Received: 17 November 2023 | Revised: 13 March 2024 | Accepted: 17 March 2024

DOI: 10.1002/glr2.12080

Grassland Research

REVIEW ARTICLE

Systems management strategies for increasing alfalfa use in warm-humid regions

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Handling Editor: Cory Matthew

Funding information
National Institute of Food and Agriculture, Grant/Award Number: 2021-70005-35690

Abstract

Alfalfa use (*Medicago sativa* L.; "lucerne") in warm, humid regions of the world represents a potential area of expansion for the alfalfa industry. The objective of this review paper is to demonstrate how alfalfa forage breeding and systems research efforts have identified opportunities for increasing alfalfa contributions in these regions, along with potential pathways for seed industry and farming operations to increase adoption. Our review draws primarily on reports from the Southeast United States and Argentina. Significant technological advancements in plant screening and selection have identified alfalfa plant populations that are more adapted to the growing conditions experienced in these regions, which are often characterized by mild temperature, long growing seasons, and multiple other abiotic and biotic stressors. Management systems research conducted in the United States and Argentina has demonstrated the use of alfalfa for conserved forage, grazing, or dual-purpose use in monoculture or mixtures with warm-season grasses such as bermudagrass (*Cynodon* spp.). These trials report increased forage production, nutritive value, and ecosystem services of alfalfa–grass mixtures when compared with traditionally N-fertilized warm-season grass-based systems. Grazing-based alfalfa systems in Argentina have demonstrated methods for utilizing alfalfa as part of beef, dairy, and finishing systems. Some approaches for expanding alfalfa production in the region include targeted marketing efforts for adapted varieties and demonstrating alfalfa applications within existing farming frameworks. This includes educational programming efforts and on-farm demonstrations to promote alfalfa use as a component of the livestock diets, integration into grass-based systems, crop rotations, and wildlife use. Continued emphasis on a systems approach to alfalfa inclusion represents an opportunity for improved forage and livestock production in warm, humid regions of the world.

KEYWORDS

alfalfa, forage legumes, systems management

INTRODUCTION

Alfalfa (*Medicago sativa* L.; "lucerne") is a perennial forage legume known for its high forage nutritive value. It is high-yielding and well-suited for conserved forage, grazing, or dual-purpose use (Smith et al., 2021; Tucker et al., 2021). Alfalfa production is primarily concentrated in the Mediterranean, semi-arid, or more arid regions of the world, with an estimated 30 million ha planted globally (National Alfalfa Forage Alliance [NAFA], 2023).

Warm-humid areas of the world include the tropics and the subtropics (regions from 34° N and 34° S) and represent the potential areas for alfalfa expansion (Moore et al., 2020). These areas are characterized by alternating warm and cool temperatures, drought and flooding conditions, and multiple biotic stresses, including fungi, viruses, insects, and nematodes. The adoption of legumes in forage systems in warm-humid regions has historically been limited by (1) perceived lack of persistence, (2) lack of awareness of adapted varieties,

(3) knowledge of management requirements (Shelton et al., 2005), and (4) coupling management with the growing conditions in the region (Silva et al., 2021). Integration of legumes in warm-humid regions has many benefits including improved forage nutritive value in predominantly C_4-grass regions of the world, reduced reliance on synthetic N fertilizer, and the potential for improved animal performance, ecosystem diversity, and economic returns (Muir et al., 2014; Sollenberger & Dubeux, 2022).

This review explores alfalfa management scenarios from the Southeast United States and Argentina with a view towards using these examples as a model for expanding the scope of reach of alfalfa in warm, humid regions. The objective of this paper is to collectively review alfalfa plant breeding, management strategies, and opportunities for alfalfa expansion in warm, humid regions based on these reports.

BREEDING AND GENETICS

Nearly all alfalfa cultivars are synthetic autotetraploid populations (Bouton, 2001; Li & Brummer, 2012). Most synthetics are broad-based, usually containing more than 100 parents for the development of the population. Breeding has mostly been conducted as phenotypic recurrent selection using among and within half-sib family selection (Casler & Brummer, 2008). The development of cultivars in the late 1900s focused on selecting for fall dormancy groups adapted to the growing region, winter hardiness, and a broad genetic base for pest resistance and disease resistance (Bouton, 2001). The level of fall dormancy is a key trait for alfalfa adaptation to warm and humid regions. Growth in alfalfa is affected by fall dormancy, which refers to the characteristic growth reduction and decumbent shoot orientation that typically occurs in late summer and early autumn as the temperature declines and the photoperiod shortens (Castonguay et al., 2006; McKenzie et al., 1988). The dormancy level of alfalfa is determined using a standard test that compares the fall growth for a new variety relative to the growth of known checks (Teuber et al., 1998). The most-dormant alfalfa types (fall dormancy rating 1–4) will remain very short after the last cut in late summer, and the least-dormant types (fall dormancy 8–11) will continue growing during the fall and winter. Nondormant varieties (fall dormancy 8–11) are suited to regions with little frost, such as the southern United States and the Central Valley of California, and Northern Argentina, Paraguay, Uruguay, and Brazil (Vilela et al., 2018). There is a tradeoff between fall dormancy and yield, and nondormant cultivars show faster growth and higher yields under the right environmental conditions, but stand persistence is lower than dormant cultivars (Ventroni et al., 2010). Nevertheless, management practices such as cutting or grazing interval and stubble height will determine whether greater productivity is achieved with nondormant cultivars (Sheaffer & Marten, 1990; Ventroni et al., 2010). In areas with limited frost or freezing temperatures, reduced dormancy can potentially improve yield, especially from late summer through early winter (Sheaffer & Marten, 1990). Other complex traits (quantitatively inherited) are also important breeding targets, including dry matter yield (Acharya et al., 2020; Adhikari et al., 2019; Biswas et al., 2021; Sakiroglu & Brummer, 2017; dos Santos et al., 2018), grazing tolerance (Smith & Bouton, 1993), low bloat potential (Goplen et al., 1993), and potato leafhopper resistance (McCaslin, 1994).

Dry matter yield, nutritive value, stand persistence, and resistance to biotic and abiotic stresses are critical traits in alfalfa breeding programs, and they are complex, quantitatively inherited traits that show moderate to low heritability (Acharya et al., 2020; Bowley & Christie, 1981; Brummer & Casler, 2014; Fernandes Filho et al., 2023; Hawkins & Yu, 2018; Riday & Brummer, 2004). Quantitative traits with complex inheritance patterns require more effort to achieve satisfactory genetic gains. For example, a comparison among cultivars developed over five different decades revealed that modern cultivars only performed better in environments under strong biotic and abiotic stresses. Cultivars performed similarly in favorable environments, suggesting that genetic gain for yield was more due to adaptation and resistance to biotic and abiotic stress rather than for yield per se (Lamb et al., 2006). The low rate of genetic progress for dry matter yield, which averaged 0.50% per year (Lamb et al., 2006), can be ascribed to long breeding cycles due to the perennial nature of alfalfa, the harvesting of the entire plant (inability to make gains in harvest index), multiple harvests per year, significant genotype-by-environment interaction, high costs on phenotyping, tetrasomic inheritance, and high level of nonadditive variance (Acharya et al., 2020; Annicchiarico, 2015; Annicchiarico et al., 2016). Due to the quantitative nature of these important traits, new tools and methods are needed to increase genetic gain.

The use of molecular markers is an excellent tool for alfalfa breeders to improve the rate of genetic gain for complex traits. Various molecular marker systems have been developed for alfalfa over the past 30 years, including low-throughput markers (Brummer et al., 1993; Robins et al., 2008), and high-throughput single nucleotide polymorphisms (SNPs) markers using arrays (Li, Han, et al., 2014), genotyping-by-sequencing (Li, Wei, et al., 2014), target-enriched sequencing (Andrade et al., 2022), and more recently, a public mid-density (3000 loci) DArTag assay (Zhao et al., 2023). These marker systems have been applied in alfalfa for research purposes, but the adoption in breeding programs has been limited due to costs and/or the lack of molecular breeding methods used in alfalfa. The DArTag assay has the power to make routine genotyping a reality for alfalfa breeders due to lower costs compared to other systems. In addition, the DArTag assay uses custom-designed oligos to amplify targeted SNPs before next-generation sequencing, and the target SNPs were selected from 40 cultivated alfalfa plants and founders from North American breeding programs (Zhao et al., 2023).

The use of molecular markers to aid the selection of elite germplasm in plant breeding, a method known as genome-wide selection, has potential to increase genetic gain for complex traits in alfalfa (Andrade et al., 2022;

Annicchiarico, 2015; Biazzi et al., 2017; Fernandes Filho et al., 2023; Jia et al., 2018; Li, Wei, et al., 2014). Andrade et al. (2022) reported predictive abilities ranging from 0.2 to 0.4 for dry matter yield and canopy height in alfalfa family bulks. The first five harvests each year provided enough data to make accurate predictions for the cumulative dry matter yield. Therefore, the use of genomic selection can result in reductions in data collection and breeding decisions by 50% in nondormant alfalfa breeding programs. In a follow-up study, the inclusion of enviromics data (weather and soil data, and basic physiological parameters) in prediction models resulted in greater predictive ability for complex traits by modeling dry matter yield across multiple harvests (Fernandes Filho et al., 2023).

The application of remote sensing is becoming a routine method in plant breeding for fast and non-destructive high-throughput phenotyping. Breeding alfalfa for dry matter yield requires frequent and multiple phenotyping efforts, and up to 10 harvests could be achieved per year in warm, humid regions (Acharya et al., 2020; Andrade et al., 2022). High-throughput phenotyping has been shown to enable efficient and nondestructive estimation of dry matter yield and other traits in alfalfa (Biswas et al., 2021; Cazenave et al., 2019; Feng et al., 2022). This phenotyping process can also detect small differences in alfalfa yield when screening diverse germplasm sources (Cazenave et al., 2019) and improve the efficacy of the selection process for biomass in small plots (1.52 m × 0.30 m) and larger plots (6 m × 4 m) (Feng et al., 2022; Tang et al., 2021). The use of high-throughput phenotyping in nondormant alfalfa grown in Florida showed that vegetation indices can be used to predict dry matter yield in small plots with an average R^2 of 0.60. In addition, the implementation of bivariate models combining high-throughput phenotyping and ground-based measurements for dry matter yield showed that ground-truth dry matter yield measurements can be reduced up to 70% without compromising genetic gain in nondormant alfalfa (Biswas et al., 2021).

Advances in alfalfa improvement made use of recombinant DNA to modulate the expression of genes involved in multiple traits, including nutritive value, herbicide resistance, and stress tolerance (Bouton, 2001, 2012a). Transformation allows for the transfer of DNA sequences of interest into the plant genome to either enhance or silence the expression of target genes that determine important traits. A survey showed that many value-added traits are being pursued in alfalfa breeding via biotechnology methods (Samac et al., 1998), and most of these traits are qualitative in nature. Future studies and breeding efforts should target the integration of genomics, enviromics, and phenomics to increase the prediction ability of models in nondormant alfalfa grown in warm, humid regions, and ultimately increasing genetic gain for complex traits.

Breeding for warm, humid regions

Breeding alfalfa for adaptation to warm, humid regions needs to combine traditional and novel breeding methods. Subtropical climate transition zones are ideal regions for breeding forage species with climate adaptation because breeding populations are regularly exposed to extreme weather events, such as hot and cold temperatures, drought and flood conditions, and a multitude of biotic stresses (Quesenberry et al., 2022).

Nondormant cultivars have been adopted in the southern United States (Bouton, 2012b). The alfalfa breeding program at the University of Florida (UF) began in 1950. Early efforts led to the release of Florida 66, which showed improved adaptation to the state's agroecosystem (Horner, 1970). Additional evaluation and selection resulted in the release of Florida 77, which had superior yield and persistence (Horner & Ruelke, 1981). After additional field selection for growth and vigor, Florida 99 was released for its improved resistance to the spotted alfalfa aphid. Recently, the cultivar UF_AlfPers_2015 was released for its improved dry matter yield and persistence when grown in Florida (Rios et al., 2023). All the cultivars released by UF had fall dormancy ratings of 9. The cultivar Bulldog 805, a fall dormancy rating of 8, was released for its adaptation to grazing systems and high yields in hay fields in Georgia (Bouton et al., 1997), and it is widely grown in the Southeast US Nondormant cultivars like Florida 66 and Florida 77 produced high dry matter yield across 3 years in Puerto Rico (Velez-Santiago et al., 1984). Winter weather in warm-humid regions is mild, grazing seasons are long, and producers are fundamentally grazers. Developing adaptive, grazing-tolerant varieties such as "Alfagraze" (Bouton et al., 1991), along with embracing new research on grazing management, therefore was an important step. Those who did not want to harvest alfalfa so often or worried about unpredictable rainy weather were able to practice targeted grazing.

Stand persistence is critical for alfalfa, especially in warm-humid regions and under grazing. It is defined as maintenance of an adequate number of plants over time (Bouton, 2012b). Assessing persistence takes several harvests and must be evaluated over multiple years. Persistence is a complex trait as it depends on several characteristics and environmental factors such as drought, temperature, grazing/harvest pressure, aluminum-toxicity tolerance, fall dormancy, and disease resistance, among other factors (Rimi et al., 2014). Due to the complexity of evaluating persistence, De Assis et al. (2010) proposed an indirect method to measure persistence by regressing yield over time. Therefore, persistence could be estimated through the regression coefficient, and it is expected to be negative as the plant stand decreases over time.

ALFALFA SYSTEMS MANAGEMENT STRATEGIES

Ensuring adequate soil pH conditions and fertility management are keys for establishment success with alfalfa, especially in more naturally acidic soils (Haby, 2002; Tucker et al., 2021) often found in warm-climate regions of the world. Required soil pH ($CaCl_2$) range for successful alfalfa establishment in topsoil (0–15 cm depth) is 6.5–7.0, and additionally, a subsoil

(15–30 cm depth) pH at a 5.5 or greater is preferred (Tucker et al., 2021). Inoculation of alfalfa seed with the appropriate *Ensifer meliloti* strain is needed if purchased seed is not preinoculated; however, most seed is purchased as precoated with an inert material, the necessary inoculant, and starter micronutrients (Mo and B) recommended for successful alfalfa establishment (Lacefield et al., 2019; Tucker et al., 2021).

Alfalfa can be grown in monoculture or mixtures with grasses. Perennial C_4 grasses are prevalent in warm-humid regions, and represent potential for increasing alfalfa plantings (Cassida et al., 2006; Hoveland et al., 1988). The majority of the published literature on alfalfa integration in C_4 grass-based systems is from the Southeast United States with bermudagrass, which is the focus of the discussion herein. Research has demonstrated the complementary growth distribution of alfalfa when planted in mixtures with bermudagrass (Baxter et al., 2023; Beck et al., 2017a, 2017b, 2017c; Brown & Byrd, 1990; Hendricks et al., 2020; Stringer et al., 1994).

The growth rate of C_4 grasses is slower in colder temperatures, with a cardinal base temperature of 10°C and higher, and optimum daily air temperature of 30–35°C (Moore et al., 2004). Hanna and Sollenberger (2015) recorded that bermudagrass grows best above 24°C mean daily temperatures. Alfalfa growth is inhibited at temperatures above 30°C with a wide optimum range of 15–25°C (Brown et al., 1972). McKenzie et al. (1988) reported 27°C as the optimum temperature for herbage growth and 12°C for optimum root growth of alfalfa. Thus, when grown in mixtures together, the seasonal growth distribution of alfalfa and bermudagrass combined with fluctuations in seasonal temperature create an ebb-and-flow relationship in terms of stand species composition. While alfalfa production may not cease during extended periods of hot weather, it can undergo slowed growth, often referred to as summer slump (McKenzie et al., 1988). As an example, recent studies focused on alfalfa integration into bermudagrass in Tifton, GA, have reported greatest proportions of alfalfa and lowest contributions of bermudagrass occurring in the spring (March–June; up to 80% of the stand composition from alfalfa), followed by increased bermudagrass contributions in the summer (July–September) (Burt et al., 2023; Hendricks et al., 2020). These projects confirmed earlier work conducted by Brown and Byrd (1990) and all report the lowest proportions of alfalfa occurring during the summer months; however, the alfalfa contribution remained at or above 30% throughout the growing season months (Burt et al., 2023; Hendricks et al., 2020). Further, Hendricks et al. (2020) evaluated stand composition beyond September each year and reported another seasonal transition leading to increased alfalfa contributions (30%–50% of the stand) in the fall (September–November) and decreased bermudagrass due to seasonal dormancy. Burton (1976) reported in the early 1950s that interplanting "Coastal" bermudagrass with alfalfa "blended nicely with the grass" and produced excellent yields in a southern Georgia location (5-year DM averages of 8720–9859 kg ha^{-1} depending on P and K application levels). Brown and Byrd (1990), in a northern Georgia location in the 1980s, found yields of an alfalfa–bermudagrass mixture to average 9701 kg ha^{-1} and were similar in yield to bermudagrass fertilized with 200 kg N ha^{-1}. Hendricks et al. (2020), working at the same location as Burton, found mixture yields for 3 years (2016–2018) to range from 14 755 to 22 654 kg ha^{-1}, while bermudagrass alone with 336 kg N ha^{-1} to range from 7877 to 11 788 kg ha^{-1} depending on the year. Brown and Byrd (1990) reported that at least 200 kg N ha^{-1} are replaced by incorporating alfalfa into bermudagrass-based systems. By comparing bermudagrass yields at increasing nitrogen fertilizer levels with alfalfa mixture in replicated plots, Stringer et al. (1994, 1996) demonstrated that at least 224 kg N ha^{-1} is replaced in an alfalfa–bermudagrass stand (with recommended P and K levels and 20 cm row spacing) versus nitrogen fertilization of pure stand bermudagrass. These studies also reported that mixed alfalfa–bermudagrass stands attained the highest crude protein concentration (greater than 12% CP) compared to bermudagrass alone. The effects of alfalfa incorporation into bermudagrass stands on yield, nutritive value, and extended forage production illustrate the compatibility of these forages species. These trials all included 3–5 years of data collection, with alfalfa accounting for at least 30% of stand botanical composition. These observations mirror the United States national alfalfa production trend data, where the yield follows a bell-shaped curve. In years 2 and 3 of stand life, alfalfa stands in the United States generally illustrate the greatest DM yield, followed by decreased yield in years 4 and 5 (Russelle, 2013; Tucker et al., 2021). Some studies have also evaluated alfalfa production and persistence characteristics in bahiagrass (*Paspalum notatum* Flüggé, White et al., 2021), which illustrates another potential application for alfalfa in mixtures with perennial grasses, although persistence characteristics of alfalfa in this system were limited to about 3 years of useful stand life.

Alfalfa as conserved forage

Alfalfa is traditionally conserved as dry hay, ensiled as baleage or silage, grazed, or managed for dual-purpose use (grazing and conserved). In warm-humid regions of the world, frequent rainfall and humid conditions often limit the dry down window for hay and create challenges for preserving a high-quality product. A rise in the use of chemical preservatives (Killerby et al., 2022) and baleage technology creates flexibility in conserved forage management decision-making, where, based on weather conditions, farmers can decide if conditions will better fit hay or baleage production (Hersom et al., 2007; Pruitt & Lacy, 2013). Baleage requires less dry down time to reach the target dry matter and ensiles forage for a time of later use. Recent work from Georgia demonstrated that alfalfa–bermudagrass mixtures are a viable option in the region and provide a high-yielding, high-quality feed source for livestock as hay or baleage (Hendricks et al., 2020). Total seasonal forage production of alfalfa–bermudagrass, when harvested as baleage, averaged 18 873 kg DM ha^{-1} with six to eight harvests per year over the 3-year evaluation, two to four more harvests per year than bermudagrass monoculture stands.

Alfalfa grazing management systems

Grazing alfalfa is not a common practice in the United States but is more widely practiced in other regions of the world (Basigalup, 2023; Bouton, 2012b; Smith et al., 2021). Besides its ecosystem benefits, such as nitrogen fixation, deep root systems, and adding plant biodiversity in otherwise monoculture grass systems, alfalfa is a desirable crop for grazing because of its high yield potential and nutritional value. Historically, a major limitation of alfalfa in grazing systems has been lack of persistence under continuous stocking and soil acidity limitations, which are characteristic of many warm-climate regions of the world (Hoveland, 1989, 1992). Alfalfa breeding programs have made progress with regard to both limitations with the release of more acid-tolerant alfalfa and dual-purpose cultivars for grazing and/or conserved forage production (Bouton et al., 1986). Compared with confined animal production systems, direct grazing has some advantages, such as lower operational costs, better use of alfalfa quality relative to conserved forage (hay, baleage, or silage), beef produced on pastures having less intramuscular fat content, and a higher unsaturated fatty acids omega-3/omega-6 relationship. However, when pure stands of alfalfa are used as a sole source of cattle feed, there can be some disadvantages, such as risk of bloat, longer animal finishing periods in beef operations, or lower milk production on an individual cow basis. Nonetheless, depending on the operation goals, the latter can be overcome by increasing stocking rate to maximize production per unit area, or increasing profitability by reducing feeding costs (Basigalup, 2023).

Many grazing systems have been proposed for improving animal performance while maintaining pasture quality, persistence, and forage species balance. Grazing methods are in fact variations of two complementary concepts: spatial distribution (fences) and temporal distribution (grazing/resting periods, which allow root and crown reserves to be replenished). Leach and Clements (1984) noted that alfalfa is unable to regenerate from seed or vegetatively within the pasture and persistence is dependent on retaining original plants in the stand. Proper alfalfa grazing management, in order to complement high animal production with high levels of pasture yield and persistence, must be based upon the particular growing pattern of the plant (Bouton & Smith, 1998; Smith et al., 2021). Therefore, rotational stocking of alfalfa has been recommended to combine adequate levels of grazing intensity with appropriate resting time while maintaining alfalfa stand persistence (Bates et al., 1996; Wolf & Allen, 1990). Alfalfa can tolerate intensive grazing periods if they are not overly frequent, such as a grazing period of every 21 days, grazing at 15–20 cm stubble height, or grazing at 350 growing degree days (GDD) or 8–10 nodes throughout the growing season. Repeated interruption of the reserve accumulation cycle leads to loss of plants from the stand and the subsequent decrease in animal production. Under continuous stocking, Bates et al. (1996) noted that a forage allowance of 1.0 kg forage per kg of animal body weight provided the longest stand life, acceptable animal gains, and stand persistence in a 3-year grazing trial in Eatonton, Georgia.

Forage quality also plays a very important role in animal performance. If alfalfa pastures were grazed at full bloom (stage at which forage yield and reserves are very high), digestible DM content would be very low. Grazing initiation and stocking management decisions are based on alfalfa plant morphology and growth cycle to better optimize alfalfa forage yield, nutritive value, and persistence (Lu et al., 2018; Pedreira et al., 2020; Smith et al., 1989). For example, grazing at early stages of development (15–20 cm height, 8–10 nodes, or 350 GDD) from mid-spring to mid-summer has been proposed for improving animal performance based on animals consuming alfalfa forage of higher quality (Berone et al., 2020; Hoppen et al., 2022).

For alfalfa cultivars with a fall dormancy rating of 5–10 used in the Pampa Region (temperate climate and no irrigation), many studies conducted by INTA for beef production utilized an average grazing period of 4–7 days, with an average rest period of 28–42 days, depending on the season (Basigalup, 2023). Stocking rates were variable (from 3–6 cattle units ha^{-1}) in these trials based on spring, summer, fall, or season-long grazing. Likewise, forage allowance in one trial ranged from 3.3% to 7.9% of live weight (lw) in spring and from 2.4% to 4.9% in summer, and in another trial from 3.5% to 5% throughout the growing season. In one trial (Ustarroz et al., 1997), pasture utilization in spring ranged from 75% (with a forage allowance of 3.3% lw) to 39% (with a forage allowance of 7.9% lw), and in summer, from 84% (2.4% lw) to 60.5% (4.9% lw). Since different environmental conditions impacted on forage availability, forage allowance, and stocking rates, it is extremely difficult to extrapolate results. As an overall average, best results (in terms of DM production and persistence) for beef operations in the Argentine Pampa region were obtained with cycles of 4–6 days of grazing and 28–42 days of resting across the growing season (Romero et al., 1995).

Previous grazing work with alfalfa–bermudagrass under rotational stocking (21-days rest period) in Arkansas found that adding alfalfa can improve forage production, nutritive value, and animal performance in beef cattle systems while reducing the need for synthetic nitrogen fertilization when compared to bermudagrass monoculture systems (Beck et al., 2017a, 2017b, 2017c). Rushing et al. (2022) reported greater stocker cattle performance (initial body weight ~288 kg; 0.83 kg d^{-1} ADG and 311 kg animal gain ha^{-1}) and for alfalfa–bermudagrass systems under rotational stocking compared with bermudagrass monocultures fertilized with 112 kg N ha^{-1} (0.55 kg d^{-1} ADG and 237 kg animal gain ha^{-1}). The authors estimated that an alfalfa–bermudagrass system had a net revenue of \$186.75 ha^{-1}, compared with −\$65.45 ha^{-1} for nitrogen-fertilized bermudagrass systems. Alfalfa persisted in the mixed stand, with a contribution of 30% or greater to total forage yield in a 2-year trial by Burt et al. (2023). The enhancement of overall stand nutritive value from alfalfa contributions of 30% or greater in comparison with fertilized and nonfertilized bermudagrass has been well documented (Beck et al., 2017; Burt et al., 2023; Hendricks et al., 2020; Rushing et al., 2022). Reported variations in alfalfa persistence within grazed stands are directly related to grazing length, season, and stocking density.

The main goal for any grazing system is a high degree of forage utilization through an adequate grazing pressure. In doing so, it is important to take into account that the effect of pasture use intensity on individual live weight gains is different throughout the year. As a general rule, systems that include high stocking rates produce more beef per unit area, but at the cost of decreased individual live weight gains (Mott, 1960). However, losing some degree of the potential individual animal weight gain may delay the finishing process and negatively influence the profitability of the operation and/or time to achieve return on investment. To remediate this, farmers may consider using a variable stocking rate or implement a leader–follower grazing system, in which the leader group may take advantage of a higher-quality herbage (Basigalup & Ustarroz, 2007).

Grazing alfalfa and bloat

Probably the greatest concern when grazing tender, high-quality alfalfa is the risk of bloat. Direct animal loses and indirect (subclinical) effects are important when conditions predisposing to bloat are elevated, that is, tender pasture (bud stage or 10% blooming, high plant growth rate), fasted animals, presence of dew, frosted plants, high soil fertility, and high individual animal susceptibility. In this context, this fear of bloat makes farmers graze more mature alfalfa, when forage quality is much lower. Feeding overmature alfalfa forage usually results in greater economic losses from low beef cattle weight gain or dairy milk production than the potential losses from bloat itself (Van Keuren & Marten, 1972).

Since there are many factors contributing to bloat, it is very difficult to define a unique approach for preventing and controlling it. Although breeding for elevated levels of condensed tannins in the leaves of forage legumes, including alfalfa, is suggested (Hancock et al., 2014), the current management recommendation is to reduce the probability of reaching a bloat threshold in the rumen. To achieve this, it is advisable to implement a combination of antibloat products with a number of complementary management measures that reduce bloat incidence. Strategies for reducing the risk of bloat may include, but are not limited to, growing alfalfa–grass mixtures, acclimation of livestock to alfalfa before turnout on pastures via limit grazing or by providing roughage for rumen fill, monitoring animals at turnout, and feeding bloat-reducing compounds, such as poloxalene or monensin, before and during turnout onto alfalfa pasture (Smith et al., 2021).

Dual-purpose use systems

Trials with grazing-tolerant alfalfa varieties in the 1990s demonstrated potential fit, production capacity, and persistence in warm-humid environments (Bouton & Gates, 2003). Farmers may consider dual-purpose use of alfalfa for both conserved forage and grazing. A 2-year study was conducted in Alabama and Georgia to evaluate forage and animal responses when alfalfa–bermudagrass mixtures were managed in a dual-purpose use system (Tucker et al., 2021). The integrated dual-purpose cut-and-graze system in this evaluation was harvested for conserved forage production early in the growing season, followed by rotational grazing. During mid-to-late summer, the stand was allowed to regrow for a time of later use, where forage was stockpiled for deferred grazing from October to November. The dual-purpose system supported two mechanical harvest events per season during the summer months, with an average of 2769 kg DM ha^{-1} per harvest during the 2-year evaluation, similar to the cut-only system in yield, with 2279 kg DM ha^{-1} per harvest, but with 5.25 harvest events per season. Likewise, animal performance did not differ among animals grazing in the graze only (GO) and dual-purpose (DP) systems, reporting 235 and 241 kg LWG ha^{-1} (GO and DP) and 261 and 248 kg LWG ha^{-1} (GO and DP) in Alabama and Georgia, respectively (Burt et al., 2024).

While this system did not provide the greatest animal live weight gain or harvestable yield compared to grazing or hay production alone, it was able to optimize the utilization of the mixture in that it resulted in greater alfalfa stand persistence than grazing only, and required less mechanical harvesting, labor, and associated costs than the cut-only system. Further, it allowed for harvesting options during wet periods when hay harvests would have been delayed, provided a forage rest period during stressful drought months, and allowed for use of the area well into the winter months without negatively impacting persistence of the alfalfa integrated into bermudagrass (Tucker et al., 2023).

ALFALFA EXPANSION OPPORTUNITIES AND CHALLENGES

Targeted seed marketing and growth opportunity gaps

Warm-humid climates are found throughout the world, with planted alfalfa area usually low within these climatic zones, especially in the tropics and subtropics. For example, alfalfa in the subtropical, warm, humid Southeast United States (especially the Gulf of Mexico and Atlantic coastal states) is low in comparison with that in the warm-dry Southwestern United States even at similar latitudes (United States Department of Agriculture National Agricultural Statistics Service, 2023). Crop maps and market projection reports of the tropics and subtropics demonstrate that the planted area of alfalfa remains very low in these regions. These low numbers surely had a negative influence on the national and international seed trades targeting alfalfa sales for those regions.

Throughout the 20th century, livestock production in warm-humid regions was largely achieved using grasses as forages. These were managed as either native grasslands or cultivated grasslands (Klotz & Bouton, 2021). Cultivated grasslands are often planted and made up of a small number of plant species (including alfalfa), management is intensive with high inputs, whereas rangelands are complex ecosystems consisting of numerous native plant species, management is extensive with limited inputs. There are now tens of millions of hectares of grasses in cultivated (planted) pastures and hay fields in warm-humid areas, especially in the eastern half of the United States (Lark, 2020). Similarly, a report from Embrapa (Anonymous, 2022) estimated that there are 180 million hectares of pastures in Brazil, with 80% of these planted with one grass genus, *Brachiaria* (Syn. *Urochloa*).

The main reason for the discrepancy between planted alfalfa area and grasses was that alfalfa production was seen as less dependable and higher risk by farmers (Bouton, 2021). The planted area and use of alfalfa were never high compared with grasses, and seemed to increase and decrease depending on the cost of nitrogen fertilizer and the occurrence of periodic droughts. Therefore, farmers, and especially the alfalfa seed industry, in the past adopted a self-fulfilling prophecy: alfalfa use and sales in warm-humid regions will not increase substantially. Thus, there was little incentive to invest heavily in research and marketing efforts. This position is puzzling today based on obvious opportunities. For example, according to the USDA NASS, warm-humid regions in the United States (from Texas-Oklahoma east to the Atlantic Ocean) contain about 40% of the nation's beef herd, a significant and growing percentage of the nation's dairy herd, and 140 million ha of cultivated crop land suitable for alfalfa (United States Department of Agriculture National Agricultural Statistics Service, 2023).

Emphasizing cultivars developed for warm-humid regions

Developing adapted cultivars with ideal fall dormancy, winter hardiness, and pest and disease resistances, mainly for temperate regions, dominated early breeding efforts in both the public and private sectors (Bouton, 2001). Later, more complex traits (quantitatively inherited) such as grazing tolerance, improved nutritive value, and potato leafhopper (*Empoasca fabae*) resistance were added, resulting in the expansion of alfalfa use into other geographic regions including warm-humid areas (Bouton, 2012a, 2012b). Dry matter yield, however, has historically been, and continues to be, a main breeding target trait for alfalfa. However, due to its being quantitatively inherited with moderate to low heritability, yield has proven difficult to improve (Brummer & Casler, 2014). Difficulties underpinning yield are also similar to other traits that limit alfalfa use in warm-humid regions such as acid soil and aluminum tolerance (Bouton, 2012b).

The addition of the Roundup Ready trait (RR) through transformation technologies into modern alfalfa cultivars gave producers a good management tool for controlling problem weeds, especially those ubiquitous in warm-humid regions (McCaslin, 2005). In some cases, RR was combined with grazing tolerance of different dormancy versions of the first proven, grazing-tolerant cultivar, "Alfagraze." These products were recommended for many producers who were grazers in these regions (Forage Genetics, LLC, n.d.; Silva et al., 2021). The reduced lignin trait stacked with RR (sold as HarvXtra®) is also increasing alfalfa's competitiveness as a high-value feed in dairy operations (Fisher, 2017; Silva et al., 2021). Successful transformation to increase condensed tannin expression in white clover (*Trifolium repens* L.) also offers a future approach toward reducing, and even eliminating, bloat in pasture legumes including alfalfa (Woodfield et al., 2019).

Understanding barriers and challenges of farmers

Expansion of alfalfa in warm-climate regions of the world requires legumes to be both an enterprise management and socially relevant fit for the farming operation. A survey of forage-livestock operators in the Southeast United States reported potential barriers for expansion of alfalfa in the region (Silva et al., 2021). Responses were limited to farmers from the following states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and Texas. These forage-livestock producers were asked to select one primary response for perceived opportunities and challenges associated with growing alfalfa in the Southeast United States. Key reasons for growing alfalfa were identified as (1) greater forage nutritional value, (2) greater profit potential from high-quality forage in the form of a marketable, conserved forage product or reduced animal supplementation costs, and (3) "other." Other reasons included diversifying and extending the grazing season in the region and focusing on ways to better serve the equine clientele.

Costs of establishment, stand longevity, and "other" received the majority of responses from participants as challenges or barriers to alfalfa adoption. In the "Other" category, while some management limitations were low soil pH and lack of familiarity with alfalfa as a forage crop, farmers also noted consistent use of soil-residual herbicides as a limiting factor for alfalfa establishment in the operation. These herbicides are often used in perennial, grass-based monocultures as weed control. This illustrates the relative familiarity with management requirements and the ease of management of grass monocultures relative to mixed species stands or legumes. A combination of lack of familiarity of management and perceived complexity in management of legumes is a potential barrier associated with their adoption. Muir et al. (2014) reported that farmers may be more comfortable managing grass-based systems, where production responses to practices such as fertilization, chemical weed suppression, and yield are often quite visual for farming operations. Nitrogen fixation and other ecosystem benefits of legumes are harder for farmers to conceptualize and see immediately tangible benefits from their use.

Educational strategies to showcase alfalfa management systems

The literature on legumes in warm-climate regions reports that perception of lack of legume persistence and low adoption rate of adapted legumes are often aligned (Muir et al., 2014; Shelton et al., 2005). Successful utilization of alfalfa in warm-climate regions requires an integrated, targeted approach. "Alfalfa in the South" Extension workshops are now educating forage-livestock producers on overcoming perceived problems and emphasizing the establishment, management, and economic value of the crop (Tucker et al., 2019; Silva et al., 2021). Partnerships with the forage seed industry and through USDA grant initiatives have fostered the development of several on-farm demonstrations in Georgia, Florida, Alabama, and South Carolina (United States). Farmer demonstration sites showcase alfalfa establishment, management, quality and persistence in conserved forage, grazing, or dual-purpose use systems. Through USDA grant initiatives, several on-farm demonstrations are supported as part of the program, thereby combining field research data and farmer experiences from a more holistic perspective. Participants in the program partner with forage seed industry and Extension educators to provide real-world perspectives on alfalfa performance. The seed industry, in partnership with Extension efforts such as "Alfalfa in the South," needs to continue and expand its educational role. The industry also needs to increase its marketing and sales efforts in all warm-humid regions. Success of past direct marketing and sales efforts in the Southeast United States such as the "Alfagraze" program (Grigson, n.d.), and more recently, the "GotBermudagrass?" initiative (Forage Genetics International, LLC, n.d.) are notable. These efforts increased seed sales and planted area substantially and demonstrated what can be done in the short term. For example, seed sales reported in Georgia were sufficient for an estimated 8090 ha to be planted in the Southeast United States region (Athens Seed Company, personal communication, 2020).

Opportunities for improving alfalfa use in livestock systems

Demonstrating applications of alfalfa use in livestock operations is another strategy to increase awareness in warm-climate regions. This requires a cross-disciplinary approach, from establishment and management of the forage crop to utilization by the end user. Discussion of crop production and animal use is often in differing "silos" at higher education institutions and within the agricultural industry, which represents an area for greater collaboration in the forage industry. Because of the economic value of alfalfa, it is often recommended to feed alfalfa to livestock with the greatest nutritional requirements. In a dairy versus beef cattle scenario, lactating dairy cattle have greater nutrient demands than beef cattle. Alfalfa has long been considered a key component of dairy cattle diets as a high-quality, palatable forage or feed alternative for this purpose (Tarnosky et al., 2023). Large herd dairies are now common in these regions and corn silage is their main, on-farm crop of choice. However, dairy producers who planted a silage corn crop after a corn crop on the same land are seeing lost productivity. They are realizing that alfalfa is still the best rotation crop, and the only forage with the yield and quality, to solve this problem in dairy operations.

Opportunities exist for creep grazing, limit grazing, or rotational stocking of alfalfa stands in beef cattle operations, where alfalfa may be used as a primary or supplemental grazing crop for beef cattle (Burt et al., 2023; Cassida et al., 2006; Hoveland et al., 1988; Rushing et al., 2022). With increasing feed prices and sporadic availability of many byproduct feedstuffs, alfalfa may play a greater role in beef cattle diets than has previously been recognized by Extension-industry educators. Alfalfa-based conserved forage may also play a role in drylot-based diets to meet dietary roughage requirements while reducing the need for commodity feed-based supplementation strategies.

Additionally, alfalfa is also now an integral part of polyculture seed blends for both pastures, cover crops, and wildlife plots. These blends allow local seed dealers to substantially increase their forage seed sales. Better storage opportunities with baleage wrapping and newer preservative formulations for dry hay also overcome harvesting and storage issues created by the region's high rainfall climate. These trends create expanding markets for alfalfa seed sales.

Areas of emphasis for expansion into warm-humid regions in the future include (1) increasing the seed industry commitment to marketing and sales efforts in these regions emphasizing alfalfa's unique traits and use opportunities, (2) for alfalfa breeders to continue to develop better varieties that overcome inherent problems (e.g., soil acidity), and (3) for researchers and farmers to continue to find ways to incorporate and manage alfalfa's use across the region's varied livestock production systems.

CONCLUSIONS

Planted area of alfalfa in warm-humid regions is low, but represents a global area for expansion. Better, adapted cultivars, along with improved management systems that capture the crop's beneficial characteristics, are starting to make an impact for future expansion of areas planted in alfalfa. Future breeding efforts need to combine technologically based selection methods (transgenics, genomics, and phenomics) with tried and true phenotypic/genotypic selection but in a cost-effective manner. Alfalfa will never replace perennial grasses as the base forage in these regions, nor should it, but alfalfa shows real potential for supplemental use or even interplanting into warm-season grasses to solve limitations of high nitrogen fertilizer use and low nutritional value. It also has potential to serve unique roles in existing farming frameworks in warm-humid regions such as integration into beef and dairy diets, crop rotations, and as a component of multispecies, pasture, and wildlife mixes. Targeted marketing efforts by the seed industry for adapted cultivars, continued outreach programs such as "Alfalfa in the South," and demonstrating on-farm alfalfa applications in these regions need to be enhanced.

AUTHOR CONTRIBUTIONS

Jennifer J. Tucker: Conceptualization; data curation; funding acquisition; investigation; project administration; supervision; validation; writing—original draft; writing—review and editing. **Mary K. Mullenix**: Conceptualization; funding acquisition; project administration; writing—original draft; writing—review and editing. **Esteban Rios**: Conceptualization; investigation; methodology; writing—original draft; writing—review and editing. **Daniel Basigalup**: Conceptualization; methodology; writing—original draft; writing—review and editing. **J. H. Bouton**: Conceptualization; methodology; validation; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

The authors would like to thank USDA NIFA for their support of this manuscript and symposium on this topic held at the 2023 International Grassland Congress in Covington, KY. This review is a collation of individual papers presented by the authors during the thematic session, "Alfalfa in Warm Climates," at the 2023 International Grassland Congress, Covington, KY. It summarizes into this current paper each presented paper under the main topics of breeding and genetics (Rios et al., 2023), alfalfa systems management strategies (Basigalup, 2023; Tucker et al., 2023), on-farm use opportunities and educational strategies (Mullenix et al., 2023; Tucker et al., 2023), and seed industry perspectives, challenges, and opportunities (Bouton, 2023). Any interested reader is encouraged to read these individual papers for more information on each topic.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support this review are openly available in the references provided in this manuscript.

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How to cite this article: Tucker, J. J., Mullenix, M. K., Rios, E., Basigalup, D., & Bouton, J. H. (2024). Systems management strategies for increasing alfalfa use in warm-humid regions. *Grassland Research*, 1–12. https://doi.org/10.1002/glr2.12080