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Sustainable, low-input, warm-season, grass–legume grassland mixtures: mission (nearly) impossible?

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Abstract

Grazing lands in warm-temperate and subtropical North America have become less diverse. Pastures are typically grass monocultures, while rangelands are generally managed for the grass components. Overstocking, selective herbicides, fire exclusion and heavy rates of nitrogen fertilizer have contributed to near exclusion of native, warm-season legumes. The simplicity of managing grass monocultures, pasture production responses to nitrogen fertilizer and profitability of grass-only systems have limited interest in legume-based approaches. Changing economics and ecological concerns with ecosystem accumulation of industrial inputs contribute to an increasing interest in legumes. Unlike the development of temperate pasture legumes and recent research in the tropics, legumes tolerant of both freezing temperatures and hot weather have received less attention. Poor establishment, limited persistence and potential invasiveness limit currently available introduced species. Native, herbaceous, warm-season legume species occur throughout warm-temperate North America, but little attention has been directed to these plants as potential forage species. Some success with a few native legume species, primarily in the genus *Desmanthus*, suggests potential for expanded assessment of forage value of the many species available. Current assessments of native legumes, primarily for conservation purposes, provide an opportunity to expand evaluations of these species for pasture and rangeland potential while economics of livestock production and public interest in ecosystem health are supportive. Experiences with legumes of warm-temperate origin in North America, along with results with temperate and tropical pasture legumes globally, provide a starting point for future efforts at incorporating greater legume diversity in pastures and rangelands of subtropical and warm-temperate regions around the world.

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Introduction

If inputs are not limiting, it is possible to grow abundant forages on nearly any land in warm climates where temperatures and solar radiation provide potential for extended growing seasons. Irrigation, fertilizers, herbicides, insecticides, mowers, repeated cultivation, annual seed inputs, grazing pressure and controlled stocking rates are examples of management options that can affect forage production on a pasture. However, only when inputs are inexpensive and/or animal product prices are high will many of these options become economically feasible. This scenario rarely occurs, and, as a consequence, pasture and rangeland managers are usually forced to design and manage pastures and rangelands that are self-sustaining without continual inputs, yet which yield sufficiently to feed themselves and society at large. For productive, sustainable grasslands, mixing grasses and legumes tops the list of available management options.

Grass–legume mixtures have been widely used in regions where both temperate grasses and temperate legumes are well adapted. Historical development of pastures in north-eastern North America involved temperate grass species along with temperate legumes such as alfalfa (*Medicago sativa*), white clover (*Trifolium repens*) and red clover (*Trifolium pratense*), which were all introduced from Europe (Ahlgren, 1949). Similarly, in some tropical regions, combinations of grass species, primarily from Africa, with tropical legumes, mostly from the Americas, have been extensively evaluated and widely used in livestock production systems as illustrated by pasture development in tropical portions of Queensland, Australia (Walker and Weston, 1990). In the area between the temperate and tropical climatic regions, however, persistent combinations of pasture grasses and legumes are rare and monocultures are common. Exceptions include some subtropical locations where sustained research efforts have provided useful species combinations such as those developed for southeast Queensland, Australia (Schulke, 2000; Jones and Bunch, 2003) and peninsular Florida (Sollenberger *et al.*, 1987b; Aiken *et al.*, 1991a,b). In the subtropical and warm-temperate latitudes, a wide range of persistent warm-season perennial grasses is available, and these commonly occur as near-monoculture grass pastures or as naturally occurring, mixed-species, grass-dominated rangeland. In addition, a tremendous variety of largely unappreciated native warm-season legumes persist as remnant populations in isolated, protected locations across much of these regions, as exemplified by nearly forty distinct native herbaceous legumes identified by Diggs *et al.* (1999) in north-central Texas, USA. These warm-season legumes of warm-temperate origin produce their primary growth during the summer season, which typically approaches the length and temperature intensity of tropical summer seasons, and also survive winter weather with repeated frosts and freezing temperatures.

Native legume populations have declined because of land use change, selective grazing, extensive use of herbicides for broadleaf weed and brush control, and transition of open vegetation to dense herbaceous plant communities or even woodland, often associated with exclusion of fire. Under most circumstances, grasses out-yield herbaceous forbs such as legumes (Pitman *et al.*, 1992; Whitbread *et al.*, 2009) and provide greater quantities of digestible fibre to ruminants than legumes (Maasdorp and Titterton, 1997). Grasses have fibrous root systems that give them an advantage when competing for shallow moisture and soil nutrients. They also tend to establish more easily, grow more rapidly and recover from grazing more quickly. Only when soil N is low are grasses at a disadvantage relative to legumes. Excessive harvest of grasses can also mine soil nutrients, which grazers convert into animal protein (Phillips, 2009). If subjected to excessive grazing pressure or hay removal, native or cultivated grasslands can deplete soil nutrients such that the entire ecosystem may deteriorate and eventually collapse, or transition to a stable but less-diverse plant community, which is less desirable for livestock or biomass production (Tilman *et al.*, 1996; Craine *et al.*, 2002).

Forbs have their advantages and drawbacks as well. In the case of legumes, the ability to fix atmospheric nitrogen (N) is an asset to low-N soils or low-input systems such as native grasslands (Piper, 1998; Temperton, 2007). In addition, legumes have taproots that, especially in the case of perennials, allow them to penetrate deeper into soil profiles in search of moisture and nutrients. Their disadvantages include slow recovery from herbivory, less seed production and poor seedling vigour compared with most grasses. But under appropriate grazing pressure, natural grasslands sustain forb populations that contribute to diversity and biomass (Weaver, 1954). This may surprise the modern land manger accustomed to thinking of ideal pasture as monoculture.

In locations with a distinct dry season, addition of legumes can improve the amount and distribution of forage, while in locations with less-variable weather patterns, such as the humid subtropics and tropics where rainfall is more reliable, addition of legumes improves diet quality ('t Mannetje, 1997). Grasses provide most of the digestible energy, and legumes, usually a minority component of diets, contribute crude protein (CP), minerals such as phosphorus and rapidly degraded soluble fibre (Wilson, 1994; Jung and Allen, 1995; Frame, 2005). Figures 1 and 2 include data from

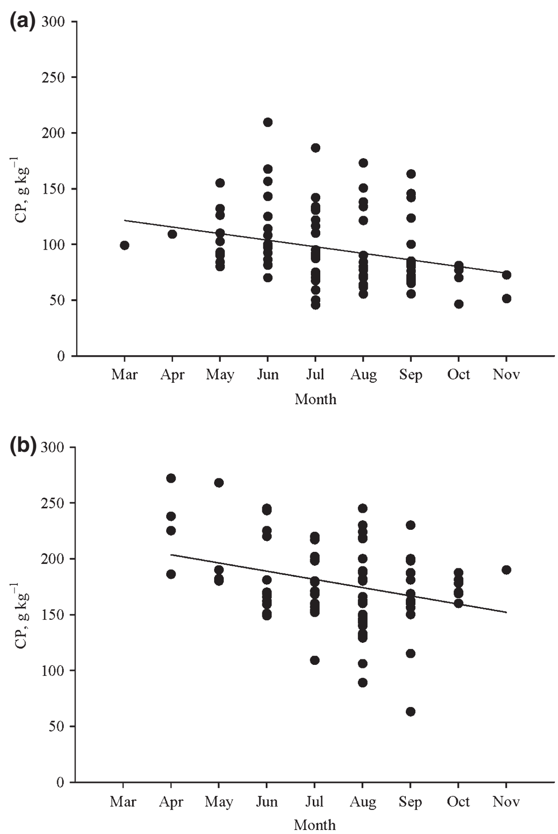

Figure 1 Crude protein (CP) concentrations on a dry-matter basis of (a) warm-season grasses and (b) herbaceous legumes (data from Clavero and Holt, 1987; Brink and Fairbrother, 1988; Sollenberger *et al.*, 1989; Aiken *et al.*, 1991a; Mandebvu *et al.*, 1999; Williams and Hammond, 1999; Johnson *et al.*, 2001; Van Man and Wiktorsson, 2003; Hernandez Garay *et al.*, 2004; Arthington and Brown, 2005; Ezenwa *et al.*, 2006; Rao and Northup, 2009; Foster *et al.*, 2009a).

the literature of CP and digestibility estimates of warm-season grasses and herbaceous legumes throughout the growing season in the northern hemisphere. Grasses include bahiagrass (*Paspalum notatum*) (two cultivars), bermudagrass (*Cynodon dactylon*) (three cultivars), buffelgrass (*Pennisetum ciliare*, syn. *Cenchrus ciliaris*), creeping signalgrass (*Urochloa humidicola, syn. Brachiaria humidicola*), elephantgrass (*Pennisetum purpureum*), guineagrass (*Panicum maximum*) (two cultivars), limpograss (*Hemarthria altissima*) and stargrass (*Cynodon nlemfuensis*). Legumes include aeschynomene (*Aeschynomene americana*) (two cultivars), alyceclover (*Alysicarpus vaginalis*), carpon desmodium (*Desmodium heterocarpon*), cowpea (*Vigna unguiculata*) (three cultivars), lablab (*Lablab purpureus*) (two cultivars), mung bean (*Phaseolus aureus*), phaseybean (*Macroptilium lathyroides*), perennial peanut (*Arachis glabrata*) (two cultivars), sericea lespedeza (*Lespedeza cuneata*) and soybean (*Glycine max*) (two cultivars).

Often, the most important ruminant nutrition contribution legumes provide in a grass–legume mixture is CP. A meta-analysis was conducted with data presented in the literature for which warm-season herbaceous legumes or grasses were sampled repeatedly throughout a growing season, and CP and a laboratory estimate of digestibility (*in vitro* dry-matter digestibility, IVDMD; *in vitro* organic matter digestibility, IVOMD; *in vitro* true digestibility, IVTD) or apparent digestibility was measured. The rate of seasonal decline in CP concentration and digestibility as estimated by various laboratory measures was determined as the slope of a linear regression equation and minimum and maximum values estimated using SAS 9.1. The slopes, minimum and maximum values were compared with PROC MIXED analysis including plant type (grass or legume) as the dependent variable and study as a random variable. Throughout a growing season, the CP concentration decreases (mean slope $-0{\cdot}03 \pm 0{\cdot}007$ for grasses and $-0{\cdot}04 \pm 0{\cdot}008$ for legumes; $P < 0{\cdot}39$) at similar rates for both plant types (Figure 1). However, because the CP concentration is greater in legumes than grasses throughout the growing season, with a few exceptions, CP concentration of legumes typically does not fall below 70 g kg^{-1}, whereas warm-season grass CP concentration may (minimum CP concentration of grasses was 78 ± 9 g kg^{-1} and of legumes was 151 ± 9 g kg^{-1}; $P < 0{\cdot}0001$). Intake is expected to be limited when CP concentration is below 70 g kg^{-1} (Poppi and Mclellan, 1995). While many environmental and morphological aspects cause the digestibility of forages to vary, the variability among legumes is greater than that among grasses (Figure 2). The digestibility of grasses tends to decline through the growing season more rapidly than that of legumes (slope of $-0{\cdot}09 \pm 0{\cdot}01$ for grasses and $-0{\cdot}07 \pm 0{\cdot}01$ for legumes; $P = 0{\cdot}13$), and the digestibility of legumes is generally greater ($P < 0{\cdot}03$) than that of grasses. The maximum digestibility estimate for grasses was 586 ± 53 g kg^{-1} and minimum was 493 ± 39 g kg^{-1}, whereas the maximum digestibility estimate for legumes was 793 ± 61 g kg^{-1} and minimum was 624 ± 43 g kg^{-1}. Because of the increased CP concentration and digestibility of legumes, addition of legumes to a low-quality grass diet usually increases digestibility and intake, thereby improving animal performance with minimal inputs (Pitman *et al.*, 1992; Weder *et al.*, 1999; Foster *et al.*, 2009b,c).

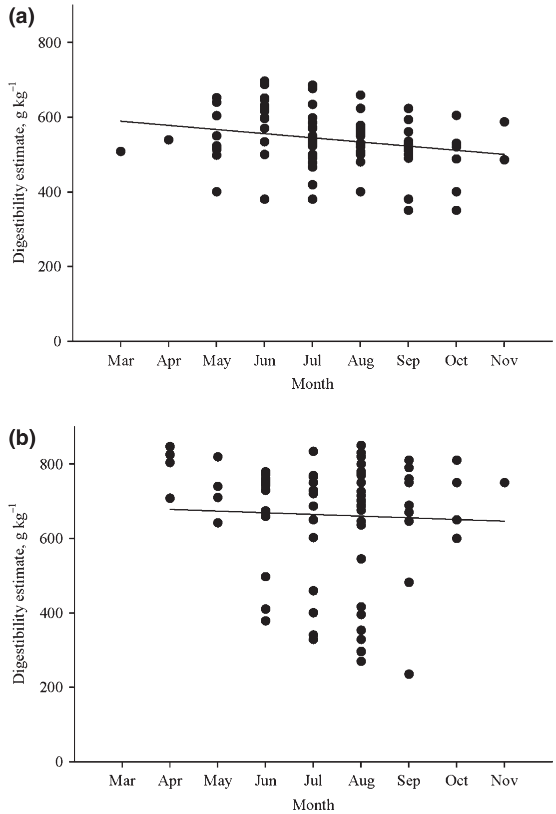

Figure 2 Digestibility estimate [from *in vitro* total, dry matter (DM), organic matter and apparent digestibility on a DM basis] of (a) warm-season grasses and (b) herbaceous legumes (data from Clavero and Holt, 1987; Brink and Fairbrother, 1988; Sollenberger *et al.*, 1989; Aiken *et al.*, 1991a; Mandebvu *et al.*, 1999; Williams and Hammond, 1999; Johnson *et al.*, 2001; Van Man and Wiktorsson, 2003; Hernandez Garay *et al.*, 2004; Arthington and Brown, 2005; Ezenwa *et al.*, 2006; Rao and Northup, 2009; Foster *et al.*, 2009a).

Mixtures of warm-season grasses and legumes have advantages over monocultures when they bring together the benefits of the different components while minimizing their disadvantages (Piper, 1998; Springer *et al.*, 2001; Gerrish, 2003). *The goal is to maximize long-term natural resource stability while still allowing short-term utilization as managers harvest vegetation through animal products in a sustainable manner.* Native warm-season, subtropical and tropical grasslands throughout the world, when free of human interference, contain a rich diversity of both grasses and forbs (Fabian and Germishuizen, 1997; Diggs *et al.*, 1999; Van Oudtshoorn, 1999). On removing broadleaf herbicides, excessive grazing and heavy N fertilizer application from cultivated monoculture grass pastures, these also tend to increasingly rich diversity. In contrast to temperate legumes, which typically fail to survive the summer season in subtropical and warm-temperate climates, and tropical legumes, which are not sufficiently cold-hardy for such climates, adapted warm-season legumes of subtropical and warm-temperate origin can survive the adversities of both seasons. These species, however, have not been extensively developed as a forage resource. We review much of what has been learned about mixing legumes, particularly warm-season species, and grasses from around the world and enumerate some of the remaining challenges. This review is focused on the south-eastern USA experience, because this is the primary location of research on legumes that are neither specifically tropical nor temperate in origin and are used for support of warm-season ruminant production systems based on pastures and rangeland.

Designing mixtures

Planning, planting and managing mixtures of forage grasses and legumes that are both productive and persistent are far more involved than focusing on single-species pastures. If we consider a few basic principles, however, these difficulties become less daunting.

Sod-forming grasses vs. bunchgrasses

Where annual rainfall exceeds 800 mm, sod-forming grasses tend to predominate in cultivated monoculture pastures (Moser *et al.*, 2004). Bermudagrass and bahiagrass are prime examples found in southern portions of central and eastern North America. These are widely used because they are adaptable to a range of soils, climates and management systems. In other words, these grasses persist because they are forgiving of abuse and neglect. The very fact that they are aggressive invaders makes them poor choices for consociation with legumes (Muir and Pitman, 2004). Only in low-nitrogen soils do legumes stand a chance of surviving alongside sod-forming grasses (Valentim *et al.*, 1985; Valencia *et al.*, 1999), and, even then, grazing management must be such that grazers or browsers are not allowed to selectively graze legumes out of the mix.

Bunchgrasses tend to dominate grasslands where annual rainfall is <800 mm and soils are well drained (Diggs *et al.*, 1999; Moser *et al.*, 2004). Their advantage in mixtures is that they allow forb seedling establishment in the space between plants (Springer *et al.*, 2001). Their disadvantage is that, in general, they do not tolerate heavy grazing pressure during vegetative growth and have poor nutritive value when mature (Muir and Jank, 2004). There are numerous native, warm-season bunchgrasses presently available on the seed market in the USA. These native grasses include big bluestem (*Andropogon gerardii*), eastern gamma grass (*Tripsacum dactyloides*), Indiangrass (*Sorghastrum nutans*), little bluestem (*Schizachyrium scoparium*), sideoats grama (*Bouteloua curtipendula*) and switchgrass (*Panicum virgatum*) cultivars. Introduced bunchgrasses include buffelgrass, kleingrass (*Panicum coloratum*), lovegrasses (*Eragrostis* spp.) and old world bluestems (*Bothriochloa* spp. and *Dichanthium spp.*).

Plant functional groups

Plants are grouped into ecological functional types based on such characteristics as season of growth, pattern of resource use, life cycle, response to disturbance and effects on the ecosystem. Plant communities that include appropriate combinations of the various plant functional groups can enhance such ecosystem qualities as structure, function and stability (Brown, 2004). Within the warm-season (C_4), perennial grass functional group, a plant strategy in limited-N environments is to maintain large amounts of biomass with low-N concentrations (Craine *et al.*, 2002). In contrast, the legume plant functional group produces tissue of higher N concentration and accelerates ecosystem N cycling (Craine *et al.*, 2002). Combinations of these characteristics provide complementarity for the benefit of both grazing livestock and overall ecosystem function. Within functional groups, additional variation among plant species provides further enhancement of ecosystem function and stability (Tilman *et al.*, 1996; Brown, 2004).

The large variation among species within the warm-season legume group suggests substantial benefits from the use of multiple species in pasture plantings and rangeland renovation. Although substantial quantities of N can be fixed by some native legumes, individual species vary widely in N fixation (Hiers *et al.*, 2003; Muir *et al.*, 2005b). Wide variation among the warm-season legumes native to southern North America, for example, also exists in growth form, adaptability, competitiveness and acceptability to grazing herbivores (Diggs *et al.*, 1999; Muir *et al.*, 2005b).

Spatial vs. temporal mixtures

Another consideration when formulating grass/forb mixtures is whether to have them in direct competition with each other or to separate them by time or space. In very rare cases, legumes out-compete grasses (Valencia *et al.*, 1999), but the opposite is usually the case. If grasses are simply too competitive, protecting legumes by over-seeding them onto dormant grass is one proven strategy (Evers, 2009). It can be argued whether this is a genuine mixture or not, but growing cool-season legumes on the same land but at different times from a warm-season, perennial grass is a useful agronomic strategy. This approach is used successfully, although perhaps less extensively than the benefits justify, throughout much of the bermudagrass/bahiagrass pasture region in south-eastern North America (Muir and Bow, 2011). Nonetheless, such cool-season legume production on closely defoliated, dormant grass sod requires intensive management and does not provide the benefits of supplementing the legume forage to the lower-quality grass diet during the warm season.

Planting legumes in strips free of grass is another approach (Adjei, 1995; Muir and Pitman, 2004; Whitbread *et al.*, 2009), but the width of each strip and palatability differential need to match species compatibility as well as animal production objectives. Some research indicates that separating grasses and legumes over space decreases yields vis-à-vis mixtures (Shehu and Akinola, 1995; Springer *et al.*, 2001); however, it can be less difficult to manage grazed forages when they are separated spatially. For example, using legumes in forage banks instead of in mixtures (Muir, 1993) greatly increases the chance that both the grass and the forb will persist.

Matching legumes to grasses

Species selection, planting patterns and grazing strategies can make all the difference when designing stable pasture or rangeland mixtures. The more complementarity among species, the more likely that mixtures will out-produce monocultures (Aarssen, 2001; Springer *et al.*, 2001). Grasses generally have the advantage when grown in close proximity to legumes, but this competition can be mitigated by selecting legumes that can, for example, tolerate shade if they are shorter (Muir and Pitman, 1989; Muir *et al.*, 2009), climb grass structures (Maasdorp and Titterton, 1997; Muir *et al.*, 2005a), etiolate into the grass canopy (Muir *et al.*, 2005b) or outgrow the grass in low-N soils (Valencia *et al.*, 1999).

Palatability, which varies considerably among legumes (Sheaffer *et al.*, 2009), also plays a role in designing a stable mixed-forage ecosystem. In a pasture or rangeland where animals will do the harvesting, mixing grasses and legumes with fairly similar appeal or accessibility to the grazer is essential if the system is to maintain stable plant proportions. Knowing the preferences and grazing strategies of the herbivore is also important. A goat or white-tailed deer will select different plants or different plant parts from within a mixture than will a bulk grazer such as a horse or cow (Lechner-Doll *et al.*, 1995).

If a perfect match is not possible, then grazing strategies that force animals to graze all species somewhat similarly before moving on can sometimes equalize the effects of grazing defoliation. This can be achieved through such approaches as rotational grazing, successive waves of selective versus bulk grazers or hay harvest following short-duration grazing (Sollenberger *et al.*, 1987a,b).

What we know so far

The accumulated information base to date provides several general principles that can be used in the search for sustainable warm-season grass/legume mixtures:

1. Perennial systems tend to foster diversity and are therefore likely more stable than systems based on annuals (Tilman *et al.*, 2006). Disturbed ecosystems seeking long-term equilibrium will also tend towards complexity. If properly managed, by either nature or man, forage and rangeland plant mixtures will recruit diversity; conversely, poorly managed pastures and rangeland will deteriorate towards mono-specific plant communities where the most aggressive and least palatable survive all others in the original mix. Use of herbicides will produce the same tendency. Conversely, poorly designed or managed mixtures can degrade to weedy diversity where unpalatable grasses, forbs and woody species predominate. Examples of these in south-eastern North America include forbs such as horsenettle (*Solanum carolinense* Cav.) or common nettle (*Urtica dioica* L.), grasses such as broomsedge bluestem (*Andropogon virginicus* L.) and smutgrass (*Sporobolus* spp.), or woody species including honey mesquite (*Prosopis juliflora* var. *glandulosa* (Torr.) Cockerell) and ashe juniper (*Juniperus ashei* Buchholz).
2. Nitrogen fertilizers lead to grass dominance and decreased species diversity. If legumes and general diversity are to survive in mixtures with grasses, the latter cannot be heavily fertilized with N (Andreata-Koren *et al.*, 2009). Because legumes fix their own N, they gain an advantage in low-N systems that endow them with additional survival vis-à-vis companion grasses. Amending soils with

heavy rates of N will tilt the balance towards the grass component.

3 Low inputs lead to lower yields. Even though there is lower production, in some cases, there may be greater net return with an appropriate low-input system. Low-input systems such as rangelands and multi-species pastures can sometimes maintain more balanced mixtures (Tilman, 1996). The price, of course, is lower productivity per area.

4 Sustainable, low-input multi-species pastures are complex. This complexity can lend stability over time (Tilman *et al.*, 2006) but also requires deeper knowledge and greater analysis from managers if mixtures are to be maintained over the long term. Increased complexity in animal species, such as a combination of grazer and browser species, both domesticated and native fauna, can also benefit plant community diversity (Vangilder *et al.*, 1982; Van Rooyen *et al.*, 1989; Rutter, 2006).

5 Managing plants means managing animals and soils as well. The initial choice of species to plant together is important, but to maintain the balance of that mixture over time, managers must learn to manage animals (stocking rates, grazing duration, species mixtures) (Rutter, 2006) as well as the soil under those plants (fertility, organic matter, micro-organism health) (Eisenhauer, 2009). This requires far greater knowledge and experience than the current, simpler monoculture approach prevalent in North America.

6 A multi-species approach may sometimes work when insufficient information is available to guide species selection when establishing mixtures. Including multiple grass, legume or other forb species in pastures or rangeland seed mixtures with varying slopes, soils, weed pressures or grazing pressure may result in a less-uniform pasture but can also result in more successful establishment across the entire diverse landscape (Harris, 2001).

7 Diversity lends itself to more even forage distribution and nutritive value over seasons and years. As weather conditions change during the year and as one group of species in the mix fades, others fill in the herbage gap (Gerrish, 2003). This is driven by differential climatic adaptation, growth patterns and reproductive strategies among other factors.

8 Grass–legume mixtures may provide greater animal productivity, defined as milk produced or average daily gain, than monoculture grazing systems. This is a product of increased and/or more consistent forage productivity, improved digestibility and/or intake (production per animal) or increased stocking rate (production per ha) because of the addition of legumes (Pitman *et al.*, 1992; Tilman, 2001; Evers, 2009). Translation of improved forage distribution and nutritive value into increased milk or meat product is evidence that there is economic benefit to the inclusion of legumes in warm-season grass pastures (Deak *et al.*, 2010).

9 Grasslands become woodlands with increasing moisture. From west to east across southern North America, for example, there is a general increase in rainfall with associated plant communities progressing from desert to grassland to savannah/woodland and then to forest when undisturbed. Understanding this pattern becomes important when selecting and maintaining forage species mixtures. In much of the natural grassland portion of the region, woody plants often occupy low-lying areas along drainage systems where runoff water accumulates.

10 Woodlands can become diverse grasslands with judicious use of fire. Historically, grassland communities in the woodland and forest environment were naturally maintained by periodic fires, and such burning can be particularly useful for maintaining herbaceous forb species (Harshbarger *et al.*, 1975; Hendricks and Boring, 1999). In moist environments, maintenance of low-input grasslands, especially forb components, may be substantially enhanced by appropriate burning practices. Establishment and maintenance of fire-tolerant forbs within sylvopastoral or savannah landscapes can likewise be enhanced with fire.

Warm-season legumes over-shadowed by temperate and tropical species

Development of temperate legumes for use in pastures has a rich heritage with early progress in Europe carried to temperate regions of North America, Australia and New Zealand even during colonial periods. As pastures were developed in warmer regions, temperate legumes were often used as temporary pastures during the cool season. A major portion of the subsequent forage research effort in warm-temperate areas, and even in more subtropical areas to some extent, has been directed to the development of germplasm and management approaches for the use of temperate legumes as cool-season pasture plants. Some temperate perennials, such as *Medicago sativa* and *Trifolium repens*, can even grow during the warm season on some sites with adequate moisture, which is often provided by irrigation.

Development of tropical legumes for use as pasture plants has been more recent. Initial early introduction and screening of a small number of tropical legume species in Queensland, Australia, was in progress in the late 1800s (Clements and Henzell, 2010). Rather modest efforts with tropical legume evaluation and development continued in Australia through the early portion of the twentieth century. A period of dramatic progress with tropical legume development began in Australia in the mid-1940s (Clements and Henzell, 2010) and was particularly productive from the 1960s through the 1980s with substantial contributions in both Australia and tropical America. During this period, tropical pasture legumes, often the Australian cultivars, were extensively evaluated in tropical locations across Africa and Central and South America. These legumes of largely tropical origin were assessed for adaptation to a wide range of environments including those extending beyond tropical latitudes. A rather impressive list of the important tropical legumes including *Aeschynomene americana, Aeschynomene falcata, Desmodium intortum, Desmodium uncinatum, Lablab purpureus, Lotononis bainesii, Macroptilium atropurpureum and Macroptilium lathyroides* were reported to be adapted to some subtropical locations (Humphreys and Riveros, 1986; Jones and Bunch, 2003).

Perennial species of even the best-adapted tropical legumes in subtropical locations were found to tolerate only occasional and very light frost, thus limiting their usefulness in areas with any substantial or repeated freezing winter weather. In peninsular Florida, *Aeschynomene americana* was successfully used in pastures as a reseeding annual escaping winter temperatures (Hodges *et al.*, 1982), while the perennial *Desmodium heterocarpon* possessed sufficient cold tolerance to survive the infrequent frosts (Kretschmer *et al.*, 1979). The perennial *Vigna* species, *V. adenantha* and *V. parkeri*, survived peninsular Florida winter conditions, but photoperiod effects on flowering allowed only minimal seed production before defoliation of above-ground vegetation each winter.

Perhaps the earliest evaluated legumes from actual warm-temperate climates were species native to the warmer parts of Japan and nearby Korea and eastern China. The annual species *Kummerowia striata* was introduced from this area to Monticello, Georgia, USA, in 1846 (Helm, 1953) and to Queensland, Australia, in 1886 (Clements and Henzell, 2010). Another annual, *Kummerowia stipulacea*, was introduced from Korea to the USA in 1919 (Helm, 1953). These two annual legumes proved useful for forage and other purposes in farming systems in the south-eastern USA prior to widespread availability of low-cost nitrogen fertilizer. Some use as forage plants also occurred during this period with other warm-season annual legumes such as cowpea. Interest in the annual warm-season legumes in the USA greatly diminished with the availability of low-cost nitrogen fertilizer in the mid-twentieth century. The viney perennial kudzu (*Pueraria montana*) was introduced to the USA from Japan in 1876 (McKee, 1953) and was used as a forage crop in the south-eastern USA particularly during the mid-1900s. Sericea lespedeza (*Lespedeza cuneata*), also native to the eastern China, Japan, Korea region, was first evaluated for use as a forage in the USA in 1896 (Hoveland and Donnelly, 1985) with some continuing rather localized use.

Although the initially available legumes with warm-temperate origins were dominated by species from the warmer parts of Japan, Korea and eastern China, forage systems based on these legumes were not developed in their native region. As noted for Japan (Oizumi, 1985), pasture development in the region was very limited until the middle of the twentieth century, and the emphasis was primarily on more intensively managed, nitrogen-fertilized grass systems. In Australia, legume development for use in the transition zone between areas of primary use of temperate and tropical legumes has largely involved extending the range of the most cold-tolerant tropical species into the region from the tropics and extending the range of the best-adapted temperate species into the region from the opposite direction. Development of legumes of warm-temperate origin has received minimal attention. In the warm-temperate zone of southern Africa, grasslands primarily occur in arid (125–500 mm of rainfall) and savannah (500–800 mm of rainfall) biotic zones (Burns *et al.*, 2004). Predominance of summer rainfall supports primarily warm-season species that are mostly grasses. Pasture legumes are largely restricted to the temperate perennial *Medicago sativa*, which is intensively managed with irrigation. Somewhat similarly, in the warm-temperate portion of South America, rather extensively managed native grasslands dominated by grasses and intensively managed temperate forage species comprise the primary pasture resources. In the warm-temperate portion of North America, climatic (primarily rainfall) and economic conditions have combined to provide incentive for the development of legume resources for use during the summer growing season. Such incentives have not developed sufficiently for an emphasis on the warm-season legumes with pasture potential in warm-temperate regions outside of North America.

Warm-season legumes for grassland diversity in southern North America

Warm-season grasslands in the southern latitudes of North America have become increasingly grass dominated or, where non-grass diversity exists, invaded by unpalatable species. Native grasslands, both savannahs and prairies, were once rich with hundreds of herbaceous species (Weaver, 1954; Diggs *et al.*, 1999). Change from native grazers to domesticated herds, overstocking, continuous grazing as a result of fencing, and exclusion of fire have reduced the diversity of palatable forage species to a handful on any given rangeland. Cultivated pastures are likewise diversity-poor despite decades of agronomic research looking for new grass and forb, mostly legume, species (Aiken *et al.*, 1991a; Muir and Pitman, 1991; Pitman, 2009a). True tropicals such as *Macroptilium atropurpureum* that have had some success in frost-free regions (Muir, 1993) do not persist in regions where temperatures dip below freezing for any length of time. To survive in these latitudes, warm-season legumes must thrive in temperature extremes via annual seed production or winter dormancy. Despite these challenges, interest in multi-species rangeland reseeding mixes or cultivated pasture establishment is growing (Springer *et al.*, 2001), accompanied by a gradual increase in the number of legume species available for the varied climates, soils and management systems in the region, as listed in Table 1. Species used in more tropical environments, which have been described previously (Loch and Ferguson, 1999; Pitman and Kretschmer, 2007), may have some potential in the extreme southern portion of the region.

Some of the most widely planted warm-season forage legumes in the south-eastern USA have been the lespedezas. These include the perennial sericea lespedeza and the annuals striate and Korean lespedeza (formerly classified as *Lespedeza* species but now in the genus *Kummerowia*) (Ball *et al.*, 2007). Sericea lespedeza presents somewhat of a paradox. Poor seedling vigour and limited grazing tolerance early in the growing season have led to the failure of plantings, while naturalization of this introduced legume in some regions has led to its designation as invasive in some ecosystems (Pitman, 2009a; USDA, 2011). The annual lespedezas provided reseeding populations on some forested rangelands and low-input pastures in the humid south-east, but such extensively managed grazing is not currently practised to any substantial extent. Despite its recognized forage value (Corley *et al.*, 1997) and successful use in the south-eastern USA, kudzu is a highly invasive species in the absence of ruminants (USDA, 2011) and thus is no longer widely planted. Rhizoma, or perennial, peanut (*Arachis glabrata*) is another introduced warm-season legume with rather narrow adaptation to well-drained sites in the warmer regions of North America but requires extensive investment because of vegetative propagation (Butler *et al.*, 2006). The costs and risks of establishment, invasiveness and lower productivity of forage legume pastures, compared with the relative ease of managing N-fertilized warm-season grass pastures have limited interest in the introduced warm-season legumes during recent decades. The rise in fertilizer costs as fossil-fuel costs increase may increasingly favour legumes over N fertilizers.

Collection and evaluation of native legumes were initiated in the southern Great Plains by the USDA, Soil Conservation Service [now Natural Resources Conservation Service (NRCS)], Plant Materials Centers several decades ago. Release of the Illinois bundleflower (*Desmanthus illinoensis*) selection Sabine in 1984 provided a widely adapted native legume useful for forage and wildlife food plantings across much of Texas and Oklahoma and extending eastward on some sites (TAES, 1984). Despite limitations including insufficient seedling vigour for establishment under aggressive competition (Muir and Pitman, 2004) and low leaf digestibility even with CP concentration exceeding 20% (Adjei and Pitman, 1993), Sabine Illinois bundleflower has potential to contribute to grazing lands and ecosystem function on non-agricultural lands substantially beyond the current use. The subsequent release of the partridge pea (*Cassia fasciculata*) cultivar Comanche in 1986 provided an annual native legume with value for land reclamation and food plantings for granivorous avian species but insufficient palatability for use as a forage plant (TAES, 1986).

Along with early native legume releases by the NRCS Plant Materials Center in Texas, releases by the NRCS Plant Materials Center in Kansas provided plants useful in the southern Great Plains. These included Kenab purple prairieclover (*Dalea purpurea*) released in 1975 and the more recent releases of Kanoka roundhead lespedeza (*Lespedeza capitata*), Reno Germplasm Illinois bundleflower and Riley showy partridge pea released in 2007. Recent NRCS native legume releases in Texas include Hondo Germplasm velvet bundleflower (*Desmanthus velutinus*), Crockett herbaceous mimosa select germplasm (*Mimosa strigillosa*), Cuero Germplasm purple prairie clover, Plains Germplasm prairie acacia (*Acacia angustissima*) and yellowpuff littleleaf lead tree (*Leucaena retusa*). Other recent releases from the Plant Materials Center in Mississippi for the humid south-eastern USA include the annuals Lark Selection partridge pea and Hopefield Selection trailing wildbean (*Strophostyles helvula*) primarily for wildlife food plantings. Smooth-seeded wildbean (*Strophostyles leiosperma*) cultivar Rio Rojo has also been released for use in Texas and Oklahoma (Butler and Muir, 2010). In addition, the development of BeeWild bundleflower (*Desmanthus bicornutus*) by the Texas Agricultural Experiment Station provided a legume with wildlife and forage value adapted particularly well to southern Texas and northern Mexico (Ocumpaugh *et al.*, 2004).

Recent NRCS evaluations have led to the release of native legume selections primarily for restoration and conservation purposes rather than primarily for grazing value. Pre-variety germplasm release categories were developed to provide more rapid availability of certifiable native plant seed where existing ecotypes satisfy somewhat urgent conservation needs (Young *et al.*, 2003). This mechanism has increased the number of released native warm-season legumes. Seed availability,

Table 1 Herbaceous legume species evaluated and/or currently commercially available for use in pastures and rangeland in combination with warm-season grasses in south-eastern North America.

Latin name	Release name	Common name	Growth habit	Release/study	Seed/rhizomes available	Limitations	Reference
Introduced							
Aeschynomene americana		Aeschynomene, American jointvetch	Erect annual		Yes	Restricted adaptation Poor self-reseeding	Hodges *et al.* (1982)
Alysicarpus vaginalis		Alyceclover	Erect annual	Release	Yes		Ball *et al.* (2007)
Arachis glabrata	Multiple	Rhizoma peanut	Rhizomatous perennial	Release	Yes	Vegetative propagation	Butler *et al.* (2006), Skerman (1977)
Glycine max	Multiple	Forage soybean	Viney annual	Release	Yes	Poor self-reseeding	Ball *et al.* (2007), Skerman (1977)
Indigofera hirsuta	Flamingo	Hairy indigo	Erect annual	Release		Poor self-reseeding Limited palatability	Mckee (1953)
Kummerowia striata		Striate lespedeza	Erect annual		Yes	Poor self-reseeding	Ball *et al.* (2007)
Kummerowia stipulacea		Korean lespedeza	Erect annual		Yes	Poor self-reseeding	Ball *et al.* (2007)
Lablab purpureus	Rio Verde	Lablab, Hyacinth bean	Viney annual	Release	Yes		Ball *et al.* (2007), Skerman (1977)
Lespedeza cuneata	Multiple	Sericea lespedeza	Erect perennial	Release	Yes	Potentially invasive	Ball *et al.* (2007), Skerman (1977)
Mucuna pruriens	Multiple	Velvet bean	Viney annual	Release	Yes	Poor self-reseeding	Skerman (1977)
Macroptilium lathyroides		Phaseybean	Erect annual		No	Requires high moisture	Pitman *et al.* (1986)
Pueraria montana var. *lobata*		Kudzu	Viney perennial		Yes	Aggressive invasive	Ball *et al.* (2007), Skerman (1977)
Vigna unguiculata	Iron-clay	Cowpea	Viney annual	Release	Yes	Poor reseeding	Ball *et al.* (2007), Skerman (1977)
Native to southern USA							
Acacia angustissima	Plains	Prairie acacia	Erect perennial	Release	No	Weak seedlings	Muir *et al.* (2005b)
Amorpha canescens		Leadplant	Erect woody perennial		Yes		Towne and Knapp (1996)
Amorpha fruticosa		False indigo	Erect woody perennial		Yes	Unpalatable	Sheaffer *et al.* (2009)
Baptisia australis		Blue wild indigo			No		Sheaffer *et al.* (2009)
Chamaecrista fasciculata	Comanche, Lark	Partridge pea	Erect annual	Release	Yes	Forage unpalatable	TAES (1986)
Dalea purpurea	Kenab, Cuero	Purple prairie clover	Erect perennial	Release	Yes		Sheaffer *et al.* (2009)

Table 1 (Continued).

Latin name	Release name	Common name	Growth habit	Release/study	Seed/rhizomes available	Limitations	Reference
Dalea candida		White prairie clover	Erect perennial		Yes		Towne and Knapp (1996)
Desmanthus bicornutus	Beewild	Bundleflower	Erect perennial	Release	Yes	Freeze susceptible	Ocumpaugh *et al.* (2004)
Desmanthus illinoensis	Sabine	Illinois bundleflower	Erect perennial	Release	Yes		Sheaffer *et al.* (2009)
Desmanthus velutinus	Hondo	Velvet bundleflower	Erect perennial	Release	No		Muir *et al.* (2005b)
Desmodium canenscens		Hoary tick clover					Mcgraw *et al.* (2004)
Desmodium paniculatum		Panicled tick clover	Erect perennial	Study	No	None to date	Muir *et al.* (2005b)
Lespedeza capitata	Kenoka	Roundhead lespedeza	Erect perennial	Release	Yes		Mcgraw *et al.* (2004)
Leucaena retusa	Yellowpuff	Little lead tree	Erect woody perennial	Release	No		Felker *et al.* (1999)
Mimosa strigillosa	Crocket	Herbaceous mimosa	Trailing perennial	Release	No	Low seed production	USDA-NRCS (2000)
Senna hebecarpa		Wild senna					Sheaffer *et al.* (2009)
Strophostyles helvula	Hopefield	Trailing wild bean	Viney annual	Release	No	Dehiscent pods	Muir *et al.* (2005a)
Strophostyles leiosperma	Rio Rojo	Smooth-seeded wild bean	Viney annual	Release	No	Dehiscent pods	Muir *et al.* (2005a)

however, has not necessarily followed, and elevated price of available seed is a substantial limitation to extensive use of some available native legumes. Usefulness as forage plants and management requirements for sustained populations of many of these legumes in grazed ecosystems have not been assessed. Rather unique characteristics of individual legumes such as the dense, stoloniferous ground cover of herbaceous mimosa and the rhizomatous spread of prairie acacia suggest tolerance to livestock grazing. Even less-palatable legume species not contributing much to livestock diets, however, may contribute to ecosystem productivity through N contribution and wildlife benefits.

What needs further development

1. Land manager education based on a culture of sustainable grassland resources is just beginning. The most sustainable warm-season and subtropical pasture and rangeland systems around the world are a result of accumulated knowledge gleaned from generations of managers (Hardesty and Box, 1984). If that knowledge flow between generations is interrupted or social values change, the systems tend to collapse. The degradation of North American mixed grass/forb rangeland ecosystems in the last 200 years is a result of drastic socio-cultural transition from Native American to northern European cultures. Too few generations of newly arrived European land managers have lived on the land to accumulate the necessary experience to guide future generations.
2. Availability of seed of useful legume species is highly inadequate. Variability among the potentially useful native legume species is so great that there is limited transfer of knowledge and technology regarding seed production and processing from species to species (Muir *et al.*, 2005b; Dittus and Muir, 2010). This uniqueness of seed production methodology for each species along with a somewhat common list of seed production limitations among many warm-season legumes discourages commercial seed production. Warm-season ecotypic legumes are often very specific in geographic location requirements for profitable seed production, many have an indeterminate growth habit, flowering is often limited or poorly synchronized, seed typically matures over an extended time and shatter as they mature, and even available seed at harvest is often recovered at low levels of yield (Wheeler and Hill, 1957; Ferguson *et al.*, 1999). As a result, an established forage seed production industry exists in only portions of the region. These limitations combine to restrict oppor-

tunities for commercial seed production of new species and provide high costs for any available seed.

3 Increases in commercially available germplasm of adapted native and introduced warm-season legumes are needed in North America and for other regions of the world where they are potentially useful. As an example, numerous exotic and native grasses are available within south-eastern North America. By contrast, very few introduced legumes, sufficiently adapted to warm-season North American edapho-climatic conditions, exist that can persist in mixtures with grasses in warmer latitudes. Those that are currently used, such as *Lespedeza cuneata* (Mosjidis, 2001) and *Arachis glabrata* (Valencia *et al.*, 1999), are usually found in monocultures but can contribute to well-managed mixtures. A hazard of easily propagated, well-adapted introduced warm-season legumes with forage value is potential invasiveness (Pitman, 2009a). A concerted effort to find additional candidates for pasture mixtures may correct this but only with greater investment in time and risk.

4 Native legume research is needed to move development beyond the preliminary stages. Native legumes are candidates for rangeland restoration as well as cultivated pasture mixes. Typical of most warm regions, there is a paucity of commercially available native herbaceous-legume seed collected from warmer latitudes of North America. Illinois bundleflower, partridge pea and more recently, *Desmanthus bicornutus* are presently the only commercially available species with documented results from grazing-land plantings. None of these are as yet widely recommended in cultivated pasture seed mixtures because of the lack of seedling vigour, low productivity and persistence, and anti-quality factors (Posler *et al.*, 1993; Berg, 1996; Jackson, 1999; Nguluve *et al.*, 2004). Some natives recently evaluated for grazing-land use include the annual smooth-seeded wildbean (*Strophostyles leiosperma*) as well as herbaceous mimosa (*Mimosa strigillosa*), tickclovers (*Desmodium* spp.), prairie acacia (*Acacia angustissima*), prairie clover (*Dalea* spp.), prairie bundleflower (*Desmanthus leptolobus*), leadplant (*Amorpha canescens*), false indigo (*Amorpha fruticosa*) and *Rhynchosia latifolia* (Posler *et al.*, 1993; Muir and Bow, 2008; Muir *et al.*, 2008; Pitman, 2009b). To date, none have proven compatible with sod-forming grasses, while a few that are able to establish in native perennial bunchgrasses (Posler *et al.*, 1993; Muir and Pitman, 2004) have yet to prove persistent under grazing over the long or even medium term.

5 A general body of applied knowledge and experience with adapted species is lacking. Research, extension and land managers have often avoided working with complex pasture and rangeland reseeding mixtures in the past. This is not surprising as grass monocultures are much easier to manage. With the prospect of increasing industrial N fertilizer prices and environmental dangers of N leaching and run-off (Day *et al.*, 2009), however, forage and rangeland management can no longer afford to sidestep the solution offered by mixing legumes and grasses in low- or no-input cultivated and natural pastures (Deak *et al.*, 2010). The science and art of maintaining healthy multi-species herbaceous pastures and rangeland are growing (Springer *et al.*, 2001; Whitbread *et al.*, 2009) but have a long way to go, especially in strongly market-driven systems such as North America.

Conclusions

Experience to date with warm-season legumes in native grass/legume stands, along with the failure of many warm-season legumes to establish in cultivated warm-season grass pastures reflects the difficulties of multi-species pasture management. The science of establishing such mixtures in warm-temperate climates has yet to be fully developed, and the art of maintaining the mixtures once established is even further outside our experience to date. This should not discourage us from trying; if natural warm-season grassland ecosystems, left to themselves, have scores of native grasses and forbs, including legumes, in stable ecosystems, we should be able to emulate them once we have identified the appropriate germplasm and management principles that have so far not been discovered or understood. A tremendous variety of potentially useful germplasm, especially native, is available for evaluation throughout the regions of the world where subtropical and warm-season pastures and rangeland provide forage potential. Plant improvement and ecosystem management approaches successfully used with temperate forage plants and food crops have not been employed with this resource for domesticated livestock production. Potential benefits justifying continued effort are becoming more apparent as our society demands more sustainable ecosystems, less movement of sediment, pesticides and nutrients with run-off water, increases in ecosystem services including viable wildlife populations, and reduction in industrial inputs in food production. The tremendous gap in extent of development between that of temperate pasture legumes and the warm-season legumes of warm-temperate origin exists at least to some extent because of the much more recent recognition of the potential usefulness of the latter. Development of this resource is certainly possible, but continuing and sustained efforts by researchers and grassland managers will be required.

Our objective then becomes deceptively simple: design and manage warm-season pasture and rangeland grass/-legume mixtures, which yield meat, milk and other products with minimal input year in and year out. Achieving this is far more challenging than one would expect, mostly because our present ruminant *production* systems, as exemplified by ranching in the south-eastern USA, are geared not to sustainability but to extracting *product* by *producers*, just as the prevailing extension terminology implies. If land managers take a step back from this singular focus on land exploitation such that broader, long-term husbandry guides their pasture and rangeland management, they will be much closer to stable forage systems based on *productive* warm-season mixed-species pasture and rangeland ecosystems.

Are productive yet cost-effective mixed grass–legume grasslands possible in climates with warm summers and freezing winters? Our conclusion is that they are. Do we have all the tools to create and manage these mixtures? Unfortunately, we do not. But the mission is not impossible if we approach the question from the long-term land husbandry perspective.

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