and fallow, or a three-year

rotation of wheat, followed by either grain sorghum (*Sorghum bicolor* L.) or maize (*Zea mays* L.), and fallow (Dhuyvetter et al., 1996; Holman et al., 2021; Jaenisch et al., 2021). Meanwhile, as the weather transitions to sub-humid in central and eastern Kansas (Sciarresi et al., 2019), typical rotations become more intensive and either consist of continuous wheat (one crop per year), or wheat in rotation with summer crops (i.e., maize, soybean, and grain sorghum, allowing for up to three crops in two years) (Jaenisch et al., 2021; Simão et al., 2023). Wheat planting in Kansas normally occurs in the fall, between late September and early November and harvesting in the early summer, usually from late May to mid-July, depending on factors such as wheat variety, weather conditions, and the desired level of grain maturity and moisture content. Warm-season crops are typically planted in the spring, between April and June and harvested in late summer or early fall, between September and October. Grain sorghum and maize are primarily grown for grain production, although they can also be used as silage or forage crops. Another common crop rotation system particularly in eastern Kansas is maize-soybean-wheat rotation. This sequence involves planting maize in one season, followed by soybean in the next, and wheat in the subsequent season. Other crop rotation systems in Kansas involve incorporating sorghum, alfalfa, or other forage crops, depending on the specific needs and objectives of farmers in the region. The choice of crop rotation may vary depending on factors such as soil type, climate, market demand, and individual farm management practices.

While grain crops seem to dominate the agricultural landscape in Kansas, forage production is also one of the key sectors of the Kansas agricultural economy. In 2021, Kansas ranked 2nd in sorghum silage production, 4th in all hay production, and 9th in feed and fodder export in the U.S. (Kansas Department of Agriculture, 2021). Additionally, the state ranked 3rd in total cattle and 16th in dairy production. Each year, the forage industry provides jobs for more

than 7500 individuals and contributes over $500 million to the Kansas economy. On average, approximately 5.5 million tons of different types of forage hay are harvested annually from approximately 1 million hectares of land in the state (USDA-NASS, 2023). The diverse range of soil, climate, and topography in the state, including rolling hills, prairies, and plains, creates a suitable environment for growing various forage crops during winter and summer seasons.

Alfalfa (*Medicago sativa* L.) is the most commonly grown perennial forage crop in Kansas with an average annual production of 2.3 million tons (USDA-NASS, 2023). Grass hay is another significant forage crop in Kansas. Grass hay such as tall fescue (*Schedonorus arundinaceus* L.), bermudagrass (*Cynodon dactylon*), ryegrass (*Lolium perenne* L.), big bluestem (*Andropogon gerardii* L.), little bluestem (*Schizachyrium scoparium* L.), Indiangrass (*Sorghastrum nutans* L.), switchgrass (*Panicum virgatum* L.), Eastern gamagrass (*Tripsacum dactyloides* L.), sideoats grama (*Bouteloua curtipendula* L.), buffalo grass (*Buchloe dactyloides* L.), blue grama (*Bouteloua gracilis* L.) and western wheatgrass (*Pascopyrum smithii* L.) have been grown in many parts of the state for pasture and hay production and are often used as a winter feed supplement for cattle. Sorghum-sudangrass (*Sorghum bicolor x Sorghum sudanese*) and maize (*Zea mays* L.) silage are also produced as a summer annual forage particularly in the western Kansas. In addition to these major forage crops, other forages such as clovers, small grains, and legumes are also grown in Kansas. These crops are often used as cover crops to prevent soil erosion, improve soil health, and provide additional forage for livestock.

The beef industry in Kansas has experienced significant growth, with beef and beef product exports increasing from $193 million in 2004 to $1,950 million in 2022 (USDA-FAS, 2023). However, the forage production in Kansas has been gradually declining over the past few decades, from 7.9 million tons in 2001 to 5.6 million tons in 2022 (USDA-NASS, 2023) despite

fairly stagnant yields (Fink et al., 2022). This trend suggests that farmers depend more on concentrated feed as an alternative to forage.

Despite the growing demand and economic value, forage production in Kansas faces several challenges, including shortages at different times of the year. Various factors contribute to these shortages, such as traditional practices, the competitive advantage of growing other cash crops like wheat, maize, and soybean, the expansion of the feed and ethanol industry, rising fertilizer prices, and unpredictable weather events such as drought, hail, and extreme cold and wet winters (Roozeboom et al., 2008). These factors can lead to crop failure, delays in harvesting, post-harvest losses, and increased storage costs, resulting in higher expenses associated with livestock production.

It is crucial for beef cattle producers in Kansas to plant alternative annual forages after wheat to address the summer shortage of high-quality forages. While approximately 12% of Kansas wheat farmers typically grow wheat as a dual-purpose crop and graze their cattle during late fall and early spring seasons (Lollato et al., 2019), there is still forage shortage from late July through November. Therefore, additional forage supply is needed to ensure a sustainable wheat-based forage production system during this shortage period.

Wheat, soybean, and maize are the primary field crops driven by market demand and economic value in Kansas. These crops have well-established supply chains and markets, and their expansion is incentivized by grain-based feed industries, bread industries, and ethanol industries. In contrast, forage crops require specific varieties, management practices, and conditions that are not as widespread in Kansas. Low rainfall and high temperatures during the summer cause moisture stress conditions in many parts of Kansas (Kansas Mesonet, 2023). Improved varieties of wheat, soybeans, and maize have been extensively researched and

developed to thrive in the region, leading to higher yields and better economic returns. In contrast, limited studies have been conducted on forage crops compared to other field crops. Although forage crops like alfalfa are essential for livestock feed, many farmers in Kansas rely on pasture and range grasses for grazing and reduce the need for extensive cultivation of forage crops.

Additionally, the prices of fertilizers in the United States have significantly increased after 2020 (Schnitkey et al., 2022), adding to the challenges of forage production. High fertilizer prices contribute to higher production costs, potential yield decreases, and the need for farmers to adjust their management practices. Addressing these consequences requires innovative approaches to optimize fertilizer use, reduce input costs, and ensure the continued production of high-quality forage for livestock feed or identify alternative crops that are well-suited to the Kansas environment and require fewer production inputs.

To overcome these challenges and meet the year-round demand for quality forage, it is essential to explore alternative crops that offer higher yields, better quality, and more profit. Thus, the primary objective of this study was to evaluate the forage yield, nutritive value, water use efficiency, and profitability of various summer forage crops grown under rainfed conditions with the ultimate goal of exploring alternative summer forage crops suitable for wheat-based rainfed cropping systems in Kansas and the surrounding Great Plains region.

2.2 Materials and Methods

2.2.1 Description of study location

A three-year field experiment was conducted at the Ashland Bottoms Experiment Research Station in Manhattan, Kansas, USA (39.124945°N latitude and -96.635112°N longitude, 314 altitude), beginning from October 2019 till October 2022 (**Figure 2.1**).

The soil type at the site was Wymore silty clay loam with 0 to 1% slope. The soil pH, total nitrogen, carbon, Mehlich extractable phosphorus, potassium, bulk density and the volumetric water content at the 0 to 20 cm depth were 6.4, 0.13%, 1.38%, 20.44 μg/g, 323 μg/g, 1 g cm^{-3} and 33%, respectively. The previous cropping system of the site was sorghum-soybean-wheat conventional tillage rotation.

The 30 yrs average summer crop growing season rainfall (March-October) was 710 mm, ranging from 46.5 mm in March to 122.7 mm in June and temperature was 18.5°C, ranging from 7.1°C in March to 26.6°C in July (**Figure 2.2**). In the spring (March to May), temperatures gradually rise, with average highs ranging from 14.2°C in March to 24.9°C in May. Spring is a relatively wet season, with moderate rainfall and occasional thunderstorms. Summer (June to August) is characterized by warm to hot temperatures. Average highs range from 30.3°C in June to 33.1°C in July. Autumn (September to November) brings cooler temperatures as the season progresses. Average highs range from 27.6°C in September to 13°C in November. Winter (December to February) is cold and often accompanied by snowfall. Average highs range from 6.6°C in December to 7.8°C in February. Winter nights are often chilly, with temperatures dropping below freezing. The average frost-free period is approximately 179 days (Kansas Mesonet, 2023).

2.2.2 Cropping systems design

The experimental design consisted of a randomized complete block with four replications. The size of each plot was 12.19 meters wide and 15.24 meters long. The study designed seven treatment combinations, each varying in terms of cropping sequence, cropping intensity, and diversity. The year-wise cropping sequence, as shown in **Figure 2.3**, included a combination of winter and summer crops cultivated for forage and grain purposes. The cropping

intensity included: 1) Baseline (traditional), 2) Adaptive forage, 3) Adaptive grain, 4) Dual-purpose semi-intensive with first and third summer fallows, 5) Dual-purpose semi-intensive with second summer fallow, 6) Dual-purpose intensive and 7) Dual purpose intensive with perennial legume. The specific crops were winter wheat, triticale (×*Triticosecale Wittmack*), cowpea (*Vigna unguiculata* L.), moth bean (*Vigna aconitifolia*), tepary bean (*Phaseolus acutifolius*), soybean, forage soybean [*Glycine max* (L.) Merr], and alfalfa (*Medicago sativa* L.).

2.2.3 Field management

The individual crop rotations resulted in systems that were either planted at the optimum or late, the latter in the case of double cropping. Within the optimum planting dates, winter wheat and triticale were sown from mid to late October whereas summer legumes were sown from mid-May, depending on the year. Within the late planting dates, winter crops were sown from early to mid-November and summer crops from early to mid-July. Wheat and triticale were sown with a row spacing of 19 cm using a 9-row Great Plains 506® no-till drill (Great Plains Manufacturing Salina, Kansas, USA). Immediately after harvesting wheat and triticale, forage soybean, maize, sorghum, cowpea, and soybean were sown with a row spacing of 76 cm. Moth, tepary, and alfalfa were planted with a row spacing of 38 cm using a 2-row John Deere 7000® planter (John Deere Moline, Iowa, USA). All crops were planted using no-tillage techniques. The details of crop management is given in **Table 2.1**.

2.2.4 Forage dry matter yield estimation

The samples were collected from a randomly selected 0.14 m^2 area of each plot at vegetative stage with second trifoliate leaf (V2) and third trifoliate leaf (V3), and reproductive stage one with the beginning of flowering (R1) and reproductive stage three with the beginning of pod (R3) stages. Plants were cut about 2-5 cm above ground level using a hand sickle and then

dried at 60°C for 72 hours. The dried samples were weighed and the obtained value of each sample from 0.14 square meter was converted to DMY in Mg ha^{-1}.

2.2.5 Forage nutritive value analysis

The dried samples were ground (< 1 mm) using Wiley mill (Wiley® Mill 4 1/2 HP Thomas Scientific, New Jersey, USA). Major forage nutritive value parameters such as crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF, in-vitro dry matter digestible (IVDMD), relative feed value (RFV) and relative forage quality (RFQ) were analyzed using near infrared reflectance spectroscopy (NIRS). The details of the NIRS method are available in Marten et al. (1985).

2.2.6 Data analysis

The analysis of variance (ANOVA) for DMY and forage nutritive value (FNV) for each crop was performed using PROC GLIMMIX in SAS 9.4 (SAS Institute Inc, 2013). In this analysis, the crop, growth stage and planting dates were treated as a fixed effect factor, while production year and replications were considered as a random effect. The pairwise comparison of least square means for DMY and FNV were performed through Tukey-Kramer method using LSMEAN function in SAS 9.4. All the figures were generated using TIDYVERSE package in R 4.3.0 (Wickham et al., 2019). We verified all the assumptions of the model by examining residuals and quantile-quantile plots.

2.2.7 Water use efficiency estimation

Water use efficiency (WUE) was calculated as the ratio of the forage dry matter yield obtained from the experiment field to the crop evapotranspiration (ET_c). The ET_c was computed using crop coefficient (K_c) methods introduced in the FAO Irrigation and Drainage Paper No 56, also known as FAO56, published in 1998 by the Food and Agriculture Organization (FAO) of

the United Nations (Allen et al., 1998). The K_c method is a widely accepted approach for estimating evapotranspiration (ET) in agricultural systems (Pereira et al., 2015). Following this method, daily ET_c was calculated as the product of the daily reference evapotranspiration (ET_o) obtained from Kansas Mesonet located approximately 150 meters from the experiment field, and the K_c value specific to the particular crop and its growth stage, as given by Allen et al. (1998). The equations for calculating actual crop ET and WUE are as follows:

$$ET_c = ET_o \times K_c \quad (1)$$

Where:

ET_c = Actual crop evapotranspiration from planting to forage biomass harvesting time

ET_o = sum of daily reference evapotranspiration from planting to forage biomass harvesting time obtained from Kansas Mesonet

K_c = Crop coefficient at particular growth stage

$$WUE = DMY/ET_c \quad (2)$$

Where:

DMY = forage dry matter yield of particular crop expressed in Kg

WUE = Water use efficiency, the ratio of the forage DMY produced by a crop to the amount of water used or transpired by that crop from planting to harvesting period, expressed in kilogram (Kg) per millimeter (mm).

2.2.8 Net farm income estimation

The net farm income was computed using observed DMY harvested at late bud stage for alfalfa and at the beginning of reproductive (R1) growth stage for other summer legumes, with a deduction of 20% for assumed harvesting and storage loss (Idowu et al., 2013; Orloff & Mueller, 2008; Undersander, 2001). The seed and chemical input costs were determined according to K-

State Research and Extension recommendations for particular crop (Ciampitti et al., 2016b; K-State Research and Extension, 1998) and the current market value. Variable costs such as seed cost, planting cost, harvesting and baling cost were based on the Kansas Custom Rates 2022 (Kansas Department of Agriculture, 2022), while land rent rates were determined using the Kansas 2022 Farm Real Estate Value and Cash Rent (USDA-NASS, 2022c). The analysis included the entire haying operation, including cutting, conditioning, raking, baling, hauling, and stacking. The hay price was determined based on the average price of hay reported by Kansas Direct Hay Report during the study period (USDA-AMS, 2023b). Additionally, a 5% overhead cost and a 4.5% interest rate were incorporated into the overall expenses. The price of hay used in this analysis was based on the average farm gate price of good quality hay as defined by the USDA-Agricultural Marketing Service (USDA-AMS, 2023a). This analysis is based on one hectare of land for the study period which may vary based on farm size, location, and timeframe. The Kansas sales tax rate of 6.5% was added to the total sales income to get net farm income. The net farm income was calculated by deducting total revenue from the total cost. The total revenues were the income generated from the sales of good quality hay and the total costs were the sum of variable costs, fixed costs, depreciation costs, loan interest, overhead costs, and sales tax.

2.3 Results

2.3.1 Forage dry matter yield

Dry matter yield varied across different crops and growth stages. Planting times affected forage yield. Forage soybean had the highest DMY of 13.9 Mg ha^{-1} when planted at optimal planting time and harvested at R3 growth stage. Soybean and alfalfa followed closely with a DMY of 13.2 Mg ha^{-1} and 13.1 Mg ha^{-1}, respectively (**Figure 2.4**). Cowpea had a DMY of 8.4

Mg ha^{-1} whereas moth and tepary bean had the lowest yield performance among the crops, with a DMY of less than 5 Mg ha^{-1}.

Similarly, the forage soybean had the highest yield of 13.3 Mg ha^{-1} when planted at the optimal time and harvested at the R1 stage which is the optimum forage harvesting stage. However, late planted forage soybean resulted in a lower yield of 10.2 Mg ha^{-1}. Similarly, soybean yielded 7.3 Mg ha^{-1} with optimum planting and 4.7 Mg ha^{-1} with late planting (**Figure 2.5**). Unfortunately, cowpea, moth and tepary bean were planted only at late planting dates and had the DMY values of 8.4 Mg ha^{-1}, 4.9 Mg ha^{-1}, and 3.6 Mg ha^{-1}, respectively.

2.3.2 Forage nutritive value

2.3.2.1 Crude protein

Crude protein content exhibited variations based on the crops, growth stages and planting times. In general, early growth stages and late planting times resulted in higher CP values compared to later growth stages and optimum planting times. Soybeans planted late had the highest CP values, with 28.3% at the R1 stage and 27.7% at the V3 stage. For forage soybeans, there were no significant differences in CP content for optimum and late planting time but varied with growth stage. The average CP was observed 22.1% at V2 and 18.6% at R3 stage. In the case of cowpea, moth and tepary bean harvested at the R1 growth stage, the average CP contents were 18.3%, 15.8%, and 15.9% respectively (**Figure 2.6**). For alfalfa, the CP content was 24.5% at the late bud stage (**Figure 2.7**).

2.3.2.2 Acid detergent fiber

The ADF content response to crop, growth stage and planting dates were found to be different. ADF increased as the growth stage progressed and decreased with delayed planting than recommended planting time. Forage soybean had the highest ADF content at 37.7% when

planted at the optimum planting time and harvested at the R1 stage (**Figure 2.8**). Soybean had the second highest ADF content at 34.3%. Cowpea, moth and tepary bean had ADF contents of 28.5%, 27.5%, and 27.5% respectively when harvested at the R1 stage. The lately planted crops had a lower ADF content (<35%) compared to the crops planted at optimal time (**Figure 2.9**). Among the legumes, alfalfa had the lowest ADF content of 24.8% at late bud stage.

2.3.2.3 Neutral detergent fiber

The NDF content also varied with crop, growth stage and planting dates. Like ADF, the NDF content increased with the stage of maturity and decreased with delayed planting. Notably, forage soybean had the highest NDF content, reaching 43.3% when planted at the optimal time and harvested at the R1 stage. Soybean ranked second with 38.6%. Cowpea, moth and tepary bean had NDF contents of 30.2%, 31.1%, and 31.5%, respectively, upon reaching the R1 stage (**Figure 2.10**). Like ADF, NDF content in late planted crops was lower value (<38%) than the optimum planted crops (**Figure 2.11**). Among the legumes, alfalfa had the lowest NDF content, at 25% during the late bud stage.

2.3.2.4 In-vitro dry matter digestibility

The IVDMD varied with crops, the growth stages and planting times. Cowpea and moth bean had the highest IVDMD, approximately 90%, when planted late and harvested at R1 stage (**Figure 2.12**). Late-planted soybean, and tepary bean had an average IVDMD value of 86% at R1 stage. Similarly, alfalfa also had a comparable IVDMD value of 86.4%. However, soybean and forage soybean planted at the optimal planting time and harvested at R1 stage showed IVDMD values of 80% and 75% respectively (**Figure 2.13**).

2.3.2.5 Relative feed value

The RFV depended on the crops, growth stages and planting times. As anticipated, the early growth stage had higher RFV value (**Figure 2.14**). Cowpea, moth, and tepary demonstrated RFV values exceeding 200 when planted late and harvested between the V2 to R1 growth stages. Forage soybean, when planted late, had an average RFV value of 185, but it dropped to 165 when planted at the ideal time (**Figure 2.15**). Likewise, late-planted soybean showed an average RFV of 241 when harvested between V3-R1 stage, which decreased to 161 when optimal planting time. Cowpea and moth had the highest RFV value of approximately 350 at V2 stage.

2.3.3 Water use efficiency

Alfalfa had a water use efficiency of 18.8 kg mm^{-1}. This means that, on average, it 18.8 kg yield mm^{-1} water consumed. Forage soybean had a higher water use efficiency of 21.3 kg mm^{-1} than alfalfa. Soybean had a slightly higher water use efficiency of 22.1 Kg mm^{-1} than forage soybean. Cowpea had the highest water use efficiency among the crops tested at 26.8 kg mm^{-1}, while moth and tepary had a relatively lower water use efficiency (<15 kg mm^{-1}) (**Figure 2.16**).

2.3.4 Net farm income

The estimated profit or loss obtained per hectare of farmland dedicated to growing each respective crop for forage purpose is given in **Table 2.2**. A positive net profit indicates that the revenue generated from the crop exceeded the associated costs, resulting in a profit. Conversely, a negative net profit implies that the costs outweigh the revenue, resulting in a loss. Forage soybean and alfalfa had the highest net profit, amounting to $322 and $877 per hectare, respectively. Cowpea also showed a positive net profit, albeit at a lower value of $4.04 per hectare. On the other hand, soybean, moth and tepary produced negative net profits if cultivated

for marketing purpose. However, the net profit may vary because this calculation was based on the average cost of production inputs and hay price of Kansas of the study period.

2.4 Discussion

This study focused on forage yield, quality, WUE and net farm income of various summer crops including alfalfa under rainfed wheat based cropping system. The findings revealed notable variability in DMY among the crops, their growth stages and planting times which is practical for the forage growers for better planning and management of their crops. Forage soybean, soybean, and alfalfa demonstrated higher DMY values, while cowpea, moth and tepary bean had the lower yield performance. The lower yield performance of later three legumes particularly cowpea may be due to late planting (08 July) and periodic drought observed during planting and vegetative growth in 2020 (NOAA-NIDIS, 2023). The cumulative forage growing season rainfall was only 287 mm (Kansas Mesonet, 2023).

The study found that forage soybean emerged as the top-performing forage crop regarding DMY when planted at the optimal time and harvested at the R3 growth stage. Soybean and alfalfa also had relatively higher DMY values compared to cowpea, moth and tepary bean. Cowpea showed a moderate yield, while moth and tepary bean had the lowest yields, indicating limitations in forage production for these crops.

Besides higher biomass yield, we also observed another important characteristic of forage soybean which is its extended period of vegetative growth compared to other legumes. For example, when the grain soybean was at R3 stage, the forage soybean planted at the same time was still at vegetative (V3-V5) stage. The longer vegetative growth period allows forage soybean to accumulate more biomass, resulting in increased forage production. This can be advantageous for livestock owners who rely on high-quality forage for animal feed. The prolonged vegetative

stage of forage soybean provided a longer window for grazing or harvesting. Farmers can take advantage of this extended period to optimize the timing of grazing or harvesting, ensuring a sufficient supply of forage for their animals or efficient hay production. As forage soybean remains in the vegetative stage for a longer duration, it has more time to accumulate nutrients and maintain higher nutritional quality. This can result in improved feed value, providing animals with a more balanced and nutrient-rich diet.

Like other crops, optimal planting resulted in higher forage yields than late planting (1.5 to 2 months later). Late planting had fewer growing degree days for plant growth and the risk of crop failure is high (Drewnoski & Redfearn, 2015). We observed 23% yield loss in forage soybean and 36% in soybean when planted after June. These findings underscore the importance of appropriate planting times and optimal growth stages for achieving higher forage yields. Forage soybean and soybean, although less commonly grown for forage purposes in Kansas, demonstrated the highest potential for DMY when planted and harvested at the optimal times. Delayed planting negatively impacted yield, suggesting the need for timely planting practices.

Similarly, this study also found the variations in forage nutritive value based on the crop, growth stage, and planting time. Generally, the forage quality diminishes as it matures (Ball et al., 2001). Our results showed that early growth stages and late planting times resulted in higher CP contents. Late planted soybeans had the highest CP content, while forage soybeans showed no significant difference between planting times but varied with growth stage. Cowpea, moth, and tepary bean had relatively lower CP contents. ADF content increased with the growth stage and decreased with late planting dates. Forage soybean had the highest ADF content, while alfalfa exhibited the lowest. NDF content increased with maturity and decreased with late planting times. Forage soybean had the highest NDF content, while alfalfa had the lowest.

IVDMD varied according to crop, growth stage, and planting time. Cowpea and moth bean had the highest IVDMD, followed by late-planted soybean, tepary bean, and alfalfa. Soybean and forage soybean planted at the optimal time had lower IVDMD values. The RFV value differed based on crop, growth stage, and planting time. Early growth stages generally had higher RFV values. Cowpea, moth, and tepary had RFV values exceeding 200 when planted late, while forage soybean had lower RFV values when planted late.

The quality of hay and its market value is determined by factors such as CP, ADF, NDF and RFV value. According to hay quality guidelines provided by the United States Department of Agriculture, Agricultural Marketing Service, alfalfa hay is considered good quality with CP content above 18%, ADF below 32%, NDF below 40%, and RFV between 150-170. Conversely, poor quality hay is characterized by CP below 16%, NDF above 35%, ADF above 44%, and RFV below 130 (USDA-AMS, 2023a). The normal market price of good quality hay in Kansas is above $200 per ton (USDA-AMS, 2023b). Moreover, animals of different types and classes have specific forage quality preferences. For example, the forage with RFV above 140 is highly recommended for dairy cows in their first trimester of pregnancy and dairy calves whereas, the recommended RFV for heifers aged 12-18 months and lactating beef cows is between 115 to 130 (Ball et al., 2008). The nutritive value analysis results showed that all selected crops met the criteria for good quality hay when harvested between the V2 to R3 growth stages and the requirements for all types and class of animals, regardless of planting time differences. Based on the findings of forage yield, quality and forage quality guidelines, this study suggests that farmers can grow forage soybean and soybean for forage purpose, immediately after wheat is harvested in Kansas to get higher market value and meet the nutritional requirements of livestock while providing good quality forage.

Among the listed crops, cowpea demonstrated the highest water use efficiency, suggesting its efficient use of water resources for yield production. In contrast, moth and tepary had relatively lower water use efficiencies, indicating their lower yield production relative to water consumption. While alfalfa is commonly recognized as a water-efficient crop due to its deep tap root system (Angus et al., 2001; McCallum et al., 2001; Ward et al., 2002), the cowpea, forage soybean, and soybean exhibited even higher WUE (**Figure 2.16**). This result suggests that these crops can be grown successfully in the rainfed area where alfalfa is commonly grown.

By analyzing cost and benefit of each individual crop, it is evident that forage soybean, alfalfa and cowpea are the economically viable forage crops, indicating their potential as profitable forage crops in wheat based rainfed cropping system for Kansas and the surrounding regions. On the other hand, soybean, moth, and tepary may not be feasible in terms of generating revenue when grown for marketing purposes. Farmers need to consider these factors when making decisions regarding crop selection and maximizing profitability on their farmland.

While alfalfa can grow massively in the Southern Great Plains, it may not always be the first choice for farmers because alfalfa is a cool season perennial crop while winter wheat is the main cash crop in this region. Furthermore, alfalfa demands comparatively higher amount of water than other field crops (Orloff et al., 2015; Schneekloth & Andales, 2017; Shewmaker et al., 2011; Ward et al., 2002), often goes dormant during hot summer particularly in July and august, casing forage shortage in these two months.

Moreover, the moderate to severe drought conditions observed in many parts of Kansas during alfalfa growing season (NOAA-NIDIS, 2023) can have a significant impact on alfalfa yield, quality, and persistence (Boyer, 1982; Hamidi & Safarnejad, 2010; Liu et al., 2018; Takele & Kallenbach, 2001). In addition, the repeated cycles of freezing and thawing that commonly

occur in Kansas have potentially detrimental effects on the survival of the plant, potentially causing its death. (Adhikari et al., 2021; Bao et al., 2020). At the same time, pest and disease pressure such as alfalfa weevils, root rot, and leaf spot are commonly seen in the state (K-State Research and Extension, 1998; Whitworth et al., 2011). Managing these issues can require additional input and management practices that may not be cost-effective for commercial farmers.

Therefore, based on the findings of this study, it can be inferred that forage soybean has the potential to be a favorable choice for summer forage crop. This is due to its competitive advantage such as prolonged vegetative growth, high DMY, ability to meet animal nutritional requirements, efficient water use, profitability, available at shortage period as well as positive impact on soil health through its symbiotic nitrogen fixation property. The findings of the study provide valuable insights for farmers and researchers in selecting suitable crops, determining optimal planting times, and maximizing forage yield and quality in rainfed wheat-based cropping system in Kansas. Additional studies focusing on feeding trials could be conducted to evaluate the palatability, digestibility, and animal performance (growth, milk production, etc.) when using forage soybean as a primary source of animal diets. These trials would provide more insights into the practical validation of forage soybean in meeting the nutritional requirements of different livestock species.

2.5 Conclusion

This study focused on exploring alternative forage crops for rainfed wheat-based cropping systems in Kansas. Forage soybean, soybean, and alfalfa emerged as the top-performing crops in terms of yield, while cowpea, moth, and tepary had lower yield performance. Planting time played a significant role in maximizing yield. Additionally,

variations in forage nutritive value were observed based on crop, growth stage, and planting time. Soybean, alfalfa and forage soybean had higher crude protein content. The relative feed value of all selected crops met the recommended nutritional requirements of the livestock animals. Among the listed crops, cowpea exhibited the highest water use efficiency, indicating efficient use of water resources. In contrast, moth and tepary had relatively lower water use efficiencies. The economic analysis revealed that forage soybean, alfalfa, and cowpea are economically viable options, while soybean, moth, and tepary may present challenges in terms of generating revenue. Considering the favorable characteristics of forage soybean, forage soybean has the potential to be a suitable summer forage crop in wheat based rainfed cropping system in Kansas and its surroundings, offering advantages in terms of forage dry matter yield, forage nutritive value, water use efficiency, profitability, availability at forage shortage period and soil health perspective.

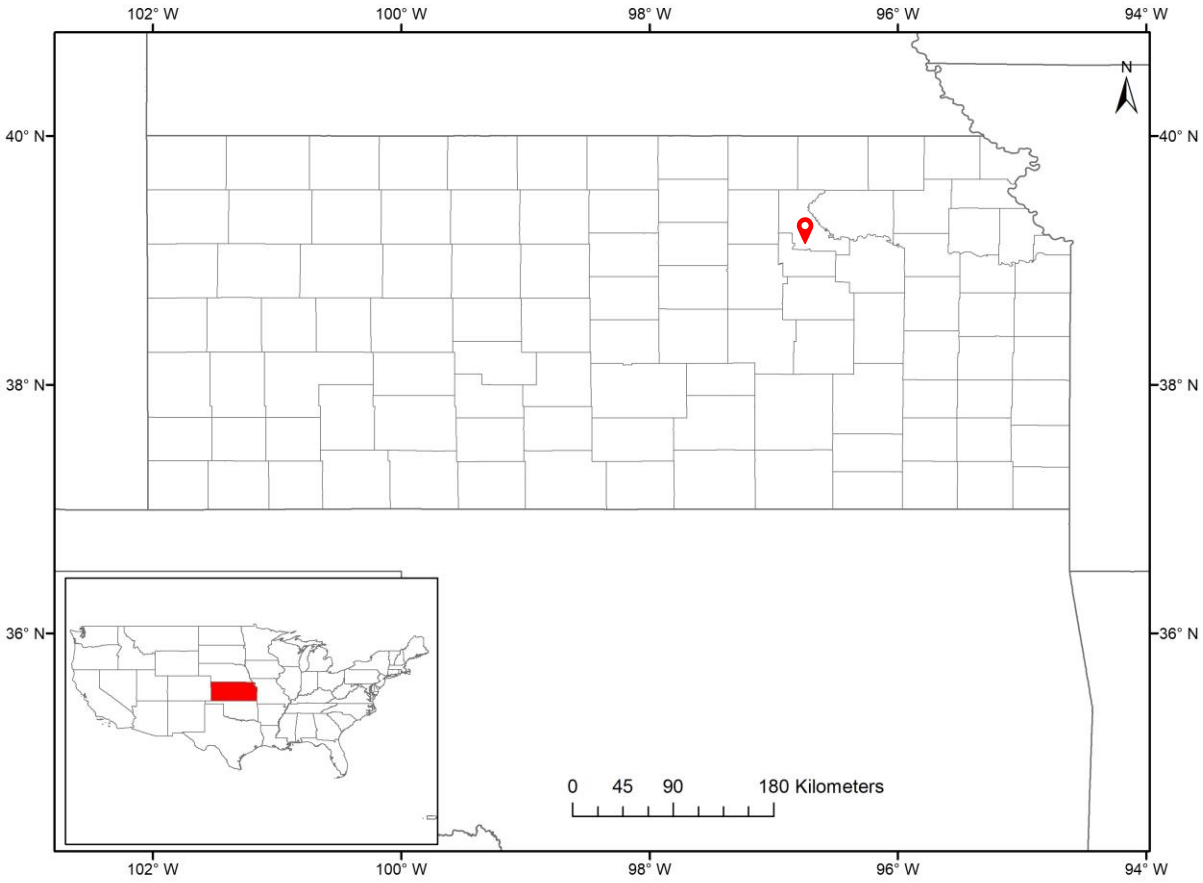


Figure 2.1. Map of Kansas State showing study location.

The red location icon represents study location (Ashland Bottoms, Manhattan Kansas USA). The red color within the continental U.S. in the inset shows Kansas State.

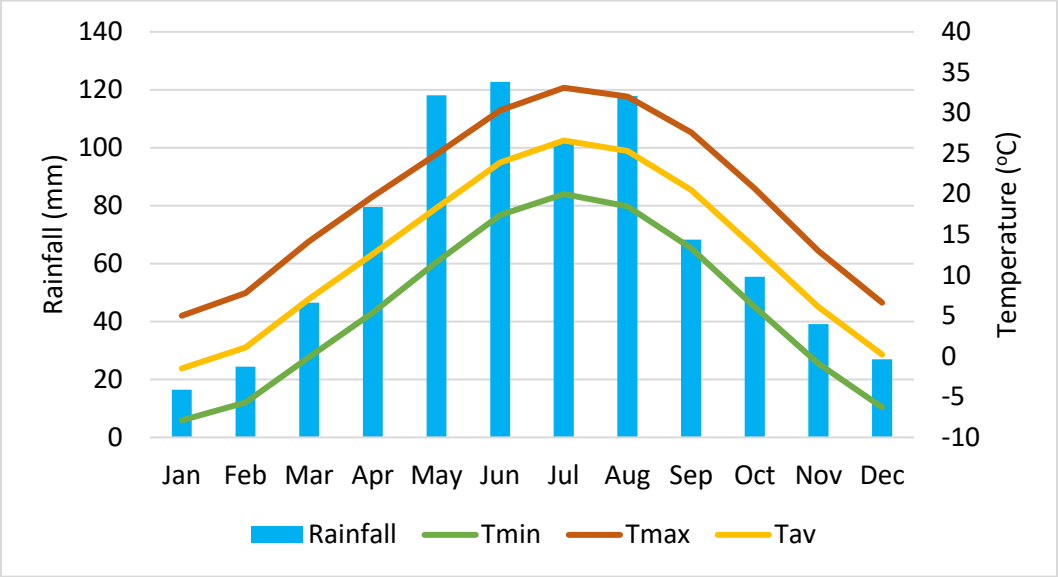


Figure 2.2. The monthly climate Normals (1991-2020) of study location.

The figure represents average monthly rainfall, minimum temperature (Tmin), maximum temperature (Tmax) and average temperature (Tav) Normals (1991-2020) of Ashland Bottoms Manhattan Kansas (ACIS, 2023).

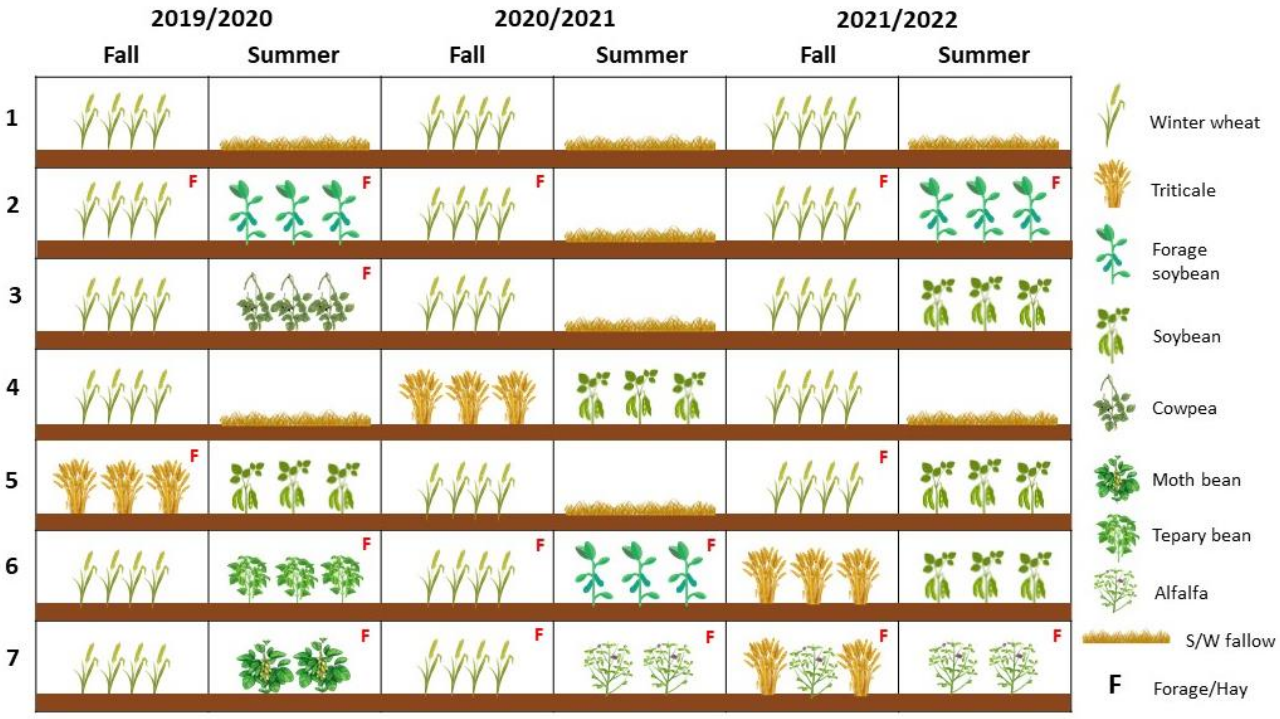


Figure 2.3. Cropping systems designed for the field experiment.

Cropping sequence included 1: Baseline; 2: Adaptive forage; 3: Adaptive grain; 4 and 5: Dual-purpose semi-intensive; 6; and 7: Dual purpose intensive. s/w fallow=summer or winter fallow

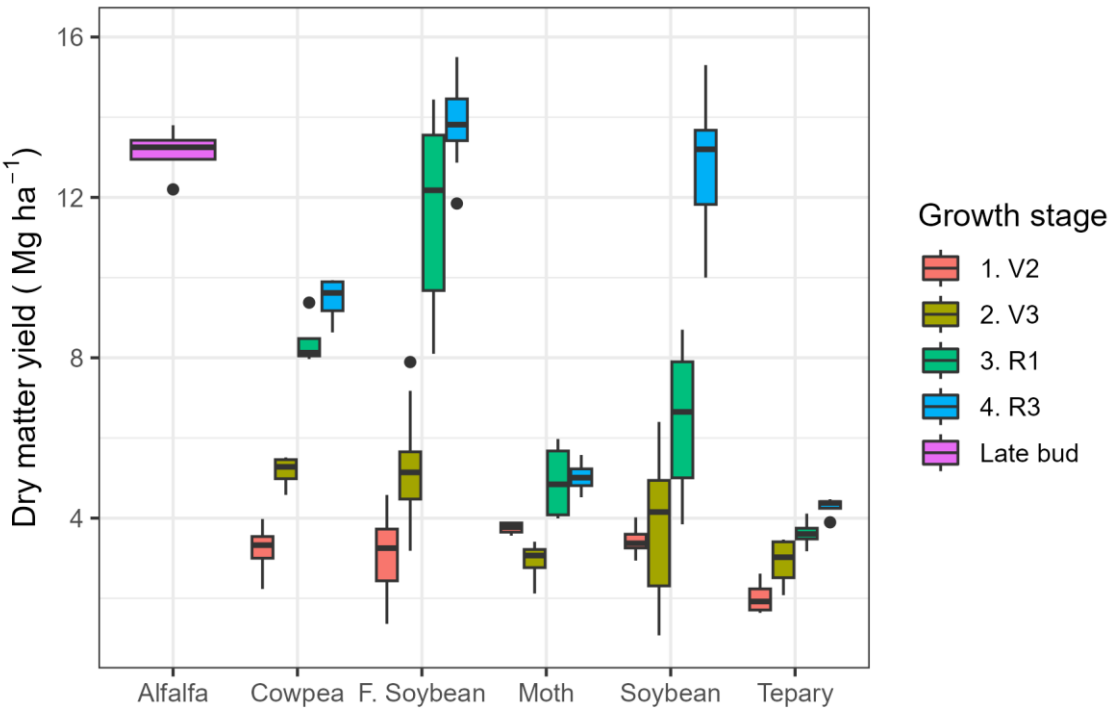


Figure 2.4. Forage dry matter yield of summer legumes by growth stage.

The crops were planted at optimum planting time and harvested at different growth stages. In the legends, V2 represents vegetative stage two which had second trifoliate leaf, V3: Vegetative stage three with third trifoliate leaf, R1: Reproductive stage one with the beginning of flower and R3: Reproductive stage three with the beginning of pod.

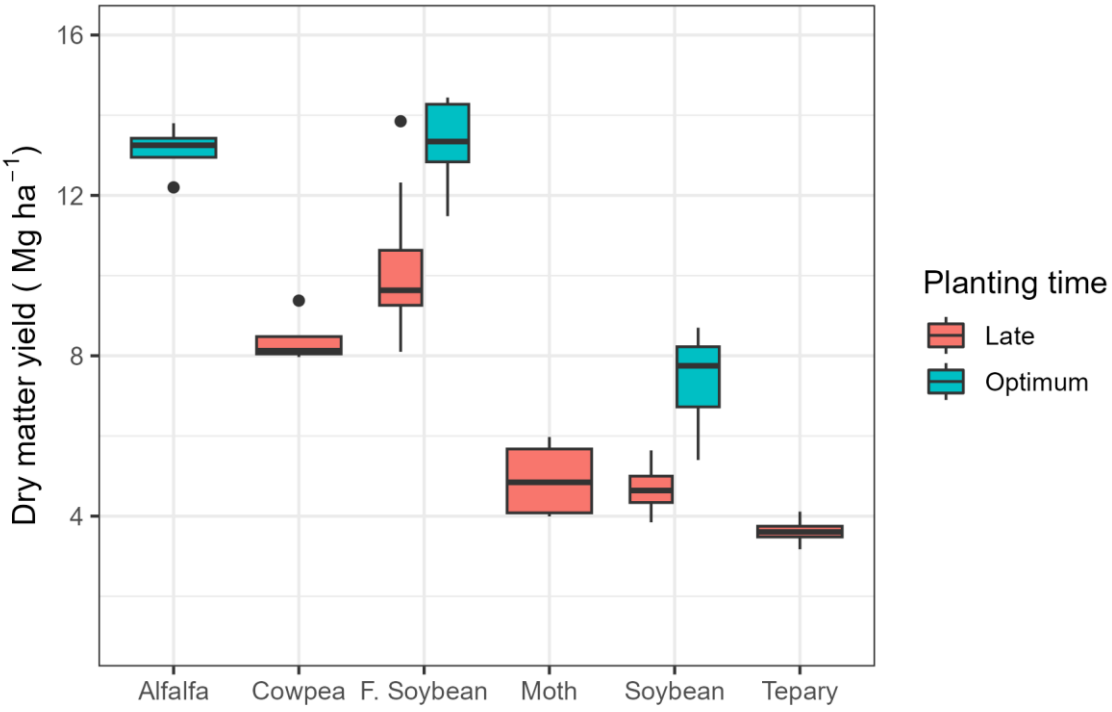


Figure 2.5. Forage dry matter yield of summer legumes by planting time.

The crops were planted at optimum and late planting time and harvested at late bud stage for alfalfa and R1 stage for other legumes. The optimum planting represents recommended planting date ranged from May 14-22 and late planting ranged from July 06-12, depending on production year.

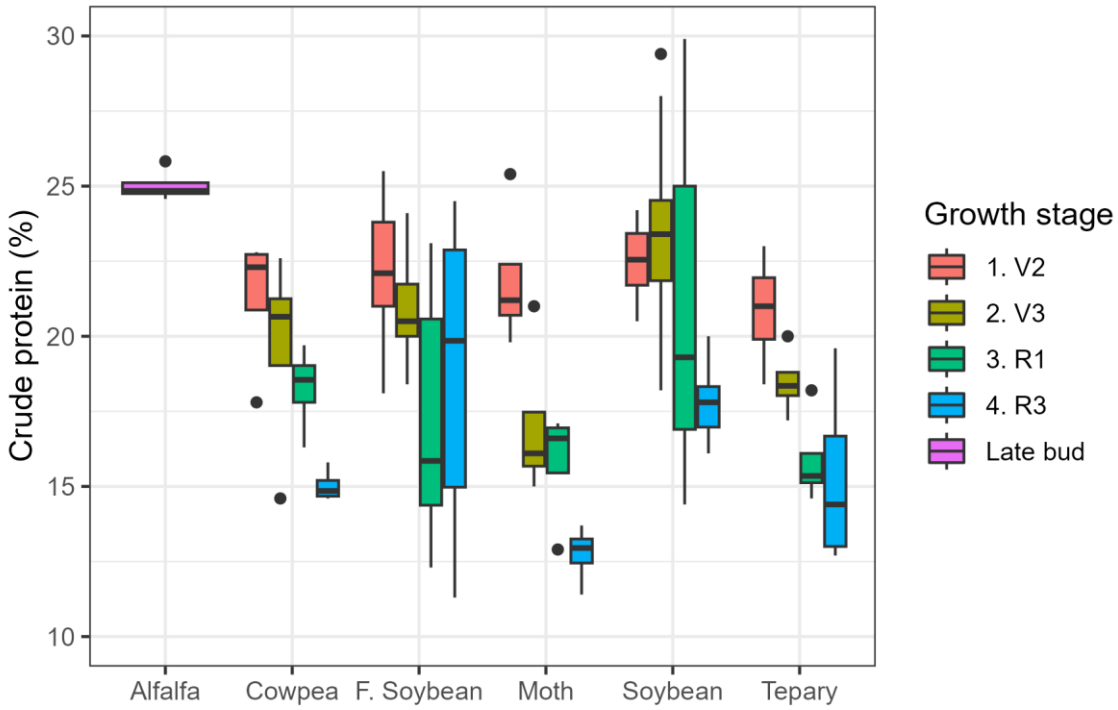


Figure 2.6. Crude protein content of summer legumes by growth stage.

The crops were planted at optimum planting time and harvested at different growth stages.

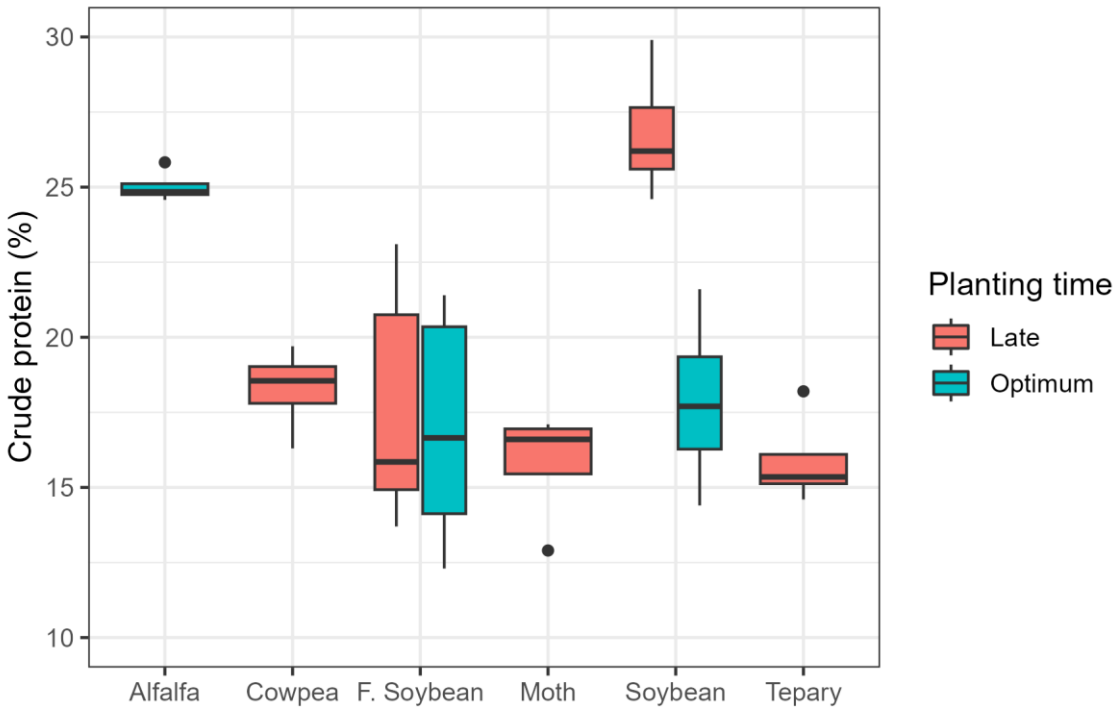


Figure 2.7. Crude protein content of summer legumes by planting time.

The crops were planted at optimum and late planting time and harvested at late bud stage for alfalfa and R1 stage for other legumes.

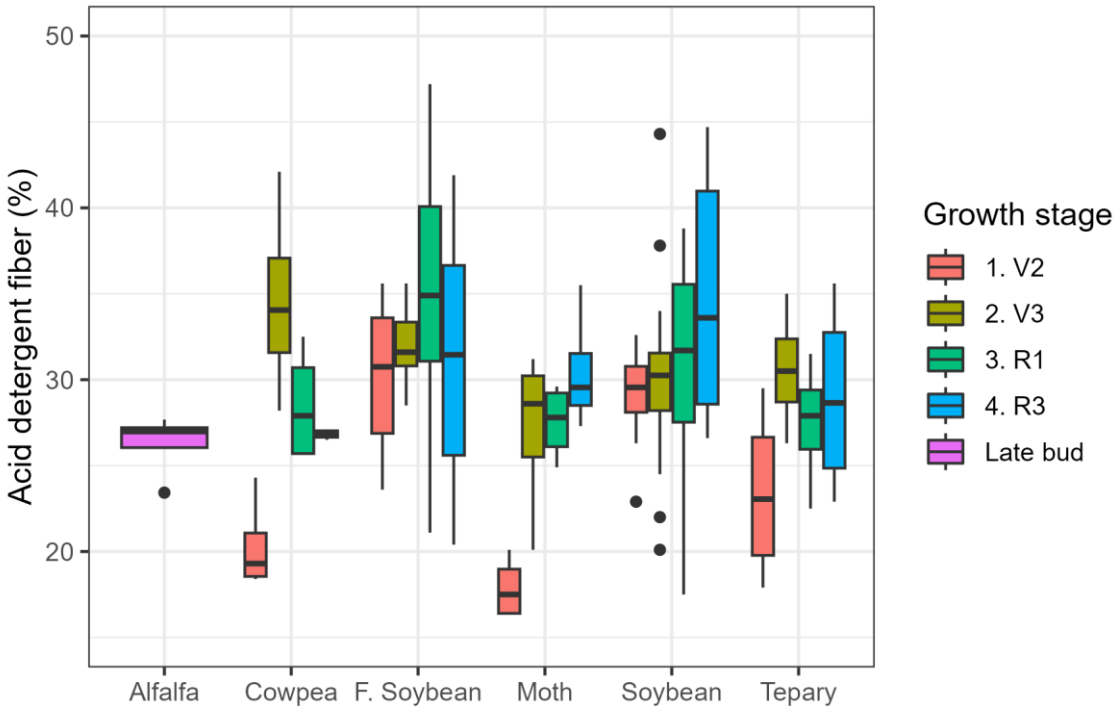


Figure 2.8. Acid detergent fiber of summer legumes by growth stage.

The crops were planted at optimum planting time and harvested at different growth stages.

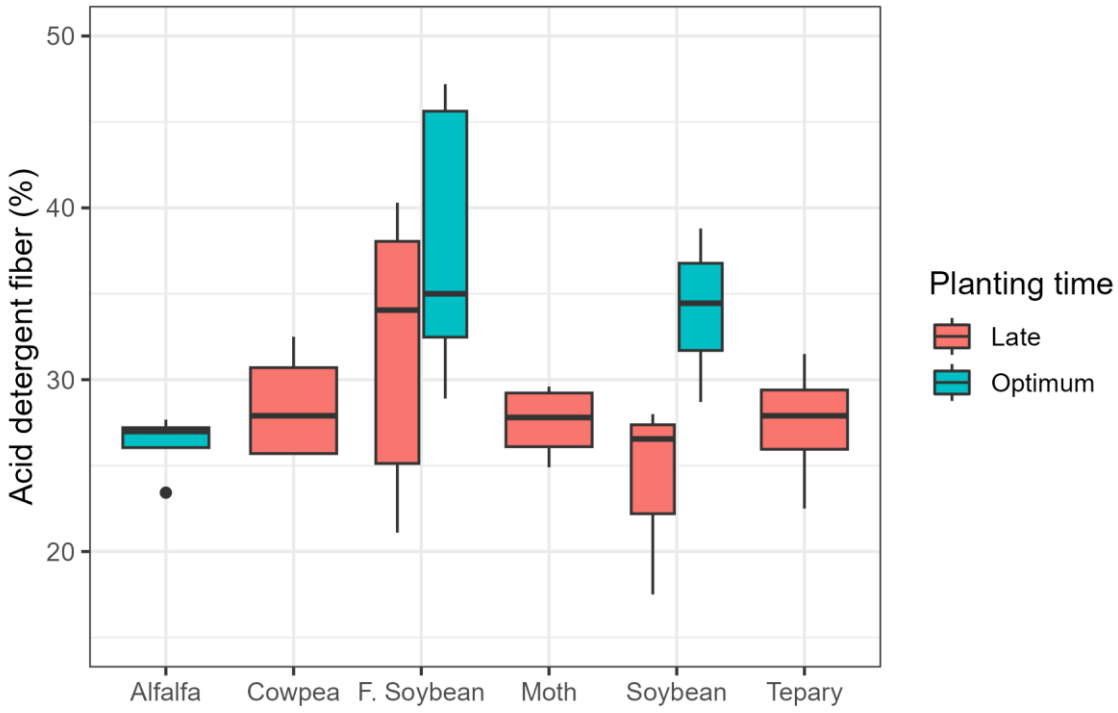


Figure 2.9. Acid detergent fiber of summer legumes by planting time.

The crops were planted at optimum and late planting time, and harvested at late bud stage for alfalfa and R1 stage for other legumes.

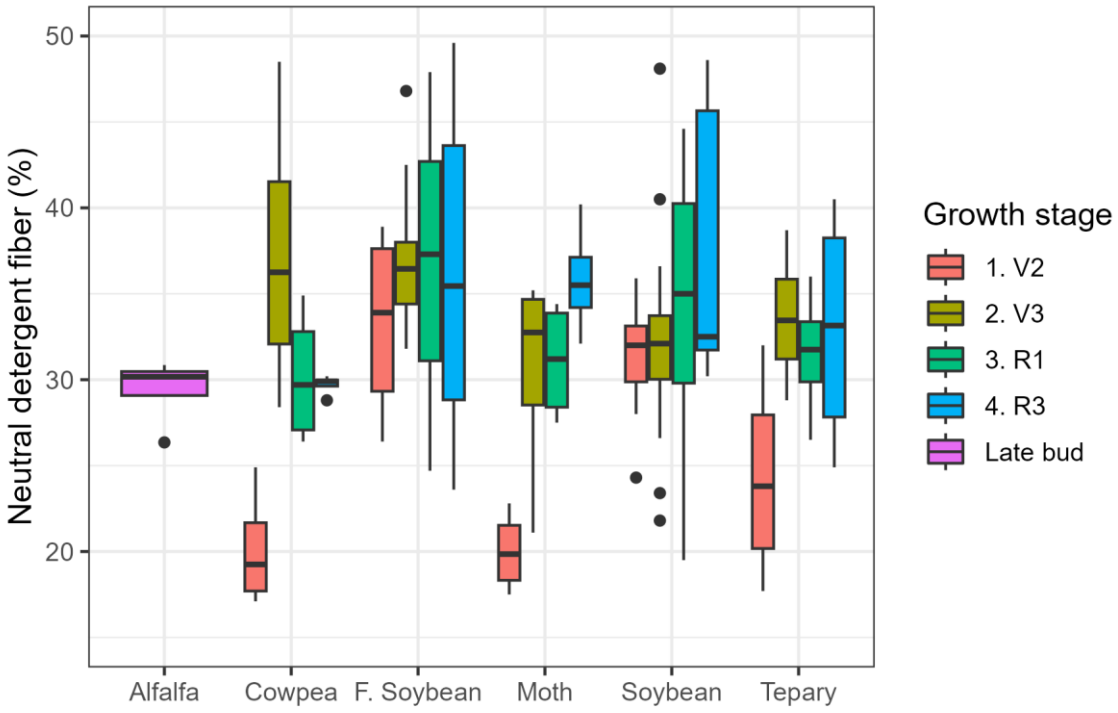


Figure 2.10. Neutral detergent fiber of summer legumes by growth stage.

The crops were planted at optimum planting time and harvested at different growth stages.

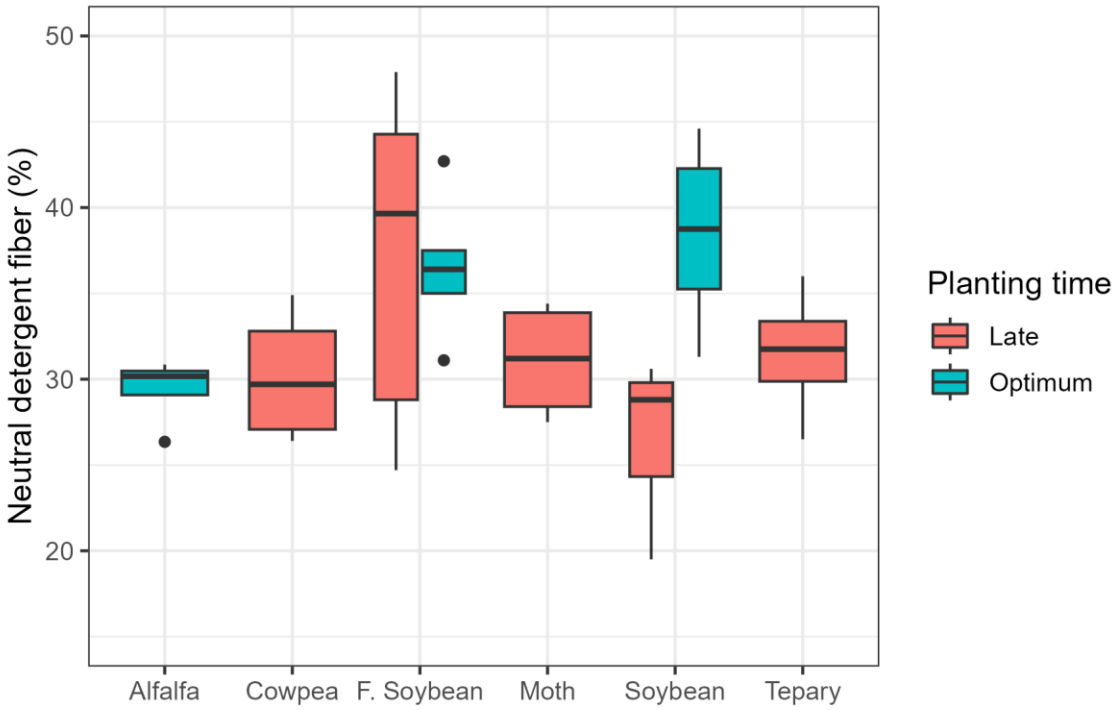


Figure 2.11. Neutral detergent fiber of summer legumes by planting time.

The crops were planted at optimum and late planting time and harvested at late bud stage for alfalfa and R1 stage for other legumes.

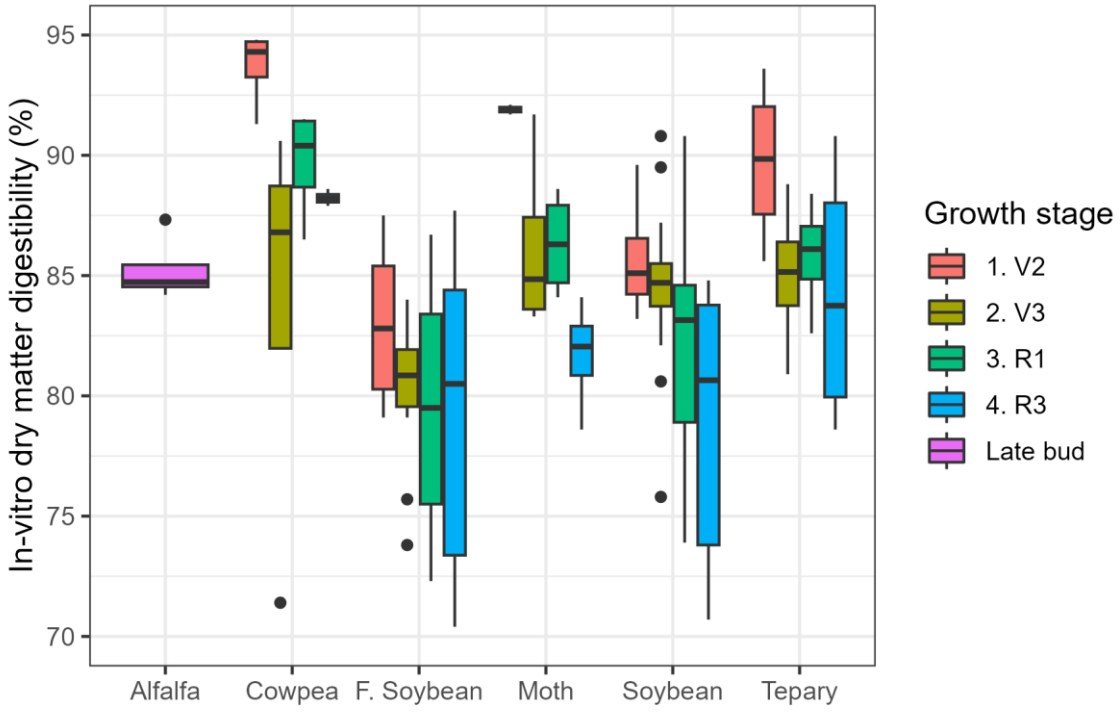


Figure 2.12. In-vitro dry matter digestibility of summer legumes by growth stage.
The crops were planted at optimum planting time and harvested at different growth stages.

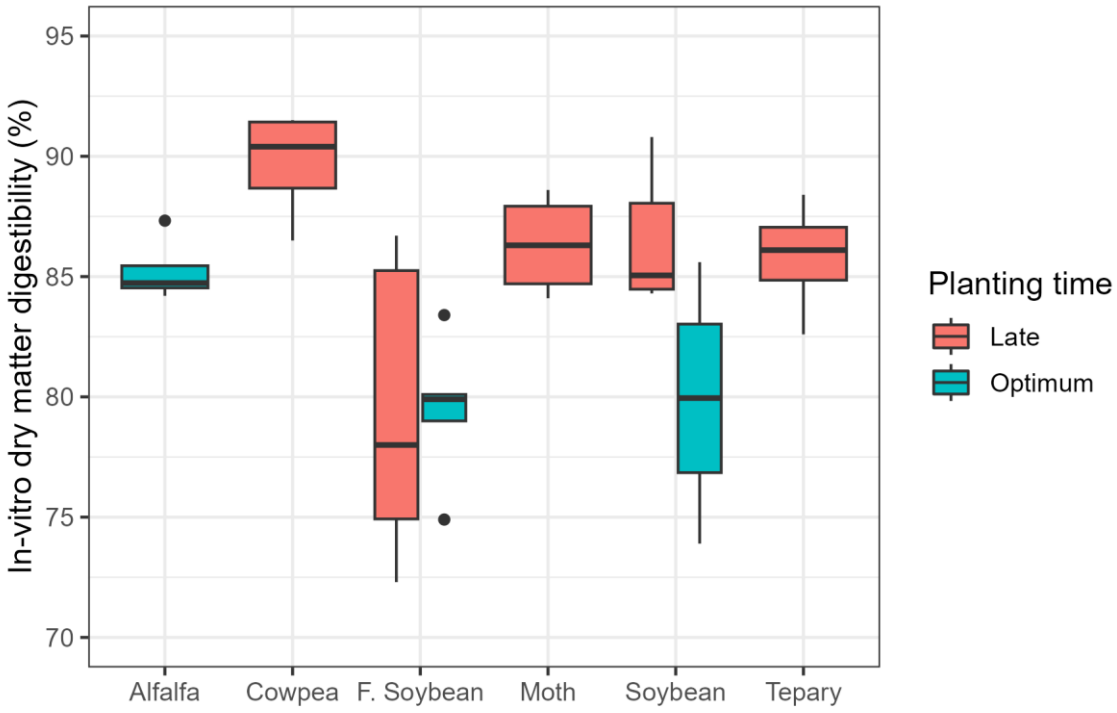


Figure 2.13. In-vitro dry matter digestibility of summer legumes by planting time.

The crops were planted at optimum and late planting time and harvested at late bud stage for alfalfa and R1 stage for other legumes.

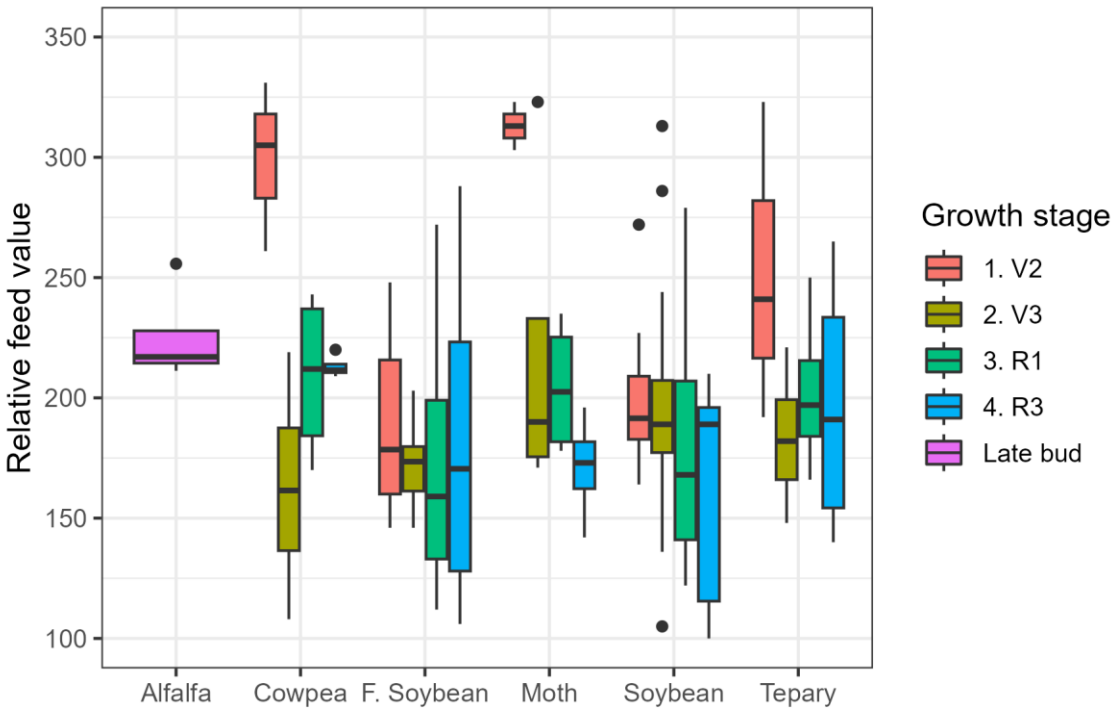


Figure 2.14. Relative feed value of summer legumes by growth stage.

The crops were planted at optimum planting time and harvested at different growth stages.

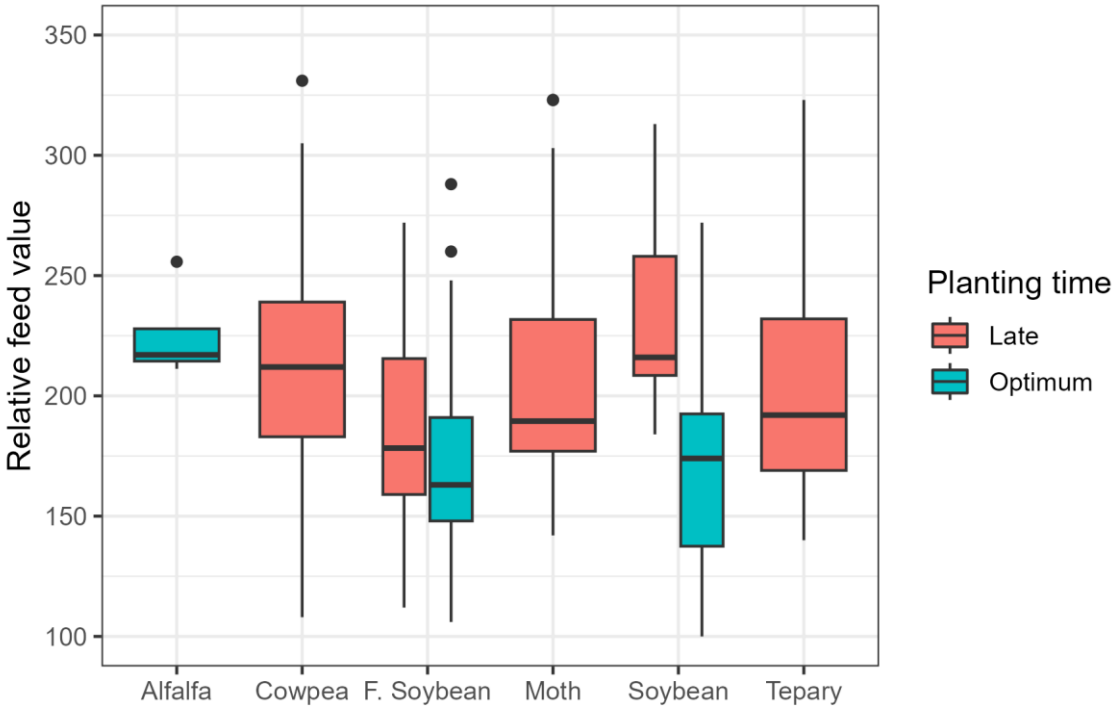


Figure 2.15. Relative feed value of summer legumes by planting time.

The crops were planted at optimum and late planting time and harvested at late bud stage for alfalfa and R1 stage for other legumes.

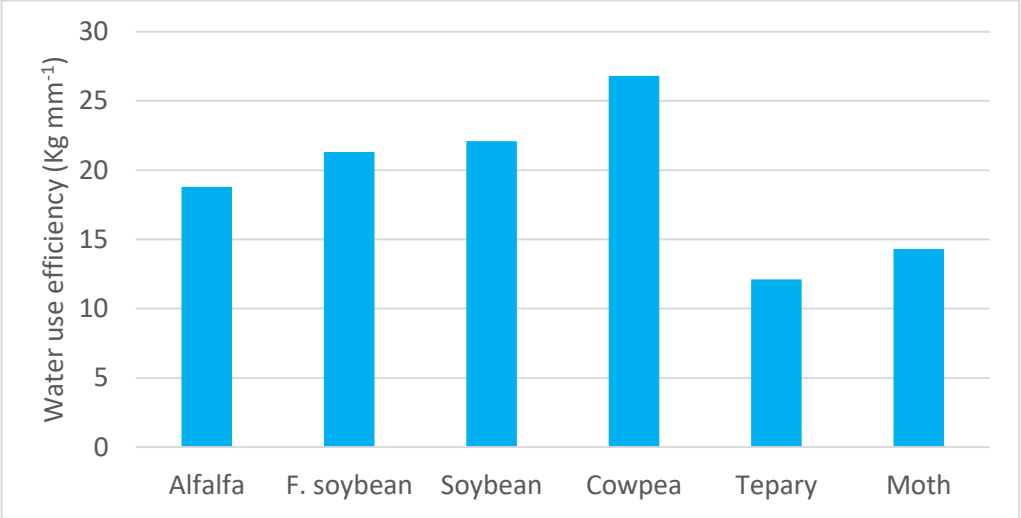


Figure 2.16. Water use efficiently of summer legumes.

Alfalfa was harvested at late bud stage whereas soybean, forage soybean, cowpea, moth and tepary bean were harvested at R1 stage for forage purpose.

Table 2.1. Crop management description.

Crop	Variety	Seed rate			Planting date			Row spacing	Plant sampling
		Early	Optimum	Late	Early	Optimum	Late		
Wheat	Zenda™	22 kg ha^{-1}	18 kg ha^{-1}		Sept 24-Oct 05	Oct 15-24		19 cm	Jointing and late boot
Triticale	Shortbeard Thunder™	22 kg ha^{-1}	18 kg ha^{-1}		Sept 24-Oct 05	Oct 15-24		19 cm	Jointing and late boot
Soybean	P40T19™	-	56656 seeds ha^{-1}	64750 seeds ha^{-1}		May 17-22	July 06-12	76 cm	V2, V3, R1, R3
Forage soybean	Large Lad RR™		56656 seeds ha^{-1}	64750 seeds ha^{-1}		May 17-22		76 cm	V2, V3, R1, R3
Cowpea	Red ripper						July 08	76 cm	V2, V3, R1, R3
Tepary								38 cm	V2, V3, R1, R3
Moth							July 08	38 cm	V2, V3, R1, R3
Alfalfa	Roundup Ready		22 kg ha^{-1}				July 06	38 cm	Late bud

Table 2.2. Net farm income of summer legumes including alfalfa in Kansas.

Financial parameters	Soybean	Forage soybean	Cowpea	Tepary	Moth	Alfalfa
Variable cost	169.99	248.11	206.74	148.92	165.93	493.46
Fixed cost	91.62	91.62	91.62	91.62	91.62	91.62
Total production cost	261.61	339.73	298.36	240.54	257.55	585.08
Revenue	260.00	470.00	300.00	130.00	180.00	940.00
Net profit ($/acre)	-1.61	130.27	1.64	-110.54	-77.55	354.92
Net profit ($/hectare)	-3.97	321.90	4.04	-273.15	-191.62	877.04

Chapter 3 - Assessing forage yield, nutritive value and net farm income of alfalfa under different water regimes

Abstract

This study investigated the effects of different water regimes, maturity stages, and subsequent cuttings on forage dry matter yield (DMY) and nutritive value in alfalfa production. Two conventional and three lower-lignin alfalfa varieties were planted in a randomized complete block with split plot design under drought, rainfed, and irrigation conditions in 2020 in Manhattan Kansas USA. The DMY and forage nutritive value were evaluated at late bud, early flowering and 7 days after early flowering stage. The results showed that DMY was significantly influenced by soil water availability, production year and maturity stages. Comparing drought-stressed and irrigated conditions, significant variations in DMY were observed during different stages of maturity in both 2021 and 2022. Drought-stressed plots exhibited a decline in DMY, ranging from 5% to 38% in the second year. The DMY showed an increasing trend from the late bud to 7 days after early flowering in rainfed and irrigated conditions, however, the trend was reversed in drought-stressed conditions. This study also assessed the forage nutritive value, revealing that crude protein (CP) and in-vitro dry matter digestibility (IVDMD) were influenced by water regimes and growth stages but not by varieties. The CP, IVDMD and relative forage quality (RFQ) had a negative correlation with soil moisture and the advancement in the maturity stages. Acid detergent fiber (ADF) and neutral detergent fiber (NDF) were influenced by water regimes, with higher values observed in irrigated conditions. Delayed harvesting resulted in lower yield but higher quality under drought conditions and higher yield but lower quality under irrigation. Early harvesting led to lower yields but higher protein content and digestibility. Subsequent cuttings showed an increasing trend in CP, IVDMD, and RFQ under normal

conditions. Both conventional and lower-lignin varieties demonstrated comparable performance in terms of yield and quality, even with delayed harvesting. The findings also suggest the importance of harvesting time during drought years, with no significant impact on forage quality. Additionally, this study provides insights for producers to make informed decisions regarding variety selection, harvesting time and irrigation investments.

3.1 Introduction

Alfalfa (*Medicago sativa* L.) is a widely cultivated cool-season perennial forage belonging to Fabaceae family. It is grown worldwide as a high-value forage crop for livestock feed due to its wide adaptability, long growing season, multiple harvesting, substantial yield, superior forage quality and significant economic value (Baral et al., 2022; USDA-NASS, 2023). It is rich in nutrients, including proteins, vitamins A, C, E, and various B vitamins, minerals, and dietary fiber (Hadidi et al., 2023; Plaza et al., 2003). It is particularly beneficial for livestock health, promoting growth and milk production in dairy cows. More importantly, alfalfa is used as a cover crop or a rotation crop due to its ability to improve soil fertility, prevent erosion, suppress weeds, reduce pests, and benefit subsequent crops (Entz et al., 2002; Franke et al., 2018). The ability of alfalfa to fix atmospheric nitrogen through a symbiotic relationship with nitrogen-fixing bacteria makes it an excellent natural fertilizer and enriches the soil with nitrogen for subsequent crops, with estimates ranging from approximately 135 to 605 kg N ha^{-1}. (Heichel et al., 1981; Putnam et al., 2001).

One of the notable characteristics of alfalfa is its strong taproot system, which can reach to a depth of 3 to 6 m under favourable conditions (Undersander et al., 2021; Weaver, 1926), enabling the crop access water and nutrients from deeper soil layers and making it resilient to drought. Under limited water conditions, alfalfa also has a high potential water productivity, with

a potential of up to 34 kg of dry matter ha^{-1} mm^{-1} water available (Fink et al., 2022). The deep root system also helps to improve soil structure and infiltration rates by breaking up compacted soil (Lacefield et al., 2009).

Through the application of phenotypic selection and various other breeding methods, breeders have successfully developed many transgenic alfalfa varieties that exhibit both winter hardiness and drought tolerance (Adhikari et al., 2022). These improved varieties are now commercially available to farmers. In terms of market value, alfalfa hay has a higher price compared to other types of hay. In the United States, the price of alfalfa hay typically ranges from $100 to $300 per bail (equivalent to one U.S. ton), depending on the quality and time of purchase (USDA-AMS, 2023b). Premium quality alfalfa hay is priced at the higher end, while lower quality or less desirable bales may be priced lower. The demand for alfalfa hay increases during periods of limited fresh forage availability, such as winter or hot and dry summers, potentially leading to higher prices.

The United States (U.S.) is one of the leading producers of alfalfa globally, with a total production area ranging from 7 to 9 million hectares annually and average yield of 6 to 7 Mg ha^{-1} (USDA-NASS, 2023). Despite its multiple benefits, there has been limited progress in yield and production in the U.S. for decades. However, previous studies have shown that yields of 13 to 19 Mg ha^{-1} or more are achievable with proper management practices and favourable growing conditions (Baral et al., 2022; McDonald et al., 2021a).

Soil moisture is a critical factor influencing alfalfa yield and quality, as it directly affects stand growth, nutrient uptake, and overall physiological processes. A recent review of 193 papers on drought stress in alfalfa and determined that the intensity and duration of drought stress exposed to non-transgenic alfalfa exhibits various morphological, physiological, and biochemical

responses (Diatta et al., 2021). They stated that drought stress reduces membrane permeability, stomatal conductance, net photosynthetic rate, and the release of plant growth regulators such as cytokinin, auxin, and gibberellin. These effects result in decreased nutrient and water uptake, diminished root and shoot growth, compromised biological nitrogen fixation, and ultimately reduced biomass yield in alfalfa. The closure of stomata due to drought stress leads to negative implications for gas exchange, which impairs transpiration, photosynthesis, growth, reproduction, enzymatic activities, and the metabolism of nitrogen and carbon, among other metabolic processes (Cerezini et al., 2020; Christophe et al., 2011; Sinclair et al., 2007). Previous studies have found that soil moisture stress can lead to poor seedling emergence, reduced shoot growth, fewer stems, thereby affecting overall yield potential in alfalfa (Orloff et al., 2015; Undersander & Cosgrove, 2011).

Besides yield, insufficient soil moisture can limit nutrient availability, impairing nutrient uptake and utilization by crop, decreasing protein content, increasing cell wall thickness and lignification and therefore directly influencing the quality attributes of alfalfa forage (Liu et al., 2018; Peterson et al., 1992; Staniak & Harasim, 2018). In turn, the quality of forage directly impacts animal performance, forage value and eventually on net farm income. The body weight gain, milk production and reproductive efficiency of animals depend on feeding time, feeding quantity and feed quality. Thus, it is equally important to understand the dynamics of forage nutritive value parameters under different production environments and management practices.

Stage of maturity is another important factor affecting yield and forage quality in alfalfa (Ball et al., 2001; Fick & Mueller, 1989; Jungers et al., 2020; Min, 2016; Orloff & Putnam, 2010; Sayar et al., 2022; Yari et al., 2012). Generally, as the forage stand matures, its nutritive value changes in terms of chemical composition and digestibility. Early vegetative stages

typically have low biomass yield but high crude protein content, high digestibility, and lower acid and neutral detergent fiber content (Putnam, 2021). In contrast, late flowering stages have significantly higher biomass yield and fiber content, and lower protein content and dry matter digestibility compared to earlier stages. The lignification of the stand increases, making it less palatable and less nutritious. Therefore, it is essential to effectively manage the cutting time and frequency in order to improve both the yield and quality of forage.

Considering the findings of previous research, it is essential to effectively manage soil moisture and harvest timing in order to optimize both yield and the nutritive value of forage. It is important to assess the nutritive value of forage among conventionally bred varieties marketed as high in nutritional content, as well as lower lignin varieties, which are known to be high yielding in various production environments. Therefore, it is crucial to investigate the effect of different soil moisture levels and harvesting time on forage yield, nutritional quality as well as overall profitability of commercially cultivated alfalfa. In this study, our primary objective was to evaluate the effect of different water management strategies and harvesting time on forage yield, nutritional quality, and profitability of commercially grown alfalfa varieties.

3.2 Materials and Methods

3.2.1 Description of study location

The study was conducted from August 2019 to November 2022 at Kansas State University North Agronomy Farm in Manhattan, Kansas, USA (96° 35” W to 39° 12” N, 314 meter above sea level) (**Figure 3.1**).

The soil type at the site was identified as Smolan silt loam with 1 to 3% slopes. Prior to the study, the experimental area was cultivated with winter canola. The soil samples were taken from 0 to 30 cm depth from multiple locations within plots at the end of spring 2020 and, fall

2021 and 2022 to examine the soil fertility status of the plots. Various soil nutrients such as nitrogen, phosphorous, potash, calcium, magnesium, soil organic matter as well as soil pH were analysed at the Kansas State University Soil Testing Lab (**Table 3.1**).

The climate of the study area is classified as humid continental (**Table 3.2**). The summer season is hot and humid with significant rainfall, and mostly clear skies. On the other hand, winters are cold with snowfall, strong winds, and partially cloudy conditions. Throughout the year, the temperature range typically spans from -7.9°C in January to 33°C in July. The monthly average rainfall ranged from 16.5 mm in January to 122.7 mm in June with the annual average of 817 mm (Kansas Mesonet, 2023).

3.2.2 Experimental design and plant establishment

The experiment involved three different water treatments: drought imposed, rainfed and irrigated and five commercial alfalfa varieties. The five commercial varieties included two conventional (AmeriStand 455TQRR and HybriForce-3400) and three lower-lignin alfalfa (HighGest AFX460, HVXMegaTron, and HVXHarvaTron). The experimental design was a split plot arrangement in a completely randomized block design with four replications. The water treatment was considered as whole plot factor, and the variety as subplot. With this design, we examined the main effects of each factor and their interaction effects as well.

A recommended seeding rate of 22.4 kg of pure live seed per hectare was seeded on April 21, 2020. Each variety was randomly assigned for 0.6 m x 9 m size sub-plot. The seeds were sown in 5 rows per sub-plot at a depth of 0.5 to 1 cm with a row spacing of 15.24 cm using a 2-row John Deere 7000® planter from John Deere in Moline, Iowa, USA. Each variety was replicated four times under each water treatment, resulting in 60 individual sub-plots across varieties, water treatments, and replications. Whole plots were established using rainout shelters

for the drought treatment, while two open fields in close proximity were assigned for the rainfed and irrigation treatments (**Supplemental Figure 3.1**). Based on soil test report, a recommended dose of triple super phosphate (114 kg ha^{-1}) was applied on rainfed plots. Mustang Maxx, a pyrethroid group of insecticide at the rate of 0.29 litre per hectare was sprayed two times at the interval of 20 days to manage alfalfa weevil (*Hypera postica*) and aphids (*Acyrthosiphon kondoi*).

3.2.3 Soil moisture measurement and irrigation management

For each whole plot, twelve watermark sensors were installed at three different depths: 0.15, 0.46 and 0.91 meters (**Supplemental Figure 3.2**). These electrical sensing devices, manufactured by Irrometer Company Inc. in California, U.S.A. were used to measure soil water tension in centibars (or kPa). The detail information about this sensor is documented by Orloff et al. (2000). The measurements were taken at three to four days interval throughout the growing season with a handheld data logger manufactured by the same company. Irrigation water was applied at the irrigated treatment when the soil water tension exceeded 60 kPa. According to a study by Orloff et al. (2000), this value serves as the critical threshold for sandy soils, prompting the need for irrigation. In total, 2276 litre of water was irrigated through overhead sprinkler at each irrigation event, which was equivalent to 20 mm rainfall at the 113.8 m^2 plot (including boarder). To induce drought conditions, stress was initiated in the rain-out shelters approximately three weeks before next each cutting. The shelters were closed to impose drought conditions during any impending rainfall event, and once the rain stopped, they were returned to their original position, allowing the alfalfa plots to expose in natural environmental conditions. In the drought-imposed plots, a single irrigation event of 20 mm was applied immediately after each cutting to prevent permanent wilting of the plants.

3.2.4 Sampling procedure

Forage sampling involved plant biomass collection, drying, weighing, grinding, and labeling. The sampling spots were randomly selected to represent the entire plot. Samples were collected at late bud, early flowering, and seven days after early flowering stage. In this study, the term "late bud" refers to a specific growth stage characterized by the presence of three or more nodes containing visible buds. Likewise, "early flowering" is defined as the stage at which plants exhibit 10% bloom. The stands were cut about 2-5 cm above the ground level using 0.14 m^2 quadrants. After collecting each sample, the plots were mowed using a 40” sickle bar mower attached to a hand operated tractor (Model BCS 718, powered by Honda GX200 engine) manufactured by BCS America Oregon city Oregon, U.S.A. In total, 900 samples were collected each year (2021 and 2022) from three water treatments, five varieties, three growth stages, four replications and five cuttings.

3.2.5 Forage dry matter yield estimation

The collected samples were dried inside hot air dryer at 60^{o}C for 72 hours. The dried samples were measured using a digital weighing balance, and the weight obtained for each sample from a 0.14 square meter area was converted into dry matter yield (DMY) expressed in megagrams per hectare (Mg ha^{-1}).

3.2.6 Forage nutritive value analysis

The dried samples were ground using a Willey mill, passing through a 1 mm mesh size. Ground samples were placed in appropriately labeled 50 g containers and sent to the Ward Laboratory in Kearney, Nebraska for forage nutritive value analysis. The laboratory analyzed different forage nutritive value parameters including crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), in-vitro dry matter

digestibility (IVDMD), lignin, calcium (Ca), magnesium (Mg), phosphorous (P), potassium (K), net energy for maintenance (NEM), water and ethanol soluble carbohydrates, as well as relative feed value (RFV) and relative forage quality (RFQ) using NIRS procedure. The description of NIRS procedure can be found in Marten et al. (1985).

3.2.7 Statistical analysis

The effect of water treatment, variety used and stage of maturity on forage yield and nutritive value was evaluated through analysis of variance (ANOVA) test using PROC GLIMMIX in SAS 9.4 (SAS Institute Inc, 2013). In this model, the production year was treated as a fixed effect factor, while the variety was considered as a random effect. The pairwise comparison of least square means for both DMY and FNV were performed through Tukey-Kramer method using LSMEAN function in SAS 9.4. All the figures were generated using TIDYVERSE package in R 4.3.0 (Wickham et al., 2019). We verified all the assumptions of the model by examining residuals and quantile-quantile plots.

3.2.8 Cost-benefit analysis

The alfalfa hay cost of production is estimated using data from multiple sources. The production inputs such as the amount of seed and chemical inputs (such as lime, fertilizers, and pesticides) were considered based on the recommendations of K-State Extension (Ciampitti et al., 2016a; K-State Research and Extension, 1998), with their prices reflecting the market rates during study period. Variable costs, including tillage, fertilizer and pesticide application, machinery and operator hiring, harvesting, and baling, were used based on the Kansas Custom Rates 2022 (Kansas Department of Agriculture, 2022). Depreciation cost for farm machinery, except for irrigation equipment, was not included in this analysis since the costs of other machinery usage are based on custom hiring. Land rent was calculated based on the average of

the estimated county-level cash rental rates for non-irrigated cropland in Kansas for 2022 (USDA-NASS, 2022c). Overhead costs of 5% and an interest rate of 6% were added to the total expenses. Land rent, crop insurance, and soil testing costs were considered fixed costs.

The financial analysis was conducted with the assumption of five production years. For the revenue calculation, we used the average DMY at late bud stage obtained from production year 1 and 2 (2021 and 2022) for each water treatment. For the production years 3 to 5, the DMY were predicted based on the assumption of 15% yield loss in the succeeding year due to stand age (Undersander, 2001).

Furthermore, a deduction of 20% was made from the overall DMY to account for potential losses occurring at different stages of harvesting process due to factors such as the harvesting method, environmental conditions, equipment, and management practices (Idowu et al., 2013; Orloff & Mueller, 2008; Undersander, 2001). This can be caused by leaf shattering, leaf loss during conditioning or raking, harvesting delay due to unfavorable weather, rainfall damage and residual material left in the field after baling.

Additionally, the average hay price in Kansas, as reported monthly in the Kansas direct hay report by the United States Department of Agriculture, Agricultural Marketing Service (USDA-AMS, 2023b) were used for this calculation. By incorporating these yield projections and the average hay prices, the financial analysis aimed to assess the profitability and viability of the production system over the five-year period. We did not include the inflation rate in this analysis. The price per ton used was the farm gate price of good quality alfalfa hay (crude protein>18% and relative feed value or relative forage quality>150). This financial analysis focused specifically on one hectare of land for the study year. It is important to note that the total cost and benefit vary depending on factors such as farm size, location, and time. The Kansas

sales tax of 6.5% was also included to calculate the final net profit. The total revenue was the income received from the sales of good quality hay. On the other hand, the total cost included the sum of variable costs, fixed costs, depreciation costs, loan interest, overhead costs, and sales tax, all expressed in US dollars.

3.3 Results

In the statistical analysis presented in **Table 3.3**, it was observed that the production year had a significant effect on DMY, ADF, NDF, TDN, IVDMD, Lignin, and RFV/RFQ, while CP and NDFD remained unaffected. The water treatment was significantly influenced on all the variables measured in the study. The interaction of production year and the water treatment also influenced NDF, NDFD, TDN, IVDMD, Lignin, and RFV/RFQ, but it did not affect to DMY, CP, and ADF. When considering the variety, it only showed a significant effect on CP and NDFD. Importantly, there was no interaction effect observed between year and variety, water treatment and variety, year and water treatment and variety, variety and growth stage, year and variety and growth stage, and water treatment and variety and growth stage across all the measured variables. Interestingly, the three-way interaction between year, water treatment, and variety highly influenced DMY. The growth stage showed a significant effect on DMY, CP, NDF, NDFD, IVDMD, and Lignin, but not on ADF, TDN and RFV or RFQ. In terms of interaction effects, the combination of year and growth stage substantially affected DMY, ADF, NDF, IVDMD, and Lignin, but not CP, NDFD, TDN and RFV or RFQ. Similarly, the interaction between water treatment and growth stage showed a significant effect on all the measured variables, excluding CP and ADF. Furthermore, the interaction effect of year, water treatment and growth stage showed a significant effect on NDF, NDFD, TDN, IVDMD, Lignin, and RFV or RFQ, but it didn't affect DMY, CP, and ADF.

3.3.1 Forage dry matter yield

In 2021, DMY at late bud stage was 15.1 Mg ha^{-1} under drought conditions and increased to 17.2 and 19.3 Mg ha^{-1} under rainfed conditions and irrigated conditions (**Figure 3.2**). Overall, the DMY in irrigated conditions was 54% higher compared to drought-imposed conditions and 22.8% higher compared to rainfed conditions (**Supplemental Table 3.1)**.

When comparing the DMY between drought-stressed and irrigated conditions in 2021, there was a variation in DMY ranging from 27.8% at the late bud stage to 65.7% at 7 days after flowering. In 2022, the variation ranged from 34.3% to 104%. In both rainfed and irrigated conditions, there was an increasing trend in DMY from the late bud to 7 days after early flowering. However, in drought stressed conditions, the trend was reversed, showing a significant decrease in DMY over the same period (**Figure 3.3**). Although there was statistically insignificant among varieties, conventional variety HybriForce-3400 consistently showed high DMY, approximately 16 Mg ha^{-1}, across all conditions and growth stages (**Figure 3.4**).

3.3.2 Forage nutritive value

The CP content was measured at 27.1%, 24.2%, and 24% under drought, rainfed and irrigated condition respectively. At the late bud stage, the CP content was found to be 27.7%. It further decreased to 24.1% at the early flowering stage and reached 23.5% at 7 days after early flowering (**Figure 3.5**).

Our results showed higher ADF content in irrigated and lower in drought stressed condition. The average ADF values observed at late bud stage were 22.5% in drought-stressed, 22.6% in rainfed, and 24.7% in irrigated fields (**Figure 3.6**).

Similarly, the NDF values at late bud stage were found to be 25.3% in drought-stressed, 25.8% in rainfed, and 27.9% in irrigated conditions (**Figure 3.7**).

Likewise, the IVDMD values at late bud stage were found 87.9% in drought stressed, 88.1% in rainfed and 86.6% in irrigated conditions which were slightly lower when delayed harvesting (**Figure 3.8; Supplemental Table 2a, 2b, 2c**). Overall, the IVDMD value decreased with increased soil moisture and stages of maturity.

An average, the RFQ values at late bud stage were found 280.6 in drought stressed, 289.9 in rainfed and 264 in irrigated condition. There was no significant difference in the RFQ value during the late bud, early flowering, and 7 days after early flowering stages in our study (**Figure 3.9; Supplemental Table 3.3, 3.4 and 3.5**).

Our study also noted that the CP, IVDMD and RFQ increased with subsequent cuttings. Specifically, the CP content of rainfed (normal) condition increased from 23.5 to 25%, IVDMD improved from 85.3 to 90.1%, and relative forage quality increased from 241.5 to 314.9 when compared between first and fifth cutting (**Figure 3.10; Supplemental Table 3.6**).

3.3.3 Net farm income

The **Figure 3.11** provides the cost-benefit of alfalfa hay production under different conditions (drought, rainfed, and irrigated) over a period of 6 years in Northeast Kansas. The net farm income was estimated based on five years production starting from 2021, after considering all costs and taxes. The first year of alfalfa production resulted in a loss, with no revenue generated and high variable and fixed costs. However, over the subsequent five years, the revenue increased gradually, and as a result, the net profit improved as well. The average net profit per hectare across all six years was $2,494.67 under drought, $2,894 under rainfed and $2,755 under irrigated condition. The summary of financial analysis is listed in **Supplementary Table 3.7**. The net profit margin was found 62% in drought, 64% in rainfed and 52% in irrigated

production. Interestingly, there was no substantial difference in profits between rainfed and irrigated conditions (**Figure 3.11; Supplemental Table 3.7**).

3.4 Discussion

Both researchers and farmers always aim to achieve higher quality alfalfa forage while minimizing the reduction in yield. However, finding the optimal balance is challenging due to various factors such as climatic conditions, soil fertility, cultivar regrowth capacity, livestock nutritional needs, and production expenses. Another concern is that delaying the harvest time not only affects forage quality but also leads to more leaf loss during the haymaking process (Orloff & Putnam, 2010; Undersander, 2001).

The findings of this study suggested that the amount of DMY and forage nutritive value varies depending on different factors such as the year of production, availability of soil water, and the stages of maturity. In 2021, DMY varied across drought, rainfed, and irrigated conditions, with the highest yield observed under irrigation. The comparison between drought-stressed and irrigated conditions showed significant variations in DMY, ranging from 27.8 to 65.7% depending on the stage of maturity during harvest. In 2022, the variations ranged from 34.3 to 104%. DMY exhibited an increasing trend from the late bud to 7 days after early flowering in rainfed and irrigated conditions, while drought-stressed conditions showed a reverse trend. We observed 5% yield decline at late bud stage and 38% at 7 days after early flowering stage in the drought affected plots in the second year. In addition, there was a decline in yield in drought-imposed plots in the second production year, attributed by the adverse effects on the number of stems per plant and overall plant growth. The average height of the stands was 30 cm in drought-imposed plots, whereas it was recorded 50 cm in irrigated plots. The subsequent

cuttings also showed a decrease in DMY, with the last cutting producing less than half of the first one.

Our findings are supported by several previous investigations (Baral et al., 2022; Boyer, 1970; Diatta et al., 2021; Holman et al., 2016; Lindenmayer et al., 2011; Orloff et al., 2015; Peterson et al., 1992; Schneekloth & Andales, 2017; Shewmaker et al., 2011; Takele & Kallenbach, 2001; Undersander & Cosgrove, 2011), who found positive correlation between alfalfa DMY and soil moisture. Schneekloth and Andales (2017), Shewmaker et al. (2011), and Takele and Kallenbach (2001) claimed that alfalfa requires a significant amount of water compared to other field crops. FAO (2022) recommends between 800 to 1600 mm water per hectare per season, depending on climate, elevation, growing season, number of cuttings, latitude, and fall dormancy rating of the alfalfa variety. Our previous study estimated up to 58% yield loss due to water-limited conditions in the United States where more than 65% of alfalfa is grown under rainfed conditions (Baral et al., 2022). Peterson et al. (1992) observed up to 66% yield loss whereas Takele and Kallenbach (2001) reported up to 72% due to moderate to severe drought stress conditions during alfalfa growing season.

We also found yield variation by production year. These variations can be caused by the combined effect of drought stress, unpredictable weather conditions, the age of the stands, phosphorous deficiency, and pressure from pests and weeds. In 2022, the annual rainfall exceeded 800 mm (Kansas Mesonet, 2022), which promoted the growth of noxious weeds during the summer of the second production year. Besides water deficit in drought-imposed plots, we observed the presence of alfalfa weevil (*Hypera postica*), aphids (*Therioaphis trifolii*), and various weed species such as Barnyardgrass (*Echinochloa crus-galli*), blue mustard (*Chorispora tenella*), yellow foxtail (*Setaria pumila*), horseweed (*Erigeron canadensis*), kochia (*Kochia*

scoparia), large crabgrass (*Digitaria sanguinalis*), johnson grass (*Sorghum halepense*), Canadian thistle (*Cirsium arvense*), common lambsquarter (*Chenopodium album L.*), henbit (*Lamium amplexicaule*), and few pigweed (*Palmer amaranth*) and waterhemp (*Amaranthus tuberculatus*) in the summer of second production year. These weeds not only compete with the alfalfa crop for water and nutrients but also serve as alternative hosts for many insects and diseases. We also observed leaf damage from alfalfa weevil and aphids in April through June of 2022. Additionally, the phosphorous level in the rainfed plots was found to be below 25 ppm in Spring 2021, which is a crucial nutrient required for regrowth after winter survival. Overall, these findings suggest that during a drought year, producers should not delay the harvest of alfalfa and instead consider harvesting earlier to maximize yield.

The forage nutritive value analysis results showed that there is an inverse relationship between soil moisture and crude protein content, where lower soil moisture levels (as seen in drought conditions) could potentially lead to higher crude protein content in the forage. The results also indicated that the CP content of alfalfa decreased as the plant progressed in its growth stages. ADF and NDF were influenced by water regimes, with higher values observed in irrigated conditions. The higher IVDMD and RFQ values indicate better digestibility and nutrient availability, making the hay more valuable for animal consumption. The IVDMD and RFQ decreased with increased soil moisture. Furthermore, we also observed that the drought-imposed treatments resulted in higher dry matter digestibility, net energy, and relative forage quality, while irrigated treatments had lower values of these parameters. The timing of harvest plays a significant role in determining both yield and quality of alfalfa (Min, 2016; Orloff & Putnam, 2010). Typically, forage quality decreases over time or with the stages of maturity. However, there was no substantial change in the RFQ value during the late bud, early flowering,

and 7 days after early flowering stages in our study. This indicates that a slight delay in harvesting does not significantly impact the overall forage quality, while also potentially increasing the yield of hay.

Previous studies have also observed that early harvesting leads to lower yields but higher protein content and digestibility. Our results are consistent with previous studies (Petit et al., 1992; Seguin et al., 2002) who documented higher forage quality under drought conditions and lower under irrigation. Numerous other researchers observed a decrease in CP and increase in ADF, NDF, and lignin content with the advancement of maturity (Balde et al., 1993; Fick & Mueller, 1989; Jungers et al., 2020; Yari et al., 2012). The correlation between soil moisture levels and crude protein content was observed negative but it was positive with ADF and NDF in a greenhouse experiment on alfalfa conducted in Quebec, Canada by Petit et al. (1992). This finding was further supported by field studies carried out in Southwest Kansas by Holman et al. (2016) and in Northwest China by Li and Su (2017). Typically, when the concentrations of ADF and NDF increase, the consumption of forage tends to decrease. According to USDA hay quality designated guidelines, the good quality hay should have ADF value below 35 and NDF value below 40 (USDA-AMS, 2023a).

Earlier studies conducted on lower-lignin transgenic alfalfa varieties claimed that producer can delayed harvesting without losing forage quality (Barros et al., 2019; Undersander et al., 2009). Our study revealed that delaying the harvest of forage from the late bud stage to seven days after early flowering did not have a significant effect on its quality regardless of conventional or lower-lignin varieties. Another notable finding from this study is that both conventional alfalfa varieties and lower lignin varieties exhibited similar performance in terms of yield and quality, even with delayed harvesting. Getachew et al. (2018) compared the forage

nutritive value between two lower-lignin and two conventional alfalfa varieties using NIRS procedure. They also found similar results and reached the conclusion that there were no significant differences in DMY, CP, ADF and NDF concentration between the lines when harvested every 28 days interval. This conclusion is further supported by Damiran et al. (2022), who also found no significant differences in CP, IVDMD, and RFQ between lower-lignin and conventional lines. Overall, all the nutritive value parameters meet the higher quality hay as per the hay quality standard guidelines published by United States Agricultural Marketing Service.

The net farm income from alfalfa hay production can vary depending on location, labour and input costs, farm management practices, market demand, and specific circumstances including pest and weed management, storage and transportation, weather condition. Producers should carefully analyse and manage these factors to optimize the cost-effectiveness of alfalfa production. The financial analysis indicated that the alfalfa is a highly profitable crops, with an estimated profit margin ranging from 52% to 64% ($2,495 to $2,755) per hectare under different soil moisture condition.

More importantly, this study suggests that investing in irrigation does not provide significant profits for farmers. This could be attributed due to the initial investment for irrigation facility and the ample rainfall received throughout the growing season, which exceeds 700 mm in the study area (Kansas Mesonet, 2022). Because our analysis estimated the cost of a pivot irrigation system for 50 hectares of land for Kansas which was $127,500, amounting to $2550 per hectare. But the payback period of investing irrigation system for 50 hectares of land was found less than 2 years, indicating that irrigation investment can prove to be profitable in regions where the growing season rainfall amount is less than the plant requirement. The drought-stressed plots also showed a significant amount of profit. However, we did not completely

imposed drought for the regrowth period. To save the plant from permanent wilting point we irrigated once immediately after each cutting. Furthermore, considering the performance of the stand, younger stand performed more than older stand (Undersander et al., 2021). Therefore, it is uncertain whether this profitability under prolonged drought will continue in the following production years.

Further research endeavours, such as the physiological and molecular mechanisms underlying alfalfa's tolerance to water stress and conducting long-term study to examine the cumulative effects of drought over multiple production years, would provide a better understanding of the impact of drought on alfalfa production and aid in the development of drought-tolerant alfalfa varieties. This research could involve studying gene expression patterns, metabolic pathways, and water-use efficiency in alfalfa plants under different water regimes. Moreover, the financial analysis in the study provided an estimate of net farm income and profitability. However, conducting further economic analysis considering different market conditions, price fluctuations, and input costs would provide more realistic and practical insights for alfalfa producers..

3.5 Conclusion

The study examined the forage dry matter yield and nutritive value of alfalfa under different water regimes, alfalfa varieties and stages of maturity. The results demonstrated that both forage yield and nutritive value varied across different water conditions and maturity stages. However, there was no difference on DMY and quality among varieties. The highest yield was observed under irrigation at 7 days after early flowering, while the highest relative forage quality was found under drought stressed conditions at the same stage. Rainfed and irrigated conditions

showed an increasing trend in forage yield from late bud to 7 days after early flowering, whereas drought-stressed conditions exhibited a reverse trend.

The study also assessed the forage nutritive value of alfalfa. The CP content decreased over time, with lower levels observed in drought conditions. The ADF, NDF and IVDMD were influenced by available soil moisture, with higher ADF and NDF in irrigated conditions. The IVDMD values decreased with increased soil moisture and stages of maturity. The RFQ values indicated higher nutritional value and overall quality under drought conditions.

The financial analysis showed that investing in irrigation did not yield significant profits due to ample rainfall in the study area. However, in regions with lower rainfall, irrigation investment could be profitable.

Practically, the findings of this study have important implications for alfalfa producers. Firstly, during drought years, it is more beneficial for producers to harvest alfalfa earlier rather than delaying it, as this does not negatively affect forage quality. Delaying harvesting slightly increases the dry matter yield without notable impacts on overall quality. Additionally, the study showed that both conventional and lower-lignin varieties perform equally in terms of yield and quality, providing producers with flexibility in variety selection. Moreover, the study suggests that farmers should critically evaluate the cost-effectiveness of irrigation practices in alfalfa production, as investing in irrigation may not result in significant profits. Overall, this study provides insights for producers and scientists to deepen their understanding of alfalfa production, improve yield and quality, develop sustainable management practices, and enhance the overall profitability of alfalfa farming.

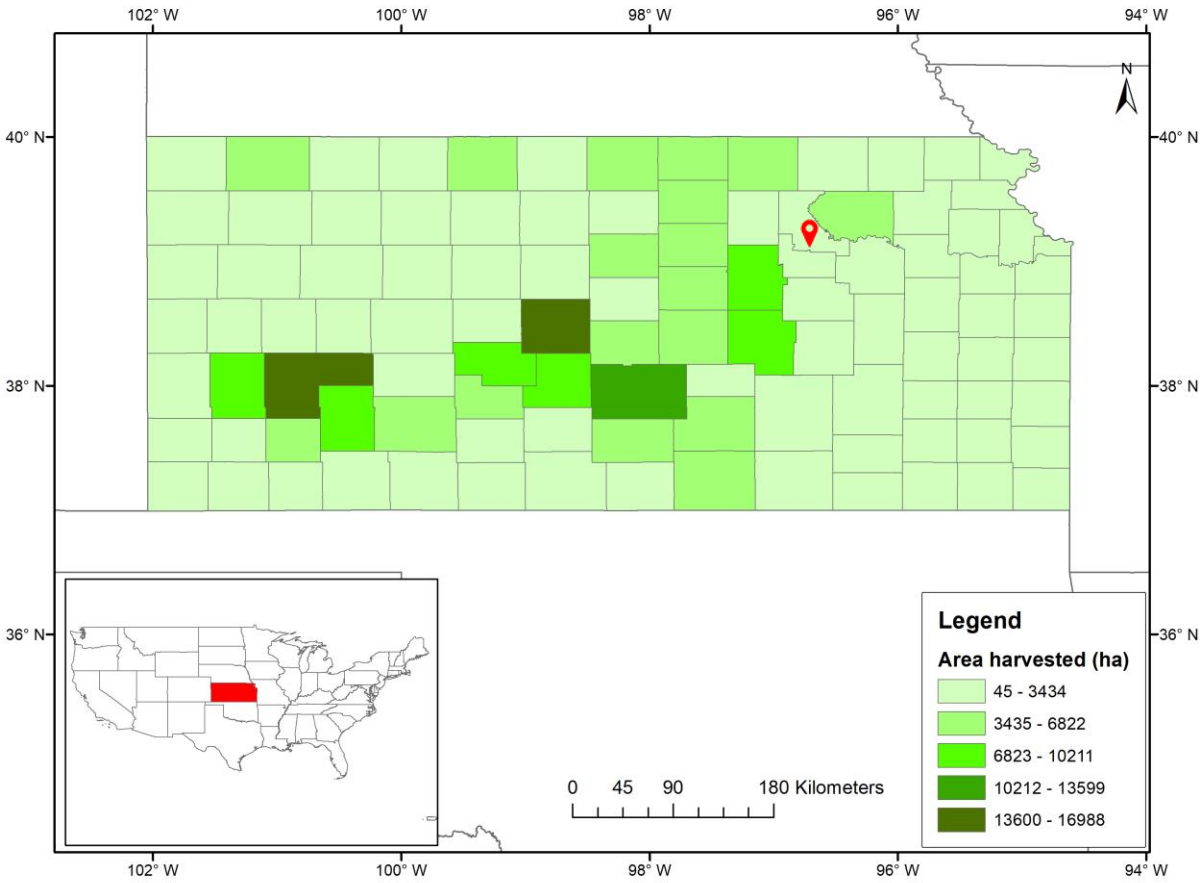


Figure 3.1. Map of Kansas State showing major alfalfa growing counties.
The variation in green color represents the variation in yield among counties. The location icon represents study location. An inset is also included, highlighting Kansas State in red within the US continents.

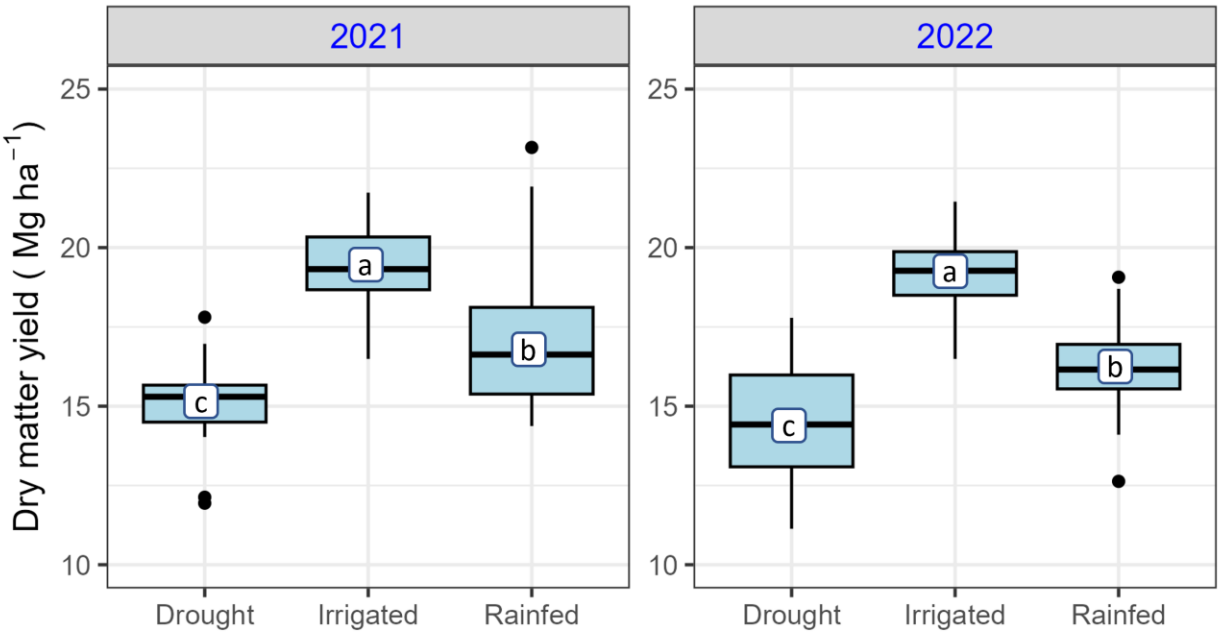


Figure 3.2. Forage dry matter yield of alfalfa grown under drought imposed, rainfed and irrigated conditions in 2021 and 2022.

The letters inside the inter quartile range denote the difference in DMY in 2021 and 2022 grown under three water regimes.

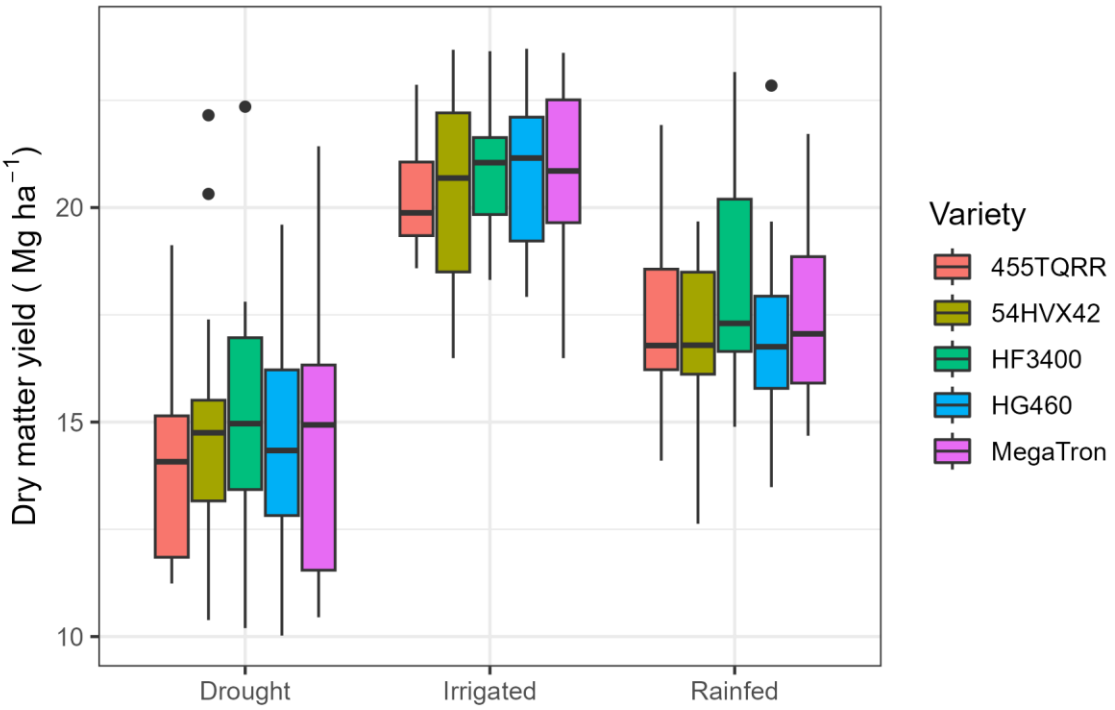


Figure 3.3. Forage dry matter yield of alfalfa varieties grown under drought imposed, rainfed and irrigated conditions.

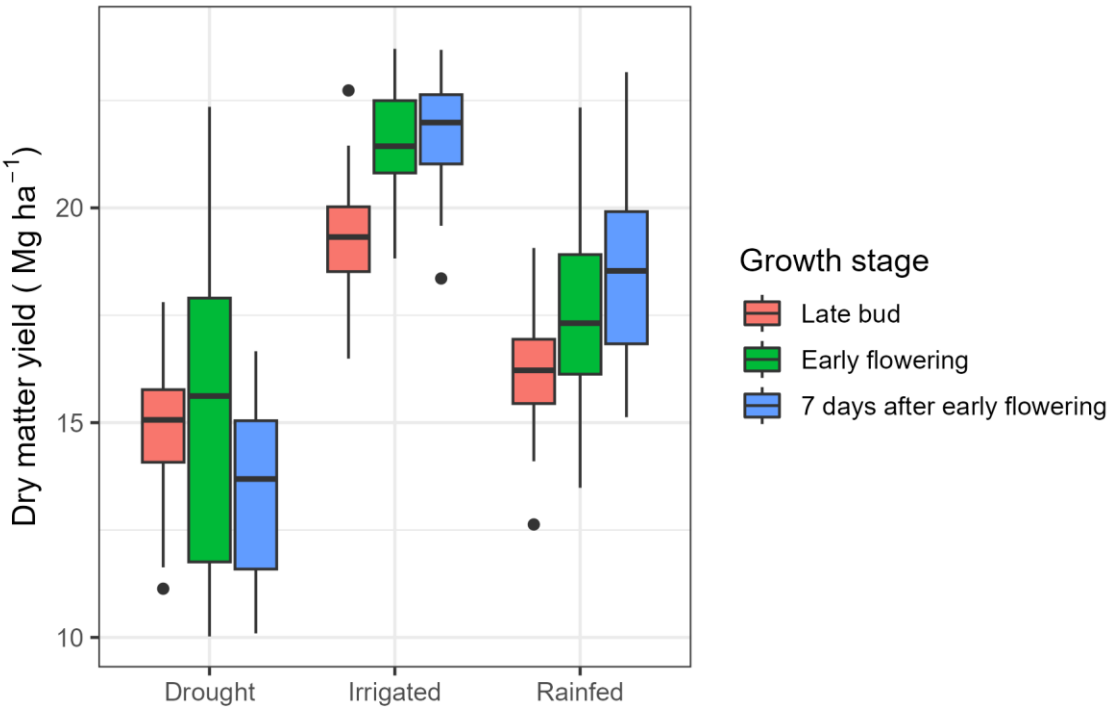


Figure 3.4. Forage dry matter yield of alfalfa grown under drought imposed, rainfed and irrigated conditions and harvested at different growth stages.

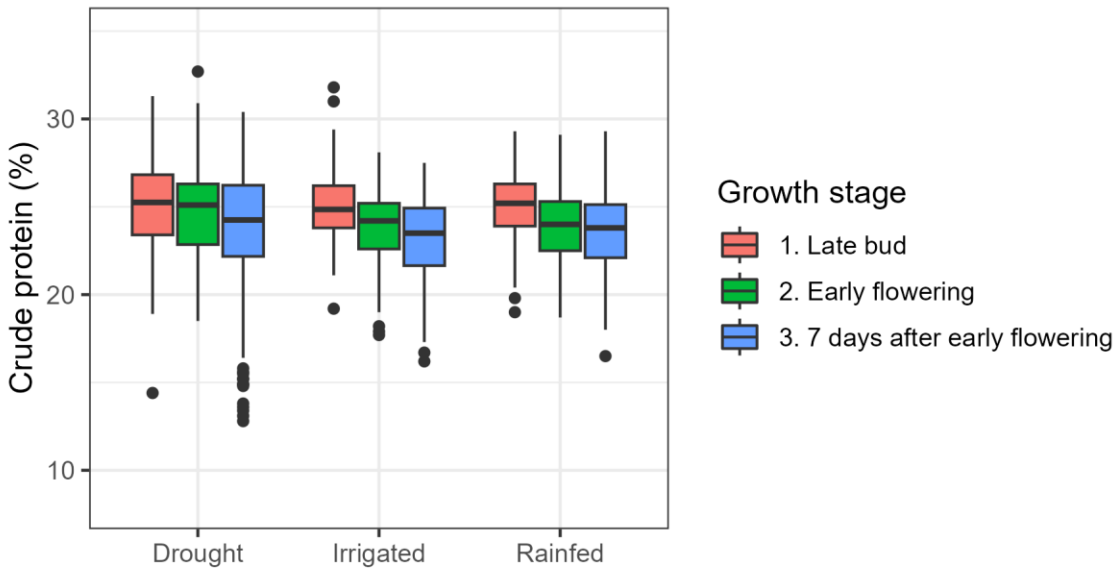


Figure 3.5. Crude protein content of drought imposed, rainfed and irrigated alfalfa by growth stage.

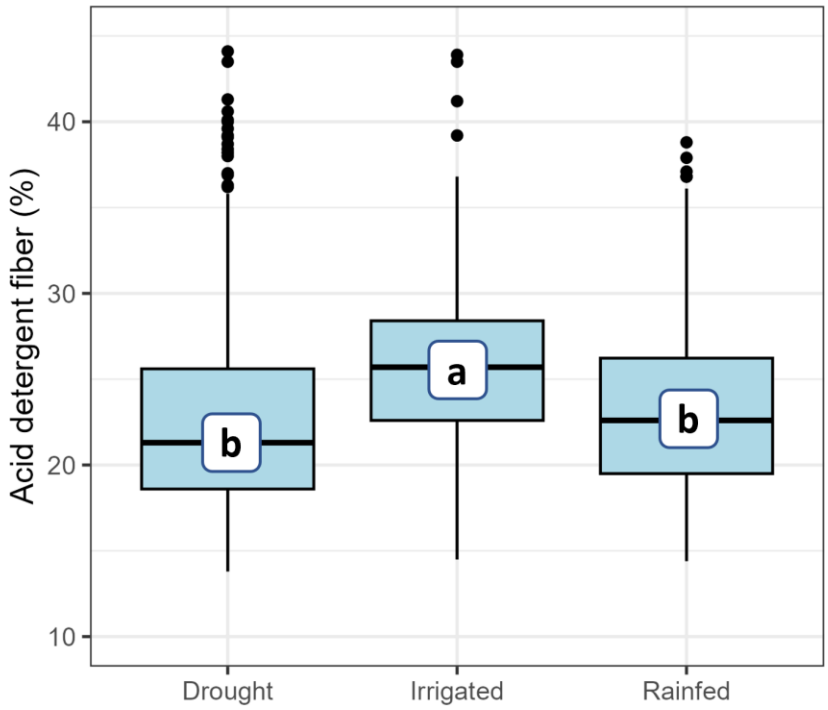


Figure 3.6. Acid detergent fiber of alfalfa grown under drought imposed, rainfed and irrigated conditions.

The letters inside the inter quartile range denote the difference in ADF values among three water regimes.

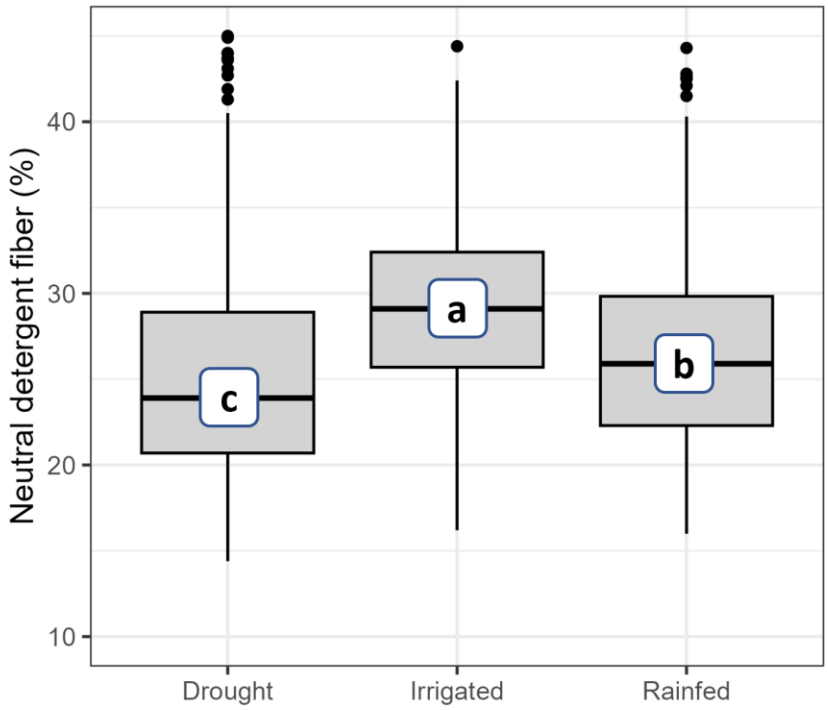


Figure 3.7. Neutral detergent fiber of alfalfa grown under drought imposed, rainfed and irrigated conditions.

The letters inside the inter quartile range denote the difference in NDF values among three water regimes.

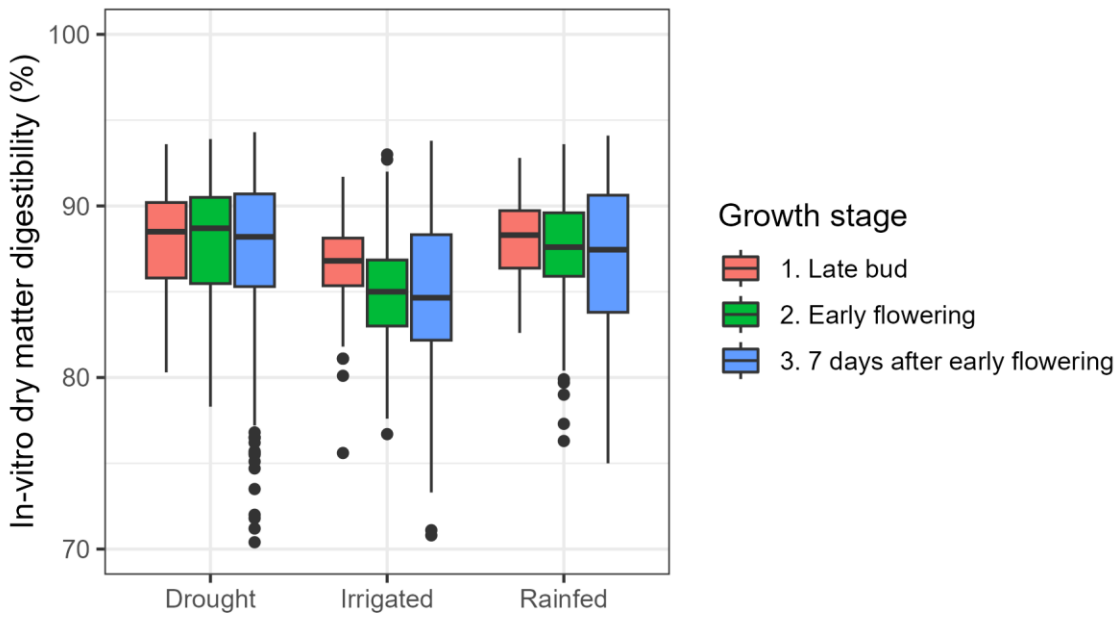


Figure 3.8. In-vitro dry matter digestibility of alfalfa grown under drought imposed, rainfed and irrigated conditions and harvested at different growth stages.

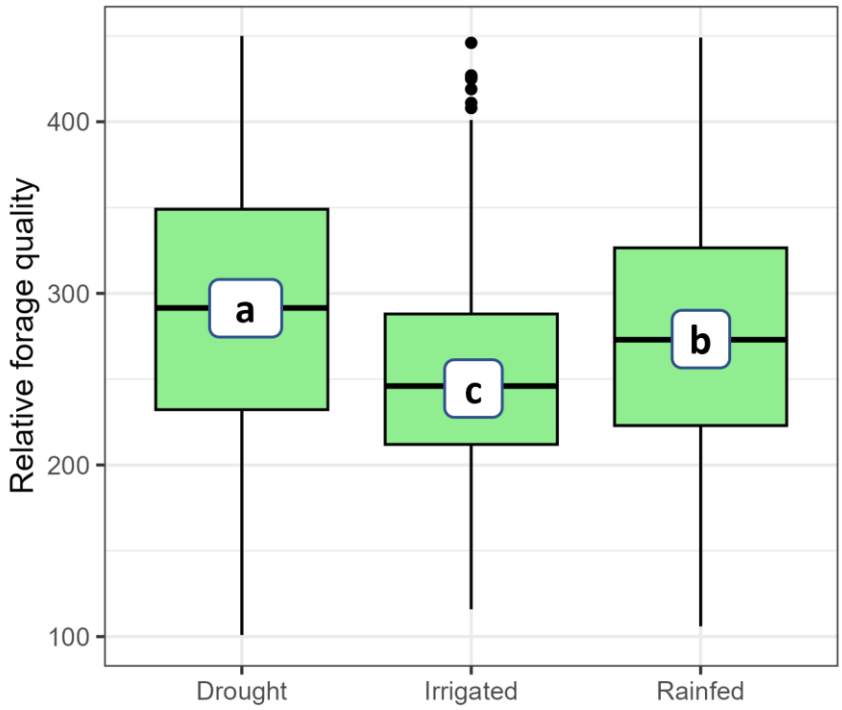


Figure 3.9. Average relative forage quality of alfalfa grown under drought imposed, rainfed and irrigated conditions.

The letters inside the inter quartile range denote the difference in RFQ value among three water regimes.

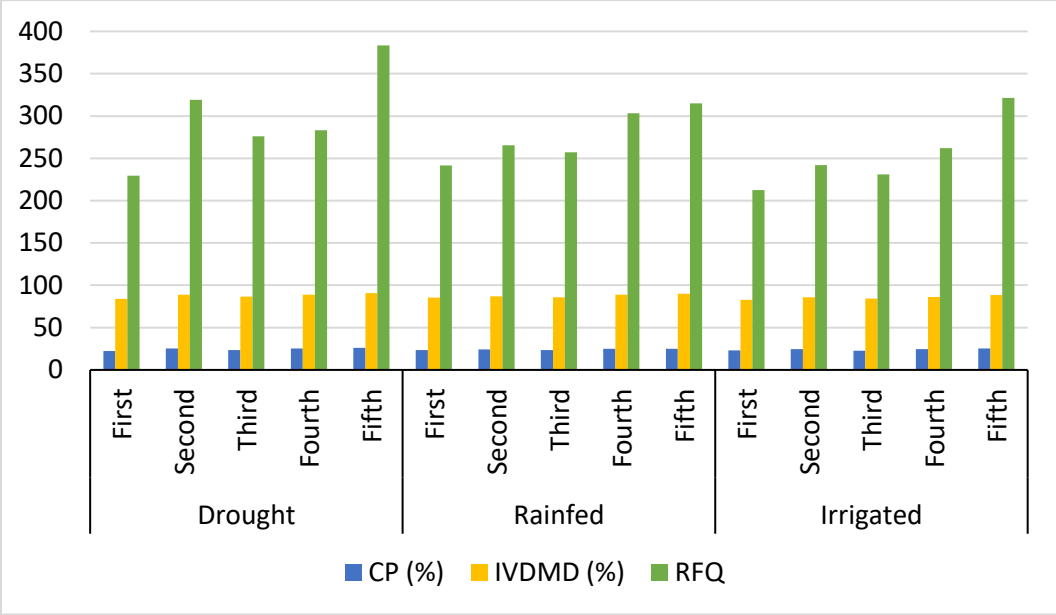


Figure 3.10. Cutting-wise average crude protein, invitro dry matter digestibility and relative forage quality of alfalfa grown under drought, rainfed and irrigated conditions in 2021 and 2022.

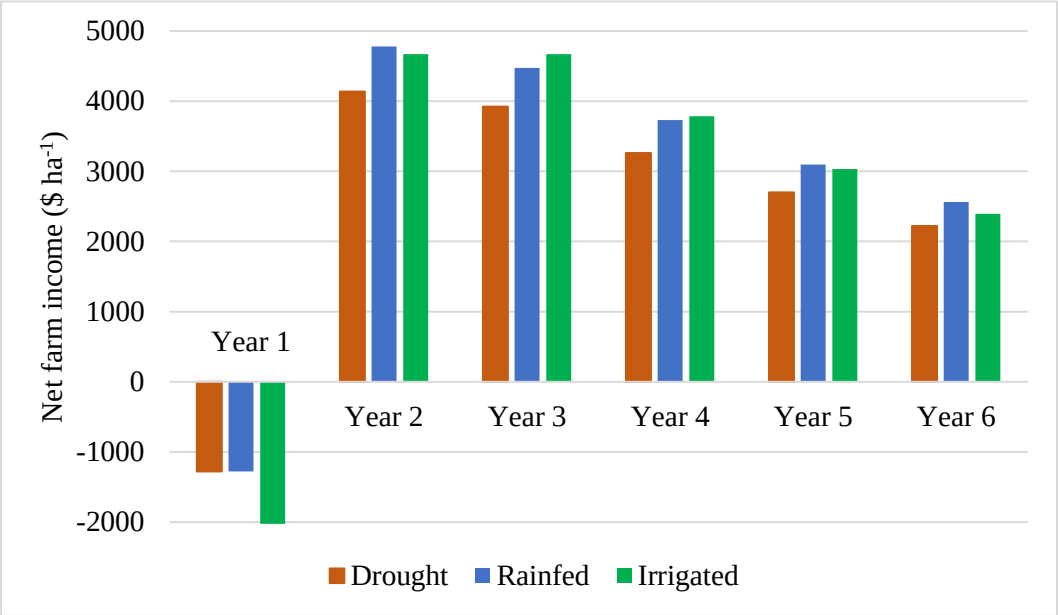


Figure 3.11. Net farm income of alfalfa hay production under drought, rainfed and irrigated condition in Kansas

Table 3.1. Soil fertility status of experimental field before alfalfa establishment and before second production year.

Parameter	Spring 2021			Fall 2021			Fall 2022		
	Drought plot	Irrigated plot	Rainfed plot	Drought plot	Irrigated plot	Rainfed plot	Drought plot	Irrigated plot	Rainfed plot
pH	7.2	6	7.1	-	-	-	7.3	7	6.6
Organic matter (%)	3.4	2.7	3	-	-	-	-	-	-
Phosphorus (ppm)	273.5	26	13	577.4	28.3	45	564	38	56
Potassium (ppm)	539.5	266	300	3390.3	2859.2	2051.7	494	192	169
Calcium (ppm)	3559.5	2683	3196	584.05	275.6	236.1	3511.5	2517	1741
Magnesium (ppm)	543	523	610	443.85	571.8	393.8	411.5	447	299
Sodium (ppm)	50	29	33	37.15	63.6	39.7	22.5	39	11
Ammonium (ppm)	-	-	-	12.4	14.5	15.2	10.35	11.4	6.8
Nitrate nitrogen (ppm)	-	-	-	15.35	3.2	2.5	10.75	4.3	4.2
CEC Sum. (meg//100g)	23.95	28.1	22	-	-	-	-	-	-

Table 3.2. Average temperature and rainfall of the experiment location during the study period (Kansas Mesonet, 2023).

Month	2020		2021		2022		30-yr average	
	Average temp (°C)	Rainfall (mm)	Average temp (°C)	Rainfall (mm)	Average temp (°C)	Rainfall (mm)	Temp (°C)	Rainfall (mm)
January	3.6 (±2.6)	17 (±1.7)	1.6 (±3.7)	22.9 (±2.8)	1.1 (±5.2)	6.9 (±1.0)	-1.5	16.5
February	5.5 (±3.3)	20.1 (±2.5)	0.3 (±6.5)	2.5 (±0.3)	2.7 (±6.1)	2.0 (±1.3)	1.1	24.4
March	9.3 (±4.6)	64.3 (±5.4)	9.5 (±5.0)	91.7 (±6.9)	7.0 (±6.5)	56.6 (±4.9)	7.1	46.5
April	13.7 (±5.1)	49.3 (±5.3)	12.6 (±6.2)	52.3 (±3.2)	12.6 (±5.8)	25.9 (±3.7)	12.6	79.5
May	16.5 (±4.9)	141.2 (±10.0)	16.6 (±4.8)	134.1 (±10.5)	19.1 (±6.6)	235 (±13.8)	18.3	118.1
June	25.6 (±3.1)	88.9 (±6.9)	25.3 (±3.8)	66.8 (±6.8)	24.9 (±4.1)	177.8 (±11.7)	23.9	122.7
July	26.1 (±2.0)	168.4 (±10.8)	25.3 (±2.8)	161.8 (±19.3)	26.2 (±3.6)	100.1 (±11.3)	26.6	101.9
August	24.6 (±3.2)	45.5 (±4.6)	26.5 (±3.5)	71.4 (±4.8)	25.5 (±3.5)	33.3 (±3.5)	25.3	117.9
September	19.3 (±5.3)	54.6 (±5.6)	22.9 (±3.8)	69.1 (±8.3)	21.8 (±5.0)	58.2 (±6.0)	20.5	68.3
October	12.8 (±7.1)	16.8 (±1.9)	15.1 (±5.1)	82.8 (±10.1)	14.5 (±6.1)	30.0 (±3.1)	13.4	55.4
November	11.2 (±5.3)	60.2 (±5.6)	8.7 (±4.9)	29 (±4.8)	5.4 (±7.5)	90.7 (±11.0)	6.1	39.1
December	5.3 (±3.1)	24.4 (±4.0)	5.8 (±4.9)	8.1 (±1.5)	0.3 (±5.8)	29.7 (±3.1)	0.2	26.9

Table 3.3. Analysis of variance showing effect of year, water treatment, varieties and their interaction on alfalfa dry matter yield and forage nutritive value.

Source of variability	Effect on								
	DMY	CP	ADF	NDF	NDFD	TDN	IVDMD	Lignin	RFV/RFQ
Year	***	NS	***	***	NS	***	***	***	***
TRT	***	***	***	***	***	***	***	***	***
Year*TRT	NS	NS	NS	***	***	***	***	***	***
Variety	NS	***	NS	NS	***	NS	NS	NS	NS
Year*Variety	NS	NS	NS	NS	NS	NS	NS	NS	NS
TRT*Variety	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year*TRT*Variety	***	NS	NS	NS	NS	NS	NS	NS	NS
Growth stage	***	***	NS	***	***	NS	***	***	NS
Year*Growth stage	***	NS	***	**	NS	NS	***	***	**
TRT*Growth stage	***	NS	**	***	***	***	**	***	***
Year*TRT*Growth stage	NS	NS	NS	***	***	***	**	***	**
Variety*Growth stage	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year*Variety*Growth stage	NS	NS	NS	NS	NS	NS	NS	NS	NS
TRT*Variety*Growth stage	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year*TRT*Variety*Growth stage	NS	NS	NS	NS	NS	NS	NS	NS	NS

Definition of abbreviations: TRT=Water treatment; DMY=Dry matter yield; CP=Crude protein; ADF=Acid detergent fiber; NDF=Neutral detergent fiber; NDFD=Neutral detergent fiber digestibility; TDN=Total digestible nutrient; IVDMD=In-vitro dry matter digestibility; NEM=Net energy gain; RFV=Relative feed value; RFQ=Relative forage quality epinephrine; NS=Non-significant; ***=Significant at *p-value* 0.001, **=Significant at *p-value* 0.01 and *=Significant at p-value 0.05

Supplemental Figure 3.1. Aerial photo of the experimental field.

The photo shows drought imposed in two rainout shelters (upper left), irrigated plot (upper right) and rainfed plot (down).

Supplemental Figure 3.2. Watermark sensors installed in the experimental field.
The white PVC tube connected with water mark sensors installed at 0.5, 1.5 and 3 fit depths.

Supplemental Table 3.1. Forage dry matter yield (Mg ha^{-1}) of drought-imposed, rainfed and irrigated alfalfa by growth stage.

Treatment	Variety	2021			2022		
		Late bud	Early flowering	7 days after early flowering	Late bud	Early flowering	7 days after early flowering
Drought	455TQRR	14.6	16.7	13.9	13.5	9.8	10.1
	54HVX42	14.5	18.6	14.4	14.7	10.2	9.7
	HF3400	16	18.7	15.2	14.8	11.6	10.3
	HG460	15.2	17.4	14.2	14.3	9.6	12
	MegaTron	15.4	20.3	15.8	14.6	11.6	11.2
	Average	**15.1**	**18.3**	**14.7**	**14.4**	**10.5**	**10.6**
Rainfed	455TQRR	16.2	18	20.8	15.4	16.7	17.2
	54HVX42	17.7	17.7	19.1	15.2	16.2	16.7
	HF3400	17.2	20.1	20.5	17.1	16.7	17.1
	HG460	17.8	17.6	18.5	16.4	14.6	17.4
	MegaTron	17	18.1	21.1	17	16	17.8
	Average	**17.2**	**18.3**	**20**	**16.2**	**16**	**17.2**
Irrigated	455TQRR	19.4	22.1	24.8	19.6	22.5	22.2
	54HVX42	18	21.8	22.1	18.8	21.8	21.3
	HF3400	20.1	22.6	25.9	19.8	21.7	21.4
	HG460	19.7	23.2	25.5	19.3	23	21.4
	MegaTron	19.4	21.1	23.4	19	21.5	22.4
	Average	**19.3**	**22.2**	**24.3**	**19.3**	**22.1**	**21.7**

Supplemental Table 3.2. Forage dry matter yield (Mg ha^{-1}) of drought-imposed, rainfed and irrigated alfalfa by cutting and growth stage.

Treatment	Cut	2021			2022		
		Late bud	Early flowering	7 days after early flowering	Late bud	Early flowering	7 days after early flowering
Drought	First cut	5.9	6.8	4.3	4.6	3	2.6
	Second cut	2.9	3.9	3.8	3.2	2.8	2.6
	Third cut	2.1	3.3	3.2	2.9	2.1	2.4
	Fourth cut	2.1	2.3	2.1	1.9	1.4	1.9
	Fifth cut	2.1	2	1.3	1.8	1.2	1.2
Rainfed	First cut	4.6	6.7	6.2	4.4	5.5	6.1
	Second cut	4	4.6	4.4	4.4	4.2	4.4
	Third cut	3	3.9	4.2	3.1	2.8	2.9
	Fourth cut	2.8	2.3	2.7	2.4	2	2.2
	Fifth cut	1.9	1.4	3.1	1.9	1.5	1.6
Irrigated	First cut	4.6	6.5	6.3	4.6	7	6.7
	Second cut	4.4	4.7	5	4.5	5.2	5.3
	Third cut	3.7	4.5	5.5	4.3	4	4.1
	Fourth cut	3.8	3.7	3.7	3.2	3.6	3.5
	Fifth cut	2.9	2.7	3.8	2.7	2.3	2.2

Supplemental Table 3.3. Forage nutritive value of five commercial varieties of alfalfa grown under drought, rainfed and irrigated conditions and harvested at late bud stage in 2021 and 2022.

Treatment	Variety	CP	ADF	NDF	IVDMD	Lignin	NEM	RFQ
Drought	455TQRR	24.6	22.1	25.8	87.5	5.1	0.68	278.8
	54HVX42	25.6	22.4	25.4	88	5.1	0.69	279.1
	HF3400	25.2	22.9	25.3	87.5	5.1	0.69	278.9
	HG460	25.2	22.3	24.7	88.1	4.9	0.7	285.3
	MegaTron	25.4	22.6	25.2	88.4	5	0.7	280.8
	Average	**25.2**	**22.5**	**25.3**	**87.9**	**5**	**0.7**	**280.6**
Rainfed	455TQRR	25	22.6	25.7	87.9	5.1	0.68	281
	54HVX42	25.2	22.5	25.7	88.3	5.1	0.69	283.8
	HF3400	25.2	22.7	25.9	88	5.1	0.69	272
	HG460	25	22.5	25.7	88.1	5.2	0.69	276.1
	MegaTron	24.7	22.9	25.9	88.1	5.1	0.68	286.9
	Average	**25**	**22.6**	**25.8**	**88.1**	**5.1**	**0.7**	**279.9**
Irrigated	455TQRR	24.9	24.7	27.9	86.5	5.5	0.65	264.4
	54HVX42	25.4	24.2	27.4	87.2	5.3	0.66	273.1
	HF3400	25.2	24.7	28.1	86.5	5.5	0.65	260.5
	HG460	25.1	24.4	27.6	86.6	5.5	0.7	266.2
	MegaTron	24.6	25.3	28.6	86.1	5.6	0.6	256.0
	Average	**25.0**	**24.7**	**27.9**	**86.6**	**5.5**	**0.7**	**264.0**

CP = Crude protein, ADF = Acid detergent fiber, NDF = Neutral detergent fiber, IVDMD = Dry matter digestibility, NEM = Net energy (maintenance) and RFQ = Relative forage quality

Supplemental Table 3.4. Forage nutritive value of five commercial varieties of alfalfa grown under drought, rainfed and irrigated conditions and harvested at early flowering stage in 2021 and 2022.

Treatment	Variety	CP	ADF	NDF	IVDMD	Lignin	NEM	RFQ
Drought	455TQRR	24.3	22.6	25.7	87.5	5.1	0.7	281.8
	54HVX42	25.3	21.6	24.3	88.4	4.9	0.7	317
	HF3400	24.4	22.7	25.8	87.3	5.2	0.7	284.3
	HG460	24.5	22	25	87.9	5	0.7	299.3
	MegaTron	25.1	21.4	24.1	88.7	4.9	0.7	320.1
	Average	24.7	22	25	87.9	5	0.7	300.5
Rainfed	455TQRR	24	23.2	26.5	87.3	5.4	0.7	260.4
	54HVX42	24.2	22.9	26.2	87.8	5.2	0.7	285.6
	HF3400	23.8	23.9	27.5	86.7	5.5	0.7	246.5
	HG460	24.4	22.3	25.5	88	5.2	0.7	292
	MegaTron	23.7	23.6	27.1	87.1	5.4	0.7	267.5
	Average	24	23.2	26.5	87.4	5.3	0.7	270.4
Irrigated	455TQRR	23.7	26.3	29.8	84.7	6	0.6	245.6
	54HVX42	24.4	25.7	29	85.7	5.7	0.6	257.9
	HF3400	23.8	26.5	30.1	84.6	5.9	0.6	243.3
	HG460	23.7	26.1	29.5	85.1	5.8	0.6	248.6
	MegaTron	23.5	27.1	30.4	84.5	6.0	0.6	242.5
	Average	23.8	26.3	29.8	84.9	5.9	0.6	247.6

CP = Crude protein, ADF = Acid detergent fiber, NDF = Neutral detergent fiber, IVDMD = Dry matter digestibility, NEM = Net energy (maintenance) and RFQ = Relative forage quality

Supplemental Table 3.5. Forage nutritive value of five commercial varieties of alfalfa grown under drought, rainfed and irrigated conditions and harvested at 7 days after early flowering stage in 2021 and 2022.

Treatment	Variety	CP	ADF	NDF	IVDMD	Lignin	NEM	RFQ
Drought	455TQRR	23.2	23.3	26.0	86.9	5.3	0.67	304.7
	54HVX42	24.1	22.9	25.5	87.3	5.2	0.67	317.2
	HF3400	24.2	22.2	25.0	87.6	5.1	0.68	320.2
	HG460	23.6	22.8	25.4	87.3	5.1	0.67	321.0
	MegaTron	23.4	23.6	26.3	87.1	5.3	0.66	305.7
	Average	**23.7**	**23.0**	**25.6**	**87.3**	**5.2**	**0.7**	**313.8**
Rainfed	455TQRR	23.4	23.6	26.8	86.9	5.5	0.66	287.4
	54HVX42	24.1	22.9	26.3	87.6	5.3	0.68	287.9
	HF3400	24.0	23.5	27.0	86.9	5.5	0.67	282.8
	HG460	23.1	23.9	27.5	86.4	5.6	0.67	271.1
	MegaTron	23.4	23.9	27.2	87.0	5.5	0.67	266.6
	Average	**23.6**	**23.6**	**27.0**	**87.0**	**5.5**	**0.7**	**279.1**
Irrigated	455TQRR	23.0	26.3	30.0	84.5	6.1	0.63	247.0
	54HVX42	23.4	26.1	29.8	85.0	5.9	0.64	257.2
	HF3400	23.3	26.6	30.4	84.3	6.0	0.63	246.3
	HG460	23.7	25.3	28.9	85.2	5.9	0.65	257.9
	MegaTron	23.0	26.1	30.0	85.0	6.0	0.65	240.6
	Average	**23.3**	**26.1**	**29.8**	**84.8**	**6.0**	**0.6**	**249.8**

CP = Crude protein, ADF = Acid detergent fiber, NDF = Neutral detergent fiber, IVDMD = Dry matter digestibility, NEM = Net energy (maintenance) and RFQ = Relative forage quality

Supplemental Table 3.6. Cutting wise forage nutritive value of five commercial varieties of alfalfa grown under drought, rainfed and irrigated conditions in 2021 and 2022.

Treatment	Cutting	2021						2022					
		CP	ADF	NDF	IVDMD	Lignin	RFQ	CP	ADF	NDF	IVDMD	Lignin	RFQ
Drought	First	20.3	31.7	36	82.5	7.1	215.2	24.5	25.1	28.9	85.3	5.9	243.8
	Second	25	24.9	27.9	87.6	5.3	269.6	25.9	19.6	21.5	90.1	4.3	368.5
	Third	22.8	26.3	29.5	84.5	6	241	24.4	21.7	24.4	88.4	4.5	311.4
	Fourth	27	17.4	20.1	90.7	4.2	278.3	23.5	22.1	25.3	86.7	5	288.1
	Fifth	26.9	18.9	20.5	90.8	4.5	391.1	25	18.1	20	90.4	4	375.7
Rainfed	First	21.5	28	31.9	84.4	6.5	233.1	25.5	25.4	29.5	86.2	5.8	249.9
	Second	24.5	24.7	28.3	86.9	5.4	251.4	23.9	24	26.7	87.3	5.2	279.8
	Third	22.8	27.7	31.6	83.8	6.3	218.5	23.9	22.5	25.6	87.8	4.9	295.9
	Fourth	26.9	18.5	21.1	90.6	4.4	323.8	23.3	22.4	25.8	87.4	5.1	282.8
	Fifth	25	20.8	23.8	89.1	5.3	315.4	25	17.3	19.9	91.1	4.1	314.5
Irrigated	First	22.1	29.7	33.8	82.6	7	218.5	23.7	28.8	33.7	82.7	6.7	206.7
	Second	24.7	26.8	30.4	85.7	5.7	239.4	24.2	26.5	29.5	85.6	5.6	244.7
	Third	22.4	29.1	32.9	83.1	6.4	211.8	23.2	25.6	29.2	85.2	5.5	249.9
	Fourth	25.5	23.2	26.1	87.3	5.2	283.9	23.8	25.6	29.3	84.7	5.6	240
	Fifth	25.8	23.1	25.8	87.3	5.6	290.5	25	18.5	21.1	90	4.3	352.6

Supplemental Table 3.7. Cost-benefit analysis of alfalfa hay production under drought, rainfed and irrigated condition in Northeast Kansas.

(values are in US$ per acre)

Treatment	Production year	Revenue	Variable cost	Gross profit	Fixed cost	Depreciation cost	Profit before tax	Sales tax (6.5%)	Net profit ($/acre)	Net profit ($/hectare)
Drought	Year 1	0.00	414.88	-414.88	101.84	0.00	-516.72	0.00	-516.72	-1276.85
	Year 2	2416.00	545.92	1870.08	79.58	0.00	1790.51	116.38	1674.12	4136.84
	Year 3	2304.00	526.59	1777.41	79.58	0.00	1697.83	110.36	1587.47	3922.72
	Year 4	1958.40	466.97	1491.43	79.58	0.00	1411.85	91.77	1320.08	3261.98
	Year 5	1664.64	416.29	1248.35	79.58	0.00	1168.77	75.97	1092.80	2700.36
	Year 6	1414.94	373.22	1041.73	79.58	0.00	962.15	62.54	899.61	2222.97
	Average	1626.33	457.31	1169.02	83.29	0.00	1085.73	76.17	1009.56	2494.67
Rainfed	Year 1	0.00	414.88	-414.88	101.84	0.00	-516.72	0.00	-516.72	-1276.85
	Year 2	2752.00	603.88	2148.12	79.58	0.00	2068.54	134.46	1934.08	4779.22
	Year 3	2592.00	576.28	2015.72	79.58	0.00	1936.14	125.85	1810.29	4473.33
	Year 4	2203.20	509.20	1694.00	79.58	0.00	1614.42	104.94	1509.48	3730.00
	Year 5	1872.72	452.19	1420.53	79.58	0.00	1340.95	87.16	1253.79	3098.17
	Year 6	1591.81	403.73	1188.08	79.58	0.00	1108.50	72.05	1036.45	2561.12
	Average	1835.29	493.36	1341.93	83.29	0.00	1258.64	87.41	1171.23	2894.17
Irrigated	Year 1	0.00	609.66	-609.66	158.60	51.00	-819.26	0.00	-819.26	-2024.43
	Year 2	3088.00	856.62	2231.38	158.60	51.00	2021.78	131.42	1890.36	4671.18

Year 3	3088.00	856.62	2231.38	158.60	51.00	2021.78	131.42	1890.36	4671.18
Year 4	2624.80	776.71	1848.09	158.60	51.00	1638.49	106.50	1531.98	3785.61
Year 5	2231.08	708.79	1522.29	158.60	51.00	1312.69	85.32	1227.36	3032.88
Year 6	1896.42	651.05	1245.36	158.60	51.00	1035.76	67.32	968.44	2393.06
Average	2154.72	743.24	1411.47	158.60	51.00	1201.87	87.00	1114.87	2754.91

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