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Enhancing food security in Latin America with forage legumes

James P. Muir¹, Luis O. Tedeschi², José C. B. Dubeux³, Michael Peters⁴, and Stefan Burkart⁴

Texas A&M AgriLife Research, Stephenville, TX. USA

Abstract. Forage legumes could enhance ruminant production in Latin America far more than they currently do. With a few instructive exceptions, decades invested in domesticating, testing and divulging pasture and rangeland leguminous species, have had limited impact. Reasons for this include lack of end-user involvement in research and development, inadequate commercial seed sources, low persistence under grazing, and substitution with industrial nitrogen fertilizer. Current efforts to improve legume adoption include research on domestication of new species especially natives, grass-legume mixtures, silvopasture, protein banks, and mitigating anti-nutritive components. Future challenges might include a greater focus on economical seed production, establishment in multi-species plantings, persistence under grazing, sustainable intensification, domesticating local germplasm, ecosystems services, multiple uses, harnessing condensed tannins, and greater crop-livestock integration of legumes. We believe that these and other innovations make the future of forage legumes very promising in Latin America.

Key words: Biologically-fixed nitrogen, Pastures, Rangeland, Sustainable intensification

Aumentar a segurança alimentar na América Latina com leguminosas forrageiras

Resumo. Leguminosas forrageiras ainda são subutilizadas na América Latina e têm potencial de melhorar a produção de ruminantes em uma escala muito maior que a atual. Com poucas exceções no ambiente acadêmico, décadas de investimento na domesticação, avaliação e divulgação de espécies forrageiras para pastagens cultivadas e naturais obtiveram impacto limitado. Razões incluem a ausência de envolvimento do usuário final na pesquisa e desenvolvimento, inadequada fonte de sementes comerciais, baixa persistência sob pastejo e substituição por fertilizantes nitrogenados. Esforços atuais para melhorar a adoção de leguminosas incluem a domesticação de novas espécies nativas, misturas de gramíneas e leguminosas, sistemas silvopastoris, bancos de proteína e mitigação de compostos anti-nutricionais. Desafios futuros incluem maior foco na produção comercial de sementes, estabelecimento de pastagens com múltiplas espécies, persistência sob pastejo, intensificação sustentável, domesticação de germoplasma local, serviços ambientais, usos múltiplos, adequação dos teores de taninos condensados e maior utilização de leguminosas em sistemas de integração lavoura-pecuária. Essas e outras inovações tornam o futuro de leguminosas forrageiras promissor na América Latina.

Palavras-chave: Intensificação sustentável, Nitrogênio biologicamente fixo, Pastagens

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¹ Correspondence author: James P. Muir: j-muir@tamu.edu

² Texas A&M University, College Station TX USA

³ University of Florida, Marianna FL USA

⁴ Centro Internacional de Agricultura Tropical, Cali Colombia

Introduction

Why legumes?

Why are forage legumes critical to food security in Latin America? In two words: amino acids. Domesticated ruminants are raised primarily for the protein they provide humans and that essential nutrient was historically derived, in large part, from forage legumes consumed by domesticated ruminants (Stinner *et al.*, 1992). Demand for animal protein is rising as human populations increase and living standards foster greater demand (Boland *et al.*, 2013). Unlike animals or most other pasture, rangeland, or native grassland/savannah plants, legumes fix atmospheric N₂ through their symbiosis with rhizobia, usually in root nodules (Temperton, 2007; Fujita and Kawaguchi, 2014). This nitrogen comprises the primary building block for plant protein (Thomas, 1995) that is selectively grazed or browsed by domesticated ruminants which, in turn, use them to build animal protein (Ørskov, 1992). Although today much of the N in cultivated pastures derives from industrial fertilizer applied to grasses (Stinner *et al.*, 1992; Bell *et al.*, 2014), greater dependence on biologically fixed N₂ (BFN) in the future should translate into more stable food security in Latin America (Muir *et al.*, 2014).

Using forage legumes to produce ruminant protein is important to human food security for many reasons although two stand out. The first is that animal protein provides humans essential amino acids and vitamins that most plant proteins cannot supply (Boland *et al.*, 2013). The second reason is broader: ruminants produce food from marginal ecosystems that are otherwise inappropriate for row crops. These include vulnerable regions with climatic extremes, ecosystems with poor soils or topography that (should) preclude cultivation (Hellstrand, 2013), referred to as “less favored areas” by Devendra (2012). Keeping these ruminant-dominated ecosystems healthy (El-Aich and Waterhouse, 1999) while still feeding humans means safeguarding perennial vegetation that provides not just feed for ruminants but also ecosystems services such as soil conservation and water quality (Bell *et al.*, 2014).

Forage agronomy, with a few instructive exceptions, has largely failed in its endeavor to include legumes in tropical and subtropical pastures and rangelands of Latin America. Despite the benefits, adoption rates are still poor for tropical forage legumes (Pengelly *et al.*, 2003; Thomas and Sumberg, 1995; Sollenberger and Kalmbacher, 2005). Shelton *et al.* (2005) group the limiting factors into three categories: a) the misperception of the benefits

of legumes by producers, b) technology failure, and c) failure in adoption approaches. Legumes are often considered less resilient than grasses and harder to manage, while providing rather long-term benefits to the production system (Peters and Lascano, 2003). Highlighting profitability, demonstrating success stories, and implementing training approaches on legume system establishment and management can overcome the issue of misperception of the benefits (Miles and Lascano, 1997; Andrade *et al.*, 2004; Mwangi and Wambugu, 2003). Technology failure can be related to either the technology itself (e.g., cultivars do not persist under grazing or technology targeted at the wrong system) or to socio-economic factors (e.g., high technology costs, lack of interest by the producer, lack of information and credit, labor shortage, or land tenure) (Elbasha *et al.* 1999; Ndove *et al.* 2004; Shelton *et al.* 2005) and leads to disappointment and decreasing interest among the involved actors (Andrade *et al.*, 2004). Missing partnerships (Miles 2001), inadequate cultivar promotion (Andrade *et al.*, 2004), a lack of reliable seed-production systems (Peters and Lascano, 2003), and absence of participatory research (Douthwaite *et al.*, 2002) can contribute to adoption failures.

Success stories

Although the promise of tropical forages legumes is not yet fully being realized, there have been success stories as summarized by Shelton *et al.* (2005) and White *et al.* (2013). Most notable are the documented adoption of at least 100,000 ha of *Calliandra calothyrsus* in Eastern Africa (Place *et al.*, 2009), *Stylosanthes* spp. in India, Thailand, China, Brazil and Australia (Ramesh *et al.*, 2005; Phaikew *et al.*, 2004; Guadao and Chakraborty, 2005; Costa *et al.*, 2009; Chudleigh and Bramwell, 1996; Rains, 2005; Noble *et al.*, 2000), *Vigna unguiculata* in West Africa (Kristjanson *et al.*, 2005), *Clitoria ternatea* (Conway, 2005) and *Leucaena leucocephala* in Australia (Mullen *et al.*, 2005; Shelton and Dalzell, 2007), *Pueraria phaseoloides* (Valentim and Andrade 2005) and *Arachis pintoi* in Brazil. These successes bode well for efforts to introduce forage legumes elsewhere.

The economic benefits of *Stylosanthes* and *Leucaena* reported in Australia point to expanding use and economic impact (Rains, 2005; Shelton and Dalzell, 2007). For *Stylosanthes* in Brazil, the estimated value of nitrogen in soils exceeded the value as a feed (Costa *et al.*, 2009). Despite substantial investment and reported adoption in Southeast Asia (Phaikaew *et al.*, 2004; Guadao and

Chakraborty, 2005; Stür *et al.*, 2007) and south Asia (Ramesh *et al.*, 2005), only one empirical analysis of

economic impact has been conducted in Indonesia (Martin, 2010).

Current efforts

Efforts throughout Latin America and beyond currently focus on enhancing forage legume contribution to ruminant production. Some of these are historical while others contain at least some novelty (Muir *et al.*, 2011).

Domestication

Much of the arboreal and herbaceous legume germplasm evaluated or commercialized throughout the tropics and sub-tropics over the last 50 years originated from Latin America (Table 1). *Leucaena* spp. stand out among the arboreals while the herbaceous species from Central and South America have become so pantropic that they are often considered naturalized wherever they are found. The reason for this wide adaptation is unclear. The Americas do not have the historic ungulate grazing and browsing pressures that have made Africa (Hempson *et al.*, 2015) the preferred pasture grass germplasm source in tropical and sub-tropical cultivated pastures. African grasses thrive, for example, in Australia (Walker and Weston, 1990) or Brazil (Savidan *et al.*, 1989; Karia *et al.*, 2006) where native species rarely exhibit persistence under (over)grazing. This may also explain why weak tolerance to grazing is historically such a concern for many of the forage legume species originating from Latin America (Curll and Jones, 1989; Hoveland, 1989).

Grass-legumes mixtures

Maintaining a healthy balance among grasses and legumes is a challenge in tropical and sub-tropical pastures and rangeland, including Latin

America. Muir *et al.* (2011) listed over-grazing, unselective broadleaf herbicides, fire exclusion, the simplicity of managing monocultures, high legume palatability vis-à-vis grasses, and historically low cost of N fertilizers as reasons for grass dominance in cultivated pastures. Other challenges might include diseases, soil characteristics, and climatic extremes. Avoiding sod-forming grasses, decreasing dependence on chemical inputs, careful selection of plant functional groups, complementarity of complex mixtures, and more precise grazing management may tilt the persistence balance toward the legume component. More radical ideas, such as designing diverse plant communities (Tilman *et al.*, 1996; Sanderson, 2010), including mixtures of legume species, and introducing multiple herbivores may balance grasses with forbs, grazers with browsers and selectors with bulk feeders to favor legume survival in grass-legume mixtures (Muir *et al.*, 2015).

Silvopasture

Silvopasture systems using tree legumes are still underexploited in Latin America (Dubeux *et al.*, 2015). Success stories from other warm-climate regions such as Australia (Mullen *et al.*, 2005; Radrizzani *et al.*, 2010), Africa (Wambugu *et al.*, 2011; Franzel *et al.*, 2014), and Southeast Asia (Hasniati and Shelton, 2005) indicate the potential of these systems in Latin America. Research projects assessing tree legumes in silvopasture systems in Latin America have already demonstrated potential, not only for livestock production, but also for other products such as timber (Xavier *et al.*, 2014; Hernández-Muciño *et al.*, 2015;

Table 1. Prime examples of Latin American forage legume genera historically studied or currently utilized widely outside the region

Common name	Genera	Uses	Citations
Forage peanut	<i>Arachis</i> spp.	Forage, cover crop, ornamental	Bryan <i>et al.</i> , 2001
Bundleflower	<i>Desmanthus</i> spp.	Forage, rangeland	Cook <i>et al.</i> , 2005
Centro	<i>Centrosema</i> spp.	Forage, cover crop	Pengelly and Liu, 2001
Tickclover	<i>Desmodium</i> spp.	Forage, cover crop	Cook <i>et al.</i> , 2005
Leucaena	<i>Leucaena</i> spp.	Forage, agroforestry, wood	Burt, 1983
Mesquite	<i>Prosopis</i> spp.	Forage, wood, honey	Mullen <i>et al.</i> , 2003
Siratiro, phasey	<i>Macroptilium</i> spp.	Forage, soil conservation	Harris <i>et al.</i> , 2003
Stylo	<i>Stylosanthes</i> spp.	Forage, rangeland	Morris, 2010
			Cook <i>et al.</i> , 2005
			Chandra, 2009

Apolinário *et al.*, 2015; Costa *et al.*, 2016). Adoption of these systems, however, is still limited.

Benefits of adopting tree legume silvopastures are numerous, including, but not limited to: 1) biological N₂-fixation; 2) enhanced nutrient cycling; 3) income in addition to livestock; 4) C sequestration by trees; 5) provision of shade for livestock; and 6) increased forage nutritive value (Dubeux, Jr. *et al.*, 2015). Once established, tree legumes are easier to maintain in a grazing system. In many cases, trees outcompete the grass in the understory. Unlike the traditional herbaceous binary mixtures of grass-legumes where the legume is the “weak link of the chain”, the grass component in silvopasture systems often requires greater attention.

Tree spacing is crucial to keep grasses productive and persistent. Light is one of the ecological factors affecting grass under the shade (Gea-Izquierdo *et al.*, 2009) but competition for soil water between trees and grasses might also limit grass growth (Dubeux, Jr. *et al.*, 2015). Managing tree spacing, pruning, or use of tree species with reverse phenology that drop leaves during the growing season (e.g. *Faidherbia albida*; Rouspard *et al.*, 1999) might reduce the light limitation for the herbaceous component in silvopasture systems.

In addition to these biotic challenges, there are abiotic factors affecting tree legume adoption in grazing systems. These include social and economic aspects. Landowner reluctance to implement changes in their system is the first barrier. If the perceived benefits are not clear and do not translate into economic reward, producers will not adopt the system. Adding trees to pastures and rangeland make management more complex, requiring greater attention from land-owners. Research, educational programs, and on-farm demonstrations may overcome these challenges (Pengelly *et al.* 2003; Dagang and Nair, 2003). Limited commercial tree legume seed supply is still a limitation in some regions. Partnership with research institutions and seed companies might solve this problem, with seed increase occurring prior to the release of a new cultivar.

Protein banks

Deferring legume pasture grazing (Staples *et al.*, 1986; Nie and Zollinger, 2012), protein banks/fodder banks planted in the rainy season to be used in the dry (Mani *et al.*, 1994; Macedo *et al.*, 2015) or silvopastoral systems in which legume trees are lopped during periods or seasons of low protein availability (Muir and Massaete, 1996; Muir, 1999) are all examples of how forage legumes can be harnessed to compliment grasses during seasons or

years in which grasses do not adequately meet ruminant needs. Legumes have taproots that favor their growth, or at least leaf retention, during droughty seasons or years vis-à-vis shallow-rooted grasses (Sulas *et al.*, 2000). These legumes provide protein to rumen microorganisms that facilitate digestibility of low-quality, dormant grasses (Nsahlai *et al.*, 1998). Persistence of these legumes is problematic, however, since they must compete with ungrazed grasses during the growing season yet tolerate grazing during seasons when grasses are dormant, and they are not (Muir and Abrão, 1999). Unpalatable, lignified, upright herbaceous species such as *Stylosanthes* spp. (Saito, 2004) or arboreal perennials (see silvopasture above) have competitive advantages in these situations because they are either less foraged than surrounding grasses or remain out of reach until managers manipulate them. After droughts, prolifically seeding legumes, such as *Leucaena* spp. or *Centrosema pascuorum*, have an advantage (Rodriguez *et al.*, 2006; Marques *et al.*, 2014). Hardseededness likewise helps to build soil seed banks from which the legume stand can regenerate years after seeding (Marques *et al.*, 2014). **Nutritive and Anti-Nutritive Values Related to Legumes**

Legume feeding value depends on its intrinsic nutritional value (i.e., digestibility) and the extrinsic voluntary feed intake (VFI) by the ruminant animal (i.e., amount consumed) (Ulyatt, 1973). Although legumes have a high nutritive value due to their great content of crude protein (CP), often above 15% (dry matter basis) (Tedeschi *et al.*, 2002; Valadares Filho *et al.*, 2006), their feeding value may be low when anti-nutritional factors (ANF) either hinder their digestibility through lower ruminal fermentability efficiency or decrease VFI due to palatability, astringency, or bulkiness characteristics of the legume. Anti-nutritional factors are defensive compounds produced by the plant to inhibit herbivory, decrease insect attack, ward off infections, and protect against UV light among many others. The main ANF groups are phenylpropanoids (condensed tannins-CT and isoflavones) and terpenoids (terpenes, saponins) (Mueller-Harvey and McAllan, 1992; Van Soest, 1994). Legumes tend to have many different ANF compared to grasses (Norton, 1994a). Baker and Dynes (1999) performed an extensive review on the feeding value of pasture legumes.

Legume digestibility is dictated by the fractional rate of ruminal degradation (kd), i.e., the rate at which legume nutrients are fermented by ruminal microbes, and by the fractional rate of ruminal

passage (kp), i.e., the rate at which legume particles escape the rumen. Anti-nutritional factors can be toxic to ruminal bacteria (Van Soest, 1994), which decreases the kd, or they can bind to specific nutrients, protecting them from ruminal fermentation and favoring their escape from the rumen. Either way, efficiency of ruminal microbial growth decreases. Similarly, legume CT also alter the uniformity of CP digestion, hampering its digestibility in tropical legumes (Shayo and Udén, 1999).

The VFI is a function of the fibrosity and the digestibility of the legume (Riaz *et al.*, 2014). Fibrosity directly affects VFI through the level of rumen fill, calculated on the legume neutral detergent fiber (NDF) content. The greater the kd or kp, the faster the turnover of legume particles in the rumen, thus increasing VFI. However, ANF can also alter VFI by reducing palatability.

Collectively, these variables determine the feeding value of the legume. Norton (1994b) suggested the feeding value of legumes be assessed based on the following characteristics: voluntary consumption potential (i.e., VFI); potential digestibility and ability to support high rates of fermentative digestion; high rates of microbial protein synthesis in the rumen relative to volatile fatty acids (VFA) produced (fermentation protein/energy ratio); high rates of propionic acids synthesis (glycogenic) relative to total VFA synthesis (fermentation glycogenic/energy ratio); and ability to provide bypass nutrients (e.g., protein, starch, and lipids) for absorption in the small intestine. While these indexes might provide an adequate characterization of the legume's nutritive value, the required variables are not easily or always available even at *in vitro* conditions. Donefer *et al.* (1960) suggested static *in vitro* digestion (i.e., a one-point digestibility measure) to compute feeding values of grasses and legumes, but alternative methods are needed to assess legume nutritive values and ANF.

In vitro gas production technique assesses nutritive values of feedstuffs based on their pattern of gas production over time. Although this technique was originally developed to predict metabolizable energy using empirical relationships (Menke *et al.*, 1979; Menke and Steingass, 1988), it can determine fermentation dynamics, microbial biomass, and volatile fatty acids (Blümmel *et al.*, 1997; Cone *et al.*, 1996; Pell and Schofield, 1993). *In vitro* gas production along with chemical composition can estimate total digestible nutrients (TDN) of corn dried distiller's grain (Tedeschi *et al.*, 2009) and compare methane (CH₄) production of different combinations of alfalfa

(*Medicago sativa*) and *Sericea lespedeza* (*Lepedeza cuneata*) or panicled-tick clover (*Desmodium paniculatum* L. var. *paniculatum*) (Naumann *et al.*, 2015a).

We propose an alternative approach to assessing legume nutritive value using the *in vitro* gas production (IVGP) technique. The data obtained by Naumann *et al.* (2013b) provide an example. Figure 1A depicts the amount of gas for CO₂ and CH₄, and Figure 1B shows the gross energy for CH₄ and VFA of eight warm-season legumes using the IVGP technique. Assuming the heat of combustion of CH₄ and acetic, propionic, and butyric acids of 13.3, 3.49, 4.94, and 5.93 Mcal/kg (Armstrong and Blaxter, 1957; Duchowicz *et al.*, 2007; Lebedeva, 1964) and the efficiency of use of absorbed acetic, propionic, and butyric acids of 65, 72, and 79% (Moe, 1981), we can compute the metabolizable energy from VFA production and the proportion of gross energy loss as CH₄, as shown in Table 2.

Based on Table 2, CH₄ gross energy was less than 10% of the total gross energy (VFA and CH₄) for *Acacia angustissima* and *Lepedeza stuevei*, but *Arachis glabrata*, *Leucaena retusa*, and *Desmanthus illinoensis* had the greatest estimated VFA metabolizable energy (Mcal/kg). Therefore, decreasing the amount of CH₄ being produced does not guarantee the legume will have greater biological value, suggesting they are independent. These calculations do not consider post-rumen digestibility or endogenous losses, and therefore may under-predict the total apparent TDN and metabolizable energy. Further calculations are needed.

The VFI is the other element in determining feeding value of legumes. In general, ruminal particle turnover and fibrosity are the main factors controlling intake (Coleman *et al.*, 2003). However, ANF, such as CT, alter forage palatability (especially in legumes) through its astringent and bitter taste (Mueller-Harvey and McAllan, 1992). Prediction of VFI by ruminants grazing legumes or grass-legume mixes that rely on dietary energy will fail because we neither possess a complete understanding of the interaction of legumes x grass x ruminant animal to predict digestibility nor can we predict animal consumption behavior of legumes. Free-ranging ruminant animals can choose from diverse herbaceous, shrub, and tree legumes, and little is known about their feeding behavior and decision process. Factors that reduce VFI include sparse distribution of legumes in the paddock or high grazing pressure, low palatability, poor adequacy of essential nutrients (including minerals), high resistance to comminution by chewing during

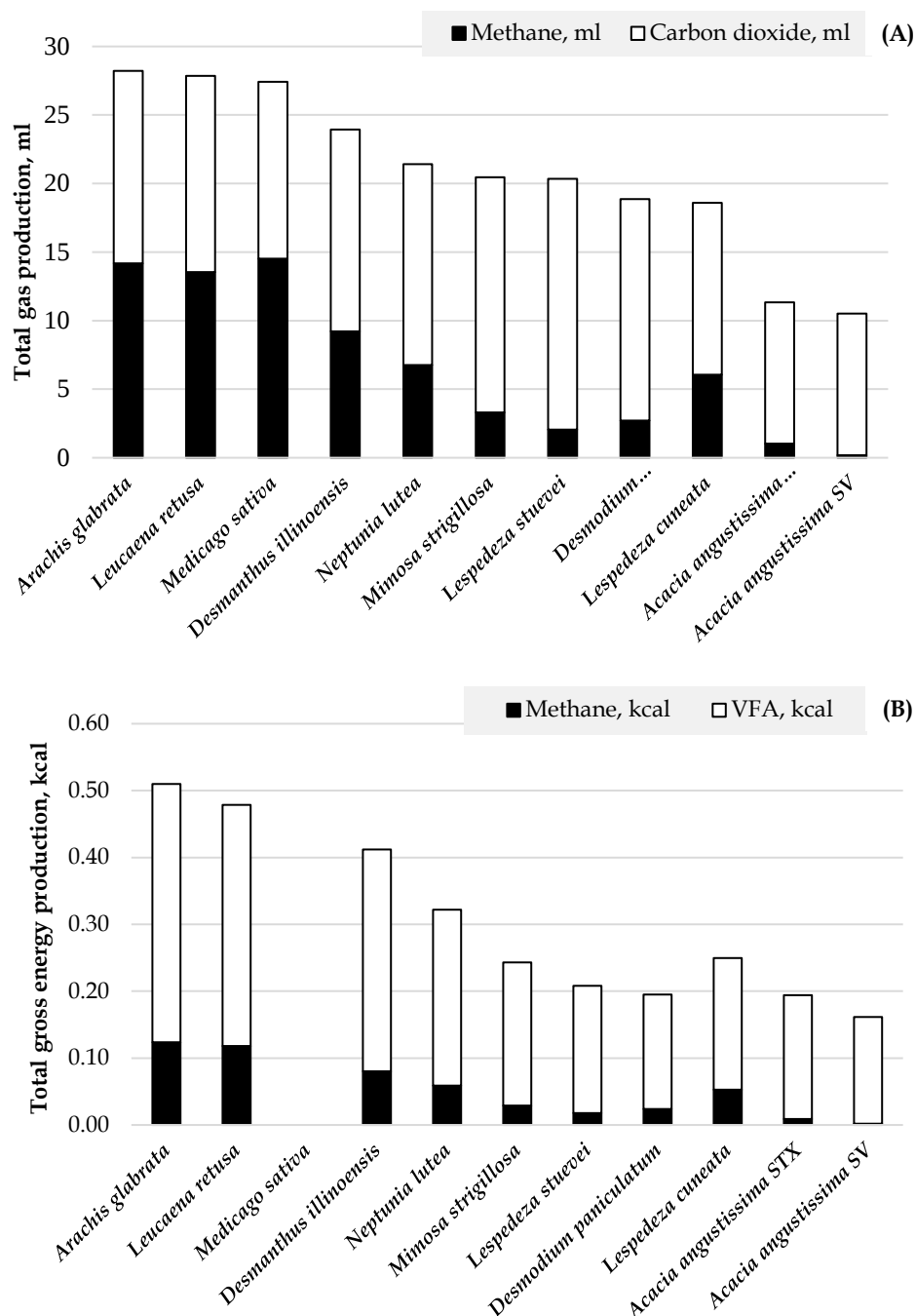


Figure 1. (A) Volume (ml) of carbon dioxide (CO₂) and methane (CH₄), and (B) gross energy (kcal) of volatile fatty acids (VFA) and CH₄ measured after 48-h fermentation of 200 mg of warm-season legumes in a 20 ml solution (rumen fluid and media) using the *in vitro* gas production technique.

Adapted from Naumann *et al.* (2013b).

mastication and rumination, poor digestibility, or high content of water, electrolytes, or ANF (Baker and Dynes, 1999). Although classical research in the 1970s studied the relationship between palatability and digestibility in ruminants (Provenza, 1995), the

limited information for ruminants grazing legumes or grass x legume mixes and the interaction of palatability x digestibility x ANF throws another wrinkle into the issue of VFI of free-ranging ruminants, including wildlife animals.

Table 2. An example of gross energy calculation (GE) and metabolizable energy (ME) content of volatile fatty acids (VFA) in warm-season legumes obtained with the *in vitro* gas production technique.

Legumes	VFA, g/L			GE, kcal ⁽¹⁾			VFA ME ⁽²⁾
	Acetate	Propionate	Butyrate	VFA	CH ₄	CH ₄ , %	Mcal/kg DM
<i>Arachis glabrata</i>	2.962	1.123	0.582	0.386	0.1236	24	1.346
<i>Leucaena retusa</i>	2.701	1.076	0.557	0.361	0.1180	25	1.259
<i>Desmanthus illinoensis</i>	2.662	1.031	0.371	0.331	0.0804	20	1.146
<i>Neptunia lutea</i>	2.041	0.826	0.333	0.263	0.0589	18	0.914
<i>Mimosa strigillosa</i>	1.663	0.680	0.264	0.214	0.0289	12	0.744
<i>Lespedeza stuevei</i>	1.480	0.646	0.195	0.190	0.0180	9	0.658
<i>Desmodium paniculatum</i>	1.342	0.529	0.218	0.172	0.0236	12	0.596
<i>Lespedeza cuneata</i>	1.464	0.595	0.303	0.197	0.0528	21	0.687
<i>Acacia angustissima</i> STX	1.323	0.739	0.169	0.185	0.0089	5	0.643
<i>Acacia angustissima</i> SV	1.213	0.616	0.122	0.160	0.0017	1	0.552

⁽¹⁾ GE was computed assuming heat of combustion of 13.3, 3.49, 4.94, and 5.93 Mcal/kg for methane and acetic, propionic, and butyric acids; and a volume of 20 mL.

⁽²⁾ ME concentration was computed assuming the VFA GE; efficiency of use of 65, 72, and 79% for absorbed acetic, propionic, and butyric acids; and 200 mg of legume sample (dry matter--DM--basis).

Future efforts

Although much has already been done by land managers, researchers, and educators, further efforts can promote forage legumes as an essential component of food security in Latin America. These include overcoming biological, social and market hurdles that will more often than not require a multi-disciplinary research and development approach.

Agronomy

Seed production. One of the challenges limiting greater use of forage legumes in Latin America is seed production. To begin with, seed production is sometimes (with notable exceptions) low in perennial, warm-season legumes (Muir *et al.*, 2005b) although it tends to be greater in annuals (Muir *et al.*, 2005a). Biological challenges such as indeterminate flowering (Akinola and Agishi, 1989), dehiscent pods (Raghu *et al.*, 2005; Chauhan and Pandey, 2014) or prostrate inflorescences (Muir and Pitman, 1991), all adaptations to grazing in natural settings, add to seed harvest limitations. These and lack of seed production knowledge contribute to the eventual cost of commercialized seed, thereby making dissemination prohibitively expensive.

Establishment under competition. Establishing forage legumes within grass-dominated pastures is challenging (Muir *et al.*, 2011). Approaches to

overcoming this inherent legume seedling weakness vis-à-vis grass robustness merits greater research efforts. Techniques that have had some success in isolated species, such as strip planting *Arachis glabrata* Benth. within *Paspalum notatum* Flugge pastures (Castillo *et al.*, 2015), depend greatly on relative palatability of grass and legume as well as grazing management. Establishing perennial legumes within already established aggressive rhizomatous grass swards such as *Cynodon dactylon* (L.) Pers., even without grazing, has been even more problematic (Muir and Pitman, 2004). Add grazing to the equation and challenges mount. Further research is needed to determine how to overcome these limitations if legumes are to be established successfully alongside grasses or within established grass swards. This includes building on recent findings that the inclusion of multiple legume species and no N fertilizer for *Urochloa decumbens* pastures in Brazil (da Costa Moreno Gama *et al.*, 2013) contributes to legume establishment. Having those multiple legume species, especially mixes of annual colonizers and perennial climax species, commercially available has to be a first step in this effort.

Persistence under grazing or browsing

In general, herbaceous legumes, especially palatable forage species, are much less persistent under heavy grazing compared to grasses (Muir *et*

al., 2011; Orr and Phelps, 2013). This is especially true when grasses originated in regions, such as Africa, with historically heavy herbivory, making

them relatively grazing tolerant vis-à-vis legumes from Latin America with historically few native grazing ungulates (see previous discussion). Legumes that do survive ruminant herbivory in natural ecosystems generally do so because of their low nutritive value or palatability vis-à-vis other forbs and grasses (Nisi *et al.*, 2015). Plant species abundance and accessibility (canopy architecture) also influence herbivore selection and, eventually, stand persistence (Agnusdei and Massanti, 2001). The ruminant species doing the selection also has a strong impact on legume persistence (Piasentier *et al.*, 2007; Bertrand *et al.*, 2011), with smaller, more selective species such as goats and sheep more likely to decrease legume persistence compared to larger bulk grazers such as bovids. Utilization rate, season and regrowth interval (rotational vs. continuous) likewise heavily influence relative persistence of pasture forbs versus grasses (Ash and McIvor, 1998).

Historically, however, forage germplasm collection and domestication in warmer climates generally focused on “promising,” ie. high yielding, digestible (high nutritive value) and palatable (preferentially consumed by animals), herbaceous legumes (Taylor and Templeton, Jr., 1973; Skerman, 1977; Mott, 1979). As a result, forage legume persistence has historically been a major challenge (Mott, 1979), the subject of entire books (Marten *et al.*, 1989), and continues to be the focus of much research (Ruiz *et al.*, 2007; Jimenez Guillen *et al.*, 2013). We suggest that germplasm domestication and development could shift to relatively unpalatable species which will be selectively grazed/browsed less vis-à-vis accompanying grasses at crucial times such as seed-set (Cooper *et al.*, 2014), thus enhancing their persistence. This will require a redirection in forage agronomic thinking that has historically selected germplasm according to yields and in the ruminant nutrition laboratory rather than under grazing/browsing in the pasture. We do not imply that persistence is not currently important in forage legume selection in Latin America, rather, that it should be given earlier and greater emphasis.

Traits that favor legume persistence over grasses and therefore merit greater research and management attention include some that are already used but could be emphasized as well as others that are more novel. For example, studying persistence under systems similar to those for which the legume is destined (Mott, 1979) should increase success rates once they are distributed to end users. Over-emphasizing traits that favor persistence, however, may end up fostering weedy legumes such as

Leucaena leucocephala (abundant hard seed; Marques *et al.*, 2014) or *Lepedeza cuneate* (unpalatable to cattle due to high CT content; Mantz *et al.*, 2013). Our proposal is that they be given greater, not absolute, weight during agronomic trials. These might include combinations of:

1. Protected growing points (>1.5 m height or prostrate growth habits)
2. Woody, unpalatable stems that discourage total defoliation
3. Plant secondary compounds that discourage too much (but not all) herbivore selection
4. Greater grass palatability during the growing season vis-à-vis the legume
5. Legume armor, including spiny branches or hirsute leaves
6. Escape protein
7. Herbivory season and intensity
8. Grazing/browsing duration and regrowth interval
9. Abundant seed yields and soil seed bank build-up

Sustainable intensification

Because land available for pasture will decrease in the future, greater sustainable intensification of ruminant production is the only viable avenue to meet growing animal product demand (Tedeschi *et al.*, 2015). Researchers and land managers can identify ways to achieve that greater production on less land from both the animal and the plant side of the equation (Muir *et al.*, 2015). Possible avenues include:

1. Low or no industrial inputs, namely fewer irrigation, herbicides or soil amendments
2. Greater diversity in pasture species composition
3. Greater herbivore species diversity, including mixed flocks/herds
4. Year-round pasture systems
5. Rangeland and cultivated pasture/silvopasture integration
6. Cover crop and pasture rotations within row-crop systems

Domesticating native germplasm

Using native legumes for cultivated pastures makes sense on many levels. Functional traits should equip them with adaptations (fitness) to local edaphic, climatic and biotic stresses which can be advantageous compared to most exotics, especially as climate changes accelerate (Mitchell *et al.*, 2015). They will also less likely become invasive because they are inherently part of local ecosystems. Historically, however, forage legume collections sought widely adapted germplasm rather than strictly for local

reuse. For example, Coradin and Schultze-Kraft (1990) reported that between 1977 and 1987, multinational, international and Brazilian entities carried out 15 such efforts focusing on *Stylosanthes* spp., *Desmodium* spp. *Centrosema* spp. among others in Brazil. Since 1987, there have been a few other focused collections in Latin America, including *Desmanthus* spp., *Arachis* spp. and numerous other species (Pengelly and Liu, 2001; Flores, 2008). This germplasm has been evaluated in many regions outside their native range, including different continents.

A very different approach seeks to collect as many different species within a defined geographic area for subsequent exclusive use within that same region. South Texas Natives, on the border with Mexico, is a successful example. It is a collaborative regional effort that brings land owners, universities, state agencies and commercial seed companies together to domesticate ecotypic species for native grassland restoration, rangeland revegetation and pasture cultivation, among them numerous forage legumes (Smith *et al.*, 2010). Although wider forage legume germplasm collections have occurred throughout Latin America, more local efforts for local use may become feasible in the future as resources and interest in native legume germplasm, rather than exotic material, lead to efforts similar to those for local revegetation in South Texas (Smith *et al.*, 2010), Eritrea (Snowball *et al.*, 2013) and Australia (Suriyagoda *et al.*, 2010).

A discussion, fueled by genetic rather than phenotypic data, is taking place around the globe on how to define "native." Just how many ecotypes of a single species do we need for our native forage programs? Can we define these genetically rather than phenologically into populations (Kulakow, 1999; Bhattarai *et al.*, 2010)? Do we need an ecotype for each different edapho-climatic environment? Region? Country? Continent? A related issue is the cost of such local efforts versus the broader historical approach in which a few cultivars are released for regional or multi-continent application. The proven benefits, both in terms of environmental stability and bio-productivity (Thakur *et al.*, 2015; Venail *et al.*, 2015) of plant diversity within grasslands, has been well documented in natural grasslands but has yet to be widely applied in cultivated grasslands within Latin America. How much, however, can researchers, seed companies or land managers afford to invest in restoring that locally native diversity? Should this eventually replace the broader approach that has historically involved far greater geographic limits and multi-institutional cooperation (Berger *et al.*, 2013)?

Ecosystems services

Ecosystem services (ES) can be broadly divided into the following categories: provisioning, regulating, supporting, and cultural services according to the guidelines of the Millennium Ecosystem Assessment report of the United Nations (MEA, 2005). Legumes are important ES providers in all these categories. Provisioning from legumes include browse, mast, timber, fuel, human food, natural medicines, and ornamentals (Dubeux, Jr. *et al.*, 2015). Biological N₂-fixation is perhaps the most notable supporting ES provided by legumes. In this same ES category, legumes also enhance nutrient cycling by adding litter with greater N concentration compared to warm-climate C₄ grasses (Boddey *et al.*, 2004), improve soil fertility and soil health (Chintu *et al.*, 2004), and increase primary productivity. Tilman *et al.* (1996) demonstrated that increasing the diversity of plant functional groups and species richness increases the efficiency of resource utilization both in time and space. Adding forage legumes in grass-based grazing systems, particularly under limited soil fertility, may be a viable way to increase primary productivity.

Regulating ES using legumes might increase C sequestration and mitigate greenhouse gases (Mutuo *et al.*, 2005), control soil erosion by contour planting or use of riparian buffers (Nichols *et al.*, 2001), provision of shade and windbreaks (Gea-Izquierdo *et al.*, 2009), and forage for pollinators (Potts *et al.*, 2009). Cultural ES include recreational, aesthetic, and spiritual values (Dubeux, Jr. *et al.*, 2017). Forage legumes are important dietary components of wildlife browsers (Piasentier *et al.*, 2007), which are key components of recreational activities in regions where hunting is part of the local culture. Legumes, for example, are often included in wildlife seed plots to supplement native ruminants such as white-tailed deer (*Odocoileus virginianus*) (Hehman and Fulbright, 1997).

Multiple uses

Encouraging greater adoption of forage legume technology may necessitate developing or divulging additional benefits beyond simply forage. Quantifying trade-offs between forage and multiple uses or exact returns on investment need further study. Advantages already discussed, include ES or reinstating ecosystem diversity. Some of the most common examples that have been proposed but could be more fully utilized include:

Human food. Multiples uses that are already apparent in many places include growing pulses and leaves as the primary human-edible crop, where forage stover is the added benefit, or in some cases,

the edible seed or leaves as a secondary byproduct after animal feed. Examples of the first include *Arachis hypogaea* or *Vigna unguiculata* (Khan, 2013; Katsande et al., 2016); documented examples of the latter include *Lablab purpureus* (L.) Sweet (Whitbread et al., 2011), with experimental work on non-traditional pulses such as *Desmanthus illinoensis* (Michx.) MacMill. ex B. L. Rob. & Fernald or *Leucaena leucocephala* (Lam.) Link (Kulakow, 1999; Roman-Cortes et al., 2014).

Lumber. Because they do not require N fertilizer inputs and are generally fast growing, legume trees can be useful building materials and fence post sources. One of the most studied is *L. leucocephala* (Pande et al., 2013). Many others are less well known, such as *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Mimosa caesalpinhiifolia* Benth., but equally useful (Apolinário et al., 2015). By far the majority have yet to be identified and studied, often falling into the “native” category of local utility.

Fuel. Legume tree branches and trunks provide fuel in many parts of Latin America (Quintanar Isaías et al., 2005; Apolinário et al., 2015). However, leguminous biofuels such as feedstock for biogases or ethanol may eventually derive directly from leaves and fine stems (Casler et al., 2009; Gresshoff et al., 2015), seeds (Biswas et al., 2011) or indirectly as N for accompanying or subsequent non-legume bioenergy crops (Jensen et al., 2012).

Green manure. Reducing inputs such as industrial fertilizers, used as pasture’s primarily N source, may reduce ruminant protein production’s environmental footprint and make it more sustainable. Also, harnessing BFN for row crops through the use of forage legume rotations and cover crops is one way to reduce dependence on industrial N soil amendments (Mundus et al., 2008; Miranda et al., 2010). Limiting the use of arable lands and increasing forage legume use as N sources directly to animals and indirectly via companion grasses is a prime example of multiple uses (Glendinning et al., 2009).

Condensed Tannins. Condensed tannins (proanthocyanidins) are polyphenolic compounds that contain many free phenolic hydroxyls that can form large molecules through polymerization, fostering strong complexation (i.e., binding to) with protein, minerals (e.g., Mg, Ca, Zn, Mn, Co, Cu), carbohydrate, lipids, and many other macromolecules (Van Soest, 1994). Because of the polymerization attribute of CT, their classification is not easy even though their base constituent is flavan-3-ols (Mueller-Harvey and McAllan, 1992). The study of CT in animal nutrition has been very challenging because of

the vast structural variability and complex behavior of CT in the ruminant animal. In developing a conceptual model of possible benefits of CT for ruminant production, Tedeschi et al. (2014) provided a comprehensive review of essential CT characteristics from *Lotus* spp., including protein nutrition, methane mitigation, and gastrointestinal parasitic suppression.

Protein Nutrition. Because of the binding characteristic of CT, it protects true protein from ruminal microbial fermentation (i.e., degradation into ammonia and carbon skeleton), bypassing it to the small intestine where the ruminant animal would be able to digest and absorb the amino acids through enzymatic digestion. Angus heifers supplemented with high-CT quebracho extract (*Schinopsis quebracho-colorado* Engl.) experienced reduced apparent CP digestibility by 14% and lowered ruminal concentration of ammonia by 12.3%, suggesting a greater CP escape from the rumen (Beauchemin et al., 2007). Another significant benefit of CT protein binding that is often overlooked is the shift in the N excretion from urinary N to fecal N, which might reduce ammonia volatilization. The expected results are not always consistent because many factors alter the CT by protein complexation such as molecular weight, protein conformation, and pH (Naumann et al., 2013a). The exact characteristics of CT that provide their protein binding ability have not been completely elucidated. In fact, Naumann et al. (2014b) reported a high correlation between CT content and protein-precipitable phenolics (r^2 of 0.81) as well as between CT content and the amount of protein bound (r^2 of 0.69), but not with CT molecular weight.

Methane. Condensed tannins may reduce CH_4 production in the rumen indirectly through a reduction in fiber digestion or directly through inhibition of the methanogens in the rumen (Tavendale et al., 2005). High-CT legumes tend to decrease CH_4 production even when used as supplements. Carulla et al. (2005) supplemented 41 g of *Acacia mearnsii* (61.5% CT) to sheep consuming ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.), and alfalfa (*Medicago sativa* L.) and observed a reduction in daily CH_4 release ($\text{kJ/kg}^{0.75}$ body weight) by 9.9% and urinary N excretion ($\text{g/kg}^{0.75}$ body weight) by 13.4%. Animut et al. (2008) fed Boer x Spanish wethers with different levels of kobe lespedeza (*Lespedeza striata* (Thunb.) Schindl.) (100, 67, 33, and 0%) for 21 days and reported a decrease of CH_4 emission through gross energy digestibility increased linearly with decreasing levels of kobe lespedeza. Replacement of alfalfa hay (*M. sativa*) with sericea lespedeza (*Lespedeza cuneate* (Dum.Cours.) G. Don) or panicled-tick clover

(*Desmodium paniculatum* (L.) DC. var. *paniculatum*) reduced CH₄ production without affecting total gas production (CO₂ and CH₄) under *in vitro* conditions (Naumann *et al.*, 2015a). However, others have failed to link the supplementation (up to 2% of DM) of CT extract from quebracho (*S. quebracho-colorado*) to reduced CH₄ production in Angus heifers (Beauchemin *et al.*, 2007). There are many more studies indicating the negative correlation between CT and CH₄ production, but consistency of the CT effectiveness lacks among these studies. Naumann *et al.* (2013b) were unsuccessful in correlating CT molecular weight (Mw) with the amount of CH₄ produced by eight North American native warm-season perennial legumes when fermented *in vitro* for 48 h. These facts suggest that not all CT have the same behavior on CH₄ reduction either because of animal specificity or bioactivity potential. Naumann *et al.* (2013a), proposed that CT Mw and concentration might be critical factors in determining biological activity for protein binding. Total CT amount or concentration might be the main driver of CH₄ reduction (Naumann *et al.*, 2015b).

Parasites. Gastrointestinal nematode parasite (GINP) resistance to commercial anthelmintic products (e.g., benzimidazoles, levamisole/morantel and ivermectin) has long been a concern in the livestock industry, especially in small ruminants (Prichard, 1990; Andrioli Salgado and de Paula Santos, 2016) and alternative venues to combat infestations are needed. Anthelmintic CT properties on GINP rests on the theory that a possible dissociation between CT and protein in the abomasum would lead to a subsequent attachment of CT to GINP, thereby reducing their motility, reproduction, and feeding ability (Novobilský *et al.*, 2011; Ramírez-Restrepo *et al.*, 2005) as well as increasing the immunological competence of the ruminant animal (Molan *et al.*, 1999; 2000, 2003). Naumann *et al.* (2013a) concluded that not all forages containing CT have anthelmintic properties. Furthermore, CT anthelmintic properties may not be only parasite-specific, but also compartment-specific (Tedeschi *et al.*, 2014): some have reported greater CT efficiency against GINP at the abomasum rather than in the small intestine. Supplementation of *L. cuneata* at 50 and 75% of the DM decreased the fecal egg count (FEC) of GINP, specifically *Haemonchus contortus*, by 84.6 and 91.9% in Boer goats (Terrill *et al.*, 2009). Minho *et al.* (2008) reported reductions in FEC and adult *Haemonchus contortus* in the abomasum of sheep when CT extracts of *Acacia molissima* (15% CT, DM basis) was fed, but no effect was observed in adult *Trichostrongylus colubriformis* in the small intestines.

Similar to CT x protein binding and CT x CH₄ reduction, CT molecular weight (552 Da from *Lespedeza stuevei* to 1,483 Da from *Lespedeza cuneata*) had a weak correlation with larval migration inhibition (LMI) of *Haemonchus contortus* (Naumann *et al.*, 2014a), although CT from *Leucaena retusa* Benth., *Lespedeza stuevei* Nutt., and *Acacia angustissima* (Mill.) Britton & Rose var. *hirta* (Nutt.) B. L. Turner decreased LMI by 65.4, 63.1 and 42.2%, respectively.

Research to date has failed to quantify CT molecular weight influence from different legume species on protein binding ability (Naumann *et al.*, 2014b), ruminal CH₄ reduction (Naumann *et al.*, 2013b), and GINP activity decline (Naumann *et al.*, 2014a). This could be because the dissimilarities among CT and high concentrations of dietary CT are needed to achieve the minimum amount of a specific CT type and molecular weight that possess the characteristics to effectively benefit ruminants. However, in doing so, we fail to detect the ideal, specific CT characteristic and end up correlating the observed benefit with the amount (or content) of CT rather than its properties. In retrospect, our studies combined different species of legumes, containing different types of CT and Mw, but we never truly tested molecular weight effect. It would have required the isolation of one type of CT and its fractionation by molecular weight, preferentially within legume species, to isolate its effect from other factors that may cover up the ability of CT to express its anticipated benefits. When this CT fractionation was performed for *L. leucocephala*, ruminal CH₄ production decreased (Saminathan *et al.*, 2015, 2016) and protein-binding affinity increased (Saminathan *et al.*, 2014) as CT molecular weight increased from approximately 470 to 1266 Da, confirming our original belief that molecular weight may govern the observed benefits of feeding CT to ruminant animals.

Future developments should include determination of legume feeding value (nutritive value and VFI) using *in vitro* techniques and chemical composition for many reasons, including low cost, quick results, breadth of application, easy methodology, and relentless lack of methodology to predict reliable estimates of VFI for grazing animals. Disadvantages of this approach include the necessity to correlate *in vitro* results with real production scenarios (i.e., *in vivo* conditions) and standardization of *in vitro* methodologies. Methods to quantify palatability of legumes need to be revisited.

Crop-livestock integration

Enhancing forage legume, pulse, biofuel and cover crops integration into livestock systems may create economic and environmental synergies for

multiple benefits beyond animal production. This is already done in many animal production systems (Bell *et al.*, 2014) but could be expanded in order to sustainably intensify animal and crop production (Tedeschi *et al.*, 2015) while improving soil health (Ceccon *et al.*, 2013) as systems adapt to changing

climate and human population demands (Russelle *et al.*, 2007; Mitchell *et al.*, 2015). Forage or multiple-use legumes can build resilience, especially in transition and mixed farming zones (Rischkowsky *et al.*, 2004) facing climate change (Mitchell *et al.*, 2015).

Conclusions

The greater inclusion of forage legumes in Latin American livestock production has the potential to not only enhance productivity, income and livelihoods, but could also provide multiple environmental benefits such as restoring degraded lands and mitigating GHG emissions. However, this potential has not yet been widely realized due to a combination of technology failures, weak adoption approaches, limitation in seed supplies and sometimes access to knowledge.

Sustainable intensification of tropical farming systems may provide specific opportunities for greater inclusion of forage legumes in Latin American

livestock production if suitable conditions exist such as a) superior and more resilient persistence and contribution, b) effective communication capacities and knowledge tools e.g. SoFT (Cook *et al.* 2005), c) incentive and resources for establishment, d) access to markets for livestock products, e) conducive policies and functional seed supply systems involving the private sector and artisanal operations. While there has been much research on evaluating forage legumes, there is need for a targeted revision to match technologies with evolving livestock systems in many cases driven by sustainable intensification (Rao *et al.*, 2015; Tedeschi *et al.*, 2015).

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