Benchmarking alfalfa water use efficiency and quantifying yield gaps in the U.S. central Great Plains

by

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Abstract

With an annual production of 116 MMt, the U.S. accounts for 21% of the global alfalfa production. Still, a benchmark for alfalfa water use efficiency (WUE, kg aboveground dry matter per mm water supply) is unavailable, the magnitude of alfalfa yield gaps (YG) remains unknown, and information about management practices to close the yield gap are scarce. Thus, our objectives were to i) benchmark alfalfa WUE, ii) quantify YG in commercial alfalfa fields, iii) characterize current crop management practices adopted by alfalfa producers, and iv) identify management opportunities to improve alfalfa yield, WUE, and reduce YG using a data-rich approach. We conducted a systematic review of the scientific literature that resulted in a final database containing alfalfa forage yield and growing season evapotranspiration (ET_a) for 195 treatment means across 24 manuscripts. The dataset was then used to fit a boundary function that resulted in a benchmark WUE of 33 kg ha^{-1} mm^{-1}. We then collected field-level management information and associated weather, soil, and yield (Ya) data from 394 commercial rainfed alfalfa fields over four harvest years (2016-2019) by interviewing alfalfa growers in Kansas, which accounts for 5% of U.S. alfalfa production, for an assessment of on-farm yield, WUE, and YG. Actual yields in our dataset ranged from 0.9 to 22.4 Mg ha^{-1}, averaging 8.9 Mg ha^{-1}. Average YG against the benchmark WUE was 57% of the water-limited yield (Yw). Conditional inference tree analyses show limited room for improvement of alfalfa yields and WUE through management, as only row spacing, and phosphorus applications were significant managerial factors. To our knowledge, this is the first study in alfalfa WUE benchmark with detailed on-farm assessment of the alfalfa yield-limiting factors, which can serve as a guideline for future studies evaluating WUE and the YG in perennial crops. Our work originated the question of

whether there are fewer opportunities to reduce YG of perennial crops through management as compared to annual crops, which could be the focus of future research.

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Chapter 1 - Review of Literature

Alfalfa Production Overview

Alfalfa (*Medicago sativa* L.) is among the most utilized perennial forages in the world. The crop has vital importance to the dairy and beef industries due to its biomass yield, high energy and protein content (Lacefield, 1988), and the ability for symbiotic nitrogen fixation (Buffum, 1900). Alfalfa can be used for hay, silage dehydrated pellets, grazing, and as a cover crop (Fick and Mueller, 1989). In the United States (U.S.), hay is the fourth most valuable cash crop, behind maize (*Zea maize* L.*)*, wheat (*Triticum aestivum* L.), and soybean [*Glycine max* (L.) Merr.]. In 2019, the U.S. produced 116 million metric tons of hay from a harvested area of 21.2 million hectares. From this total, alfalfa accounted for 43% of the production (~50 million metric tons) and 32% of harvested area (USDA-NASS, 2019). Alfalfa is primarily grown in the northwest and north central regions of the U.S., with the states of Montana (4.1 million metric tons), South Dakota (4.1 million metric tons), Idaho (4 million metric tons), and California (3.74 million metric tons) leading the country in terms of hay production (USDA-NASS, 2019).

In 2019, Kansas ranked seventh among U.S. alfalfa hay producing states with a total 2.3 million metric tons or 5% of total alfalfa hay production in the country. Average state yield was 9 metric tons per hectare and the area sown to the crop was approximately 245,000 hectares (USDA-NASS, 2019). Historically, alfalfa production has been concentrated in the semi-arid region (i.e., western Kansas) of Kansas with ~350-560 mm annual rainfall due to the predominant use of supplemental irrigation (Lollato et al., 2020). In this region, alfalfa is used primarily to supply the beef industry with large number of feedlots and cattle processing facilities. On the other hand, the dry-subhumid region (i.e. central Kansas) with ~560-800 mm annual precipitation and the moist-subhumid region (i.e. easter Kansas) with ~800-1300 annual precipitation (Sciarresi et al., 2019), lack a widespread beef industry with small volume of feedlots, thus growers tend to favor plant annual grain crops. The USDA Farm Service Agency reported a total of 152,430 hectares of dryland and 67,450 hectares of irrigated alfalfa in Kansas in 2018. Relative to alfalfa hay production, alfalfa seed production in Kansas is minute, with 235 hectares and 33,565 kg reported for the entire state in 2017 (USDA-NASS, 2017). Alfalfa yields in Kansas have been stagnant since c.a. 1980 (Figure 1.1, USDA-NASS, 2019), which creates a need for further research aimed at quantifying the yield gap and to identify the factors and current management practices that constrain alfalfa yields to better guide future management recommendations for producers.

Although the U.S. accounts for 21% of the 32 million hectares of alfalfa grown globally (Russele, 2001), a few attempts have been made to quantify the alfalfa yield gap and the underlying sources of constrained yields. Additionally, detailed studies of alfalfa water use efficiency (WUE i.e., aboveground yield per unit of water supply) based on data from commercial fields are inexistent in the U.S. or in the world, unlike soybean (Grassini et al., 2015), maize (Grassini et al., 2011), and wheat (Patrignani et al., 2014; Lollato et al., 2017). Quantifying the WUE of commercial alfalfa fields can originate a benchmark of production relative to a certain level of water supply in the most efficient fields, allowing producers to address different production problems restricting their yield to reach its water-limited potential. Thus, there is a need to develop a WUE benchmark for alfalfa production in rainfed regions of the U.S. to begin closing the alfalfa yield gap.

Definitions of Yield and Yield Gaps

Increasing world population and urbanization will inherently impact forage and livestock demand and production (Godfray et al., 2010a), calling for the need for increased global food production and efficiency in using the available resources (Foley et al., 2005; Tilman et al., 2001). As the demand for high energy foods like milk and dairy products increases (Godfrey et al., 2010b), forage production to feed this demand will be also forced to increase. Within this context, yield gap analysis can help to identify regions in which sustainable increases in food production can be achieved as a result of increasing grain and forage production (Van Ittersum et al., 2013).

Yield gaps are defined by Lobell et al. (2009) as the difference between either the yield potential (i.e., for irrigated cropping systems) or the water-limited yield (i.e., for rainfed cropping systems) and average, farmer-reported yields. Yield potential is the yield of an adapted cultivar when water and nutrients are non-limiting and biotic stresses are controlled (Van Ittersum et al., 2013). As water is the main yield-limiting factor in dryland agricultural systems, the water-limited yield considers the degree of water limitation (Connor et al., 2011) and decreases as the result of an insufficient or untimely water supply (Lobell et al., 2009). There are several methods to estimate yield potential of a crop, including using producer-reported data, crop models, and boundary functions describing the relationship between crop yields and seasonal water supply, (Lobell et al., 2009, Van Ittersum et al., 2013). Yield gaps are the result of sub-optimal manageable factors (e.g., variety selection, fertilizer, sowing date, seeding rate, pest control, etc.) precluding a given field to reach its yield potential.

One way to increase forage production is to decrease the yield gap and improving production efficiency. A number of yield gap studies are available for annual field crops like soybean (Grassini et al., 2015; Nehbandani et al., 2021; Rizzo et al., 2021), maize (Ruffo et al., 2015; ten Berge et al., 2019; Rattalino Edreira et al., 2018), rice (Laborte et al., 2012; Deng et al., 2019; Espe et al., 2016) and wheat (Patrignani et al., 2014; Lollato et al., 2017; Hochman et al., 2016). However, limited research is available regarding yield gaps for perennial and forage crops. For instance, on-farm surveys were used to evaluate oil palm yield gaps in Indonesia (Euler et al., 2016; Monzon et al., 2021) and yield gaps were explored for sugar cane in Brazil (Marin et al., 2016; 2019). For alfalfa, the yield gap in the U.S. was only quantified between average and top growers without necessarily following an established protocol (Russelle, 2013). In China, Wei et al. (2018) found that the alfalfa yield gap was 28% of the potential yield. In Iran, Soltani et al. (2020) estimated that the yield of dryland alfalfa was ~68% of irrigated alfalfa based on a crop model-based statistical framework. Clearly, the few available reports for alfalfa yield gaps around the world have followed different methodologies and the assessment of dryland alfalfa yield gaps following an established protocol may improve the (i) quantification of the actual room for alfalfa production increases; (ii) identification of yield limiting factors; and (iii) may better inform growers to better manage limited resources and make more sound economic management decisions while improving overall production and profitability.

Alfalfa Water Use Efficiency

Water use efficiency (WUE) is often defined as the relationship between the amount of biomass produced per unit of crop evapotranspiration (ET) (Sheaffer et al., 1988b; Grassini et al., 2015; Zhang et al., 2020; Lollato et al., 2019). Since water is usually the main limiting factor in rainfed cropping systems, actual crop evapotranspiration or water use can be used to benchmark production relative to a certain level of seasonal water supply and allow producers to address different production problems restricting their yield. Previous studies have quantified WUE for alfalfa by using the relationship between biomass production and seasonal crop ET (Saeed and El-Nadi, 1996; Sun et al., 2018; Bolger and Matches, 1990). Reported ranges of alfalfa WUE in the literature range from 14.8 to 23.1 kg ha^{-1} mm^{-1} (Sun et al., 2018; Bauder et al., 1978; Bolger and Matches, 1990). Cooler climates produce lower alfalfa WUE values while the opposite is true for hotter climates due to higher ET_a (Sheaffer et al., 1988b).

A boundary function can be used to define the relationship between seasonal precipitation and producer-reported crop yield to estimate the relationship between yield and water supply, usually identifying the limits for WUE and non-productive water losses (French and Schultz, 1984). A boundary function consists of an x-intercept that represents minimum soil evaporation and other unproductive water losses, and a slope defining crop WUE or precipitation use efficiency (kg grain per mm rainfall) (Grassini et al., 2015). This approach has been adopted and WUE benchmarks developed for soybean (Grassini et al., 2015), maize (Grassini et al., 2011; Zhang et al., 2014), and wheat (Patrignani et al., 2014; Lollato et al., 2017, 2019) and for many other crops and resources (Sadras, 2020). However, to our knowledge, boundary functions defining alfalfa water use efficiency and yield gap are inexistent and are needed in rainfed regions to developed a WUE benchmark and to begin quantifying how much of the yield gap is due to sub-optimal management practices.

Tradeoff Between Yield and Quality

The relationship between forage yield and forage quality in alfalfa is usually negative since as plants mature (Ackerly et. al., 2000; Putnam et. al., 2005). Producers have the ability, weather permitting, to allow their cutting schedules to fit the needs of their operation and customers in terms of yield or quality by managing the maturity of their alfalfa at harvest. Early cutting schedules with more total cuttings usually result in higher quality alfalfa but lower annual yields relative to late cutting schedules with less total season cuttings (Putnam et. al., 2005). For instance, Kallenbach et. al. (2002) reported a 23% reduction in yields when reducing the number of in-season cutting times from six times to five times, and a 28% reduction in yields when harvesting five times compared to four times. In Southwest Kansas, Min (2016) reported a 5.58 Mg ha^{-1} increase (36%) in 2-year total alfalfa yields when delaying harvest intervals from 28 days to 42 days.

Alfalfa nutritive value decreases as a result of a declining leaf-to-stem ratio and stem nutritive value due to progressing maturity (Palmonari et al., 2014; Sheaffer et al., 2000; Sanderson and Wedin, 1988). This reduced quality relates to an increase in cell wall (i.e., lignin) material concentration in the stems and leaves (Albrecht et al., 1987). Thus, harvesting alfalfa during the early flower stage relative to late flower stage usually results in higher leaf yields and lower stem yields, higher crude protein, and lower acid detergent fiber (ADF) and neutral detergent fiber (NDF); thus, cutting at the early flower stage of development should be pursued when the goal is to attain higher quality alfalfa (Sheaffer et. al., 2000).

Management Factors Impacting Alfalfa Productivity

Alfalfa Yield and Yield Components

Alfalfa yield per unit are is determined by the yield components i) plants per unit area, ii) shoots per plant, and iii) dry mass of shoots (Volenec et al., 1987). All of these components are affected by forage cutting frequency, although it is still unclear what component has the most influence on yield. For instance, while dry mass per shoot has been suggested as the most influential yield component in several alfalfa studies (Berg et al., 2005; 2007), other studies suggested that shoots per area (Undersander et al., 2011) and shoot height (Ventroni et al., 2010; Griggs and Stringer, 1988) had greatest influence on alfalfa forage yield. If studied further and a general consensus is reached, genetic efforts could be geared toward improving that particular yield component, thus perhaps achieving increased yield gains in alfalfa breeding programs.

Genotype Selection

Selecting a genotype of alfalfa is one of the most important decisions for a successful alfalfa production system as it is a 5- to 10-year investment for a persistent and productive stand (Shroyer et al., 1998). This selection should be based on disease and insect resistance, fall dormancy, and winter hardiness, alongside with the reported variety yield performance in the study region (Shroyer et al., 1998). Varietal selection should also depend on the needs of the operation. For example, dairy operations may opt for a cultivar that offers higher quality while beef producers may prefer cultivars that offer higher yields.

Fall dormancy is one of the most important characteristics to take into account when selecting an alfalfa variety. Fall dormancy is a rating system ranging from 1 to 11 (Kallenbach et al., 2001), with larger ratings reflecting reduced fall growth as a result of decreasing temperatures and day length (Tueber et al., 1998). Ratings increase from northern, colder climates, to southern, warmer climates. Fall dormancy ratings have been proven to have weak genetic relationship with winter hardiness (Brummer et al., 2002; Weishaar et al., 2005). Recommended fall dormancy rating relative to the environment it is adapted for does not always results in higher yields. Ventroni et al. (2010) found that fall dormancy rating made no difference in production over two seasons when subjected to a 20-d, 30-d, and 40-d cutting frequency schedule in temperate Argentina, concluding that short-term stands of dormant-type alfalfa varieties had the potential to succeed in temperate climates under the right cutting frequency schedule. We note that the growing conditions, in particular the thermal regime in Argentina, are not likely representative of those in the majority of the growing region in the U.S. and thus the importance of the dormancy rating may vary. These results agreed with several similar studies concluding that cutting management had a greater impact on yields than did fall dormancy rating

(Gramshaw et al., 1993; Putnam et al, 2005; Putnam and Orloff, 2005). In Kansas, fall dormancy ratings of 3 or 4 are recommended in the northern part of the state and ratings of 4 or 5 are recommended in the southern portion of the state (Shroyer et al., 1998).

Sowing Date

The primary sowing window of alfalfa in Kansas is in the late summer to early fall, but spring sowings are also common, although with an added risk for frost damage and warm-season weed pressure (Shroyer et al., 1998). Late summer to fall plantings of alfalfa in Kansas carry the risk of low soil moisture for stand establishment, but benefits of ideal temperatures and less weed competition, which outweigh the risks of planting in the fall (Shroyer et al., 1998). If sowing in the spring, it is recommended to wait until after the risk of frost to succeed at establishing a stand (Witt and Thompson, 1997). The differing climate in northern and southern central Kansas results in region-specific sowing dates. Fall plantings are recommended from mid-August in more northwestern regions of the state to later plantings in more southeastern regions. Spring planting can be done in April to mid-May in southern and southeast Kansas, while more northwestern parts of Kansas are recommended to plant later in the season (Shroyer et al., 1998). Justes et al. (2002) found that an earlier fall sowing date in France allowed the plants to accumulate root nitrogen reserves that greatly contribute to spring regrowth (Kim et al., 1993). Studies from the northern U.S. focused on spring planting dates (Mueller and Chamblee, 1984; Martin et al., 1983), suggested that sowing as early as possible alongside with appropriate management of soil fertility, variety, seeding rates, and pest management can be a solid foundation for a successful alfalfa stand (Tesar and Yager, 1985).

Plant Density

The alfalfa seeding rate is an important factor conditioning the final plant population (Bastos et al., 2020). The alfalfa seeding rate varies with differing climates, sowing dates, soil type, and soil moisture. Recommended dryland seeding rates are 9 to 13.5 kg ha^{-1} the semi-arid western Kansas, and 9 to 16.8 kg ha^{-1} in the subhumid central and eastern Kansas (Shroyer et al., 1998). Based on the typical alfalfa seed size, these seeding rates usually reflect a range from 4.5 to 8.3 million seeds per hectare, for a final stand goal of 86 to 108 plants per m^2 (Shroyer et al., 1998). Bradley et al. (2010) reported no effect of seeding rates on seeding-year yields in Missouri, Moline and Robison (1971) found that seeding rate was a significant factor on alfalfa yield two years after sowing, suggesting that seeding rates may have a long-lasting an impact on alfalfa yields. These yield effects might result from the effects that seeding rate can have on yield components of alfalfa (Stanisavljević et al., 2012) and on the retention of an adequate plant density after the establishment year (Hall et al., 2004). Expectedly, plant density increases with increasing seeding rate (Kephart et al., 1992); however, excessive seeding rates are not necessarily associated with increased seeding-year yields (Moline and Robison, 1971; Hansen and Krueger, 1973). Established stand plant density has an inverse relationship with the yield component mass $shoot^{-1}$ due to decreasing stem diameter and nodes per stem resulting from the natural compensation that occurs owing to greater competition between plants for resources (nutrients, water, sunlight, etc.) (Sinclair et al., 2020), but has the opposite effect on total yield per hectare (Volenec, 1987).

Pest Management

Kansas producers often have multiple pest management applications a year, mainly owing to alfalfa weevils (*Hypera postica*) and various weed species such as Palmer amaranth

(*Amaranthus palmeri*) and crabgrass (*Digitaria sanguinalis* L.). Weed infestations are common in newer and older stands of alfalfa and tend to infest the stand two to four years after establishment (Moyer and Acharya., 2006), negatively affecting forage nutritive value (Moyer et al., 1999; Cosgrove and Barrett, 1987) but not necessarily forage yields (Cosgrove and Barrett, 1987; Moyer et al., 1990). Dowdy et al. (1993) observed that poor weed control in combination with poor alfalfa weevil control had a 2.4 metric ton year^{-1} yield penalty as compared to the control and negatively impacted stand persistence over a five-year study in Oklahoma: In plots where weed control with herbicides was implemented, alfalfa stand density increased by 30% to 47% over the five years. The authors concluded that the added stress from the alfalfa weevil infestation negatively affected the stand's ability to compete effectively against the weeds.

Sufficient weed control can be achieved by implementing an integrated weed management approach that includes both cultural and chemical management practices (Blecker et al., 2012). Cultural management practices for weed control have been extensively studied and are effective against weed infestations. For instance, fall seeding of alfalfa, which is the most common timing for sowing in Kansas, improves alfalfa competitiveness against weeds as a result of freezing temperatures in the winter and a crop already established when spring weeds emerge (Bradley et al., 2010; Shroyer et al., 1998). Likewise, decreasing the row spacing of alfalfa allows for increased canopy cover that improves the ability of alfalfa to compete for light, water, and nutrient resources (Celebi et al., 2010). Cutting less frequently and at later maturity stages allows alfalfa to compete against the weeds and drastically lowers weed yields (Moyer et al., 1999; Hoveland et al., 1996). Controlling weeds with herbicides like those in the triazine group (i.e., active ingredients atrazine and simazine) and active ingredient bromoxynil in alfalfa stands can have consequences to forage yields due to plant injury (Swan, 1972; Harvey et al., 1976;

Tonks et al. 1991). Even so, stand persistence is positively correlated with herbicide applications and can prolong the life and productivity of a stand (Berberet et al., 1987; Dowdy et al., 1993). Executing control of weeds in thin, highly infested established stands of alfalfa at the first cutting can reduce first cutting yields but the cost of application may be justified on the basis of increased forage nutritive values; meanwhile, control of light non-yield-limiting weed infestations in dense stands of alfalfa may not be economical (Cosgrove and Barrett, 1987).

Alfalfa weevil (*Hypera postica*) was first seen in the United States in 1904 and is one of the most common and economically damaging insects for Kansas alfalfa producers (Whitworth et al., 2011). Alfalfa weevil adults are identified as being light brown with a darker brown line running down the body and have a distinct snout common amongst weevil species. Larvae are small and light green with a distinctive single white stripe down the back. Both the adults and larvae feed on the plant, although the larvae can severely defoliate plants compared to adult weevils, eventually causing the plant to become greyish and with a frosted appearance (Whitworth et al., 2011). There are known to be two strains of alfalfa weevil in Kansas – an eastern strain and a western strain. It is difficult to differentiate between the strains morphologically, although several behavioral, ecological, and physiological characteristics allow for differentiation between the strains (Pellissier et al., 2017). Western strains of alfalfa weevil pupate in cocoons in plant litter on the ground, while eastern strains pupate while attached to the alfalfa plant (Bundy et al., 2005). Western strains males cannot produce progeny with eastern strain females due to a bacterium infecting western strain males (Leu et al., 1989) and eastern strain alfalfa weevils have the ability to defend themselves against Bathyplectes parasitoid wasps, whereas western strains cannot (Maund and Hsiao, 1991). Weevil development is temperature driven with a base temperature of 9 °C (Whitworth et al., 2011). Eggs might be deposited in the fall or spring in the stems of plants, hatch when the accumulated temperature reaches 300 degree-days (base temperature of 48°F), and the majority of the damage is done by the larvae to the first cutting and to the terminal and upper leaves in the thermal window from 450-750 degree-days from the degree day equation used by Whitworth et al., (2011). The economic damage of the alfalfa weevil to the first cut can be high, even approaching 100% loss in severe infestations (Berberet et al., 1987, Wilson et al., 1979). Likewise, lingering economic damage can occur to subsequent cuts, as Wilson et al., (1979) observed a 31 to 55% yield loss in later cuts. Due to weevils becoming active early in the season, proactive scouting, sampling, and following local economic thresholds is the biggest defense against the pest. Harvesting the first cutting earlier to limit feeding damage, removing windrowed alfalfa hay has soon as possible ("greenchop"), and burning during dormancy can decrease alfalfa weevil damage (Summers, 1998). Although an integrated approach of alfalfa weevil control is encouraged to combat chemical resistance, insecticides are one of the most effective management practices against alfalfa weevils and is widely used for control in Kansas. The efficacy in controlling weevils vary by insecticide mode of action, but the most commonly used modes of action are organophosphates, carbamates and pyrethroids (Wright et al., 2015). Consequently, unintentionally controlling natural enemies of the pest and other beneficial insects is a consequence of utilizing insecticides (Pellisier et al., 2017).

Harvest Management

Decisions regarding harvest management influence forage yields, persistence, and nutritive value of alfalfa (Min, 2016; Probst and Smith, 2011; Brink et. al, 2010; Marble, 1974), and harvest management needs to be discussed within the context of the tradeoff between yield and quality, as well as stand persistence. Harvest management decisions include how many times to cut per season and how often to harvest during the season. Cutting frequency has a major impact on both alfalfa forage yields and quality, as well as stand persistence (Min, 2016; Kust and Smith, 1961; Brown et al., 1990; Sheaffer et al., 2000). Often, alfalfa is cut at early bloom stages to balance the yield and quality trade-off (Sheaffer et al., 1988a). Thus, producers seeking excellent quality of alfalfa forage often sacrifice large yields by cutting in the vegetative and early bud stages, while producers seeking high forage yields with average forage quality typically harvest forage at full bloom stage or later. Regarding stand persistence, stands cut too frequently may not have had the ability to store enough carbohydrate reserves in the fall to survive winter (Sheaffer et al., 1988a). Therefore, cutting schedules consider both the yield and quality-tradeoff and stand persistence are crucial to making harvest decisions. Inclement weather at the time of harvest can shorten or extend time between cuttings. As the interval between harvests increases, dry matter also increases (Kallenbach et. al., 2002; Brink et. al., 2010; Brink and Marten, 1989) and quality decreases (Palmonari et al., 2014; Sanderson and Wedin, 1988). Min (2016) examined the influence of four cutting intervals on dry matter yield and nutritive value in irrigated alfalfa in southwest Kansas (28 d, 35 d, 42 d, and 49 d) delaying cutting from a 28 to a 42 day harvest interval increased two-year yields by 26% and had higher crude protein levels compared to delaying cutting from a 28 day to a 49 day interval (5.58 Mg ha^{-1} vs. 2.25 Mg ha^{-1}), leading the author to conclude that a cutting interval of 42 days was optimum when considering both dry matter yield and nutritive value. However, several studies in Minnesota have concluded that the optimum harvest interval is 30 to 35 days between harvests (Brink and Marten, 1989; Sheaffer et al., 1990), with similar results in Georgia (Brown et al., 1990). As days between harvests decrease, the amount of cuttings that can be accomplished in a year increase. In Missouri, Kallenbach et al. (2002) found that alfalfa harvested four times rather than five and six, yielded 7% and 28% more, respectively.

Harvest management decisions have an effect on stand persistence and regrowth rate (Probst and Smith, 2011; Kallenbach et. al., 2002; Sheaffer et al., 1988a). Nonstructural carbohydrate reserves in the roots and crown that are accumulated in the fall by dormant varieties are used for winter survival and spring regrowth (Sheaffer et al., 1988a). Stand persistence can be achieved by indirectly managing these reserves through carefully considering harvest decisions. Intensive harvesting of alfalfa can increase yields in the short-term but yields in subsequent years can be dramatically reduced (Kust and Smith, 1961). Probst and Smith (2011) observed that a 25-day harvest interval had the highest plant mortality across five cultivars differing in fall dormancy and winter hardiness in Kentucky, concluding that a 35 day interval was optimal for stand persistence and long-term production. In contrast, Kallenbach et al. (2002) reported no effect in stand density in alfalfa subjected to different cutting schedules when soil fertility and pest control were sufficient. Cutting immediately prior to the first freeze can reduce stand persistence and winter survival of alfalfa stands (Sheaffer and Marten, 1990), while winter injury can be reduced with good soil fertility and adapted varieties (Tesar and Yager, 1985).

Fertility Management

Nitrogen

Nitrogen (N) plant availability is driven by environmental factors like air and soil temperature, soil moisture, soil pH, organic matter content, and soil texture (Raun and Johnson, 1999). Consequently, N is highly susceptible to loss by denitrification, volatilization, and leaching (Raun and Johnson, 1999). Although alfalfa can fix atmospheric N due to its symbiotic relationship with bacteria from the *Rhizobium* genus (Buffum, 1990), that has an optimum soil pH in the range of 6.5 to 7.0 to ensure nodule colonization and reach peack alfalfa forage production potential (Peters et al., 2005; Kelling, 2000; Lamond, 1998). Still, about 16.8 to 22.4 kg N ha^{-1} might be necessary at sowing if soil N is insufficient to supplement alfalfa seedlings that rely on soil N before nodulation (Lamond, 1998). No later N applications are needed for established alfalfa after ensuring proper nodulation with inoculation of alfalfa seed with the *Rhizobium* bacteria (Lamond, 1998). Additional applications of N can have a negative effect on an alfalfa stand by encouraging growth of weeds (Kelling, 2000).

Phosphorus

Alfalfa yields are influenced by the availability of P either from the soil or applied as P-containing fertilizers. Application of P can increase alfalfa dry matter yield through the yield components shoots $plant^{-1}$ and mass $shoot^{-1}$ (Jones and Sanderson, 1993). The increase of shoots per plant may be the result of a decrease in plants per area over time due to robust plants outcompeting smaller, less competitive plants (Volenec et al., 1986). However, Berg et al. (2005) observed no effect of P fertilization on shoots $plant^{-1}$ and a decline in shoots per unit area over 3 years even with the addition of P. Mass per shoot, as influenced by P fertilization, was the yield component driving increased yields in several studies (Berg et al., 2005; Jones and Sanderson, 1993).

In Kansas, it is recommended to apply P to alfalfa when Mehlich-III soil test P levels are below 25 ppm in the 15 cm topsoil, and recommendations are based on soil phosphorus levels and yield goal (Leikam, 2003). For example, a yield goal of 4.5 Mg DM $hectare^{-1}$ and a Bray P1 test value of 5-10 ppm would generate a recommendation of 84 kg of P $hectare^{-1}$. Dryland alfalfa producers in Kansas often follow a sufficiency recommendation approach for P where the rate of soil P removal by every 0.91 Mg of alfalfa harvested per hectare is 11.2 to 13.4 kg P_20_5 (Lamond, 1998). Common fertilizer supplies of P are diammonium phosphate (18-46-0), monoammonium phosphate (11-52-0), and various animal manures. Fertilizer applied to Kansas dryland alfalfa is commonly done by broadcasting, due to convenience and lower cost relative to streaming and subsurface banding methods. However, Malhi et al. (2001) observed that subsurface banding of P fertilizer resulted in higher alfalfa dry matter yields, phosphorus recovery, and net returns in Canada, despite the higher cost of application compared to broadcasting P.

Potassium

Potassium is the nutrient removed at the highest rates in alfalfa forage, averaging 67 kg K_2O ha^{-1} per metric ton of forage yield (Lamond, 1998). Thus, alfalfa stand persistence and yield relies on the presence of K in the soil or as supplied through common fertilizers such as muriate of potash (0-0-60) and K-Mag (0-0-22-22S-10.8Mg). Studies have shown that sufficient K availability increase alfalfa yields (Berg et al., 2005; Stivers and Ohlrogge, 1953). Although alfalfa stand persistence is a complex mechanism (Berg et al., 2018), where a sufficient supply of K can contribute to stand longevity and productivity (Smith, 1975; Gross et al., 1953). In growth chambers, Collins and Duke (1981) reported increases in chlorophyll concentration and nitrogen fixation rates with increasing K fertilization rates. In Kansas, K fertilizer management is similar to P, based on yield goals and soil K levels. When K levels are below 150 ppm, it is recommended to use an estimated crop removal of approximately 67 kg K Mg^{-1} dry matter harvested. For instance, a yield goal of 4.4 Mg ha^{-1} and a soil exchangeable K level of 40-80 ppm requires 62 kg ha^{-1} of K_2O (Leikam, 2003).

Sulfur

Sulfur plays many vital roles in plants, from the synthesis of amino acid (Coleman, 1966) to the formation of chlorophyll (Duke et al., 1986). It is the fourth most important nutrient in terms of plant absorption only behind N, P, and K (Tabatabai, 1984). Precipitation, mineralization of organic matter, and organic or inorganic fertilizers are the primary source of S to plants. Declining organic matter in cultivated soils relative to native vegetation (Lollato et al., 2012) and the decline of S deposited by rain due to improved air quality resulting from the 1990 US Federal Clean Air Act (Sullivan et al., 2018) are two main reasons agronomic responses to S applications are becoming more common in recent years (Wilson et al., 2020; Jaenisch et al., 2019). Organic matter is an important supplier of N and S (Stewart and Whitfield, 1965); thus, soils with less organic matter will be able to supply less S for agricultural crops. Consequently, alfalfa grown on sandier and lower organic matter soils are likely more exposed to S deficiency and will typically be more responsive to a sulfur fertilizer application as it can also increase nodule numbers (Collins et al., 1986).

Common S-containing fertilizers used on Kansas alfalfa are MicroEssentials SZ (MESZ, 12-40-10S-1Z), ammonium sulfate (21-0-0-24S), 40 rock (12-40-0-6.5S-1Z) and elemental sulfur (90-95% S). The plant available form of S is sulfate (SO_4^{-2}) (Kopriva et al., 2015), while elemental S requires several months of weathering before it is plant available (Kulczycki, 2021) to allow the conversion of the organic S to sulfate (Lang et al., 2007). The MESZ fertilizer contains a 5% to 5% mix of sulfate/organic form S and elemental sulfur, while ammonium sulfate and 40-rock contain sulfate and elemental sulfur as their sulfur source, respectively. However, Seim et al. (1969) reported no difference in alfalfa yields in Minnesota between gypsum (calcium sulfate) and elemental sulfur fertilizers despite a threefold yield difference between fertilized and untreated plots. Sulfur recommendations for alfalfa in Kansas are typically based on forage yield goal, content of soil organic matter, and sulfur levels in the soil profile (Leikam et al., 2003). Alfalfa removes 0.45 kg S for every 0.9 metric ton ha^{-1} produced (Lamond, 1998). Additionally, routine soil testing is still needed on heavier soils to determine the sulfur needs of the crop.

On-Farm Surveys

The majority of the information provided above on the impact of different management practices on alfalfa yield was developed based on small, plot-level replicated experiments where one or a few factors are manipulated at a time. Small-plot experiments are practical and have been the backbone of agricultural experimentation because they meet the assumptions that enable causal inference between the evaluated factors and yield (Hoshmand, 2006). On the contrary, field-level experiments only allow for evaluation of a few practices at a time and require replication across multiple environments to generate meaningful research findings, which can can be cost prohibitive (van Ittersum et al., 2013). Alternatively, on-farm surveys where management and yield data are collected at the field level directly from producers, offer a unique opportunity to i) quantify current management practices adopted in commercial fields; ii) identify promising management practices associated with increased yields; and iii) quantify the extent of water limitation in dryland environments, all while evaluating a large number of explanatory variables simultaneously.

The use of on-farm surveys has increased in agriculture in recent years. For instance, on-farm data has been utilized to quantify the impact of agronomic practices on yields and identify sub-optimal management with several major annual crops like wheat, soybeans, and corn (Grassini et al., 2011, 2015; Lollato et al., 2019, Villamil et al., 2012) driven by the need to close yield gaps (Rattalino Edreira et al., 2017). Data from on-farm sources have been obtained from yield contests (Villamil et al., 2012), innovative and leading farmers (van Rees et al., 2014), and on-farm surveys (Grassini et al., 2011). Results from the aforementioned analyses are promising in suggesting avenues for future yield increases. For instance, in the U.S Corn Belt, sowing date, tillage practices, fertilizer, and foliar fungicide were the most important contributors to increased soybean yields (Grassini et al., 2015). In the same environment, crop rotation, tillage system sowing date, and plant population density were more important factors leading to increased corn yields (Grassini et al., 2011). We note in passing that there are disadvantages of on-farm surveys versus replicated experiments, including the accuracy of producer-reported data, lack of control treatment and replication, and the inability to establish cause and effect relationships – only indicating significant associations instead (Mourtzinis et al., 2018; Rattalino Edreira et al., 2017; Grassini et al., 2011; 2015; Villamil et al., 2012; Lollato et al., 2019).

While substantial efforts occurred for annual crops, the impacts of management practices using on-farm data on perennial crop yields such as alfalfa, have been scarce. Euler et al. (2016) surveyed management practices and yield of oil palm growers in Indonesia, concluding that sub-optimal management practices including fertilizer application rate and length of harvest interval were mostly to blame for more than 50% smaller yields in smallholder operations relative to larger plantations. The authors suggested that changing management practices on smallholder oil palm operations could provide an opportunity to decrease exploitable yield (50%) and increase productivity in the region. A similar study in Indonesia found a 62% and 53% yield gap for large and smallholder plantations and suggested that the intensification of existing operations by improving agronomic management could potentially save 2.6 million hectares of fragile ecosystems that would otherwise be cleared for oil palm production (Monzon et al., 2021). Another example of on-farm surveys for perennial crops includes that for sugar cane, in which a yield gap of 38% was observed in Brazil, leading the authors to conclude that without a significant increase in sugar cane yields, land requirements would need to expand by 5% and 45% for low- and high-demand situations to meet future demand (Marin et al., 2016). Marin et al. (2019) suggested that sub-optimal management accounted for the sugarcane yield gap in Brazil after comparing the effect of harvest management on yield of commercial operation on-farm data to controlled experiments.

To the best of our knowledge, there have been no surveys of alfalfa management practices and associated grain yield performed in the world. A survey of alfalfa management adopted in commercial fields and its associated forage yield could help characterize current management of commercial dryland alfalfa yields, as well as identify opportunities to improve recommendations and yield, increasing productivity and WUE of dryland alfalfa. Thus, our objectives were to i) characterize current crop management practices adopted by alfalfa producers in commercial operations, ii) identify management practices associated with highest (and lowest) yields and their dependency on weather, and iii) quantify the extent of water limitation in dryland alfalfa fields in central Kansas. Our hypothesis is that most rainfed fields sown to alfalfa in central Kansas are well below their potential yield and WUE, and an on-farm survey will be useful to characterize management practices leading to increased yields and to benchmark attainable WUE.

Figures

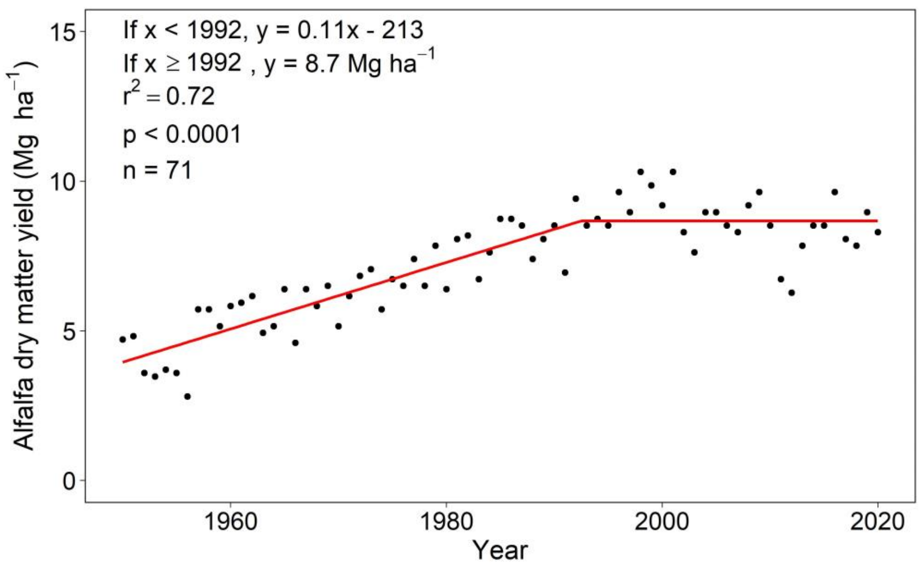

Figure 1.1. Alfalfa hay yield from 1950 to 2020 in Kansas. Data were obtained from the USDA National Agricultural Statistics Service. Relationship between alfalfa yield and year shown using fitted linear plateau model using non-linear regression.

Chapter 2 - Benchmarking Alfalfa Water Use Efficiency and Quantifying Yield Gaps in the U.S. Central Great Plains

Introduction

Alfalfa is an important perennial forage legume of high nutritional value and broad adaptation (Diatta et al., 2021). Approximately 211 MMt of alfalfa are grown annually on about 30 Mha across the world for hay, haylage, silage, and pasture (Acharya et al., 2020; Putnam et al., 2007; Research and Markets, 2020). As a perennial crop, alfalfa roots extend deep into the soil profile (Bauder et al., 1978; Carter and Sheaffer, 1983) although approximately 80% of the active root system (by mass) is usually concentrated in the upper 60 cm (Fan et al., 2016). Alfalfa is recognized as a crop able to tolerate mild soil water stresses, but forage production is often reduced by water deficit stress (Carter and Sheaffer, 1983). Management and breeding have improved alfalfa yields by increasing transpiration (Johnson and Tieszen, 1994), though WUE has stayed constant (Tanner and Sinclair, 1983). Although the U.S. accounts for as much as 21% of the area cultivated with alfalfa globally (Russele, 2001), efforts to benchmark on-farm alfalfa WUE and to quantify alfalfa YG have been scarce.

Water use efficiency (WUE) is the net carbon assimilated per unit transpiration (Fischer and Turner, 1978), many times measured as the ratio of crop dry biomass (or grain yield) over water consumed either as transpiration (T), evapotranspiration (ET), or water supply during the season (Sinclair et al., 1984). Alfalfa WUE has been quantified in individual studies as the relationship between biomass production and seasonal crop ET (Saeed and El-Nadi, 1996; Sun et al., 2018; Bolger and Matches, 1990) with WUE often ranging between 15 and 23 kg ha^{-1} mm^{-1}

(Sun et al., 2018; Bauder et al., 1978; Bolger and Matches, 1990). Lindenmayer et al. (2011) summarized a number of studies evaluating alfalfa biomass yield and water use to determine an average WUE of 16 kg ha^{-1} mm-$^{-1}$. However, these WUE estimates are considerably below a theoretical maximum WUE for alfalfa of 43 kg ha^{-1} mm^{-1} (or 32 kg ha^{-1} mm^{-1} excluding roots) at a vapor pressure deficit of 1 kPa (Tanner and Sinclair, 1983). These discrepancies between the average and the maximum theoretical alfalfa WUE have two implications: First, they suggest a considerable gap between actual and potential alfalfa WUE that can be explored to improve yields. Second, they warrant further investigation into alfalfa WUE to define a benchmark combining field measured data with a boundary function that producers can utilize to compare their productivity to at a certain level of water supply.

In drought-prone environments, where water supply is not enough to satisfy crop water requirement, water availability constrains attainable crop yield (Passioura et al., 1977). A proposed framework to determine attainable yield based on water availability is that of boundary functions, in which crop productivity is plotted against seasonal water supply (or ET) and a linear function is fitted to the most efficient points that define the upper limit of water-limited yield (Yw) (French and Schultz, 1984). At the farm level, actual yields (Ya) are usually well below the Yw due to other limiting factors (e.g., sub-optimal fertility, weed or disease control, timing of farming operations). This difference between Yw and Ya is known as yield gap (YG) (Neumann et al., 2010). Boundary functions have been used to benchmark WUE and quantify YG for a number of crops, including wheat (*Triticum aestivum* L.) (French and Schultz, 1984; Sadras and Angus, 2006; Patrignani et al., 2014; Lollato et al., 2017), sunflower (*Helianthus annuus* L.) (Grassini et al., 2009), maize (*Zea mays* L.) (Grassini et al., 2011, Zhang et al., 2014), and soybeans (*Glycine max* L. Merr.) (Grassini et al., 2015).

Likewise, efforts to quantify alfalfa YG have been limited. One of the most comprehensive alfalfa yield gap studies in the U.S., using several different data sources and methodologies suggest a YG of 50-67% for both irrigated and rainfed alfalfa production (Russelle 2013). However, despite the use of a number of approaches (i.e., survey of crop consultants, alfalfa cultivar performance trials, official census of agriculture, and on-farm yields from 1970-1980s), Russelle (2013) neither accounted for the effect of seasonal water supply when quantifying attainable yields, nor quantified the impacts of management practices on forage yields and YG. In China, the alfalfa YG was estimated from a synthesized dataset made of data collected from published articles at 28% of the potential yield (Wei et al., 2018). Crop models have also been utilized to estimate the dryland alfalfa YG at 69% of the Yw in Iran but included no data from on-farm or replicated studies (Soltani et al., 2020). To our knowledge, there have been no attempts to quantify alfalfa YG using data collected from growers, which may offer a more accurate depiction of the state of WUE and forage YG at field-level and has potential to reveal real-world management opportunities to increase WUE and close YGs.

On-farm surveys where management and yield data are collected at the field-level offer a unique opportunity to quantify current management practices adopted in commercial fields; to identify promising management practices associated with increased yields; and to quantify the extent of water limitation in dryland environments, all while simultaneously evaluating a large number of explanatory variables. The use of on-farm surveys has increased in agriculture in recent years with especial focus on quantifying the impact of agronomic practices on yields of major annual crops like wheat, soybeans, and corn (Grassini et al., 2011, 2015; Lollato et al., 2019, Villamil et al., 2012) driven by the need to reduce YG (Rattalino Edreira et al., 2017). While substantial surveying efforts occurred for annual crops, the impacts of management practices using on-farm data on perennial crop yields such as alfalfa, have been scarce. The only examples evaluating on-farm data for perennial crops that we are aware of relate to oil palm (Elaeis guineensis) in Indonesia (Monzon et al., 2021; Euler et al., 2016a,b) and sugar cane (Saccharum officinarum) in Brazil (Marin et al., 2016).

To our knowledge, no attempt has been made to benchmark alfalfa WUE, nor have on-farm surveys of management practices and associated alfalfa yield been performed in the world, despite the potential of these analyses to identify opportunities to improve yield and WUE. Thus, our objectives were to i) benchmark alfalfa WUE using a literature synthesis, ii) quantify forage yield gap and yield-limiting factors using a comprehensive on-farm survey, and iii) identify management opportunities to increase WUE and close the YG of alfalfa. We used rainfed alfalfa cultivated in Kansas, U.S., as a case study to test the hypothesis that most alfalfa fields are well below their potential yield and WUE.

Materials and Methods

Benchmarking Alfalfa Water Use Efficiency: A Literature Synthesis

A database was synthesized using published studies in the scientific literature to quantify alfalfa WUE, which was defined as the aboveground forage yield per unit of growing season actual crop evapotranspiration (ET_a). in alfalfa across a large and diverse set of studies that represented many climates and growing conditions. The Google Scholar database was searched six times for articles containing the keywords “Alfalfa + evapotranspiration”, “*Medicago sativa* + evapotranspiration”, “Lucerne + evapotranspiration”, “Alfalfa + water use”, “*Medicago sativa* + water use”, and “Lucerne + water use” in their title (accessed on July 2021). Data was retrieved from published journal articles and dissertations, the latter to avoid publication bias (McLeod and Weisz, 2004). All manuscript and dissertations in each search were downloaded and stored. Then, each document was visually screened to check for a specific minimum criteria for inclusion in the final database. Criteria for manuscript or dissertation inclusion were: i) plot experiments conducted under field conditions (i.e., simulation exercises and controlled-environment studies were disregarded) with data reported by site-year (i.e., no aggregated data across environments were included); ii) experiments reported measured ET_a or crop water use (i.e., articles reporting only potential ET were disregarded), iii) experimental location and site-year were reported, iv) forage yield and ET_a were reported on (or allowed for calculation of) a per-year basis, and v) field experiments were conducted after 1990 to avoid important time trends in yield.

Information extracted from the resulting papers included authors, journal, institution, country, experiment location and years, treatments, and variables required to compute ET_a and alfalfa yield (Mg ha^{-1}). When necessary, data were extracted from tables and figures using the Web Plot Digitizer software (https://automeris.io/WebPlotDigitizer/). The locations of the study sites were used to determine the mean annual rainfall and mean temperature of the experimental site. From this, environments were classified according to the De Martonne aridity index (I_{DM}) (Croitoru et al., 2012) which considers mean annual precipitation (P, mm) and mean annual temperature (Ta, ºC) (Eq. 1):

$$IDM = P/(T_a+10) \quad [1]$$

Classes of I_{DM} were further clustered into two groups: a semi-arid group with I_{DM} <30 (including arid, semi-arid, and Mediterranean) and a humid group with I_{DM} >30 (including semi-humid, humid, and very-humid). Crop ET_a was plotted against crop yield and their relationships were explored using linear and quantile regression (Koenker and Bassett, 1978). First, an individual linear regression across all points within each of the two I_{DM} classes (e.g., semi-arid or in humid environments) was used to quantify the average alfalfa WUE in these environments. Subsequently, a quantile regression (Koenker and Bassett, 1978) was used across the entire dataset to determine the WUE benchmark as the boundary function. Here, the range in which alfalfa yield was responsive to increases in water supply (i.e., from 47 mm to 588 mm) was split into 10 equally spaced intervals and a linear regression was fit at the 95^{th} percentile of each of the intervals. The slope of the linear equation represents maximum alfalfa WUE in kg ha^{-1} mm^{-1}, and the *x*-intercept represents the minimum water losses during the growing season.

The robustness of the WUE benchmark was tested in two different ways. First, we tested it against a previously published review of alfalfa WUE that focused on two U.S. alfalfa growing regions and that used manuscripts with field experiments conducted exclusively prior to 1990 (Lindenmayer et al., 2011). This review consisted of nine field studies that occurred from 1966 to 1987 and included experiments in eight U.S. states. Only studies with a complete report of water use were included in the review. We note that dataset from this previous review was not included in the development of our boundary function, but is provides a baseline to create a first-order approximation of the WUE computed in our study. Second, we tested the WUE benchmark against the output of a comprehensive long-term crop modeling exercise on a number of locations (see section Simulated alfalfa water use efficiency below).

Simulated Alfalfa Water Use Efficiency

We simulated daily alfalfa growth and forage yield using the SSM-iCrop2 crop simulation model, which is a simple and transparent mechanistic crop model that requires minimal inputs (Soltani et al., 2020a,b). Atmospheric variables required by the model include minimum (Tmin) and maximum (Tmax) air temperature, precipitation, and solar radiation. Soils variables include crop rooting depth, albedo, runoff, soil curve number, drainage factor, terrain slope, and volumetric water content at saturation, at the drained upper limit (i.e., field capacity), and at the lower limit (i.e., permanent wilting point). Crop simulations generated daily (i) plant phenology and development based on cumulative degree days and impacted by water stress and photoperiod; (ii) leaf area development and senescence, based on phyllochron, leaf number, and leaf area; (iii) dry matter accumulation and allocation, and (iv) soil water balance, in which transpiration is calculated based on dry matter production and vapor pressure deficit. The SSM-iCrop2 model has been calibrated and validated for a range of annual and perennial crop species (Soltani et al., 2020a,b).

In the current study, we collected parameter values from previous model application for alfalfa (Soltani et al., 2020a), as many parameters in this model are constant for a given species (Soltani and Sinclair, 2012; van Loon et al., 2018). Next, we selected 23 weather stations within the state of Kansas, US, that represented a range in climatic conditions (Sciarresi et al., 2019) and for which 30 consecutive years of daily weather data was available from the Kansas Mesonet (Patrignani et al., 2020). A detailed description of soil data, weather data, and data quality control is available in Lollato et al. (2017). In the current study, alfalfa simulations were conducted assuming rainfed conditions and spanned the period between 1986-2016, resulting in a total of 690 simulated site-years. The output of these long-term simulations were used in two different ways: First, we used the simulated alfalfa annual yield, actual ET, and crop T to ground truth the robustness of the boundary function developed using the dataset obtained from the literature. Second, the simulated data was used to develop a simple linear model of available water remaining at the onset of winter dormancy in the fall as function of growing season rainfall, which was used when determining available water in the season for fields surveyed (see section Yield gap, WUE, and Water Excess Calculations below).

Survey Data Collection

Ranking seventh in the U.S. for alfalfa hay production, Kansas produces approximately 2.3 MMt of alfalfa harvested from ~100,000 hectares (USDA-NASS, 2019), which is primarily used to supply the large number of feedlots in the west and smaller cattle producers in the east. This region serves as an interesting case-study for alfalfa YG analysis as it is characterized by severe yield stagnation since 1992 (Fig. 2.1). Yield stagnation can be a consequence of either the Ya approaching Yw, or of sub-optimal management practices limiting Ya (Grassini et al., 2013). We hypothesize that a detailed on-farm survey including information about alfalfa forage yield and management practices can disentangle which of the aforementioned causes is leading to alfalfa yield stagnation in this region. The typical weather and soils conditions in this region have been described in detail elsewhere (Lollato et al., 2020). Briefly, the annual rainfall in Kansas ranges from ~450 mm in the west and to ~1100 mm in the east. The dominant soil order in the region is Mollisols (Lollato et al., 2020). Summer crops (soybean, maize, grain sorghum), as well as winter crops, mainly winter wheat, are commonly grown in rotation.

Contact information of alfalfa growers in central Kansas were collected via electronic mail from county and district extension agents, agricultural retailers, and attendees of outreach meetings conducted prior to the beginning of this study that resulted in a total of 141 contacts. We contacted all growers on this list, and we successfully interviewed 54 growers with a success rate of 38%. A survey (Table 2.1) was completed by producers via e-mail, phone, or via in-person interviews. The questionnaire was approved by the Committee for Research Involving Human Subjects (Kansas State University Application number 9941). Producers signed a data sharing agreement that permitted the use of the individual field-year data and the presentation of aggregated data for privacy protection. Data was collected exclusively from rainfed (non-irrigated) alfalfa fields for the 2016, 2017, 2018, and 2019 cropping seasons. The resulting database represented 394 field-years consisting of one year of field-specific data (Fig. 2.2).

The survey was composed variables that allowed for calculation of 51 management practices that were either field-specific (i.e., those adopted before or at crop establishment) or field-year specific (i.e., those adopted in individual years within the same field). Field-specific variables included previous crop species, tillage method (i.e., no-till, conservation tillage, and minimum tillage), cultivar name, cultivar traits (i.e., glyphosate resistance and low-lignin), companion crop (if yes, species provided), seed treatment, seed inoculant, row spacing, seeding rate, furrow fertilizer, sowing date (month and year), grazing regime, and lime application. Field-year specific variables included applied input product, rate, application method, and timing (i.e. insecticide, herbicide, fungicide, N, P, K, S, Zn, and B fertilizer; and manure), phenological stage at cutting, prevalent pests and/or diseases, and other issues that could affect yield (e.g., flooding, weed pressure, hail, etc.). Sowing date was limited to sowing month and year due to lack of precise records from producers. Tillage method was clustered into no-till and conventional tillage groups to simplify the analysis. Other variables that were calculated from the original data included rate of nutrient applied (based on fertilizer source and rate) and stand age (harvest year minus sowing year). Producers verbally reported alfalfa hay yields as total Mg ha^{-1} or total hay bales produced per year per field, in which case they were also asked to supply an average hay bale weight.

Soil and Weather Data from Surveyed Fields

Field-specific soil available water holding capacity (AWHC) and textural class were obtained for the 0-20 and 20-180 cm depths from the USDA Web Soil Survey Geodatabase (USDA-NRCS, 2015) using the geographic coordinates of each field supplied by the grower. If a field had more than one soil series, the AWHC and soil texture class percentages were weighted based on the percent of each soil series present. Likewise, the AWHC and soil textures of the 0-20 cm and 20-180 cm sections of the soil profile were weighted to describe the full soil profile (0-180 cm). A soil profile depth of 180 cm was sufficient to represent alfalfa rooting depth (Fan et al., 2016).

Field-specific daily weather observations from 1 January 2015 to 31 December 2020 were obtained from in-situ stations from federal, regional, and state weather and climate networks. Data collected included precipitation, maximum (Tmax) and minimum (Tmin) air temperatures, solar radiation, and reference evapotranspiration (ET_o). For daily Tmax, Tmin, and precipitation, data were collected from weather stations from the National Weather Service Cooperative Observer Program and Automated Surface Observing Systems in Kansas, which includes 455 stations. The data quality control and data assurance for these stations were implemented by Applied Climate Information System for daily maximum and minimum temperature as well as precipitation (Leeper et al., 2015). For the daily solar radiation, relative humidity, and reference evapotranspiration, we used the 63 Kansas Mesonet stations across Kansas. All these station's daily data were re-assured additionally by using two criteria: (1) outliers in daily maximum and minimum temperature were identified as those stations were more than 3.5 standard deviation away from climatological mean temperature for each day of the year (Frich et al., 2002); and (2) daily homogeneity of temperature and precipitation observations were visually assessed by the monthly average time series because our study period is relatively short. Our studying site's weather data were then interpolated by using natural neighbor interpolation method (Amidror, 2002) on a daily step.

For each field-year, the growing season was determined by screening weather data for the last day in the spring and for the first day in the fall when Tmin reached -2.8℃, as this is a threshold below which substantial damage to alfalfa vegetative tissue occur, triggering dormancy (Sprague, 1955; Nath and Fisher, 1971; McKenzie and McLean, 1982). The start of the growing season was determined as the last occurrence of -2.8 ℃ in the spring, while the end of the growing season was determined as the first occurrence of -2.8 ℃ in the fall. For each field-year, weather variables were then calculated for the growing season bounded by the days determined in the analysis above, and for the preceding winter season (i.e., from dormancy of previous year alfalfa to dormancy-release of current-year alfalfa). Cumulative precipitation, solar radiation, growing degree days, and ET_o, and average Tmax and Tmin, the ratio of cumulative precipitation to cumulative evapotranspiration, and the number of days in the season were calculated for each field-year.

Yield Gap and WUE Calculations

The WUE benchmark determined based on the literature synthesis was used to estimate field-year specific Yw using water supply or WS (growing season rainfall minus the water loss and was capped at 22.4 Mg ha^{-1} or the maximum yield reported in the on-farm data (705 mm water supply). We note that this simpler approach using growing season rainfall, as well as an annual rainfall approach, resulted in similar YG rankings as compared to a more complex approach attempting to estimate available water in the season (Fig. 2.8). Yield gaps (YG) were determined for each field-year as the difference between Yw and actual field-year yield (i.e., vertical yield gap). Alfalfa WUE was calculated for each field-year as the ratio of annual alfalfa yield over total water supply in the season.

Statistical Analyses

Variation in producer-reported management practices, weather variables, and alfalfa yield were described using frequency distributions and descriptive statistics. Conditional inference trees (CIT) were used to understand the ranking and effect of weather and management on different response variables. A total of four trees were trained, one for each of the response variables yield (kg ha^{-1}), YG (Mg ha^{-1}), WUE (kg ha^{-1} mm^{-1}), and WE (mm). For each tree, a total of 57 explanatory variables were used, including 34 weather and soil variables, and 23 management variables. Management variables with greater than 40% missing observations were excluded from these analyses and a total of 11 variables excluded from the CIT analysis for this reason. The weather variables included in the CIT were cumulative rainfall, cumulative solar radiation, cumulative ET_o, number of days in the season, the ratio between cumulative precipitation to ET_o, and average temperature of the growing season, winter season, and both seasons combined. Growing season rainfall minus the water loss and annual rainfall minus the water loss were also included, as well as the seasonal water supply (water available at green-up combined with growing season cumulative rainfall, see Box 1).

Each tree was trained by first splitting the entire data set (n = 394) into 80% training and 20% test sets. The training set was then used to fine-tune the model significance level for variable selection into the tree and the maximum tree depth. Hyperparameter tuning was performed by first iterating the model on a regular grid space with all combinations between significance levels (0.01, 0.07, 0.15) and tree depth levels (2, 4, 7) using 5-fold cross validation with 10 repeats. The results from the regular grid search were then used as initial values on a gaussian process search model to explore areas of the search space in-between the grid values. The final hyperparameter values, selected from the most parsimonious model within one standard error of the greatest r^2 model, were then used to fit a final model on the training set. Model fit metrics of $r^2$and root mean-squared error (RMSE) were calculated both on the training set and testing set (unseen during training process). Each observation on the training set was classified as its corresponding terminal node in the tree, and a linear fixed-effect model was run to assess the effect of terminal node on the response variable of the tree. Model means were extracted and pairwise comparisons conducted at alpha=0.05. CIT were fit with function *ctree* from package *partykit* (Hothorn and Zeileis, 2015; Hothorn et al., 2006). Model training was performed using functions from the *tidymodels* family (Kuhn et al., 2020).

Results

Alfalfa Water Use Efficiency Benchmark

Our systematic review of the literature resulted in a final database reporting alfalfa yield and ET_a from 24 manuscripts and 195 treatment means fulfilling all the minimum criteria (Table 2). Alfalfa yield ranged from 0.6 to 22 Mg ha^{-1} and alfalfa ET_a ranged from 47 to 1049 mm. A total of 70 points were classified as semi-arid and 123 points as humid. One datapoint was excluded as it derived from irrigated alfalfa in a desert environment and had an ET_a of 2016 mm.

A boundary function between literature-reported yields and ET_a across the entire database resulted in an *x*-intercept = 25 and slope = 33 ± 2.4 kg ha^{-1} mm^{-1} (Fig. 2.3a). This slope is equal to that of boundary functions created independently by climate (i.e., slope = 29.3 ± 1.1 for humid and 29.4 ± 0.97 mm for semi-arid, data not shown). Average WUE (i.e., the linear regression across all datapoints) was also not statistically different for semi-arid and humid climates (17 ± 0.9 and 18 ± 0.6 kg ha^{-1} mm^{-1}; inset of Fig. 2.3a). The slope of the boundary function based on literature data was robust, as its confidence interval (CI, 27 to 38 kg ha^{-1} mm^{-1}) overlapped with that of a boundary function created between simulated alfalfa yield-ET_a (CI = 26-31 kg ha^{-1} mm^{-}

^{1}) (Fig. 2.3c); as well as with the slope of the boundary function derived from the re-analysis of the previous literature review by Lindenmayer et al. (2011) (CI = 17-28 kg ha^{-1} mm^{-1}) (Fig.2.3b). However, the relationships between simulated yield-ET_a, or between the previously published review on yield-ET_a, both suggested positive *x*-intercepts of 108 and 50 mm, respectively (Fig. 2.3b,c). The *x*-intercept of boundary functions is meaningful, as it represents the annual amount of annual soil water evaporative losses. Because the x-intercept from our data synthesis was 25 mm and because E usually accounts for ~20% of total ET in alfalfa (Wagle et al., 2020), we adopted a 25 mm *x*-intercept in the remaining analyses.

Growing Season Weather of Surveyed Alfalfa Fields

The start of the growing season among the surveyed fields ranged from day of year (DOY) 74 to 117, and the onset of fall dormancy ranged from DOY 285 to 326 (Fig. 2.4A). Growing season rainfall ranged from 429 to 1173 mm, with 2017 being a dryer year (612 ± 10 mm) compared to the remaining years (728 ± 5 mm, Fig. 2.4B). Seasonal water supply (SWS) across field-years averaged 780 mm and ranged from 526 to 1356 mm (Fig. 2-4C). Growing season ET_o spanned a narrower range than SWS and ranged from 829 mm in 2019 to 1163 mm in 2017 (Fig. 2.4D). Growing season average temperature ranged from 18.9 to 22.4°C and was higher in 2018 (21.4 ± 0.05 °C, Fig. 2.4E). Growing season solar radiation was lower in 2018 (3783 ± 22.2 MJ m^{-2}, Fig. 2.4F) compared to other years and ranged from 3484 to 4989 MJ m^{-2}.

Alfalfa Management Among the Surveyed Fields

Stand age averaged 3.5 years and ranged from less than one to ten years among the surveyed fields. Stand age between one and six years had no apparent effect on alfalfa attainable yield (15.5 ± 0.5 Mg ha^{-1}), but stand ages of less than one or more than six years reduced attainable yield to the 6.7-12.6 Mg ha^{-1} range (Fig. A.1). The majority of surveyed growers sowed their alfalfa fields in the fall (81%), treated their seed with fungicide and/or insecticide (84%), and inoculated their seed with rhizobium bacteria before planting (92%) (Table 3). We note in passing that fields sown in the fall had greater first-year yield than fields sown in the spring (9.4 vs. 7.4 Mg ha^{-1}) partially due to the potential for a greater number of cuts in the first year (3.9 vs 3.2 cuts) (Fig. A.2). While the majority of producers adopted conventional tillage (78%), the least adopted practices in the surveyed fields included low-lignin cultivars (2%), in-furrow fertilizer (17%), companion crops (3%), grazing (10%), and foliar fungicides (1%). Year-specific inputs such as phosphorus (38.7 ± 1.5 kg ha^{-1}, 78%), herbicides (8.66 ± 0.22 kg ha^{-1}, 66%), and insecticides (9.1 ± 0.2 kg ha^{-1}, 88%) were applied to most fields and years (Fig. 2.5). Other nutrients including potassium (20.3 ± 1.9 kg ha^{-1}, 40%), sulfur (3.7 ± 0.4 kg ha^{-1}, 32%), and micronutrients (24%), boron (0.14 ± 0.03 kg ha^{-1}) and zinc (0.3 ± 0.04 kg ha^{-1}), were adopted at lower frequency than that of phosphorus. The average number of cuttings per season was four (53% of surveyed fields), while about 22% of the fields had fewer cuts per season and about 25% of fields were cut five times per season. Number of cuts per season associated positively with annual alfalfa yield (Fig. A.3).

Alfalfa Ya, YG, and WUE

Alfalfa Ya averaged 8.9 Mg ha^{-1} and ranged from 0.9 to 22.4 Mg ha^{-1} across the surveyed fields (Fig. 2.6A). Alfalfa Yw ranged from 13.3 to 22.4 Mg ha^{-1} and averaged 21 Mg ha^{-1} (median = 22.3 Mg ha^{-1}) (Fig. 2.6B), resulting in YG ranging from null (negative or no yield gap) to 96% of Yw and averaging 57% (median = 59%) (Fig. 2.6C). The smallest average YG occurred in 2017 (53 ± 0.02%, median = 57%), while the largest average YG occurred in 2018 (66 ± 0.02%, median = 69%). Field-level alfalfa WUE averaged 13 ± 0.3 kg ha^{-1} mm^{-1} and ranged from 1 to 38.2 kg ha^{-1} mm^{-1} (median = 12.2 kg ha^{-1} mm^{-1}) (Fig. 2.6D).

Interaction of Weather, Soil, and Management Practices on Alfalfa Yield

Across all 394 field-years, the CIT explained 23% of the variability in yield, with a RMSE of 3.51 Mg ha^{-1} (Fig. 2.7a). Soil AWHC was the most important factor associated with increased Ya: In fields with AWHC greater than 354 mm, the highest yields resulted from fields receiving a phosphorus application and adopting crossed row spacing (i.e. sown again at the initial planting date at a 90-degree angle to the first sowing). Across lower yielding fields with AWHC less than 354 mm, yields depended on the winter season ET_o (split at 328 mm). The CIT for YG explained 31% of the variability in YG, with a RMSE of 3.5 Mg ha^{-1} (Fig. 2.7b). The fields with the highest YG had a cumulative growing season precipitation over 645 mm, AWHC less than 353 mm, and cumulative growing season solar radiation less than 3924 MJ m^{-2}. The lowest YG were associated with a cumulative growing season precipitation less than 645 mm and row spacing in a broadcast or crossed pattern method, as well as 13 cm and 18 cm spaced rows. The CIT for WUE explained 17% of the variability in WUE, with a RMSE of 6.1 kg ha^{-1} mm^{-1} (Fig. 2.7c). Annual rainfall was the most important factor associated with WUE: The highest WUEs resulted from annual rainfall less than 649 mm and a phosphorus application, while the lowest WUE were associated with an annual rainfall greater than 649 mm and depended on phosphorus application method.

Discussion

In the present study, we applied an established framework for benchmarking crop WUE through boundary functions to a database of alfalfa yield-ET_a constructed using a systematic literature review. Previous research using boundary functions focused primarily on annual grain crops, but in this study we successfully expanded the application of the boundary function to a perennial forage crop like alfalfa. We then used this benchmark WUE to determine the Yw and

YG in commercial rainfed alfalfa fields in Kansas from which we collected a rich weather-, management-, and soil-database as a case study. Our research has global implications for future alfalfa WUE and perennial crops' YG analyses, as well as agronomic implications in improving rainfed alfalfa Ya through improved management.

Implications for Future Alfalfa WUE and YG Research

An original contribution of the current work for future alfalfa WUE and YG analyses is the WUE benchmark against which researchers and producers can compare their yields and quantify the magnitude of their YG. The slope of the linear boundary between yield and ET_a of 30 kg ha^{-1} mm^{-1} is greater than most reported values for alfalfa studies done globally (range: 15 and 23 kg ha^{-1} mm^{-1}; Sun et al., 2018; Bauder et al., 1978; Bolger and Matches, 1990) and that average ~16 kg ha^{-1} mm^{-1} (Lindenmayer et al., 2011). While this difference was expected as we aimed at quantifying the potential rather than average WUE (Sadras et al., 2015), we note that the average WUE of our systematic literature review (17-18 kg ha^{-1} mm^{-1}) was similar to these previous efforts, reinforcing the robustness of our analysis. Our benchmark WUE was remarkably similar to the theoretical maximum WUE for alfalfa shoot biomass of 32 kg ha^{-1} mm^{-1} (Tanner and Sinclair, 1983). In their alfalfa WUE estimate, Tanner and Sinclair (1983) excluded ET measurements from the 2-week period following alfalfa cutting, as this period reduces ET to less than 25% of pre-harvest levels as it is mostly modulated by evaporation rather than transpiration (Wright, 1988). The exclusion of this period of inefficient water use from their calculations aligns with the estimate of negligible losses represented by the *x*-intercept of Fig. 2.3a.

The discrepancy in the estimations of evaporation (i.e., *x*-intercept of the boundary function) among the methods evaluated (Fig. 2.3) is likely a function of inherent attributes and assumptions of the different methodologies. We had an x-intercept of 25 mm in in our synthesized literature review (Fig. 2.3a). X-intercepts of boundary functions are usually closer to zero when the independent variable is ET_a as compared to seasonal water supply, and when the dependent variable is shoot biomass as compared to grain yield (e.g., Grassini et al., 2009; Lollato et al., 2017); which were both the case for the current study. We note that while the original alfalfa WUE analysis by Lindenmayer et al. (2011) forced the intercept to zero, our re-analyses of their data using a boundary function (rather than the weighted regression across all points) suggested an *x*-intercept of 50 mm, which was not statistically different than the *x*-intercept derived from our simulation exercise of 108 mm. While evaporation might account for as little as ~7% of alfalfa ET in a full canopy cover state (Wright, 1988), most previous research partitioning alfalfa ET suggests that evaporation accounts for 20-30% of total yearly ET (Wagle et al., 2019, 2020; Wright, 1988). These previous estimates justify the use of 25 mm water loss, as it would correspond to ~21% of total ET in our database (which averaged 498 mm). We note in passing that the distribution of data points in Fig. 2.3a suggests that alfalfa yield accumulation ceases and plateaus with ET_a > 588 mm. While the interpretation of this finding can suggest that this amount of ET_a should be adequate for alfalfa water requirements for highest yield, it can also simply be a consequence of the database yield range, which never surpassed 22 Mg ha^{-1}.

Other implications of the current research to the global alfalfa WUE literature ,and perhaps to other perennial crops grown in temperate environments, are (i) the demonstration of the potential for a simple approach (i.e., growing season rainfall minus water loss and annual rainfall minus water loss) to result in similar YG estimates to those using a more complex approach using total crop water supply, which requires the estimation of soil water available at dormancy-release plus growing season rainfall (Box 1); and (ii) the first quantification of the dependency of alfalfa's attainable yield on stand age (Fig.A.2), which is similar to other perennial crops such as oil palm (Euler et al., 2016a; Monzon et al.; 2021) and sugarcane (Marin et al., 2019).

Variability in Alfalfa Yield and Yield Gaps

Despite a large variability in yields among the surveyed fields, the average producer-reported yield in our database was surprisingly similar to the 2016-2019 average alfalfa yield for the state of Kansas (8.9 *vs.* 8.6 Mg ha^{-1}) (USDA-NASS, 2019). The wide range of Ya (0.9 to 22.4 Mg ha^{-1}) was expected given the variability in weather conditions experienced during the 4-yr study period (e.g., seasonal water supply ranging from 526 to 1356 mm), considering that the main limiting factor in rainfed perennial crop production is depletion of the soil moisture in the root zone (Kilcher and Heinrichs, 1971). We note that the yield levels in our survey were greater than the values reported by Russelle (2013), who used 2007 Census of Agriculture to suggest that half of non-irrigated producers in the U.S. had alfalfa yields below 4 Mg ha^{-1}, and half of the irrigated producers reported yields under 7.4 Mg ha^{-1}. Our surveyed yields are also greater than that of Wei et al. (2018) in China, who reported an average yield of 6.9 Mg ha^{-1}.

Likewise, we also showed a wide range in YG among the surveyed fields, typical of rainfed cropping systems with large YG (e.g., Jaenisch et al., 2021). The average YG in the current survey (57%) was remarkably similar to the YG estimate in the U.S. of 50-67% from Russelle (2013) using several approaches. When comparing to other alfalfa growing regions for which YG estimates are available, the alfalfa YG in Kansas seems to be similar to that of Iran (c.a., 69%; Soltani et al., 2020) though at much greater Ya (8.9 vs. 2.6 Mg ha^{-1}), and seems to be narrower than in China where Ya are only 28% of Yw (Wei et al., 2018).

Implications for Alfalfa Management Recommendations

We characterized crop management practices currently adopted by central Kansas rainfed alfalfa producers, as well as potential avenues for improvements in Ya and WUE and for reductions in YG through the interaction of management practices with weather and soil. While the use of 23 producer-reported management variables to characterize crop management and 34 weather and soil variables to quantify management impacts on Ya, YG, and WUE encompasses more variables than the majority of efforts to explore YG (Beza et al., 2017), our results suggested a limited potential for increases in rainfed alfalfa Ya through the management practices evaluated.

We showed that a greater first-year yield due to fall rather than spring sowing (Fig. A.2) was partially due to a greater number of cuts allowed in the first year. Previous research suggests that early fall sowings would also allow for a greater accumulation of root reserves (Justes et al., 2002) which greatly contribute to spring regrowth (Kim et al., 1993). Additionally, spring-sowing of alfalfa has an added risk of frost damage to seedlings and of warm-season weed pressure competition in the spring (Shroyer et al., 1998; Witt and Thompson, 1997), justifying the results from our survey.

The results from the CIT's suggested that only a few management practices are associated with Ya or YG. The presence of a phosphorus (as well as its method of application) was a practice that seemed to impact alfalfa yields and WUE. These results agree with a comprehensive YG review by Beza et al., (2017) that suggested fertilization practices were among the most important practices that offered opportunities to reduce YG. These results are also consistent with replicated alfalfa studies showing that the application of phosphorus can increase alfalfa dry matter yield through the influence of the yield components shoots plant^{-1} and mass shoot^{-1} (Jones and Sanderson, 1993; Berg et al., 2005). The high rate of soil P removal by alfalfa (i.e., every Mg ha^{-1} of alfalfa harvested removes around 12.3-14.7 kg P_2O_5; Lamond, 1998) also justifies the importance of alfalfa P fertilization in improving yield and WUE. Previous replicated trials also support the importance of P application method in modulating the yield of alfalfa (Sheard et al., 1971; Goos et al., 1984) and of annual crops (Randall and Hoeft, 1988; Bailey and Grant, 1990). For instance, Malhi et al. (2001) observed that subsurface banding of P fertilizer resulted in greater alfalfa yield, P recovery, and net returns. Row spacing was another management practice that appeared in the CIT for Ya and YG, suggesting that a crossed pattern seeding had a yield advantage over more spaced-out seeding patterns. While there is limited literature regarding crossed pattern row spacing in alfalfa, it may result in more uniform coverage and weed suppression (Redfearn et al., 2009), aligning with studies that suggested that decreasing the row spacing of alfalfa allows for increased canopy cover and improves the crop's ability to capture and compete for resources (Klapp 1957; Soya et al., 1997; Acikgoz, 2001).

The impact of a very few management practices on alfalfa yield and YG differ from those obtained when evaluating management surveys of annual grain crops such as soybeans and wheat, where a number of management interactions on Ya and YG could be detected (DiMauro et al., 2018; Mourtzinis et al., 2018; Lollato et al., 2019; Jaenisch et al., 2021). This finding brings into question whether a perennial crop, such as alfalfa, offers fewer opportunities to improve yields through management as compared to annual crops. Supporting this hypothesis, our findings suggested that much of the management-related opportunities to improve yield, YG, and WUE occurred at the establishment year (e.g., row spacing, phosphorus fertilizer placement) which, differently than annual grain crops, would only occur once every 5-10 years. The ground proofing of this question with available literature evaluating on-farm surveys on perennial crops was not possible as the literature is limited. For instance, Marin et al. (2019) only evaluated the impact of number of harvests on sugarcane yield. Euler et al., (2016a) evaluated a greater number of variables to suggest that most of the managerial opportunities to reduce oil palm YG were related to N, P, K, and herbicide applications. Future research could expand on this question.

Conclusion

The synthesis of a literature-reported alfalfa WUE database and a survey of 394 commercial alfalfa fields in Kansas allowed us to benchmark an alfalfa WUE, as well as use this region as a case-study scenario to estimate Ya, Yw, and YG. Additionally, these analyses allowed for a quantification of the current level of adoption of management practices in commercial fields, as well as to their interactions with soil and weather variables modulating the alfalfa forage yields in Kansas. An average YG of 57% suggests room for yield improvement, although this region yields slightly higher than the state average for the time period of the study. Results from the CIT analysis show limited room for improvement of alfalfa yields, YG, and WUE through management, as only a crossed pattern row spacing and phosphorus applications were positively associated with yield, YG, and WUE. Our results also provided preliminary evidence for a more limited opportunity to improve yield in perennial crops through management as compared to annual crops, as some management practices are only adopted once in the life cycle of the crop.

Box 1. Simplicity Versus Complexity in Estimating Water Available for Perennial Crops

We tested whether a simple approach to estimate water available for perennial crops (i.e., the use of annual rainfall) led to similar YG estimates to a more complex approach, including the estimation of available soil water at spring greenup (AWS) plus growing season rainfall separately. The simple method used annual rainfall from the onset of fall dormancy in the previous year, to the onset of fall dormancy of the harvest year. The complex approach estimated AWS separately for high- and low-AWHC soils based on the ratio between available water in the soil profile at the onset of winter dormancy of the previous year plus the total precipitation during the non-growing season, divided by the soil's AWHC (Grassini et al., 2010). Seasonal water supply was then calculated using the field-specific AWS plus growing season precipitation. The available water at the onset of the previous winter dormancy was determined as a linear function of accumulated growing season precipitation across all 686 yearly simulations (Section Simulated alfalfa water use efficiency). Yield gaps were then calculated for each field year using the equation in Fig. 2.3. The ranking of fields within year from lowest to highest YG were compared using linear regression. The slopes of the regression of field ranking based on YG magnitude between the complex and growing season rainfall minus water loss approaches were 0.96-1.0. The slopes of the regression of field ranking based on YG magnitude between the complex and annual rainfall minus water loss approaches were 0.99-1.0. The complex approach involves utilizing field-specific soil and weather data, as well as multiple calculations with associated uncertainties to estimate the different steps. Meanwhile, the simple approaches only use growing season rainfall minus the water losses or annual rainfall minus the water losses to estimate alfalfa YG. The growing season rainfall or annual rainfall approach would be simpler for growers to implement on their operations compared to the complex method, as regional annual rainfall is easier to obtain. The complex approach could be helpful in exploratory studies were a detailed approach to estimating alfalfa YG would be appropriate.

Figures

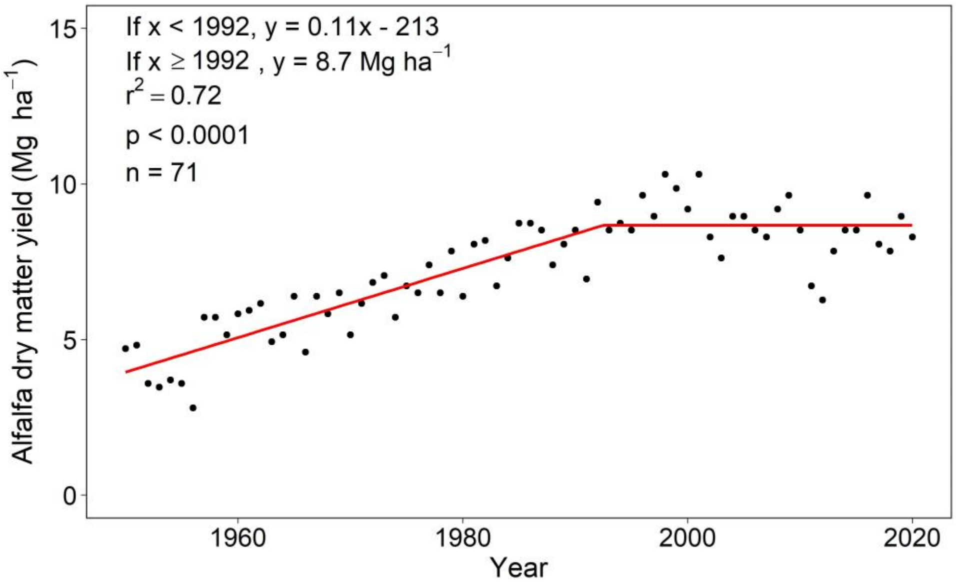

Figure 2.1. Timeline showing the yields of alfalfa dry matter yields in Kansas. Data spans the period of 1950 to 2020. Data were obtained from the USDA National Agricultural Statistics Service. Relationship between alfalfa yield and year shown using fitted linear plateau model using non-linear regression.

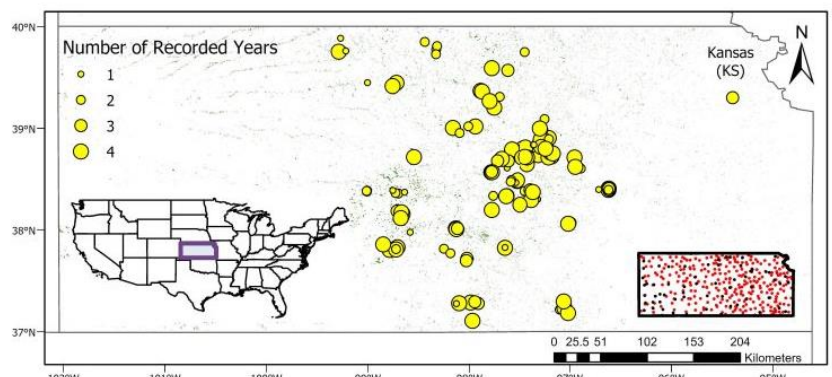

Figure 2.2. Map of the surveyed region of Kansas, United States. The green raster represents alfalfa fields, and the yellow dots represent commercial rainfed alfalfa fields (n = 394) that were surveyed during the 2016, 2017, 2019, and 2019 harvest years. Size of the dots from smallest to largest represent the number of years of data was provided from each field-site. Lower left inset shows the location of Kansas within the contiguous U.S. Lower right inset shows the weather stations used to collect daily rainfall and maximum and minimum temperature (red dots) and weather stations used to collect solar radiation and reference evapotranspiration (black dots).

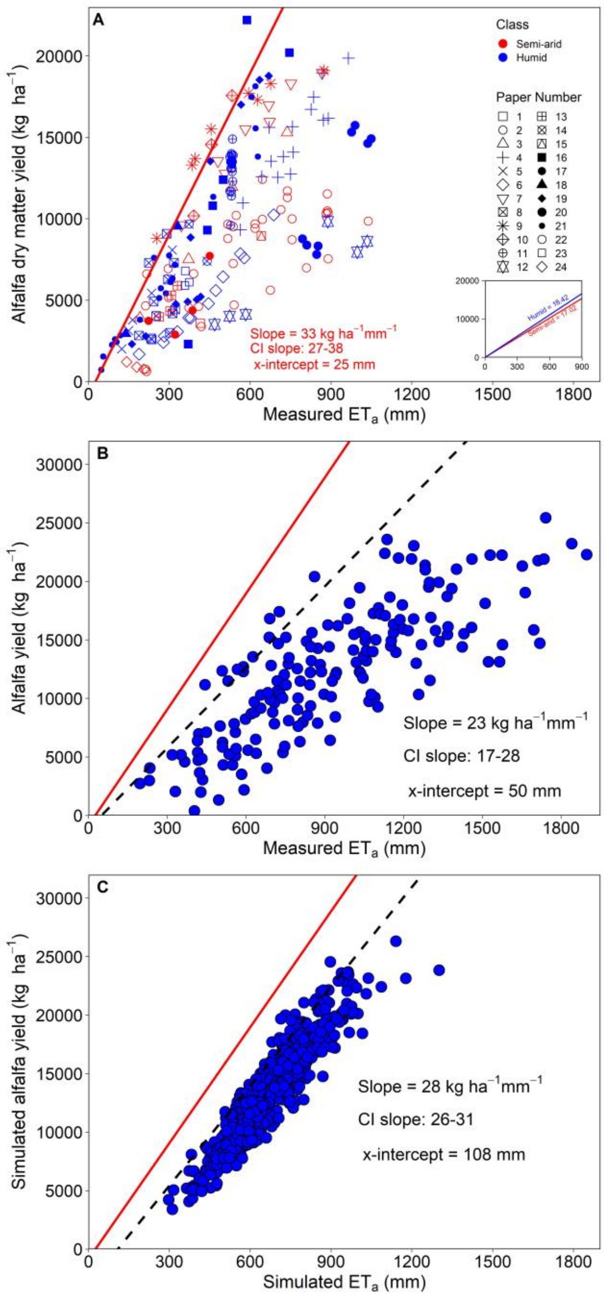

Figure 2.3. (A) Relationship between literature-reported alfalfa yield and ET_a in semi-arid (n = 70, red symbols) and humid climates (n = 173, blue symbols). Boundary function parameters (slope ± S.E.) are shown (quantile: 0.95, red line). Inset shows the yield- ET_a linear regressions developed for arid (red line) and humid climates (blue line) from the database with values showing the WUE for each climate. (B) Relationship between simulated alfalfa yields and simulated ET_a (n = 686). Dashed black line indicates the quantile regression (quantile: 0.95) for the simulated data ($r^2 = 0.24$, $P < 0.001$). Red line indicates the boundary function from our data synthesis. (C) Synthesized database from Lindenmayer et al. (2011) of literature-reported alfalfa yield and ET_a with the re-analysis of the boundary function of their data (dashed line). Red line indicates the boundary function from our data synthesis.

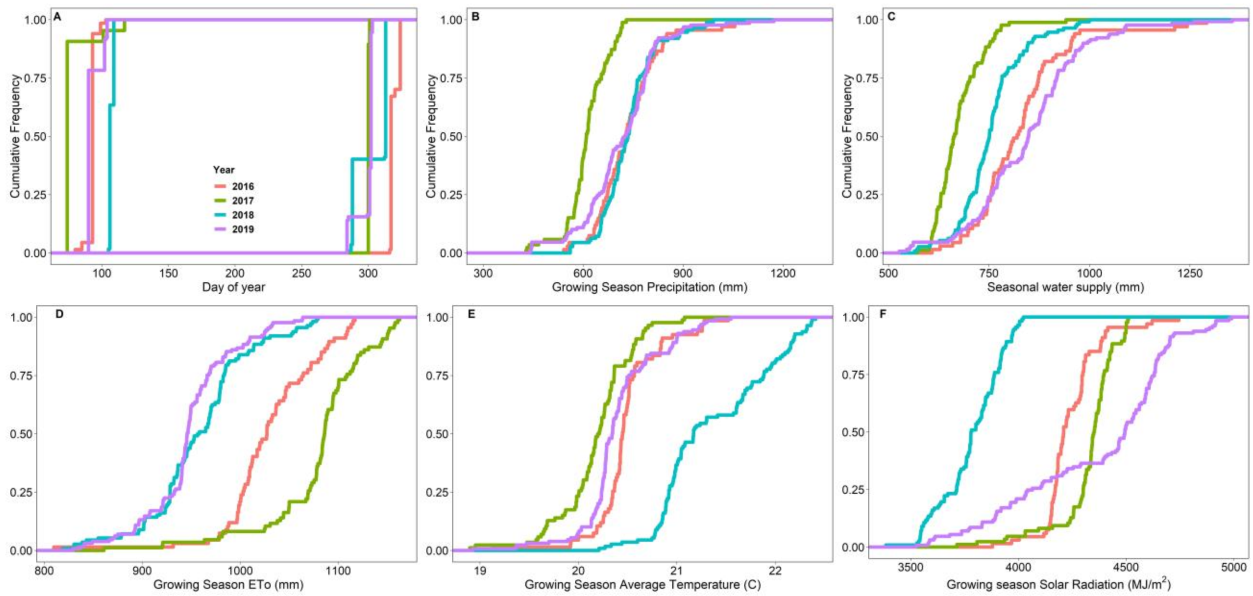

Figure 2.4. Cumulative frequency of start and end of the growing season (A), growing season precipitation (B), seasonal water supply (C), ET_o (D), solar radiation (E), and average temperature (F) for 2017, 2017, 2018, and 2019 harvest years (different colors).

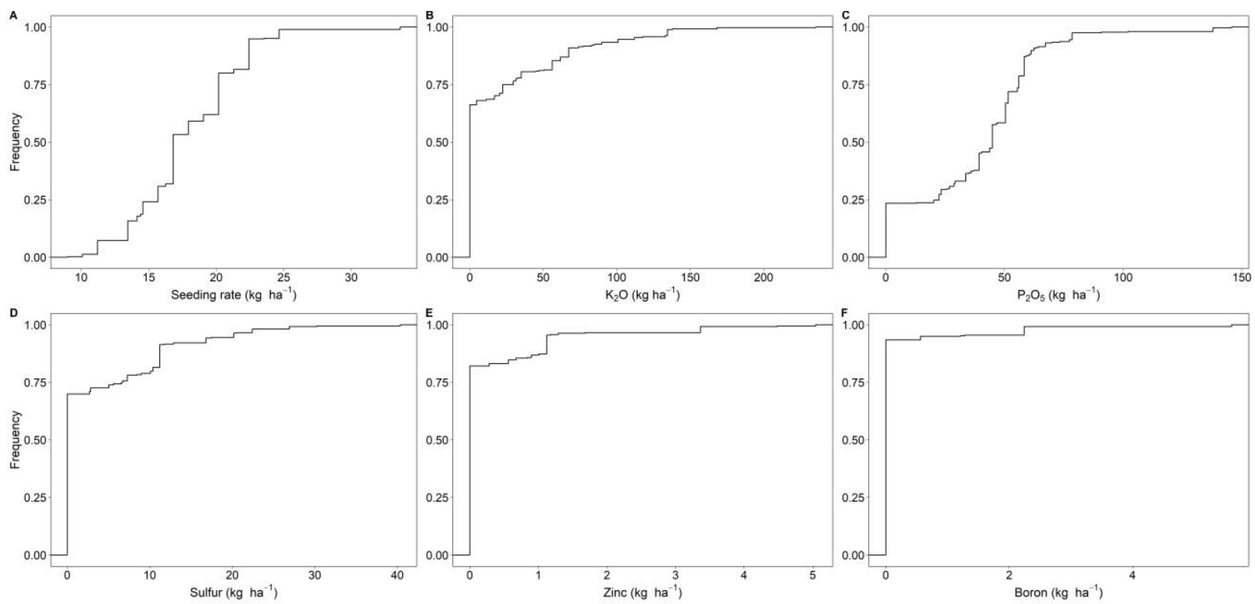

Figure 2.5. Frequency distributions of seeding rate (A) and nutrient rates (B, C, D, E, F) from producer-reported survey database.

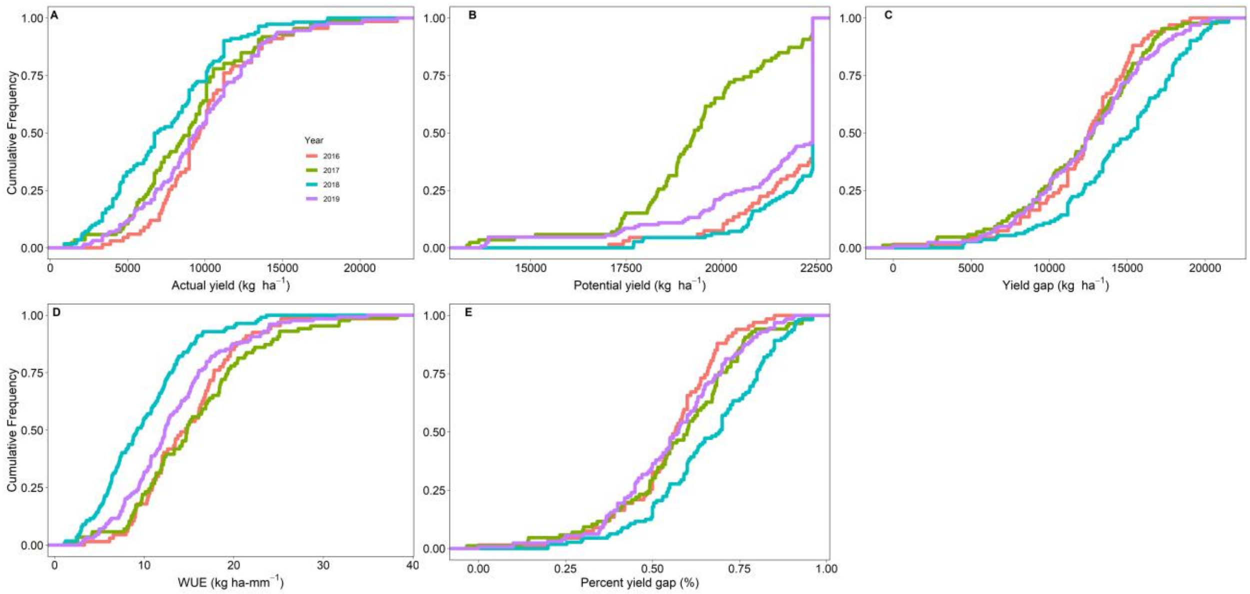

Figure 2.6. Cumulative frequency of Ya (A), Yw (B), YG (C), and WUE (D) for 2016, 2017, 2018, and 2019 harvest years (different colors).

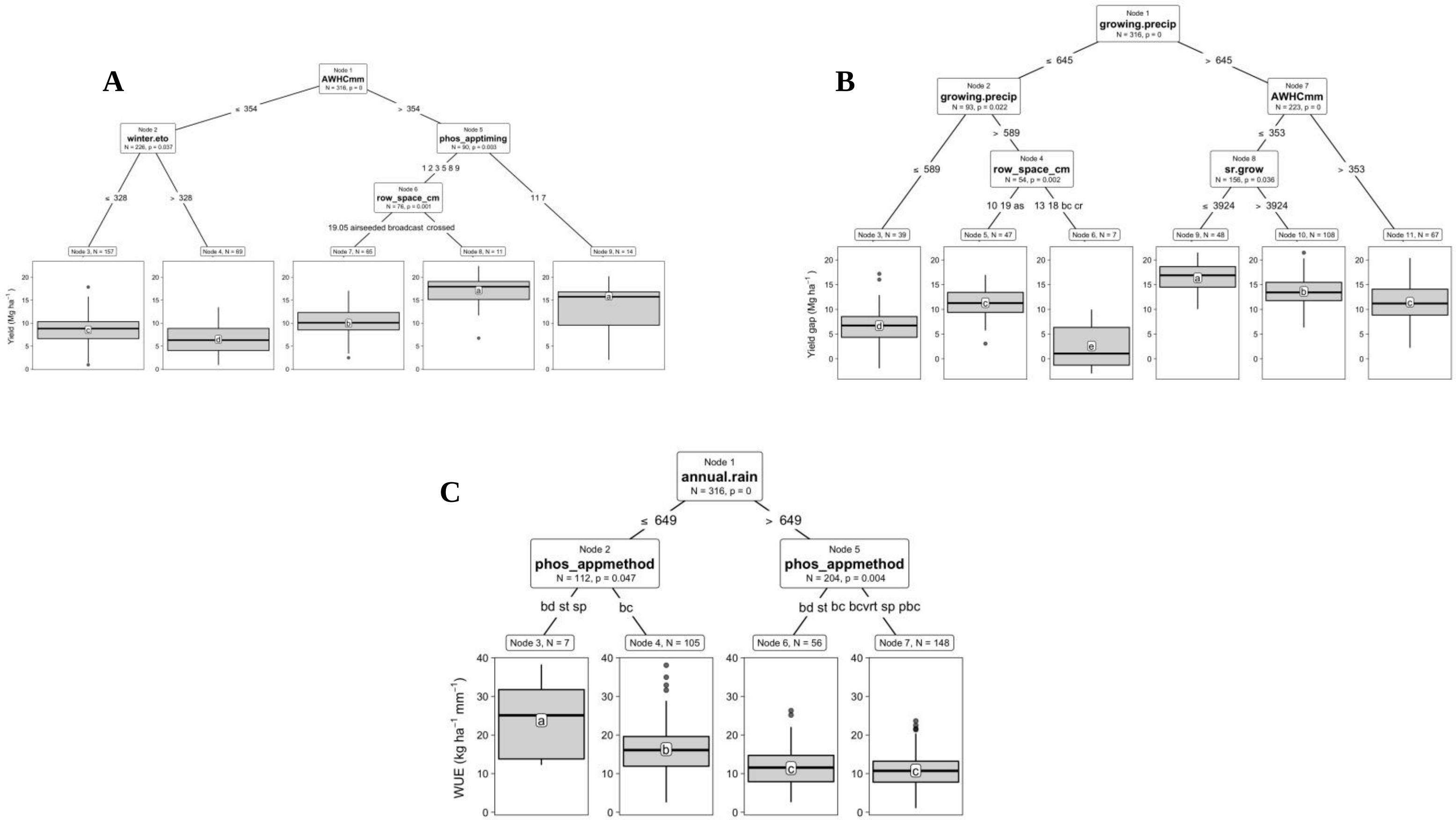

Figure 2.7. Conditional inference tree of weather, soil, and management practices of alfalfa yield (A), YG (B), and WUE (C) across 394 fields surveyed. Each boxplot represents the interquartile range (gray box), median (solid line), fifth and 95th percentiles (whiskers), and outliers (black circles). The number of observations (n) are shown. Legend: annual.rain, annual rainfall (mm); phos_method; phosphorus application method (bd = banded, st = streamed, sp = sprayed, bc = broadcast, bcvrt = variable rate broadcast, pbc = broadcast at planting); phos_apptiming; phosphorus application timing (month of year); row_space_cm; row spacing (cm); potential.yld.a_Mg ha, potential yield; winter_eto, winter ET_o; AWHCmm, Available water holding capacity (mm).

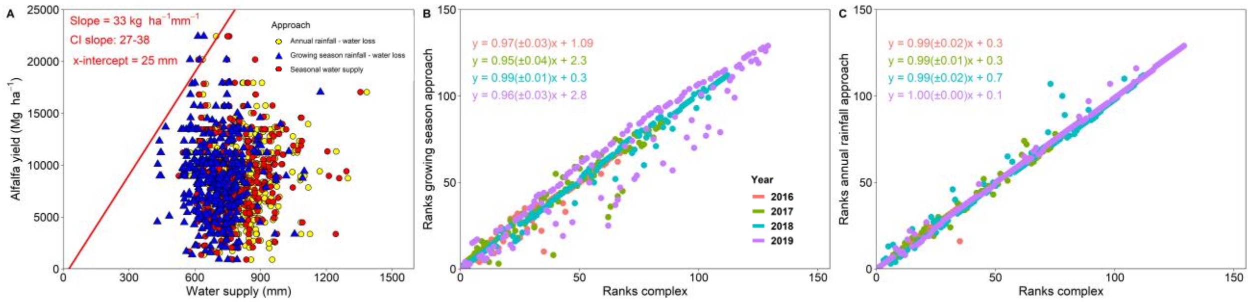

Figure 2.8. (A) Comparison between simple growing season rainfall (blue circles), annual rainfall approach (yellow circles) and complex seasonal water supply approach (red circles) versus the boundary function established based on the literature synthesis. Boundary function parameters (slope ± S.E.) are shown (quantile: 0.95, red line). Comparison between the (B) ranking of fields based on YG magnitude when YG were estimated using the complex approach (*x*-axis) and the simple approaches (*y*-axis). Colors represent years of the surveyed fields. Linear regressions of field-ranking by year of the growing season rainfall approach (B) and the annual rainfall approach (C) are shown.

Tables

Table 2.1. List of variables collected from commercial rainfed alfalfa fields in central Kansas during four crop seasons (2016-2019).

Parameters	Variables requested	Information provided
Field specific information	Field coordinates	Latitude, longitude
	Field size	ha
	Grazing regime	Yes/no (if yes, duration of grazing)
	Cultivar name	Brand of seed
	Glyphosate resistant	Yes/no
	Low-lignin	Yes/no
	Planting date	Month/year
	Seed treatment	Yes/no
	Seed inoculant	Yes/no
	Row spacing	cm
	Seeding rate	kg seed per ha
	Tillage method	No-till/minimum till/conventional till
	Furrow fertilizer	Yes/no
	Lime	Yes/no
	Previous crop	Crop species name
	Companion crop	Yes/no (if yes, crop species name)
Year specific information	Fertilizer	
	Phosphorus	
	Source	Source name
	Rate	kg P_2O_5 ha^{-1}
	Timing	Month
	Method	Application method type
	Potassium	
	Source	Source name
	Rate	kg K_2O ha^{-1}
	Timing	Month
	Method	Application method type
	Sulfur	
	Source	Source name
	Rate	kg S ha^{-1}
	Timing	Month
	Method	Application method type
	Boron	
	Source	Source name
	Rate	kg B ha^{-1}
	Timing	Month
	Method	Application method type
	Zinc	
	Source	Source name
	Rate	kg Zn ha^{-1}

Timing	Month
Method	Application method type
Manure	
Source	Manure type
Rate	kg ha^{-1}
Timing	Month
Method	Application method type
Fungicide	Yes/no
Insecticide	Yes/no
Herbicide	Yes/no
Maturity stage at cutting	Bud or early/mid/late bloom
Crop yield	Mg ha^{-1}
Prevalent pests/diseases	Pest species name
Other issues/events that could affect yield	Issue/event description

Table 2.2. Synthesized database of manuscripts meeting the minimum criteria established to perform the systematic literature review of alfalfa water use efficiency.

Paper No.	Authors	Year of study	Country	Experiment location	ET_a range (mm)	Yield range (Mg ha^{-1})	Climate classification
1	Al-Gaadi, et al., 2017	2014	Saudi Arabia	Todhia	415	3.58	Semi-arid
2	Attram, 2014	2012-13	Canada	Lethbridge	517 - 1038	4.71 - 12.4	Semi-arid
3	Carter et al., 2013	2012	USA	Powell, Wyoming	191 - 737	3.9 - 15.3	Semi-arid
4	Dardanelli and Collino, 2002	1994-97	Argentina	Anguil, La Pampa	564 - 965	9.3 - 19.9	Humid
5	Jefferson and Cutforth, 2005	1993-98	Canada	Saskatchewan	123 - 311	2 - 8.1	Humid
6	Kulslu et al., 2010	2005-06	Turkey	Erzurum	188 - 688	1.7 - 10.3	Humid
7	Li and Su, 2017	2014-15	China	Gansu Province	344 - 867	9.6 - 19	Semi-arid
8	Li et al., 2015	2010	China	Hebei Province	187 - 322	2.6 - 9.1	Humid
9	Lindenmayer et al., 2007	2006-07	USA	Berthound, Colorado	254 - 874	8.8 - 19.1	Semi-arid
10	Meng and Mao, 2010	2009	China	Shunyi County, Beijing	391 - 533	10.2 - 17.6	Semi-arid
11	Moghaddam et al., 2013	2007-08	Austria	Raasdorf, Austria	525 - 537	9.6 - 14.9	Humid
12	Radu et al., 2010	2007-09	Romania	Oradea, Romania	466 - 1034	3.5 - 9.8	Humid
13	Sanden et al., 2008	2006-07	USA	Buttonwillow, California	262 - 330	4 - 5.9	Semi-arid
14	Wagle et al., 2019	2016-17	USA	El Reno, Oklahoma	373 - 440	7.4 - 9.7	Humid
15	Singh et al., 2007	1998-99	India	Jhansi	642	8.95	Semi-arid
16	Guan et al., 2012	2004-10	China	Shaanxi Province	370 - 746	2.3 - 22.2	Humid
17	Hirth et al., 2001	1996-99	Australia	Ruthergen, Victoria	223 - 450	2.9 - 7.7	Semi-arid
18	McMaskill et al., 2016	2011-12	Australia	Hamilton, Victoria	138 - 330	2.9 - 9.5	Humid
19	Murray-Cawte, 2013	2012-13	Australia	Canturbury	161 - 669	2.3 - 18.8	Humid
20	Pembleton et al., 2011	2007-08	Tasmania	Elliott, Tasmania	794 - 1049	7.8 - 15.7	Humid
21	Sim, 2014	2010-12	New Zealand	Ashley Dene	47 - 628	0.7 - 18.1	Humid
22	Jia et al., 2009	2001-05	China	Gansu Province	212 - 418	0.8 - 6.9	Semi-arid
23	Sim and Moot, 2019	2011	New Zealand	Ashley Dene	358 - 374	5.9 – 6.8	Humid
24	Zhang et al., 2005	2001-03	Australia	Kojonup, Australia	142 - 205	0.8 – 1.2	Semi-arid

Table 2.3. Frequency of adoption (%) of management practices among the surveyed alfalfa fields across central Kansas.

Management	Adoption (%)
Grazing	10
Cultivar (Roundup Ready)	34
Cultivar (Low lignin)	2
Planting Season (Fall)	81
Seed Treatment (Fungicide/Insecticide)	84
Seed Inoculated	92
Tillage Method (NT/CT)	22/78
In-furrow Fertilizer	17
Lime	42
Companion Crop	3
Phosphorus	78
Potassium	40
Sulfur	32
Micronutrients	24
Fungicide	1
Insecticide	88
Herbicide	66
Cuttings Per Year (1, 2, 3, 4, 5)	2, 7, 13, 53, 25

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Appendix A - Supporting Figures and Graphs

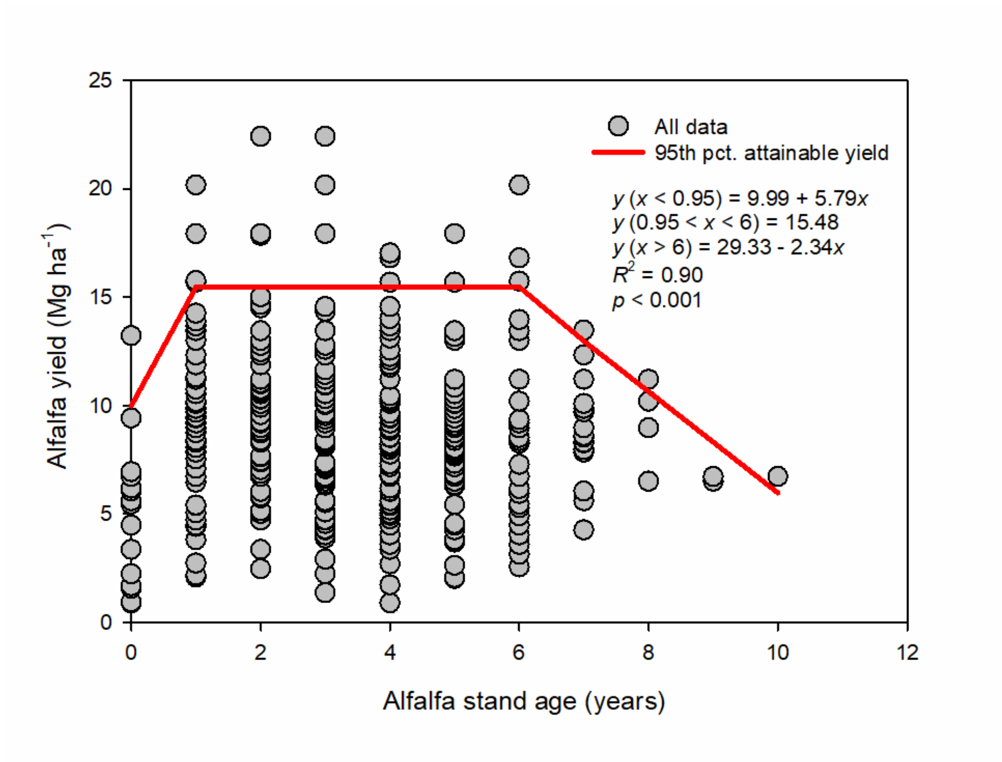

Figure A.1. Alfalfa attainable yield (solid red line) as affected by stand age in years.

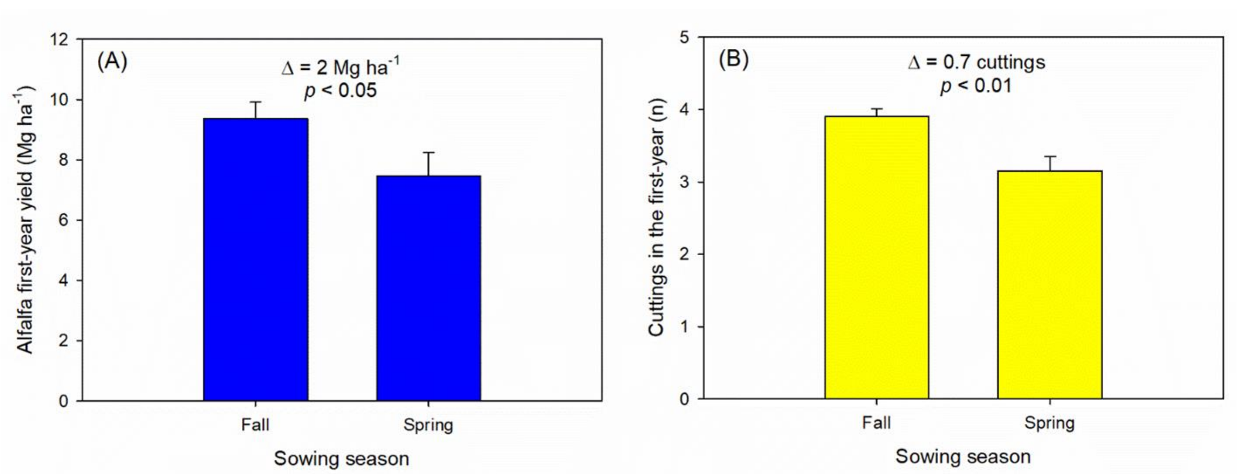

Figure A.2. Alfalfa first-year yield (A) and number of cuttings (B) as affected by sowing season.

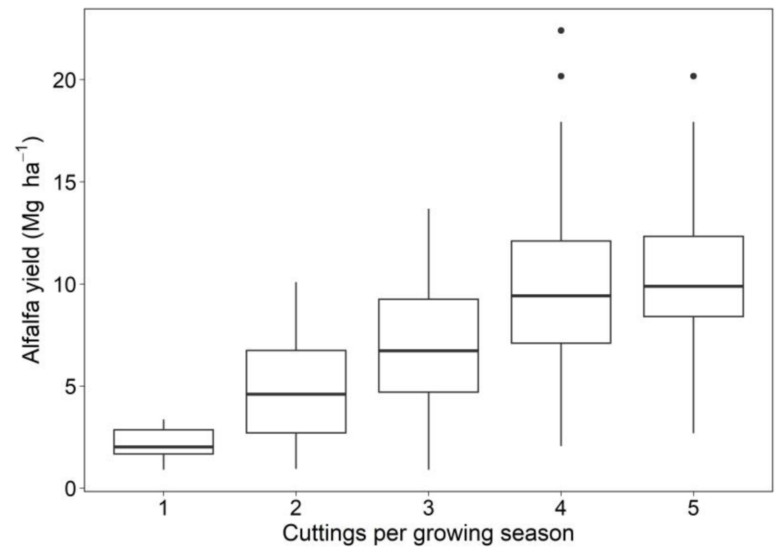

Figure A.3. Number of cuttings per growing season related positively with alfalfa yield across the entire database.

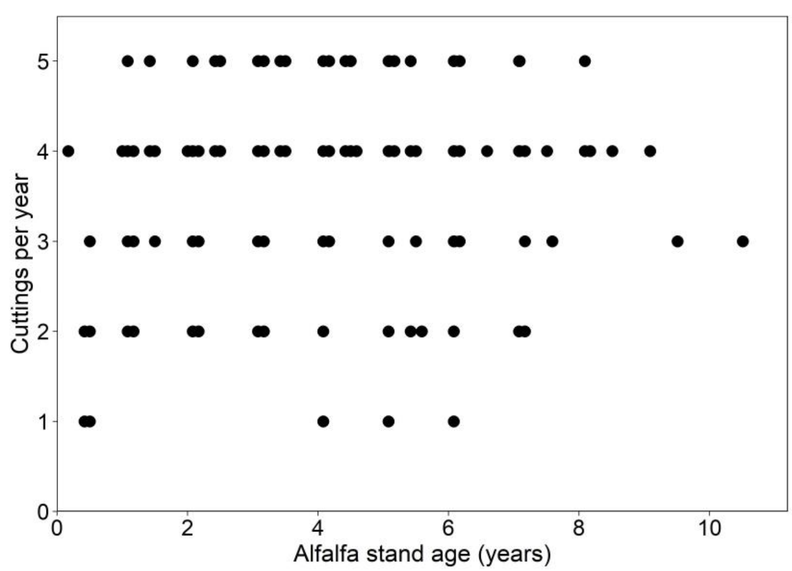

Figure A.4. Number of cuttings per year in relation to alfalfa stand age.