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Arboreal Legumes for Multiple Uses

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Cattle grazing *Gliricidia sepium*

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EDITORIAL

Arboreal legumes have been overlooked for the past decades of research and development. Although there were noticeable efforts in sub-Saharan Africa, southeastern Asia, and Australia, there is much more to be done. Arboreal legumes provide myriad ecosystem services including provisional, regulating, and supporting. Besides forage, arboreal legume provide other products and services including timber, firewood, fruits, medicinal products, pollinator habitat, recycle nutrients from deep soil layers rendering them available to herbaceous vegetation, and fix atmospheric N_2 in association with soil organisms. This special issue addresses multiple uses of arboreal legumes and identifies current resource conservation across different regions of the world. Future research efforts developing sustainable agroecosystems should consider arboreal legumes as a component. The different experiences reported in this special issue provide useful information to start a new phase where arboreal legumes will represent key roles in future agroecosystems.

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Bridging research gaps in arboreal legumes

Bridging research gaps by linking research groups with different expertise is a great way to develop an overlooked area. This special issue brings different expertise on arboreal legumes and their multiple uses across the globe. Genetic conservation and domestication are the first steps to ensure the other steps will happen. Furthermore, examples of successful stories might boost the interest in other regions of the world to follow the example. This special issue on arboreal legumes compiles expertise across the globe on many aspects of resource conservation and utilization of arboreal legumes. Multiple experiences reported in this issue might boost collaboration among research groups to multiply successful experiences. The net result will be an increase in sustainability of agroecosystems considering the multitude of uses and adaptation of this wonderful, underutilized, group of plants.

James Muir (left) and José Dubeux (right) on a bridge over San Francisco River in NE Brazil. Bridging research gaps by linking scientific community to address aspects of common interest. Both have passion for arboreal legumes and are the co-editors of this special issue.

Leguminous forage shrubs: the underutilized canopy

James P. Muir[1]*

Abstract: Shrubs are neither trees nor herbs, fitting into the 1- to 3-m canopy. Adding this canopy between the herbaceous and arboreal canopies can intercept more sunlight and reach nutrients and moisture deep in the soil. They can provide additional forage within the reach of browsing ruminants. Introducing leguminous forage shrubs into cultivated pasture and silvopasture systems as well as maintaining them in rangeland could fix additional atmospheric N_2, increase plant and animal biodiversity as well as contribute to greater ruminant production, especially domesticated and wild browsers in multi-species herds.
Key words: legume, multi-canopy, perennial, shrubby

Introduction

We need more meat and milk from less land. As worldwide demand for ruminant products rises and land availability for raising domesticated and wild species decreases, the need to intensify pasture and rangeland forage production grows. Legume forages, because they fix their own atmospheric N_2, play a crucial role in that intensification (1). Herbaceous forage legumes are already widely used and arboreal species play important roles in many ecosystems. Shrub legumes, by contrast, have been historically neglected. Why not intensify pasture, rangeland and savannah productivity by emphasizing shrub legume incorporation alongside herbs and trees? Greater sunlight interception along with plant species diversification could equate to greater forage production that leads to more herbivore animal product for human consumption (2).

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Defining shrubs

How do we distinguish leguminous shrubs from herbaceous or arboreal species? There can be a great deal of overlap but, for the purposes of this discussion, we will establish general guidelines, although exceptions and overlaps are inevitable. The first criterion is that they reach average **mature height between 1.0 to 3.0 m**. This includes under browse pressure; i.e. even under moderate herbivory from ruminants, shrubs will eventually attain the minimum height but will not normally exceed 3.0 m when herbivory is not intense. In other words, lopping down a tree such that it ratoons within the 1 to 3-m canopy layer does not create a shrub. Likewise, creating optimal growing conditions for an herbaceous species that ends up growing past 1 m does not necessarily qualify it as a shrub. In general, this height should include non-reproductive structures such as branches and leaves but exclude purely reproductive structures such as inflorescences and their supporting stalks. Definition by height therefore becomes functional (forage production).

Other characteristics can be generally applied. **Perennialism**, for example, can exclude those herbaceous annuals that can temporarily attain heights above 1 m at the end of their growth cycles. Short-lived perennials such as some pigeon pea (*Cajanus cajan*) would qualify as shrubs but annuals such as white lupin (*Lupinus albus*) whose inflorescences can grow >1.0 m would not. **Multiple basal branching** that does not include inflorescences is also associated with mature shrubs.

Figure 1. Pods of *Leucaena retusa*, a shrub legume from Texas, USA with browse potential.

Advantages

Because of their perennial growth habit, leguminous shrubs will contribute to an ecosystem over many years; IE they **do not require yearly replanting** or intensive cultivation once established. Their **deep taproots** can penetrate heavy soil pans and reach nutrients and moisture at soil depths that herbaceous species cannot normally reach. Their short height vis-à-vis trees make them more **easily accessible to browsing ruminants** or cut-and-carry harvest. If planted in cultivated pasture or maintained in rangeland, they can **complement herbaceous and arboreal canopies** when it comes to sunlight interception and herbivore preferred browsing height.

Challenges

Historical emphasis on herbaceous forage legumes with secondary interest in arboreal species means that we have very **little domesticated shrub germplasm** for silvopasture or rangeland rehabilitation. We simply do not know much about this canopy. We **know next to nothing** about their fodder production potential, leaf nutritive value for herbivores or seed value for wildlife or human consumption. That means that any system considering their incorporation must usually start the domestication process by considering native species or the very few that have been already studied elsewhere.

Opportunities

Warm climate, semi-arid regions seem to have a concentrated abundance of legume shrub germplasm, likely a result of **deep taproots that reach soil moisture** during droughts. In southwestern North America, for example, there are over 20 native legume species that might qualify as shrubs (3) of which only *Leucaena retusa* has been widely evaluated for domestication (4). Likewise, in northeastern Brazil, there are numerous species that qualify as either shrubs or trees, of which few, including *Mimosa caesalpiniifolia* and *Bauhinia cheilantha* (5), have been studied in depth. Species within semi-arid regions of Africa, such as *Albizia, Acacia* and *Dichrostachy* spp., are also often known and used locally but have not been widely considered for wider domestication (6,7). Some shrubs, such as *Medicago arborea* and *Coronilla valentina* ssp. *glauca,* from semi-arid Mediterranean regions have also been considered for their forage and seed production (8,9).

Summary

Diverse and productive leguminous shrub germplasm is abundant, especially in arid and semi-arid regions. Their potential in multi-canopy and multi-herbivore species ruminant systems, however, is under-valued and, therefore, under-utilized in cultivated pasture and rangeland rehabilitation. The few that have been researched (see examples in Table 1), indicate potential. Correcting this research and management lacuna could contribute to greater ruminant production as well as ecosystem stability in many regions around the world.

https://stephenville.tamu.edu/research-project/grassland-ecology/

TEXAS A&M AGRILIFE RESEARCH

Table 1. Examples of leguminous forage shrubs that are already under consideration for domestication.

Species	Common name	Origin	Uses
Bauhinia cheilantha	Mororó	South America	Fodder
Cajanus cajan	Pigeon pea	India	Pulse, fodder
Cratylia argentea	Cratylia	South America	Fodder
Flemingia macrophylla	Flemingia	Asia	Fodder, green manure
Indigofera zollingeriana	Indigofera	Pan-tropical	Fodder, dye
Leucaena retusa	Goldenball leadtree	North America	Fodder, wildlife seed
Medicago arborea	Shrub medic	Mediterranean	Fodder
Mimosa caesalpiniifolia	Sabiá	South America	Fodder

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Tropical agroforestry: a diversity of practices and benefits

Barbara C. Bellows[1]

Abstract: Agroforestry practices have been researched and promoted since the 1980's as low-cost methods for resource-poor farmers in the tropics to enhance yields while protecting soil. The densely-planted narrow hedge rows of coppicing legume trees used in alley cropping systems provide intercropped plants with nitrogen, weed suppression, and erosion control. In coffee and cacao plantations, legume trees serve as nurse crops while recycling nutrients and controlling against diseases. Rapidly growing legume trees provide improved fallows and help reverse desertification in the Sahel. Increasing interest in the ability of these systems to sequester carbon to mitigate against climate change is stimulating the development of ecosystem services markets to promote enhanced adoption of these beneficial practices.

Key words: agroforestry, alley cropping, improved fallows, nurse trees, carbon sequestration

Agroforestry was officially recognized as a scientific field of study in the 1970's by researchers seeking to address economic inequalities and land degradation impacts on the "poorest of the poor," particularly in tropical developing countries (1). These practices, including alley cropping, nurse trees, cut and carry feed banks, and land rejuvenating fallows, were designed to enhance farm yields and profits while reducing farmer dependency on external inputs, particularly fertilizer. While non-legume trees are critical components of many agroforestry practices, such as riparian buffers, windbreaks, and silvopastoral practices in temperate and semi-temperate locations, the ability of tree legumes to fix nitrogen and enhance phosphorus and water availability through the tripartite legume-rhizobia-mycorrhizae association have made these trees particularly appropriate for use by resource-limited farmers in the tropics.

Alley cropping involves growing crops such as corn, cassava, or vegetables, between rows of coppicing trees. Tree branches are regularly pruned and placed between crop rows as mulch, thus providing erosion and weed control prior to decomposition while enhancing levels of soil nutrients and organic matter following decomposition. Though nitrogen contributions from legume trees vary by species, soil type, and climate, the two most widely studied alley cropping trees, *Leucaena leucocephala* and *Gliricidia sepium,* produce between 140 – 170 kg N ha^{-1} year^{-1} (2). When trees are planted in closely-spaced hedge rows along the contour of slopes, alley cropping can effectively control erosion, allowing farmers to plant crops on the natural terraces that form in the space between the hedge rows. Alley cropping also improves soil health by increasing soil aggregation and populations of beneficial soil organisms such as earthworms (3).

Multistory agroforestry involves growing coffee and cacao under shade trees. Evolving within the shade of rainforests, coffee and cacao provide more sustainable yields with reduced pest and disease incidence when grown in the shade. Legume trees, such as *Gliricidia* spp., *Erythrina* spp., or *Inga edulis*, fix atmospheric nitrogen for non-legume plants, enhance nutrient cycling, decrease water loss due to transpiration, and increase ecosystem biodiversity. Deep root systems of leguminous shade trees help recycle leached nutrients, particularly nitrate and potassium, which are not effectively captured by the more superficial root systems of coffee or cacao (4). Mycorrhizal associations can enhance phosphorus uptake. Additionally, recent research using differences in the natural abundance of ^{15}N show that common mycorrhizal networks transfer fixed nitrogen directly from the legume shade tree to the commodity tree (5).

Using tree rather than herbaceous legumes allows for improved fallows of longer duration, resulting in greater biomass and nitrogen accumulation. Initially developed to assist African farmers to increase crop yields on nutrient-depleted soils, this practice has spread to central America and southeast Asia. The main genera include: *Sesbania, Tephrosia, Leucaena, Mucuna, Centrosema, Pueraria, Crotalaria, Cajanus, Indigofera,* and *Mimosa* (6). Besides being able to grow during the dry season and producing large amounts of nitrogen-rich biomass on acid, nutrient poor soils, some species also provide weed control. Studies conducted in Zambia showed that *Sesbania sesban* fallows could almost completely control the parasitic weed, *Striga asiatica* (7).

As of 2009, over 1 billion ha of land was estimated to be under agroforestry practices with over 1.2 billion farmers involved in agroforestry practices (8). Yet, more extensive agroforestry practice adoption has been limited by agronomic as well as

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Table 1. Legume trees commonly used in agroforestry practices

Species	Common names	Origin	Agroforestry practices	Benefits	Potential concerns
Leucaena leucocephala	*subabul* – Hindi *lamtoro* gung - Indonesia *ipil-ipil* - Philippines	Central America	Alley cropping Boundary hedges Nurse tree Forage Fire wood	Coppices rapidly Rapid growing High rate of N fixation High quality forage for non-ruminants	Can become invasive Does not grow well in acid soils Susceptible to psyllids
Gliricidia sepium	Madre de cacao –Central America Kakawati - Philippines Gamal - Indonesian	Central America	Alley cropping Boundary hedge Nurse tree Forage Firewood	Coppices rapidly Rapid growing High rate of N fixation High quality forage for ruminants Can reduce insect and fungal incidence in associated crops Can compete with *Imperata cylindrica*	Can become invasive Needs to be regularly pruned as cacao trees mature
Erythrina poeppigiana	Brucayo, palo de boya – South and Central America Dadap - Indonesia	Venezuela Bolivia Columbia Ecuador	Nurse tree Boundary hedge Alley cropping	Tolerates acid-infertile soils Contributes to high cacao yields High rate of N fixation	Can only be pruned twice /year Heavy defoliation results in death of nodules Loses leaves in dry season
Inga edulis	Guaba, guano - Spanish	Brazil Bolivia Columbia Ecuador Peru	Nurse tree Alley cropping Firewood	Fast growing Tolerant to acid soils, wet soils Retains leaves in dry season Edible fruit/Seeds are purgative for humans and cattle	Can produce excessive shade when grown with coffee or cacao if not pruned regularly
Sebania sesban	Jayanti, puri – Indonesia Katurai - Philippines Dien-dien - Vietnam	Throughout Africa	Forage Improved fallow Intercropping with vegetables Alley cropping Nurse crop Pulpwood	High seedling growth Rapid plant growth High rates of N fixation High forage digestibility Tolerant of acid, alkaline, saline, and waterlogged soil Leaves used as antibiotic	Cannot withstand complete defoliation Rapid growth may cause it to shade out other plants Shallow root may cause nutrient uptake competition
Faidherbia albida / Acacia albida	mkababu, mgunga - Swahili cad - Wolof umHlalankwazi-Zulu	Tropical Africa Middle East Arabia	Forage Intercropped with plants River bank stabilization Firewood	Deciduous in wet season, foliated in dry season Deep root for drought tolerance and low nutrient competition with plants Highly nutritious leaves / pods “Inverted phenology” allows for plant growth underneath Used in regreening Sahel Respiratory disease medicine	Cannot grow on heavy clay soils

socio-economic factors. Studies conducted in Kenya (9) indicated that maize yields in alley cropping systems would need to increase by 18% to compensate for the land devoted to the legume trees rather than maize. The technical skills and time required to properly manage agroforestry practices often limit practice adoption.

Both alley cropping and nurse tree systems need to be regularly pruned to reduce shading. Cacao primarily benefits from nurse-shade during early growth. As the cacao trees mature, less shade is needed, requiring producers to regularly prune and thin shade trees over time (4). Differences in biomass production, nitrogen fixation, and leaf decomposition rates require farmers to carefully synchronize pruning and mulching of alley cropping and improved fallows to obtain effective crop plant uptake of nitrogen and other nutrients from decomposing leaves of associated tree legumes (6).

Land tenure and gender are often critical barriers to agroforestry adoption, since systems involving perennial species require access to resources (10). Many leguminous trees have low immediate market value, which can limit their use in some agroforestry practices. In coffee and cacao plantations, many farmers have substituted nurse leguminous trees with timber or fruit trees species due to their increased return on investment (4).

With a growing understanding of the close relationship between soil health characteristics and carbon sequestration, funding agencies and agricultural support organizations are renewing their support for agroforestry practices. While direct assessments of carbon sequestration within agroforestry systems are limited, Nair *et al.* (2009) estimated that agroforestry above and belowground biomass carbon sequestration potential ranged from 0.29 Mg ha^{-1} yr^{-1} in fodder bank agroforestry systems of the West African Sahel to 15.21 Mg ha^{-1} yr^{-1} in mixed species stands of Puerto Rico. Furthermore, the International Panel on Climate Change (IPCC) estimated in 2000 that an additional 630 M ha of unproductive land could be converted to agroforestry, resulting in a carbon sequestration potential of 586 Gg C yr^{-1} by 2040 (8). In 2008, the UN-REDD (Reducing Emissions from Deforestation and Forest Degradation) program was developed to reduce deforestation and forest degradation as well as to promote sustainable forest manage and enhance forest carbon stocks. Initially, this program focused primarily on plantation forests, but it has evolved to include smallholder farmers who might adopt agroforestry practices. While carbon markets to pay farmers for sequestering carbon have yet to mature, initial assessments based on agroforestry systems in Kenya indicate that incentives of $6 US ha^{-1} could encourage farmers to incorporate more land into agroforestry practices, resulting in increased carbon sequestration (11). Thus, agroforestry, similar to other agricultural conservation practices, can enhancing agronomic sustainability, soil health, and carbon sequestration. However, these benefits depend on farmer adoption, which is affected by resource access, practice management skills, and practice compatibility with local conditions.

Table 2. Summary of agroforestry practices

Agroforestry practice	Method of use	Potential limitation on use
Alley cropping	One or two rows of trees planted close together and along the contour to form a barrier against erosion Maize, cassava, millet, or vegetables planted in 10 m space between tree rows Tree pruning used as a mulch to suppress weeds, control erosion, and provide nutrients to crops	Land tenure Time and labor to plant tree rows Time and labor to prune Access to seeds, cuttings, or seedlings Appropriate alley cropping trees for local conditions
Cut & carry forage	Forage trees planted on: • Field or garden boundary • Rice paddy bunds Alley cropping trees harvested for forage	Land tenure Time required to plant Time required to cut and carry to livestock
Nurse trees	Legume trees planted to serve as shade or nurse trees for coffee, cacao, tea, or other shade requiring crop	Land tenure Time required to plant Time required to prune and thin legume trees as the understory plants mature Non-legume nurse trees that can provide a better return on investment as lumber
Improved fallow	Planting of fast-growing legume trees that are grown for one to two years, cut down, and then the land is planted to maize, millet, sorghum, or vegetables	Land tenure Land out of production for 1 – 2 years Access to seeds

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Multiple ecosystem services of arboreal legumes

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Abstract: Arboreal legumes provide multiple uses, covering different types of ecosystem services (ES). Multiple uses include provisioning ES (e.g. fodder, timber, firewood, food, biomedicines, genetic resources), supporting ES (e.g. nutrient cycling, biological N_2-fixation, primary productivity, and photosynthesis), regulating ES (e.g. climate regulation, water regulation, pest and disease regulator), and aesthetic and cultural ES (e.g. recreation, landscaping). Arboreal legumes have been underutilized, although research results indicate their potential. Successful stories of adoption occurred in Africa, Asia, and Australia, with increasing interest in Latin America. Adoption of arboreal legumes is one important step forward towards the development of sustainable livestock systems and provision of multiple ecosystem services.

Key words: biological N_2-fixation, forage, pollinator, timber, tree

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Introduction

Arboreal legumes are a missing link to enhance sustainable forage-livestock systems around the globe, especially in warm-climate grasslands (Figure 1). They provide multiple uses and a variety of ecosystem services that not only benefit the land manager, but also the environment (1). Warm-climate arboreal legumes have been underexploited, with some success stories in Africa (2), Southeast Asia (3), Australia (4), and Latin America (5,6) (Table 1). Perhaps their better-known uses are fodder, firewood, and timber; however, other less obvious but still important uses/services include nutrient cycling and biological N_2-fixation, forage for pollinators, C sequestration, shade for livestock, biomedicines, and aesthetic values. Warm-climate arboreal legumes are typically fast-growing plants and, in an N-limited environment, they typically outcompete warm-season C_4 grasses. In fact, after the trees are established, the ‘weak link’ of the system will be the herbaceous plants. This is not the case for mixtures of warm-climate C_4 grasses and herbaceous legumes, when the most typical case is the disappearance of the legume component, especially when palatable legumes are managed under great grazing pressure. Thus, arboreal legumes must be further developed and adopted, since they represent an important option for sustainable intensification (7).

Ecosystem services and multiple uses of arboreal legumes

Ecosystem services are the benefit people obtain from ecosystems. They include supporting, provisioning, regulating, and aesthetic and cultural services. Arboreal legumes provide ecosystem services in all these categories. Ecosystem services are directly related to human well-being, because they deliver goods and services that improve human life. Therefore, increasing adoption of arboreal legumes and the associated ecosystem services they provide is an important way to develop sustainable production systems.

Supporting services

Arboreal legumes have the potential to

associate with soil bacteria and fix atmospheric N_2. This is a major supporting service, considering the N-limited environment prevailing in most ecosystems but especially warm-climate grasslands. Nitrogen fixed by tree legumes recycle via litter deposition or animal excreta, improving the overall N status of the system. In addition, deep-rooted arboreal legumes have the potential to take up nutrients from deeper soil layers, recycling them back to surface layers. This process benefits the herbaceous vegetation in agroforestry and silvopastoral systems.

Primary productivity tends to increase with increasing species richness and number of functional groups. Integrating tree legumes into grass monocultures tends to increase primary productivity because of complementary resource use, both in space and time. These processes combined (i.e. biological N_2-fixation, recycling nutrients from deeper soil layers, primary productivity, photosynthesis) result in enhanced soil formation because of the buildup of soil organic matter.

Provisioning

Fodder for livestock is perhaps the most known provisioning service provided by arboreal legumes. Indirectly, these legumes also enhance the provision of animal-source food such as beef and dairy products. Leaf and thin branches of tree legumes typically have greater crude protein than C_4 grasses in warm-climate regions. Therefore, especially during the dry season, fodder from arboreal legumes might be significant for livestock (6). Many species also have anthelmintic properties for ruminants. Arboreal legumes might also provide firewood and timber, which might be a significant source of income in diversified livestock systems. In fact, extra income from timber and firewood can almost double the gross income in silvopasture systems using tree legumes (5). In addition to fodder, some tree legumes also provide edible fruits for humans, such as tamarind (*Tamarindus indica* L.) and ice-cream bean (*Inga edulis* Mart.). Use of native arboreal legumes in rangelands is common in some biomes (e.g. Caatinga in NE Brazil), and it is an important way to conserve genetic resources (8). Finally, arboreal legumes might provide substrate to produce medicinal products (9).

Regulating

Arboreal legumes provide regulating services including C sequestration, water purification, recharge of aquifers, forage for pollinators, and regulation of pests and

Figure 1. Silvopasture systems with signalgrass (*Brachiaria decumbens* Stapf.) and tree legumes [*Gliricidia sepium* (Jacq.) Steud. and *Mimosa caesalpiniifolia* (Benth.)] in Pernambuco, Brazil.

diseases. Deep-rooted tree legumes used in agroforestry systems have potential to sequester more C and mitigate greenhouse gas (GHG) emissions compared to annual herbaceous crops (10). This is an important aspect of arboreal legumes, considering the urgent need to mitigate GHG emissions and reduce the side effects of global warming. Flower-rich legumes also enhance pollinator habitat, which is an important regulating service (1). In addition, tree legumes provide shade, which is important not only for livestock, but also to regulate microclimate under the tree canopy, resulting in significant effect in biogeochemical cycles.

Aesthetic and cultural

Tree legumes provide habitat for wildlife and might be an important fodder source in the diet of wildlife and game farm animals. Game farming is an important cultural activity in many societies. In fact, it is an important way to generate income and preserve natural vegetation and wildlife. Arboreal legumes might also provide important aesthetic value for landscapes, especially in areas with limited arboreal vegetation. Tree legumes are also used in urban landscaping to provide shade and aesthetic value.

Summary

Arboreal legumes are the next frontier to explore in order to develop sustainable and intensive silvopasture and agroforestry systems. They provide an array of ecosystem services resulting in multiple uses that benefit the land manager and the environment. Where research results are available, public policies must be put in place that promote adoption of selected arboreal legume species. The role of arboreal legumes is greater in warm-climate regions, because of greater floral diversity for these areas. Coincidentally, these areas are likely the ones that need the most sustainable intensification options, because of social and economic aspects. The challenge now is to put the current research knowledge to work for the benefit of society by increasing the adoption. When knowledge is still lacking, further research and development must be prioritized with emphasis on arboreal legumes.

Table 1. Agroforestry systems using tree legumes in different regions of the world

Legume species	Region	Rainfall (mm yr^{-1})	Reference
Mimosa caesalpiniifolia **Benth.**	NE Brazil	1,300	(5)
Gliricidia sepium **(Jacq.) Steud.**	NE Brazil	1,300	(6)
Acacia angustissima **(Miller) Kuntze**	Tanzania, Zimbabwe	900-2800	(2)
Calliandra calothyrsus **Meisn.**	Kenya, Uganda, Tanzania, Rwanda	> 800	(2)
Sesbania grandiflora **(L.) Poiret**	Indonesia	1,500	(3)

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Carob-tree: a multipurpose leguminous fruit tree crop

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Abstract: Carob-tree (*Ceratonia siliqua* L.) has been cultivated all over the Mediterranean region from ancient times. It is particularly adapted to drought and growers rely on its fruit – carob – to obtain a complementary revenue. In recent years, it was possible to identify and characterize new chemical compounds in fruits and leaves, which presents interesting pharmaceutical and nutraceutical properties. After industrial processing, the seeds and pulp are transformed into a multiplicity of by-products with several applications. The rusticity of this crop allows it to cope with climatic changes and to sustain an important plant cover in semiarid regions and marginal soils.

Key words: Carob; *Ceratonia siliqua*; Industry; Mediterranean; Sustainability

Figure 1. Young carob-tree growing in southern Portugal (DRAPALG Experimental Station at Tavira). It is possible to observe unripe fruits (green color).

Ecology and botany

Carob-tree (*Ceratonia siliqua* L.) is an evergreen, leguminous fruit tree crop mostly cultivated in the Mediterranean region. It is a xerophytic species adapted to long dry seasons and low rainfall due to high ecological plasticity (Figure 1). It exploits deep soil water, exhibits an efficient stomatal control, and has the ability to make tissue osmotic adjustments to cope with severe water stress. The development and distribution of this species is mainly limited by cold stress (consistent air temperatures < 10° C are critical), and it is normally found between 0 and 500 m above sea level. Carob-tree is also well adapted to different soil types. Productive orchards can be found in heavy textured limestone soils, or in soils with low organic matter content; however, excessive soil water in the root zone must be avoided.

The genus *Ceratonia* belongs to the *Fabaceae* family (= *Leguminosae* or Legume) subfamily *Caesalpinioideae*. *C. siliqua* is normally described as dioecious species, but hermaphroditic varieties have been reported. Female flowers are small and very numerous along an inflorescence axis which can be found in the inner side of 2-year-old branches; however, inflorescences are borne also in old branches and main trunks (cauliflory). Flowering period normally occurs during late summer and particularly in

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autumn, which is a critical period for insect flower pollination. Rainfall events and fog during autumn months may significantly suppress the effectiveness of pollination. The fruits are indehiscent dry pods (brown or dark brown), elongated, straight or curved, having an initial period of slow growth (January until March in Northern Hemisphere), a second period of fast growth until late June, and a period of growth decrease until August and September, when the pods are ready to harvest. At harvest, the pods are composed of pulp (90% total fresh weight - tfw) and seeds (10% tfw), both components are being currently used in the food industry. Nevertheless, that proportion is variable according to cultivars and origin.

Nitrogen use

Legumes establish symbiosis with N-fixing microorganisms. However, among the subfamily *Caesalpinioideae* only 5% of the species develop such interaction. In carob trees grown *in vitro*, it was not possible to establish symbiotic associations (1) but in 1996, El Idrissi *et al.* (2) isolated bacteria of the genus *Rhyzobium* from the root nodules of inoculated field grown carob trees in Morocco. To clarify this question, La Malfa *et al.* (3) used ^{15}N natural abundance technique to assess the role of atmospheric N in carob trees and concluded that carob-trees did not contain N derived from symbiotic fixation. Nitrogen is one of the main limiting nutrients in Mediterranean ecosystems and carob tree is also particularly efficient regarding N use. In a field experiment conducted in Portugal, N retranslocation from old leaves of mature carob-trees reached 52% in autumn and increased to 59% if trees were fertilized with ammonium nitrate (4). Although fertilization may increase leaf N reaching 2.5 % dry weight, trees grown in poor soils frequently show N values of less than 1% in mature leaves, suggesting an efficient N use and assimilation.

Fruit production and fruit quality

The southern countries of Europe, Spain, Italy, Portugal, Greece and Cyprus account for 70% of the growing area (about 85 000 ha) and 69% of the total world production. The main producer is Spain (60 000 tons) accounting for 27% of total world supply. Morocco is the leading country in seed production with 7 600 tons (5). After harvest, carob is stored and transported to local industrial processing plants. Initially, carob is kibbled (crushed) to separate pulp from seeds, which is called the first industrial transformation (Figure 2). In the second transformation, pulp and seeds are processed separately. Syrup and carob powder are obtained from pulp, which is a cacao substitute. However, the seeds are the most valuable product. One of the most important seed by-products is locust bean gum (or CBG) which is a hydrocolloid used as a thickener and stabilizer in food industry. Nasar-Abbas *et al.* (6) reviewed pharmaceutical and nutraceutical properties of carob pulp and seeds, and there is continued interest in searching for new products and applications.

Crop for the future?

Most growers rely on carob trees to obtain complementary revenue in contrasting pedo-climatic conditions (e.g. (7)). The functional traits of this crop overcome the detrimental effects of severe soil water stress (due to low rainfall for example) and nutritional stress (low organic matter) opening the opportunity to explore the crop under low-input farming. Moreover, in the current environmental conditions, the incidence of pests and diseases is minimal, avoiding the necessity to apply phytochemical treatments throughout the crop cycle. The major economic constraint are unpredictable seed by-product prices, which does not create favorable conditions to initiate new plantations. However, under a scenario of climate change (high temperatures and low rainfall) few crops will persist. In a long-term approach, *C. siliqua* is one of those species that should be reinforced by agricultural and environmental strategies in the Mediterranean countries.

Figure 2. Carob pulp kibbles. These coarse pieces are used to obtain the carob powder.

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Multipurpose leguminous trees for the lowland tropics in CIAT's genebank

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Abstract: The genebank at the International Center for Tropical Agriculture (CIAT for its Spanish acronym) conserves and distributes globally one of the world's largest collections of tropical forages. While most accessions are herbaceous legumes, the collection also includes several leguminous-tree genera such as *Acacia*, *Albizia*, *Bauhinia*, *Calliandra*, *Clitoria*, *Erythrina*, *Gliricidia*, *Leucaena*, *Prosopis*, *Senna*, *Sesbania* and *Zapoteca*. These trees have been used for a variety of purposes, including cut-and-carry feed, green manure, fences and hedgerows, wood for fuel and tools, shade and erosion control. Distribution of accessions has been relatively modest, but climate-change mitigation and restauration of tropical lowlands may increase demand for these multipurpose legume trees in the future.

Key words: feed, germplasm, soil erosion, tropical legumes

History of the collection

When CIAT was created in 1967, demand for meat and dairy products was anticipated to increase in the tropics, not only because of population growth but also urbanization and rising incomes. History confirmed these expectations (1). However, the swine and beef-production programs CIAT had established early on were dismantled by the mid-1970s when the organization decided to focus its limited resources on forages and feed for domestic animals (2). The decision was strategic for several reasons. First, quantity and quality of feed was and continues to be a limiting factor in many animal-production systems in the tropics, although not all farmers are yet convinced that nutrition and health of livestock are a foundation of productive and sustainable animal production. Second, in the American tropics, pasture degradation and soil erosion were already apparent in the 1970s and continue to be a threat to long-term productivity of pastures. Third, emissions of greenhouse gases such as methane, though not a public concern in the early 1970s, have since then found their way to the front pages (3).

Because of the Old-World origin of most livestock such as cattle, goats, sheep and horses, plants that have co-evolved with them and can withstand grazing were logical forage options. Therefore, African grasses such as *Andropogon, Brachiaria, Hyparrhenia* and *Panicum*, which had been introduced into the American tropics two centuries ago (4), were introduced into the CIAT collection starting in 1974. Permanent pastures based on these species set the challenge of continuing productivity on low fertility often acid soils. So, neotropical legumes such as *Arachis, Centrosema, Desmodium, Macroptilium* and *Stylosanthes* in association with *Rhizobium* and other nitrogen-fixing local bacteria were called upon, given the costs and poor availability of nitrogen fertilizers in the region. Grass-legume association were the principal pasture option proposed for vast swaths of lowland savannas of South America (5).

For smallholders in regions such as Central America and Southeast Asia, livestock often is only part of the total farm production (2). So, when CIAT moved beyond its mandate crops to work on agricultural systems such as hillsides, savannahs and forest margins, the topic of land restoration came into focus. This is where leguminous trees came in. In the tropics, where light does not limit growth, productivity per hectare can be increased through vertical dimension by adding one or several arboreal layers. *Inga* trees providing shade to coffee plantations have long been part of the traditional landscape in Central America and Colombia. Many smallholder farmers need wood for fuel, fences, and tools; hence the interest in genera such as *Albizia, Calliandra, Gliricidia* and *Sesbania*. They also need forages for cut-and-carry feed, green manure, or ways to control erosion.

Germplasm distribution

The distribution of leguminous-tree seeds from CIAT genebank (Figure 1) is relatively modest (Table 1) for several reasons. First, many farmers and researchers may not know that such a collection exists. Second, not all accessions are currently available for distribution because of the difficulty to produce seed free of all quarantinable pathogens. For example, CIAT genebank conserves 31 accessions of *Gliricidia sepium*

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Table 1: The most significant genera of leguminous trees in CIAT's tropical-forage collection (source: CIAT's genebank database queried in Feb 2019; a full list can be obtained, and germplasm requests can be made at https://genebank.ciat.cgiar.org/genebank/foragecollection.do; taxonomy according to (6)).

Genus	*Acacia*	*Albizia*	*Bauhinia*	*Calliandra*	*Clitoria*	*Erythrina*	*Gliricidia*	*Leucaena*	*Prosopis*	*Senna*	*Sesbania*	*Zapoteca*
No. species	7	2	1	3	1	8	1	15	1	10	14	2
No. accessions	18	6	8	28	2	41	31	196	11	26	62	5
No. accessions currently available	11	0	2	14	0	3	0	125	7	12	54	2
Times distributed within CIAT	40	6	2	80	15	23	14	762	9	28	194	11
Times distributed outside CIAT	96	18	12	180	75	72	54	3308	41	66	468	19
Times distributed internationally	25	9	8	52	29	13	25	1843	17	20	128	5
Times distributed within Colombia	71	9	4	128	46	59	29	1965	24	46	340	14

Figure 1. CIAT field collection of legume trees (photo: Gonzalez-Guzman 2019).

but none of them can be distributed currently. Nevertheless, CIAT has distributed 76 samples of 15 *Calliandra calothyrsus,* 189 samples of 19 *Sesbania sesban* and 2,675 samples of 106 *Leucaena leucocephala* accessions (Table 1). *Leucaena leucocephala* is particularly valued as ruminant forage and fuelwood by farmers throughout Southeast Asia and parts of central Asia and Africa (7). It is also planted in hedgerow systems with grass for cattle production in northern Australia, as a hedgerow species in parts of Southeast Asia and Africa, and as a shade tree over coffee and cocoa in the Americas. In Colombia, the accession CIAT 21888 was released as cultivar 'Romelia' (8).

There are other tree species conserved in CIAT's genebank which have not been widely distributed, yet they could occupy niches that are not covered by herbaceous-legume and grass species. For example, feeding goats and cattle with supplements made of *Erythrina poeppigiana* or *Gliricidia sepium* increased productivity by 20%

compared to urea supplementation (9, 10). Another case worth noting is *Calliandra calothyrsus*, a high-protein forage used not only as a supplement on nutrient-poor pastures, but also for erosion control and land rehabilitation. It provides green manure and is a source of nectar for beekeeping and is planted for shade in coffee and tea plantations (11).

To withstand grazing, many forage species are aggressive colonizers of open spaces with a capacity for quick re-growth. Not surprisingly, CIAT's collection also includes species listed in the Global Invasive Species Database (12), such as *Acacia farnesiana, Acacia mangium, Adenanthera pavonina, Albizia lebbeck, Albizia saman, Leucaena leucocephala* and *Prosopis juliflora*. Before requesting germplasm, the degree of invasiveness of a species should therefore be considered.

Funding for research into tropical forages has substantially declined over the past two decades. Climate-change mitigation and the restauration of degraded agricultural land, however, are critical research topics of growing importance to which tropical-forage collections such as that at CIAT can contribute solutions.

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Figure 2: *Leucaena leucocephala* being regenerated on the border of *Brachiaria* spp. Field collection at CIAT headquarters in Palmira, Colombia (photo: Gonzalez-Guzman 2019).

Mimosa caesalpiniifolia Benth: an important legume in Brazil semi-arid

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Abstract: Sabiá (*Mimosa caesalpiniifolia* Benth), a native legume from Brazil, has multiple uses and potential for agroforestry systems. Sabiá multifunctional roles include forage for livestock and pollinators, shade, timber and firewood, nutrient cycling through litter deposition returning up to 150 kg N ha^{-1} yr^{-1}, leaf biological N_2 fixation up to 121 kg N ha^{-1}, and nutrient absorption from deeper soil layers. In addition, sabiá stocks carbon in soil and in timber, enhances other soil attributes via root natural aeration, as well as increased cation exchange capacity. These responses are all management dependent.

Key words: agroforestry, animal performance, forage, wood

Sabiá is a promising tree legume naturally selected by browsing animals in Caatinga, as well as used for cutting and hay (1,2). Apolinário *et al.* (3) reported that sabiá aged over 4-years and 5-m tall contained 162 to 247 g crude protein (CP)/kg DM of leaf (Table 1), however, most of this protein can be fiber-bound, which reduces digestibility below 465 g kg^{-1} (1). Sabiá hay is also an alternative to feed ruminants during the dry period in the Brazilian semiarid and may contain about 182 and 106 g CP / kg DM in leaf and branch, respectively (4).

A silvopastoral system intercropping sabiá and signal grass (*Brachiaria decumbens*) in a sub-humid tropical climate in Pernambuco, Brazil, had lower forage mass (1.72 Mg ha^{-1} yr^{-1}) than signal grass monoculture (1.84 Mg ha^{-1} yr^{-1}). Cattle average daily gain (522 g d^{-1}) and gain per area (324.8 kg ha^{-1}) did not differ between systems due to greater nutritive value when intercropped (5). Costa *et al.* (2), however, reported greater green forage mass for the mixture (2.24 vs. 1.93 Mg ha^{-1}).

Some sabiá morphological factors may lead to reduced intake, such as presence of aculeus (Figure 1), low leaf/stem ratio, and metabolic factors, such as condensed tannins, which may also affect negatively the digestibility (1,2). Alves *et al.* (1) observed that condensed tannins in sabiá reduced forage intake by sheep 13.3%, but goats reduced only about 4%, indicating this is species specific. Goats are more selective than sheep, and they can neutralize tannin astringency via salivary proline.

In agroforestry systems, sabiá can contribute to nutrient cycling, soil aeration and carbon stock, as well as animal welfare in tropics promoted by shading (2,6,7). An alternative to minimize N deficiency in non-fertilized grassland would be via legume biological fixation, since according to Apolinário *et al.* (3) up to 121 kg N ha^{-1} can be fixed on leaves of sabiá (Table 1).

Sabiá nutrient cycling can be increased through different pathways. Soil fertility might increase via leaf losses up to 18.5 Mg litter ha^{-1} yr^{-1}; this litter has high biological value. Sabiá litter is rich in nutrients and organic matter, returning yearly 0.16 to 0.46 Mg N ha^{-1} and 30 kg P ha^{-1} (3,8). Sabiá litter decomposes up to 30% after 256 days of incubation. This results in reduced nutrient losses through leaching, rendering nutrients available for longer period (9). Deeper root decomposition is another mechanism to increase soil C stock in deep soil layers. Sabiá associates with diazotrophic bacteria, such as *Rhizobium* and *Bradyrhizobium*, as well as *Burkholderia mimosarum*, *B. nodosa*, *B. sage*, *B. plymatum*, *B. tuberum*, all isolated from sabiá nodules (10). This association not only provides N for the system, but also can help building soil organic matter. Tree legumes, such as sabiá, have the potential to recover nutrients from deeper soil layers and transfer them to plant biomass and eventually litter or forage. This mechanism might avoid groundwater contamination. Nutrients contained in sabiá forage consumed by livestock return to soil via cattle excreta. There are implications on spatial distribution of nutrient returned via litter vs. via excreta, with more heterogeneous distribution via animal excreta (6).

Lima *et al.* (7) reported that soil physical attributes are improved by sabiá presence in the silvopastoral system since water infiltration was faster than in signal grass monoculture (336 vs. 162 mm h^{-1}) (Table 1). This benefit was promoted by legume pivotal root system as well as by lower animal trampling below the legume canopy, leading to lower soil density (1.18 vs. 1.24 g cm^{-3}). Despite lower moisture retention under sabiá trees, the organic matter light fraction, which has faster decomposition rate, was greater than *Gliricidia sepium* (0.064 vs. 0.045 g kg^{-1}), also a tree legume, leading to a faster

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nutrient availability for companion grasses.

Multiple uses of sabiá also include hedge (Figure 1), biofuel, bee flora, leather tanning, water purification, and fabric dye. For Brazilian Northeast, this species is one of the main crops for fence posts and batten, due to its high physical-mechanical resistance, combined with greater calorific capacity (Table 1) (3,6). Stake yield varies according to ecological zone and plant density and can be estimated up to 5150 stakes ha^{-1}, when trees are over 7 years old and 7-cm stem diameter (3).

In summary, as a tree legume, sabiá can be an alternative for agroforestry systems, mainly in silvopastoral practices. Intercropping sabiá into grass pastures could lead to positive advances for the environment and economic sustainability, as well as social support in northeast Brazil and similar warm, semi-arid regions around the world.

Particularly, in Brazil semi-arid, sabiá can reduce Caatinga rangeland deforestation, relieving wood irregular extraction from species threated with extinction. Furthermore, silvopastoral practices with sabiá will reduce grazing pressure on Caatinga rangeland, mainly during dry season that last about eight months.

Table 1. Sabiá potential features in a silvopastoral system at Itambé, Pernambuco Brazil.

Forage[1]	Wood[1]	N content[1]	N fixed[1]	Potential calorific[1]	Soil organic matter[2]	Soil light fraction[2]	Water infiltration[2]
Mg ha^{-1} y^{-1}		g kg^{-1}	kg ha^{-1}	Mj kg^{-1}	g kg^{-1}	g kg^{-1}	mm h^{-1}
7.1*	25	38.5	121	17.7	48.5	0.064	420

Source: [1]Apolinário *et al.* (3); [2]Lima *et al.* (7). *considering only leaf.

Figure 1. Sabiá applied as hedge in northeast Brazil (left). Sabiá leaf, inflorescence and stem features (right).

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Leucaena species: tree legumes for warm climates

HM Shelton[1]

Abstract: The University of Queensland staged the International Leucaena Conference in 2018. Approximately 120 conference delegates shared knowledge and practical experiences regarding leucaena. These are the highlights regarding how we plant, manage and use leucaena around the world.

Varieties

Dalzell (1) noted early use of leucaena by humans was based entirely upon the very narrow germplasm of a single genotype of *L. leucocephala* ssp. *leucocephala* ('common' leucaena), that had spread pantropically from its centre of origin in Mexico. Genetic improvement began in the 1950s when vigorous 'giant' leucaena genotypes (*L. leucocephala* ssp. *glabrata*) were identified. Cultivars such as Hawaiian K8, Peru and El Salvador were selected and promoted in silvopastoral systems in Australia and in multipurpose agroforestry systems throughout the tropics. Plant breeding for improved forage production resulted in the release of cv. Cunningham in 1976 in Australia. These cultivars of 'giant' leucaena displayed broad environmental adaptation but lacked tolerance of cold temperatures (and frost) and adaptation to acid soils. The arrival of the psyllid insect pest (*Heteropsylla cubana*) from the Caribbean in the early 1980s devastated both 'common' and 'giant' leucaena all around the world. However, some giant leucaenas exhibited a degree of tolerance to the psyllid pest and were released in Australia as cultivars Tarramba and Wondergraze and in Hawaii as cv. LxL. Since the 1990s, plant breeding programs have sought to develop cultivars with greater psyllid tolerance derived from the interspecific hybridization between *L. pallida* and *L. leucocephala* ssp. *glabrata,* resulting in the release of cv. 'KX2 leucaena' in Hawaii for timber and forage production, and cv. Redlands in Australia as a forage cultivar.

Dalzell (1) identified development of sterile leucaena as a high priority. He argued that a sterile leucaena would lead to increased adoption in regions, e.g. Western Australia, where leucaena propagation is not permitted owing to concerns over potential weediness (2).

The conference endorsed the need to coordinate international G x E evaluations of existing and new leucaena cultivars and selection of elite germplasm due to limited R&D resources. It is essential that all R&D personnel involved in leucaena plant evaluation are aware of the origins of the genetic material they are using and the location of international collections of leucaena. The World Leucaena Catalogue provides detailed passport information, including origins, collector, local ID identifiers for cross-referencing with other collections, but needs updating due to better understanding of speciation within the genus (3).

Figure 1. Cattle grazing leucaena in northern Australia. (Photo HM Shelton)

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Establishment and management

Buck *et al.* (4) outlined best practice to achieve successful establishment of leucaena. In Australian grazing situations, best outcomes with existing commercial varieties occur on deep, fertile, well-drained neutral-alkaline soils in the 600-800 mm rainfall zone, while psyllid-tolerant cv. Redlands is better adapted in higher rainfall environments. Recommendations are to plant into fully prepared seedbeds with ample stored moisture and corrected for nutrient deficiencies, in double rows 6 m apart. Seed should be scarified, inoculated with rhizobium and treated for insect control prior to planting plus beetle bait after planting.

There are many reasons to develop efficient cost-effective micro- and macro-vegetative propagation methods for leucaena (2). Vegetative propagation would be advantageous for: expediting breeding programs; distribution of sterile materials; planting in non-arable locations; small-scale hand-plantings in Asia; and even for planting on smaller holdings in coastal Queensland, where commercial seedling planters might be effective. Provided soil moisture is adequate, advantages are quicker establishment plus reduced challenge from weeds, domestic animals and wildlife.

Feeding and management

Conference delegates confirmed that leucaena is a highly palatable, productive and profitable forage option used by beef producers in northern Australia (4) (Figure 1) and by beef, dairy and goat producers in Central America, South America and Asia (2) (Figure 2). In Australia, when sown with either native or exotic companion grasses, leucaena provides significant productivity, economic, environmental and social benefits. Cattle on leucaena-grass pastures will gain 250–300 kg/year, and at a higher stocking rate than on straight grass pastures, while production per hectare can be 2-4 times that from rundown buffel grass pasture. At stocking rates of 2.5-4.5 head/ha, beef cattle gained 0.65-0.8 kg/d, while dairy cows yielded 5-14 kg milk/head/d, depending on animal genetics, season and supplementation, with up to 17,000 kg milk/ha/year (2).

Goats are well adapted to leucaena and are productive in terms of live-weight gains, milk production and reproduction on diets containing up to 100% Leucaena (2). Successful feeding systems included both grazed and cut-and-carry intensive strategies.

Appropriate grazing management is necessary to maximize leucaena-grass pastures production; however, many graziers do not manage this aspect well and it can be costly to correct. In Australia, a range of commercial and home-made slashing devices are used to mechanically cut tall leucaena to bring it into the reach of grazing animals (2).

Toxicity

Leucaena contains the non-protein amino acid mimosine (2) and cattle, naïve to leucaena, can be initially affected by mimosine toxicity, showing symptoms of hair loss, salivation and loss of appetite. Mimosine is rapidly converted to DHP which is reported to be chronically toxic. However, most livestock raisers in Australia and internationally observe that symptoms are short-lived, with animals quickly recovering to show excellent production.

Figure 2. Stall-fed leucaena to Bali bulls in eastern Indonesia. (Photo HM Shelton)

The current understanding in Australia is that graziers with cattle on leucaena are wise to inoculate cattle with *Synergistes jonesii* as protection against toxicity. However, new evidence from Indonesia where Bali cattle being fed diets up to 100% leucaena showed that conjugation of DHP by the liver, and not *S. jonesii,* though ubiquitously present at low populations, was the major detoxification pathway, and inoculation was not necessary (2). Since no other country has access to the laboratory-fermented source of *S. jonesii*, this finding, if widely applicable, has the potential to remove a major world-wide barrier to adoption of leucaena for feeding ruminants.

Alternative uses

There is increasing interest in leucaena as a dual-purpose plant suitable for producing both biofuel as well as feed for livestock. Tudsri *et al.* (5) reported that the chemical composition of leucaena was excellent for heat generation on combustion. They reported that the arboreal character and wood yield of cv. Tarramba, as well as many hybrid lines, showed excellent potential as biofuel and recommended planting configurations that delivered both biofuel and livestock feed.

The environment

There are multiple environmental benefits from leucaena that provide triple bottom-line benefits (environmental, social, economic) including C storage, animal welfare and reduced enteric methane emissions (2). High-quality feed during the dry season and during droughts in Asia delivers control of many internal parasites. Organic beef production in Australia is possible from leucaena pastures on fertile soils.

Despite the many positive attributes, environmental concerns about the weed potential of leucaena remain a major issue in Australia and worldwide (6). Leucaena does not invade undisturbed ecosystems. Nevertheless, if not properly managed, current commercial varieties of leucaena produce long-lived seed that can spread outside of planted paddocks onto roadsides and along riparian zones.

Conclusions

There is huge potential to expand the area of leucaena pastures around the world. Nevertheless, there was general agreement at the conference that, despite overwhelming evidence for the high productivity, profitability and sustainability of leucaena feeding to ruminants around the world, adoption of the innovation was universally well below expectations. Delegates were unanimous in agreeing that the momentum for collaboration and information exchange established during the conference should be continued.

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Leguminous trees for silvopastoral systems

Dirk Philipp[1]

Abstract: Leguminous trees offer benefits in silvopastoral settings, chiefly N fixation and turnover to associated herbaceous perennial forage crops besides soil improvement and favorable microclimate for animals. Several species of leguminous trees have been used extensively in tropical and subtropical agroforestry settings but less so in temperate climates due to a limited number of leguminous tree species available there. Livestock production per unit land area appears to be similar in silvopastures vs. open non-wooded areas in some instances and points to increased land-use-efficiency. Future research activities should focus on determining the economics of N-turnover dynamics services. In general, adoptability of silvopastoral systems by landowners may increase in the southeastern USA and elsewhere due to expected greater climate variability during coming decades.

Key words: Leguminous trees, nitrogen fixation, silvopasture, temperate agroforestry systems

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Introduction

Leguminous, N-fixing trees contribute N to silvopastoral systems similar to herbaceous forage legumes. Although there are more than 500 tree species capable of fixing atmospheric N worldwide (1), presumed N inputs into soil pools are difficult to quantify. Similar to N-fixing forage legumes, N-fixing legume trees accumulate N into their biomass which either need to be browsed and deposited as manure or recycled in other forms before becoming available to forage crops cultivated between tree rows. Several native leguminous tree species can be found in tropical climate regions, much fewer are native to temperate climates. There are examples of ruminant production being as efficient in wooded as in non-wooded pastures, suggesting multiple benefits from silvopastoral systems.

Leguminous tree species world-wide

There are vastly more leguminous tree species native to tropical and subtropical zones than anywhere else in the world. Table

Figure 1. Although this system does not feature leguminous trees, it represents a typical agroforestry setting in the lower midwestern USA. Here, native warm-season grasses are being established in an alleyway between rows of sycamore (*Platanus occodentalis*, right) and red oak (*Quercus rubra*, left). Orchardgrass (*Dactylis glomerata*) has been established in the remaining alleyways previously (Image courtesy of D. Philipp).

1 displays examples from the tropics and subtropics as well as North America. Due to climatic factors in tropics/subtropical regions that permit year-round growth, several woody species have been used successfully in silvopastoral situations, agroforestry, or multi-cropping systems, for example *Cajanus cajan*, *Gliricidia sepium*, *Leucaena leucocephala*, *Sesbania sesban*, and *Cassia* species as indicated by Mafongoya *et al.* (2). These authors provided a comprehensive list about leaf and litter characteristics that are important for predicting N input to silvopasture systems and expected turnover rates. Some species, for example *C. cajan*, have relatively high C:N ratios and lignin contents, meaning that their decomposition rates are rather slow. Others, including *S. sesban,* have similarly high C:N ratios in their leaf litter, but faster presumed decomposition rates based on relatively low lignin concentrations in senesced biomass.

There is a host of leguminous species being used for multiple benefits (3). These authors reported that many commonly used leguminous species serve as fence rows (*Erythrina senegalensis* and *E. variegate*), windbreak plantings (*Andira inermis*, *Inga laurina*, and *Albizia chinensis*), erosion control (*Acacia nilotica*, *Parkinsonia aculeata*), and shade trees (*Pithecellobium saman*, *E. fusca*). Many tree species provide these functions simultaneously, such as in the case of *P. aculeate* or *E. variegate*. Their leaves and twigs are used as fodder for small ruminants besides N-fixing contribution. On the Indian subcontinent, *G. sepium* is used simultaneously as hedge tree and leaf litter for mulching.

There are several leguminous tree species present in the USA, but there is only occasional evidence of usage in agroforestry or silvopastoral settings. Examples in temperate areas include *Robinia pseudoacacia*, *Cercis canadensis*, and the well-known *Gleditsia triacanthos*. The latter is common to the southern USA where it can be found in a variety of locations such as along pasture edges and creeks banks (4). The trees are being used as shade for livestock while fruits are browsed by deer, small mammals, and sometimes cattle as well, and there are reports of using this species in agroforestry settings dating back several decades (5). This author reported on the opportunities this species allows for establishing forage crops underneath due to relatively open canopies. The well-known tropical legume tree *L. leucocephala* grows in the southwestern and southeastern USA is often considered invasive so its use for silvopastoral should be considered cautiously.

Nitrogen-fixing dynamics

In considering leguminous trees for silvopastoral systems, N-fixation is the driving force for which species to include and what management to impose. Similar to forage legumes, N input from trees to nutrient cycles is difficult to predict. Although the amounts of fixed N ha^{-1} yr^{-1} may be large (e.g., 100-300 kg for *G. sepium*; (6)), turn-over rates in tree/perennial cropping systems are often unknown. Many assumptions and information regarding the contribution of N from trees to associated crops may be inadequate at best, and the nutrient dynamics in silvopastoral settings are not well understood (7). Fixation and turn-over rates depend on several factors, including but not limited to climatic conditions, soil type, animal activities, and a combination thereof.

Livestock performance in silvopastoral systems and associated benefits

Livestock production is of central importance to the economic success of silvopastoral systems. Costa *et al.* (8) reported that animal performance measured via average daily gain and gain per unit area did not differ between an open area of signalgrass (*Brachiaria decumbens*) or when associated with either *G. sepium* or *Mimosa caesalpiniifolia*. Their findings referred only to the tree establishment phase (3 years) but benefits beyond that timeframe will likely include soil and microclimatic improvements as well. Dubeaux *et al.* (9) found that soil characteristics under various leguminous trees were associated with an increased level of exchangeable cations resulting in higher growth potential for pearl millet (*Pennisetum americanum*) in comparison with soil exposed to full sunlight. Microclimatic parameters also changed in silvopastoral systems located in the southeastern USA as indicated by Karki and Goodman (10). These authors reported that a generally milder climate (including temperature, humidity, and wind speed) was present within a loblolly-pine (*Pinus taeda*) / bahiagrass (*Paspalum notatum*) silvopasture compared with the open pasture treatment. Such findings are important as there are substantial numbers of livestock present in that region and summers are expected to become hotter in the coming decades. Figure 1 and 2 show examples of silvopastoral research in the southeastern USA.

Table 1. Examples of leguminous trees in tropical regions and North America (2,4) with potential for inclusion in silvopastoral systems.

Examples of leguminous trees

Tropics and Subtropics	North America
Acacia angustissima	*Amorpha fruticosa*
Cajanus cajan	*Gleditsia triacanthos*
Calliandra calothyrsus	*Gleditsia aquatica*
Erythrina sp.	*Gymnocladus dioica*
Gliricidia sepium	*Robinia pseudo-acacia*
Inga edulis	
Leucaena leucocephala	
Mimosa caesalpiniifolia	
Piptadenia buchtienii	
Sesbania sesban	
Tephrosia candida	

Implications for integrating leguminous trees into silvopastoral systems

Benefits from N-fixing leguminous trees associated with perennial forage crops are based on a combination of several factors such as soil improvement, N transfer, and microclimatic changes, which are difficult to measure independently. Most reports on silvopastoral systems with leguminous trees are related to tropical climates, not least because there are only a few leguminous trees native to temperate climates that are suitable for inclusion in agroforestry settings. Future research activities should be geared towards quantifying N turnover rates and the economic realities of managing for livestock gains and ecosystems services.

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Figure 2. In the southeastern USA, forage legumes can be planted among pine tree plantation that were established to obtain wood products for industrial purposes. In this case, white clover (*Trifolium repens*) was established in pine alleyways of different widths in central Arkansas to study the influence of varying shade on establishment and persistence. Cages were set up to determine total seasonal dry matter production if deer browsing would occur, which ultimately was not the case (Image courtesy of D. Philipp).

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Nutritive and anti nutritive factors of leguminous forage trees and shrubs

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Abstract: Leguminous trees and shrubs are valuable components of sustainable forage-livestock systems. Using these species as forage requires consideration of the many nutritive and anti-nutritive factors they produce. Anti-nutritive factors produced by legumes consist of highly species-specific plant secondary metabolites. Nitrogen-containing compounds, terpenes, glycosides and phenols produced by woody legumes may decrease performance, cause illness and even livestock death. The advantages of tree and shrub legumes in sustainable forage-livestock systems are best realized when these plants are simply a component of the system and the system is compatible with animal feeding behaviors.

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Introduction

The value of legumes in temperate, sub-tropical and tropical sustainable forage-livestock systems is well-established (1,2). Using herbaceous legumes in pasture-based systems is well-accepted compared to using arboreal and shrub legumes. It is not for lack of advantages of woody legumes in forage-livestock systems. Woody legumes produce deep tap root systems that confer drought avoidance strategies and may provide valuable forage during extended periods of water deficit (Figure 1). Associations with rhizobia to convert atmospheric nitrogen to plant-usable forms contribute to sustainable forage-livestock systems. Woody legumes produce protein-rich mast. Shade decreases maturity rate and subsequently increases understory forage nutritive value, while also reducing heat stress experienced by livestock.

Major considerations for using woody legumes in forage-livestock systems include leaf nutritive value and anti-nutritive compounds they produce. Tree and shrub legume nutritive value is exceptional. They produce large amounts of crude protein and contain lesser concentrations of structural carbohydrates than grasses of the same maturity. Woody legume leaf nutritive value declines to a lesser extent throughout maturity compared to grasses. As a result, leaves of woody legumes remain highly digestible throughout the growing season and beyond.

Anti-nutritive factors produced by legumes consist of highly species-specific plant secondary metabolites that may decrease performance, cause illness and even livestock death. However, not all anti-nutritive factors negatively impact livestock when consumed at sub-toxic doses. In moderation, some anti-nutritive compounds may have therapeutic effects on livestock. Anti-nutritive factors are classified as 1. Nitrogen-containing compounds, such as alkaloids and mimosine; 2. Terpenes; 3. Glycosides, which include cyanogenic glycosides and glucosinolates, and 4. Phenolic compounds. Specific characteristics of chemical composition determine anti-nutritional factor classification. Perennial tree and shrub legumes produce some or all of these compounds (Table 1.)

Anti-nutritive factors

Nitrogen-containing compounds

Alkaloids are compounds composed of heterocyclic rings that contain at least one N atom in their structure. Alkaloids have potent pharmacological effects on animal central nervous systems. More than 21,000 alkaloids have been characterized according to their structure-activity relationships (3). Of the many different classes produced by forage tree, shrub and sub-shrub legumes, β-Carbolines may occur most widely (4). Its most common anti-nutritional effect on ruminants is neurological disfunction.

Non-protein amino acids, another large class of N-containing compounds, are potentially anti-nutritional to ruminants. Mimosine is one example most commonly associated with *Leucaena leucocephala*. Anti-nutritional effects vary widely among livestock species. However, a common symptom of mimosine toxicity among cattle, buffalo, sheep and goats is impaired thyroid function accompanied by goiter (5).

Terpenes

The largest group of plant secondary metabolites, terpenes, are characterized as water-insoluble hydrocarbons that form oils, latex and resins in plants. They most commonly occur as mono-, di-, tri-, tetra- and sesquiterpenes. Many terpenes are volatile organic compounds that may function in plant-pollinator interactions and as defense against herbivory. Their anti-nutritive value is likely due to aroma and flavor that serve as deterrent to herbivory or to reduce palatability and intake. Of the small number of terpenes that have been reported in arboreal legumes, most appear to be associated with the floral organ (6).

Glycosides

Glycosides are compounds composed of a sugar attached to another functional group (aglycone). The aglycone can be nitrogen-containing compounds, terpenes or phenols, among others. Cyanogenic glycosides contain cyanide in their aglycone. These

Table 1. Select forage tree and shrub legume genera and commonly produced anti-nutritive compounds.

Genera	Anti-nutritive factor
Acacia	Alkaloids Cyanogenic glycosides Non-protein amino acids Saponins Tannins (primarily condensed tannins) Terpenes
Albizia	Alkaloids Saponins Tannins Terpenes
Burkea	Glycosides Saponins Tannins (primarily condensed tannins) Terpenes
Desmodium	Alkaloids Glycosides Non-protein amino acids Saponins Tannins (primarily condensed tannins
Gleditsia	Alkaloids Saponins Tannins
Gliricidia	Non-protein amino acids Saponins Tannins Terpenes
Holocalyx	Cyanogenic glycosides
Lespedeza	Glycosides Tannins (primarily condensed tannins)
Leucaena	Non-protein amino acids (mimosine) Tannins (primarily condensed tannins)
Prosopis	Alkaloids Tannins
Robinia	Alkaloids Glycosides Tannins
Sesbania	Alkaloids Saponins Tannins

compounds are not anti-nutritional in the glycoside form. However, cyanogenic glycosides are hydrolyzed by enzymes to release hydrocyanic acid following mastication by ruminants. This disrupts cellular respiration that affects the myocardium, leading to cerebral anoxia and death. Several *Acacia* species and *Holocalyx balansae* produce cyanogenic glycosides (7,4).

Saponins most commonly occur as triterpene glycosides that demonstrate both hydrophilic and hydrophobic properties. These properties form stable foams that interact with proteins when introduced to the rumen. Thus, saponins cause bloat in ruminants. However, saponins produced by *Sesbania sesban*, a leguminous tree commonly used as forage for livestock, may have nutritive characteristics. These saponins may alter rumen fermentation resulting in decreased methane production and subsequently increased metabolizable energy availability.

Phenolic compounds

Lignin is composed of a combination of phenolic monomers, *p*-coumaryl, coniferyl and synapyl alcohols, commonly present in differentiated plant cell walls. Tree and shrub legume wood contains large concentrations of lignin. Few organisms produce the enzymes to degrade lignin. This characteristic protects the wood from being over-browsed and contributes to forage resource sustainability.

Tannins are polyphenolic compounds that demonstrate biological activity by binding to organic and inorganic molecules. Two classes of tannins are generally recognized, condensed tannins (CT) and hydrolysable tannins; the latter associate with greater anti-nutritive effects on livestock. All forms of tannins may inhibit digestion by forming complexes with nutrients including protein, carbohydrates, lipids and minerals. These complexes decrease nutrient availability, which may negatively impact animal performance. Tannin-protein interactions during mastication result in astringency, which decreases palatability, forage intake and may negatively influence animal production. However, some livestock have adapted to tannin-rich forage resources and developed multiple coping mechanisms. First, they may possess more liver tissue per unit body size compared to large grazing ruminants. They may also produce proline-rich salivary proteins that bind tannins during mastication, thereby reducing activity in the digestive tract. Small ruminants may also be host to specific rumen microbes (*Streptococcus gallolyticus*) that degrade some tannin forms.

Most tree and shrub legumes produce at least some CT. However, biological activity among species varies widely. Moderate concentrations of biologically active CT are beneficial to ruminants. Proteins bound by CT may be protected from rumen microbial degradation, altering protein digestion sites.

Figure 1. Cattle browsing felled *Gleditsia triacanthos* (honey locust) during a severe drought in 2012 Missouri, USA.

An increase in rumen undegradable protein shifts protein degradation to the abomasum, increasing amino acid flow to the small intestine. Rumen microbial efficiency increases when ruminants consume CT. This may be related to reductions in amino acid deamination and ammonia production.

Condensed tannins alter rumen fermentation gaseous output. Methane production and sometimes total gas are reduced in ruminants consuming diets rich in biologically active CT (8). This may increase metabolizable energy intake, thereby increasing animal production.

Some condensed tannins demonstrate anthelmintic activity. Fecal egg counts and adult worm populations decline when ruminants consume certain CT. Condensed tannins are most effective against *Haemonchus contortus*, with activity against *Ostertagia* and *Trichostrongylus* occurring to a lesser extent.

Perspective: integration despite anti-nutritive factors

Woody legume advantages in forage-livestock systems are best realized when they are a component of a mixed forage system. This approach results in diluted dietary anti-nutritive compounds. Incorporation requires forage diversity and abundance that allows livestock to regulate intake based on individual pharmacokinetics and pharmacodynamics associated with nutritive and anti-nutritive components. Concentrate selectors, non-selective browsers and intermediate feeders may be the best options for livestock when exploiting woody legumes. However, grazing livestock may also selectively graze and browse, especially during winter or dry seasons when other forage resources become scarce.

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The arboreal legume dilemma: adaptation and weediness

Jamie L. Foster[1]

Abstract: Traits that lead to the persistence and adaptability of arboreal legumes result in potential weediness. The same traits-high seed yields, ratooning, and deep taproots-that make tree legumes beneficial multipurpose crops in tropical and subtropical regions can also make them weeds. Harnessing legume trees, including *Acacia* spp., *Leucaena leucocephala*, and *Prosopis* spp., for their different agricultural products where they have become invasive may provide a greater agricultural purpose and income to landowners and farmers while simultaneously reducing their weed potential

Keywords: Arboreal legumes; invasive; weeds

Arboreal legumes tend to establish slowly, but once established they grow rapidly and have profusive seed production (1). Their deep taproots impart drought and nutrient deficiency tolerance and provides a competitive advantage compared to surrounding herbaceous forage. Additionally, their height provides light capture advantages in grazinglands. Once mature, thick stems, thorns, and secondary compounds may deter grazing animals which tend to select leaves and tender stems, leaving meristems for regrowth. The characteristics summarized here which make arboreal legumes an ideal option for domestication and integration as a persistent legume into grazinglands, also translate into the potential for arboreal legumes to become persistent weed species. As land management changes, including fewer wildfires and prescribed burns, and overgrazed herbaceous species, native legume tree species overpopulate and become weeds. Some species introduced to new areas for ornamental or agricultural uses, spread to become aggressive, noxious weeds (2).

There are several weedy legume trees currently or potentially used for silvopasture and agroforestry, including *Acacia* spp., *Leucaena leucocephala,* and *Prosopis* spp. (Table 1). Tree legumes are multipurpose crops that can be flexibly used for fuelwood, fodder, human food, living fences, lumber, poles or posts for fence, shade for livestock and people, wildlife habitat, bee habitat and pollen sources, or soil erosion control, among others. Because of the wide range of benefits and products these tree legumes provide, especially in developing countries, whether they are considered a weed or not has been quite controversial (1) and remains so today. Even within a country, state, or province these tree legumes may only become dominant and compete with desirable plant species in site-specific locations. Chemical and mechanical control of brush, including legume trees, is an expensive undertaking for governments and landowners (3). Additional products from these weedy tree legumes, such as ruminant feed ingredients, or biofuel feedstocks may provide an agricultural product and income while simultaneously reducing their weed potential.

Acacia is a tree legume genus with a large number of genotypes native to tropical and subtropical regions of the world, but particularly in Australia (Table 1). Ten species are listed as locally invasive in Asia, Australia, Pacific Islands, the USA, and other locations. *Acacia* is an extremely important genus for livestock feed, timber, and soil stabilization in the tropics. In South Africa, where introduced species are often invasive and undesirable, biological control has been successful. Gall wasp (*Trichilogaster acaciaelongifoliae*) and a weevil (*Melanterius ventralis*) that feeds on the seed were introduced resulting in a 90% decrease in reproductive potential of several acacia species (4). Chemical means are recommended to remove remaining trees due to the ability of acacia to cope with

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Figure 1. ***Leucaena leucocephala*** **growing on the shoreline of Corpus Christi Bay, Texas, with inset of flowering. Photos by Jamie L. Foster**

frequent defoliation (5); however, timber and biofuels are also potential agriculture sectors to use acacia biomass.

Leucaena leucocephala (leucaena) is perhaps the most widely planted arboreal legume worldwide (Table 1; Figure 1) (6). Native to Central America, it was introduced to tropical and subtropical regions worldwide from the 16th to 20th centuries because of its high ruminant feed value and multiple uses (6). It is now considered an invasive species in Hawaii and other Pacific Islands, Australia, and South Africa (2). *Acanthoscelides macrophthalmus* is a beetle seed predator which was released in South Africa for biological control but is unlikely that this singular pest will stop leucaena's spread (7). However, in combination with chemical, mechanical, and grazing management, especially along waterways which is the primary method that seed is spread, *A. macrophthalmus* is an important tool considering leucaena is a very slowly spreading weed. Seedlings are slow to establish, with recommendations of 1 to 3 years after planting before grazing begins; heavy grazing during seedling stage of growth will not allow persistence. After establishment typical grazing management will not control leucaena because it resprouts after cutting/defoliation. Due to the long history of grazing leucaena by cattle, particularly in Australia, it is unlikely that grazing pressure from cattle alone would lead to control. However, goats, which closely crop browse and will strip bark off trunks with their nimble lips, may be used to control leucaena (8).

Prosopis glandulosa (mesquite) has spread beyond its normal habitat within the southeastern USA and become a weed problem (Table 1; Figure 2). Several *Prosopis* spp., including *glandulosa*, are considered invasive in Australia and Pacific Islands. These species grow in association in some regions of the USA and can dominate grazing landscapes that have been overgrazed or where fire management is removed (3). Control of mesquite in areas where it is not desired may be accomplished by fire, grazing by goats or sheep, chemicals, and/or mechanical removal, but a combinations of methods is more effective than singular treatment. Chemical and mechanical control is a financially expensive investment by landowners (3). The harvested wood is valuable for fence posts, furniture or firewood, and shavings as bedding or mulch. A unique Wood to Feed Program at Texas A&M AgriLife Research-San Angelo found that mesquite leaves and small twigs (< 5 cm diameter) can serve as the sole roughage for goats or sheep with no detrimental impacts to animal growth or development (9,10). The value of residue as a feedstuff provides enough income to pay for tree removal.

Integration of multiple control methods works best for weedy tree legume spread. Traditional mechanical and chemical controls must be used at the proper time for success. Using them for grazing by sheep or goats, timber production, or other agricultural purposes, would allow for income from their management which provides an incentive for controlling the spread of invasive tree legume species.

Table 1. Nutritive value, native habitat, and weed habitat locations of selected arboreal legumes with weed potential. The weed habitat location may be the same as the native habitat indicating that the species is considered a weed within that region where it is an undesired species.

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Arboreal legume	CP of leaves, % DM basis	Digestibility as browse, % DM	Native habitat location	Weed habitat location
***Acacia* spp.**	15-24	29-55	Tropical and subtropical regions of the world	Tropical and subtropical regions of the world
Leucaena leucocephala	18-26	50-71	Southern tropical America	East Africa, Asia, southern USA, Australia, Pacific islands
***Prosopis* spp. (except *P. strombulifera*)**	9-26	58-68	Mexico and Southeastern USA	East Africa, Arabia, Australia, Brazil, western Asia, Hawaii

Figure 2. *Prosopis glandulosa* (mesquite) growing as an ornamental in a city park in Corpus Christi, Texas, with an inset of flowering. Photos by James R. Jackson.

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Native shrub-tree legumes of tropical America with potential for domestication

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Abstract: Native legumes from tropical America are ecologically adapted and their wide biodiversity represents an important resource for plant domestication, as well as application in different agricultural systems. Some native legumes have potential for uses such as forage, wood, energy, food, human and animal medicine, restoring degraded land, N fixation or as ornamentals. Some species with this potential belongs to the genera *Adenanthera*, *Bauhinia, Desmanthus*, *Machaerium, Mimosa*, *Piptadenia* and *Poincianella*.

Keywords: agroforestry, forage, wood

Introduction

Man became a farmer when plants and animals were domesticated to provide food, fodder and other needs. This was mainly a product of empirical observation and accumulated experiences by our ancestors, especially for plants and animals domesticated for human food. Shrub-tree legume domestication is more recent and depends on little historical knowledge, resulting in a short list of domesticated shrub-tree legumes in Tropical America, such as the genera *Leucaena, Mimosa*, and *Prosopis*.

Plant domestication is a complex and slow process, which seeks to identify potential species according to farmer's needs, and involves identification, experimentation, and cultivation. In northeast Brazil, the Tropical Dry Forest (Caatinga) includes a large number of endemic tree legume species, but little is known about their productivity or uses. The Caatinga has approximately 184 shrub and 189 tree species (1). Native legume domestication might have an important role in different production systems in this environment, since these native species are adapted to prevailing factors such as periodic droughts, low native fertility and heavy grazing pressure. According to Dubeux *et al.* (2), once tree legumes are established, they are often more persistent than herbaceous legumes.

Some woody native legumes have potential for domestication (Table 1) with different uses such as forage, N_2 fixation, wood production, hedge, pulses, ornamental, and recovery of degraded land, among others. After identifying species with domestication potential, several aspects should be studied before commercial use. A concerted effort is important to identify differences and domesticate woody legumes that present multipurpose potential.

Domestication difficulties

Although several species are identified with the potential for domestication, scientific information, especially in growth and management conditions, is still scarce. For example, cultivated native plants will probably present more pests and diseases than those grown with a natural biological control and diversity in an original ecosystem

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(3). Different stages of evaluation for species domestication are required to avoid past errors, such as the introduction of *Prosopis juliflora* (Sw) DC. in several countries, which is now considered invasive despite its products and benefits. In addition, farmers naturally domesticate native woody species when selecting those that should be kept on their property.

Forage

Mororó [*Bauhinia cheilantha* (Bong.) Steud.], jureminha [*Desmanthus pernambucanus* (L.) Thellung] and espinheiro (*Machaerium aculeatum* Raddi), have variable occurrence in northeast Brazil. These legumes persist and are selected by browsing animals (Figure 1). There are large forage mass fluctuations between rainy and dry seasons and browser preference. For example, Diniz (4) observed that *Desmanthus* spp. forage mass produced 1 Mg dry matter ha^{-1} after 75 days.

Those legumes have high crude protein contents, however, most of this can be associated to fiber. They also often contain tannins. Silva *et al.* (5) reported that espinheiro grazable biomass had 170, 553, 378 g kg^{-1} of crude protein (CP), neutral and acid detergent fiber, respectively. Araújo Filho *et al.* (6) observed 207 g CP kg^{-1}, 57 g tannins kg^{-1}, and 597 g IVDM kg^{-1} for mororó in vegetative phase.

Energy and wood

In northeast Brazil, a large part of industry and home fuel demand is supplied by dry forest woody species, such as genera *Poincianella* and *Mimosa*. Thus, timber importance is often underestimated, because it is sporadically harvested and locally exploited. However, in some systems, it can provide land managers with renewable income that often exceeds that derived from animal production (2). A concerted effort to identify and domesticate arboreal legumes with hardwood characteristics could associate other desirable characteristics with timber and bioenergy quality.

Degraded land recovery and N_2 fixation

Native legumes play an important role in degraded land recovery, due to ecology adaptation, biological N fixation, as well as promoting large diversity. In an experiment with 11 shrubby-arboreal species, Pereira and Rodrigues (7) considered *Anadenanthera macrocarpa* (Benth) Brenan, *Mimosa caesalpiniifolia* Benth and *M. artemisiana* Heringer & Paula to be promising.

Table 1. Characterization of native legumes with potential for domestication.

Legume species	Region	Size	Main characteristics/use
***Anadenanthera macrocarpa* (Benth) Brenan**	Brazil	Tree	Land recovery, medicine, ornamental
***Bauhinia cheilantha* (Bong.) Steud.**	NE Brazil	Shrub-tree	Browse, persistent, ornamental
***Desmanthus pernambucanus* (L.) Thellung**	NE Brazil	Shrub	Browse, persistent, N fixation
***Machaerium aculeatum* Raddi**	Brazil, México	Tree	Browse, persistent, nectar (honey)
***Mimosa tenuiflora* (Willd.) Poir**	El Salvador, México, NE Brazil	Shrub-tree	Energy, N fixation, persistent, high-tanin, nectar (honey)
***Piptadenia stipulacea* (Benth.) Ducke**	NE Brazil	Tree	Wood, N fixation, high-tanin, nectar (honey)
***Poincianella bracteosa* (Tul.) L.P. Queiroz**	Brazil	Shrub-tree	Energy, land recovery, persistent, nectar (honey)

Table 2. Quantification of biological nitrogen fixation, dry mass of nodules and leaf C/N ratio of *Desmanthus* spp. Source: (3)

Variables	Genotypes			
	AS	5G	6G	CV %
Biological Fixation of N_2 (kg ha^{-1} yr^{-1})	61.9	93.1	78.3	5.5
Dry mass of nodules (mg $plant^{-1}$)	665.4	423.1	665.6	24.6
Leaf C/N ratio	17.6	16.3	16.1	17.4

Freitas *et al.* (8) estimated the biological N_2 fixation potential of some shrub-tree plants from Caatinga and identified some species as important fixers, such as *Mimosa tenuiflora* (Willd.) Poir, *M. sandy* (Willd.) Poir and *Piptadenia stipulacea* (Benth.) Ducke. The biological nitrogen fixation contribution was up to 68% N. However, N added annually via leaf biomass was low (2.5 to 11.2 kg N ha^{-1} yr^{-1}), due to the low proportion of fixing plants in botanical composition. Diniz (4) evaluated *Desmanthus* genotypes and observed large N amounts derived from the atmosphere (Table 2). *Desmanthus* also had C/N ratios within a mineralization/immobilization equilibrium range, evidencing lower C/N ratio than tropical grasses (9) which is an important characteristic of legumes.

Summary

The number of potential native legumes identified for domestication in the semi-arid tropical Americas is large; however, scientific information about growth and management conditions on those species is still scarce. Some shrub-tree native legumes such as *Bauhinia cheilantha* (Bong.) Steud., *Desmanthus pernambucanus* (L.) Thellung and *Machaerium aculeatum* Raddi have great persistence and are heavily selected by browsing animals. For example, in northeastern Brazil, woody *Poincianella* and *Mimosa* spp. from dry forest supply a large proportion of local fuel and lumber demand. Native legume use could also play a larger role in degraded land recovering, since they are ecologically adapted, fix N and promote increased biodiversity.

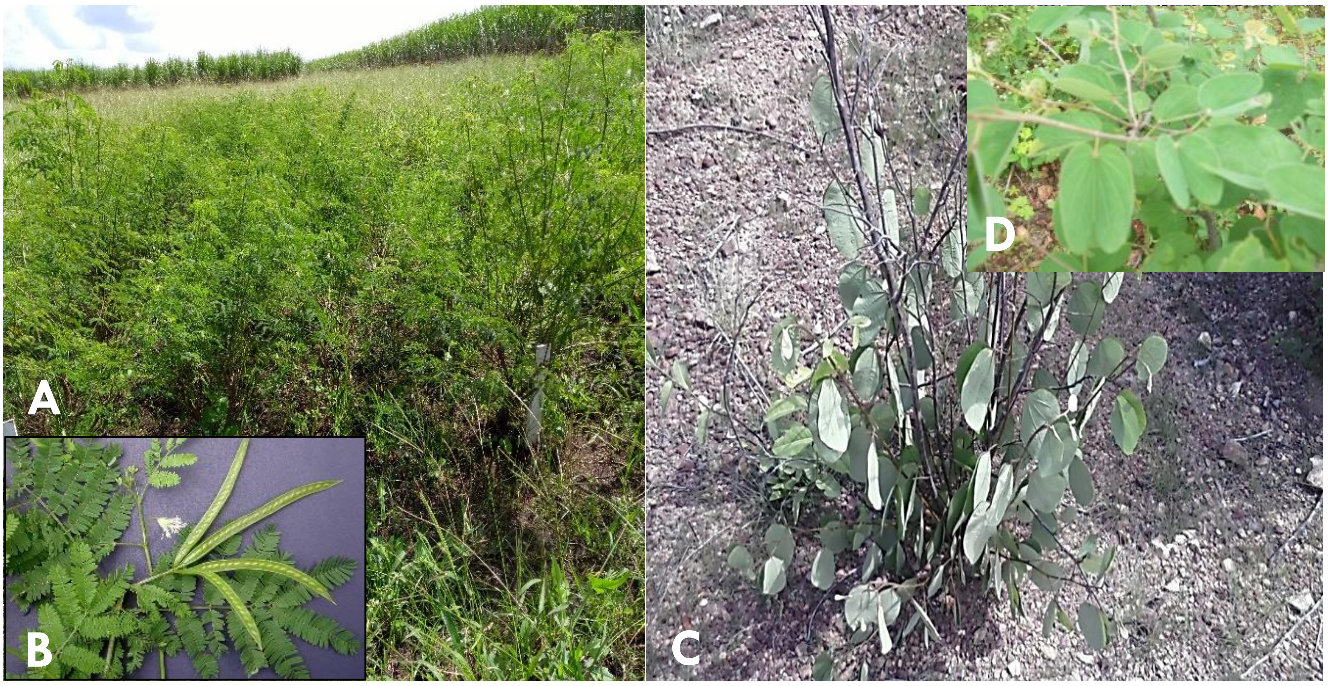

Figure 1. Native legumes with domestication and forage potential. A – *Desmanthus* spp.; B – *Desmanthus* spp. leaf, inflorescence and pod; C – *Bauhinia cheilantha* (Bong.) Steud.; D – B. cheilantha browse structure.

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Gliricidia sepium: a promising legume tree for the brazilian semiarid zone

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Abstract: In the Brazilian semiarid, there are recommendations for the cultivation of gliricidia to use as protein banks, in association with forage cactus, maize, bean, use as live fences, and as preserved forage such as hay and silage. A successful strategy is its cultivation in alleys in association with grasses for direct browsing. Integrating gliricidia into grazing systems increases carrying capacity of the pasture and promotes greater animal performance, being equivalent to N fertilization applied in the grass-monoculture pastures. Gliricidia silage or hay can substitute about 50% of the concentrate feed in lamb's diet without altering their live weight gain. These findings confirm the importance of gliricidia for the Brazilian semiarid livestock production.

Keywords: Integrated crop-livestock systems, protein banks, forage conservation

Introduction

Gliricidia sepium, Jacq. Kunth, Walp, or gliricidia as it is commonly called in Brazil, is also known as "madreado" in Honduras, "madero negro" in Costa Rica, "madre cacao" in Guatemala, "mata raton" in Colombia, and "coyote" in Mexico. It is a short to medium tree, 10 to 15 m height and 30 to 40 cm stem diameter (1). It has composite leaves and white-pink flowers 2- to 2.5-cm wide. The fruits are flat pods, pale green when immature and dark brown when ripe (2). Its propagation can be done through seeds or cuttings (3).

Native to the lowlands of Mexico and Central America, gliricidia was introduced in most tropical zones and naturalized from northern South America to Brazil, the Caribbean, Hawaii, West Africa, Asian countries such as India, Sri Lanka, Thailand, Philippines, Indonesia, and Australia. It grows in places with annual rainfall of 500 to 1500 mm and adapts to a great variety of soils (4). In Asian, African, and Central American countries, it is commonly used by small farmers, under cut and carry management, to provide animals with high-quality fodder.

Brazilian experience

In Brazil, the results of research carried out with this legume have caught producer's attention. Most research was carried out in northeastern Brazil on green manure (5,6), integrated systems (7,8), and animal feed (7). In the present review, we compared the results obtained for that region. For semi-arid conditions, gliricidia is recommended for protein banks, in a consortium with forage cactus, maize and bean, living fences, and as preserved forage (i.e. hay and silage). Gliricidia can be cultivated in alleys intercropped with grasses for direct browsing (7). This strategy was developed for coastal areas but can also be used in the semiarid conditions.

One of the important points for the sustainability of gliricidia crop is its harvest management. The resting period between each harvest and defoliation intensity will influence the speed of regrowth. In our studies, we have worked with spacing of 1.0 m between rows and 50 and 35 cm between plants in the row, resulting in populations between 20,000 and 30,000 plants/ha, depending on the availability of water and soil fertility. In sites or years with greater rainfall and more fertile soils, wider spacing between plants in the row is recommended and the opposite for sites with lower rainfall and poorer soils (Table 1). Data of tender and edible stems are not presented in Table 1. The number of cuts/year will vary mainly due to water availability.

Harvested material may be used "*in natura*"

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Table 1. Productivity and chemical composition of *Gliricidia sepium* at different cropping years. Adapted from (9)

	Rainfall	Total edible fresh Biomass yield	Leaf Fresh Biomass yeld	DM Leaves	Leaf DM Yeld	CP Leaves	NDF Leaves	ADF Leaves
	mm/year	t/ha/year	t/ha/year	%	t/ha/year	%	%	%
2010	800	106	69	20.1	13.8	22.3	35.8	26.3
2011	651	90	61	20.5	12.5	22.9	34.9	26.9
2012	375	71	42	25.2	10.5	22.0	33.7	26.3
2013	652	107	75	19.8	14.8	23.4	34.6	25.4

Figure 1. *Gliricidia sepium* intercropped with palisadegrass (*Urochloa brizantha*) for onsite browsing

or as hay or silage. In a study carried out to replace concentrate feed for Santa Inês lambs, we found that silage or gliricidia hay can substitute about 50% of the concentrate feed without altering the lambs' average weight gain that was 213 g/day (10).

Gliricidia has been used in direct browsing systems, increasing pasture carrying capacity and promoting greater animal performance, equivalent to N fertilizer applied to the pasture. In an 11-yr study by Embrapa in a dystrophic yellow soil of the coastal tablelands, livestock gains were 685 kg/ha/yr in the intercropping system of palisadegrass and gliricidia, against 497 kg/ha/yr for palisadegrass in monoculture fertilized with 240 kg N/ha/yr. In this system, gliricidia was cultivated in single rows spaced 5 m apart and 2 m between plants in the row (Figure 1). The great advantage of the palisadegrass intercropping system with gliricidia over the monoculture system is during the dry season, when grass herbage mass is low and the gliricidia biomass remains high.

In crop-livestock-forestry integrated systems, gliricidia has been used in several associations, cultivated with corn, forage cactus, palisadegrass, citrus, and coconut trees. In the case of the forage cactus, gliricidia not only adds N to the system supplying N to the cactus, but also provides high-quality fodder for the animals. Gliricidia will supply the protein fraction of the diet and the cactus the energy fraction (Figure 2a). In reports with coconut trees, besides being harvested and used by animals, gliricidia still increased coconut production by the incorporation of the biologically fixed nitrogen in the soil (Figure 2b).

Perspectives

Having in mind its great adaptability to different climatic and soil conditions of various micro-regions of the Brazilian Northeast, together with a high forage value, gliricidia is a strong ally in the search for economic alternatives, to complement the ruminant diets, especially in the semi-arid conditions. In addition, it has shown to be very efficient in the composition of crop-livestock-forest integration systems, increasing the nitrogen input in soil and providing shade and feed to the animals.

There is currently a great demand for information on cultivation technologies and use of gliricidia by farmers and technical assistance agents. Although many technologies are already available to meet most of those demands, the lack of a recognized quality seed production and distribution system has been the main bottleneck for the expansion of this crop. Such lack is mainly due to the absence of registered cultivars of this species. In this sense, Embrapa initiated a selection program of gliricidia accesses, aiming at the registration and market launch of cultivars with proven agronomic performance.

Figure 2. A) Gliricidia integrated with forage cactus, and B) with coconut trees.

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Arboreal legumes for human consumption

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Abstract: Arboreal legumes are an important food source in various regions of the world. Edible plant fractions include pod pulp, buds, resin, seeds, flower, green pods, and leaves. Medicinal and herbal uses are also reported. There are a variety of genera including *Parkis, Prosopis, Inga, Tamarindus, Tetrapleura, Leucaena, Ceratonia, Dialium,* and *Hymenaea.* In addition to edible fractions, these arboreal legumes often provide other products and services such as lumber, firewood, shade, and forage. There is a need to identify more of these legumes, make their usefulness more widely known, and domesticate additional species that are currently not considered for human consumption.

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Introduction

Arboreal legumes are common, especially in semi-arid savannas and forests in the tropics, sub-tropics and warmer temperate regions. These play important ecosystem functions such as diversity, biological atmospheric N_2 fixation, and browse for ruminants. Some of them produce copious quantities of seed. However, very few have been examined, much less exploited, for direct human consumption. Based on indigenous knowledge as well as novel research, leaves and seeds could be exploited as vegetables, pulses and pharmaceutical products.

Most of our common herbaceous pulses have ancestors whose seed were laced with anti-herbivore protections. These included alkaloids, tannins, terpenoids and isoflavonoids that were gradually eliminated by informal crop breeding, i.e. farmer selection (1). In arboreal legume pulses that have undergone less selection for human consumption, these phytochemicals are more prevalent.

Known examples from around the world

The genus *Parkia* populates warm-climate Asian and African savannahs and contains many species whose flowers, seeds and green pods feed human populations around the world. For example, despite having phenols and lectins, the tree bean (*Parkia timoriana* DC. Merr.) is widely consumed in India because these components are heat-labile. Besides being rich in protein (15-36%), fatty acids and minerals, reproductive portions provide antioxidants, α-glucsidase, and α-amylase inhibition (2). Pods can have up to 18.8% protein while seeds up to 28.8%. Essential amino acid contents are particularly well suited to meeting young children's dietary requirements. Similarly, *Parkia clappertoniana* Keay, native to western Africa, is semi-cultivated for its fruit, leaves and bark.

Tetrapleura tetraptera (Schum & Thur.) Taub., *Dialium guineense* Willd., *Brachystegia* *nigerica* Hoyle & A. Jones, and *Pentaclethra macrophylla* Benth. are examples of leguminous African trees whose leaves, pods and seeds may be edible (3). They also have pharmaceutical, bactericidal and insecticidal properties that indicate plant secondary constituents that may cause concern to humans if not properly neutralized.

Leucaena species are native to the New World, mostly from Central America. They were utilized by native Americans as a pulse and some of these traditions persist. For example, humans consume *L. esculenta* leaf buds, flowers, seeds and young pods in Mexico (4). *Leucaena leucocephala* (Lam.) de Wit. is the best-known leadtree species, grown around the world as a forage, firewood and green manure. One of its least known uses is as a human food, with dehulled raw seed digestibility of only 25% which increase to 89% after exposure to heat (5). Its oil content is low but crude protein high, 6.4 and 27.6%, respectively in one report (6). There are numerous other *Leucaena* species throughout the Americas whose seed and pod utility for human consumption is no longer known as Native American civilizations have faded. These include *Leucaena retusa* Benth. (Fig. 1), an abundant seed producer in northern Mexico and southcentral USA, whose potential as a pulse is completely unknown (7).

Another genus that has been an historically important arboreal pulse throughout the Americas is *Prosopis* (8). These include *P. pallida* in Peru whose pod sugar (48%) and crude protein (8.1%) content, in one trial, were both superior to *Ceratonia siliqua* L., a Mediterranean legume with edible pods (carob) (9). *Prosopis juliflora* (Sw) DC in the USA and Mexico has up to 14% crude protein and 34% sugar in pod pulp and seeds, making it an excellent human food (10). In Brazil, flour made from these pods is used for human consumption as well as honey, liquor and a coffee substitute (11). *Prosopis cineraria* (L.) Druce, utilized as a pulse (as well as firewood) in India, contains glycosidic isoflavone conjugates that defend seeds against herbivory (12). These include isoflavonoids, terpenoids, and alkaloids.

Hymenaea is another important genus. In Brazil, *Hymenaea courbaril* L. wood is highly prized while fruit and seeds are used as human food and medicine (Fig. 3). Pulp and seed oils are being considered for new industrial, cosmetic and pharmaceutical products. The most abundant bioactive substances are α-tocopherol and β-sitosterol for oils while oleic (46.09%) and linoleic

Figure 1. *Leucaena retusa* seeds of unknown human food potential collected in southern North America.

Figure 2. *Inga flagelliformis* (Vell.) Mart pod pulp is consumed by humans in northeastern Brazil.

Figure 3. ***Hymeneae courbaril*** **L. are consumed as pod pulp in northeastern Brazil. The figure illustrates the seeds.**

47.91%) acids, from pulp and seed, respectively (13). The resin is used in folk medicine for treatment of several pathologies and is rich in terpenoid compounds, mainly diterpenes (14).

Future efforts

Much of the information available on edible arboreal pods, pulp, seed or pubs is from the previous century or recently gathered from indigenous cultivation systems that are threatened by mainstream cultivation (Table 1). That means we are losing or have lost much of the knowledge we once had of their value around the world. Many arboreal pulses currently not used for human consumption may have been used at one time or need to be explored for their potential. As climates change and land available for annual row crops declines around the world, utilizing these deep-rooted, N-self-sufficient trees to feed humans directly as well as contribute to environmental services, fuel or ruminant forage may provide humanity with calories and protein they could not otherwise glean from marginal ecosystems.

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Table 1. Arboreal legumes from around the world with reported edible and pharmaceutical seed, pod and leaf bud properties.

Latin binomial	Regions	Edible parts	Other uses	Reference
***Ceratonia siliqua* L.**	Mediterranean	Pod		(9)
***Dialium guineense* Willd.**	Western Africa	Pod pulp, leaves	Firewood	(3)
***Hymenaea courbaril* L.**	South America	Seed, pod pulp, resin	Lumber	(13,14)
***Inga edulis* Mart.**	South America	Pod pulp		J. Dubeux (personal communication)
***Leucaena leucocephala* (Lam.) de Wit.**	Central America	Seeds, pods	Firewood, forage	(5)
***Leucaena esculenta* Benth.**	Central America	Buds, seeds, green pods		(4)
***Parkia timoriana* DC. Merr.**	Southeast Asia	Flowers/green pods/seeds	Pharmaceutical insecticidal, bactericide	(2)
***Parkia clappertoniana* Keay,**	Western Africa	Fruit, leaves, bark		(3)
***Prosopis cineraria* (L.). Druce**	Southeast Asia	Pods/seeds	Firewood, pharmaceutical	(12)
Prosopis species	South America	Pods & seeds	Firewood, gum, forage	(8)
***Prosopis juliflora* (Sw) DC)**	North and Central America	Pod & seed	Firewood	(8,10)
***Tamarindus indica* L.**	Tropical Africa & Asia	Pod pulp, flowers leaves & seed		(15)
***Tetrapleura tetraptera* (Schum & Thur.) Taub**	Western Africa	Fruit	Pharmaceutical (bark), vitamins	(3)

Opportunities and limitations to use leguminous trees for bioenergy

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Abstract: N-fixing tree species have many qualities that make them suitable bioenergy sources. There are no planting, irrigation, or fertilization costs for naturally-occurring trees, and harvesting from invasive stands would yield value-added agricultural and ecological benefits. Wood of many legume trees from semi-arid regions is low in moisture and has a high heating value that generates energy yields similar to dedicated energy crops. Growth form, physiological, and reproductive advantages support sustainability as bioenergy sources, including the ability to resprout after harvest and produce prolific amounts of seed. The biggest challenges to increase their utilization for bioenergy are harvest and transport constraints.

Keywords: bioenergy, bio-heating, legumes, N-fixing trees, resprout

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Introduction

Globally, governments are increasingly looking at the potential of various crops to produce bioenergy and ameliorate the effects of climate change (1). Criteria set for species to be ideal bioenergy crops include 1) high dry matter yield per land area, 2) low energy inputs for production, 3) minimum cost requirements for cultivation and harvest, 4) composition containing minimum contaminants, and 5) minimum external nutrient requirements. Drought and pest resistance are important characteristics as well (1). Many nitrogen-fixing, leguminous tree species meet most of these requirements. The two genera of naturally-growing leguminous trees most commonly assessed for bioenergy potential are *Acacia* and *Prosopis* (family Fabaceae, sub-family Mimosoideae) (2,3). Other N-fixing woody genera that have been considered for bioenergy purposes include *Leucaena*, *Senna*, and *Robinia* (3,4).

Suitability of legume trees as bioenergy sources

Although biomass production rates of legume trees may not be as high as some dedicated energy crops, there are several advantages of using them for bioenergy feedstocks. First, many legume tree species that are suitable for bioenergy grow on land that is not suited to growing food or fiber crops, and thus will not impact agricultural food markets like maize grain ethanol has done (5). Second, there are no cultivation, irrigation, or fertilization costs for naturally-occurring leguminous trees (6). Third, in the warm, dry climates where N-fixing trees typically grow, trees could be harvested nearly year-round which would reduce feedstock storage costs. Fourth, wood of many legume trees has a high heating value that will generate similar energy yields per ton to dedicated energy crops (6). Fifth, wood from N-fixing trees growing in semi-arid regions often has a much lower moisture content at harvest than wood from other SWRC system species (4). Thus, drying costs would be minimal. Sixth, harvesting invasive N-fixing species and similar brush species would yield value-added agricultural and ecological benefits, including increased herbaceous production for livestock forage, wildlife habitat quality, biodiversity, and lower soil erosion due to greater herbaceous cover (6) and reduce costs of government programs designed to contain invasive woody plants (7).

Sustainability of legume trees as bioenergy sources

Legume trees have growth form, physiological, and reproductive advantages that support their sustainability as bioenergy sources. Many N-fixing tree species have dimorphic root systems; lateral roots are used to capture shallow soil moisture, while the tap root accesses water deep within the soil profile (8). Many woody legumes reduce water loss through reduced transpiration or whole-plant leaf area and increase the ability of roots to absorb soil water through reductions in tissue water potential and accumulation of osmotic substances.

Many N-fixing tree species vigorously sprout from dormant basal meristem after above-ground portions of the plant are damaged or destroyed (Figure 1) (2). Ansley *et al.* (2) found that total aboveground biomass of 14-year-old honey mesquite regrowth was equal to that of 33-year-old undisturbed trees of the same height (Figure 2).

These species produce prolific amounts of long-lived seeds, although total quantities depend on annual environmental conditions. The seeds are highly sought out by livestock and wildlife (primarily due to pod sugar content) which facilitates introduction of seeds to new areas through defecation (9).

Figure 1. View of 32-year-old single-stemmed undisturbed mesquite, 3.8 m tall (top), and multi-stemmed 14-year-old regrowth mesquite, 4.6 m tall (bottom) (Adapted from (2). Copyright 2019 by John Wiley and Sons. Reprinted with permission).

Limitations to legume trees as bioenergy sources

Because many of these species have become invasive when introduced to new regions, care must be taken when establishing new plantations for bioenergy purposes. Harvesting biomass from already-existing natural stands may be the best option, but it has its own logistical challenges. Because naturalized stands typically occur in remote locations, transportation costs of hauling feedstock from source to refinery must be minimized. It may be necessary to develop smaller-scale, conversion facilities located near feedstock sources to reduce transport costs (Figure 3) (6). Since production rates may be lower than other SRWCs, management approaches for using N-fixing trees for biomass may need to encompass more land area to allow for longer regrowth intervals when compared to more traditional SRWC systems (6).

Specialized equipment commercially available for harvesting trees and shrubs in natural stands do not currently exist, though designs have been attempted in the past (2). Naturally-occurring woody legumes are clustered in variable densities, and harvesting must occur in a much more scattered pattern than would be found in planted orchards. Thus, harvesting equipment must be multi-directionally mobile. Moreover, there is a need for development of machinery that can easily harvest multi-stemmed regrowth as current technology designed for quick harvesting of single stemmed trees such as pines cannot be applied to natural woody legume systems. Wood of N-fixing trees is typically harder (more heartwood) than other woody bioenergy species and not symmetrical, which also plays a role in applicability of harvesting equipment. Tree harvest may disturb understory vegetation, but this is temporary. For mesquite, increased grass growth is observed for about

8-10 years after harvest before mesquite regrowth suppresses grass growth. At that time a second harvest is recommended.

In developed countries, transport and socio-economic challenges may arise when attempting to collect wood from multiple geographically dispersed, isolated properties with different landowners. A supply area for an individual bioenergy plant would likely be comprised of multiple landowners that would agree in long-term leases to allow tree harvest and regrowth to occur for future harvest (Figure 3). This has important consequences, especially if a regional goal among landowners is to enhance wildlife habitat for recreational income via hunting or ecotourism. Bioenergy cooperatives may need to be developed to coordinate individual landowner and regional objectives.

In developing countries, 1.5 billion people derive over 90% of their energy requirements from wood and charcoal. Although wild harvesting of woody biomass for fuelwood provides most of the energy needs, it remains an underutilized resource. Most domestic fuelwood is harvested from indigenous or naturalized stands (10). Village commons and wastelands are especially important areas to gather domestic fuel wood and graze livestock. Community-focused bioenergy-production programs can assist with coordination and prioritization of land use for multiple purposes. However, if development of private, large-scale plants is prioritized over smaller decentralized community power plants, local communities may have little control over resource appropriation.

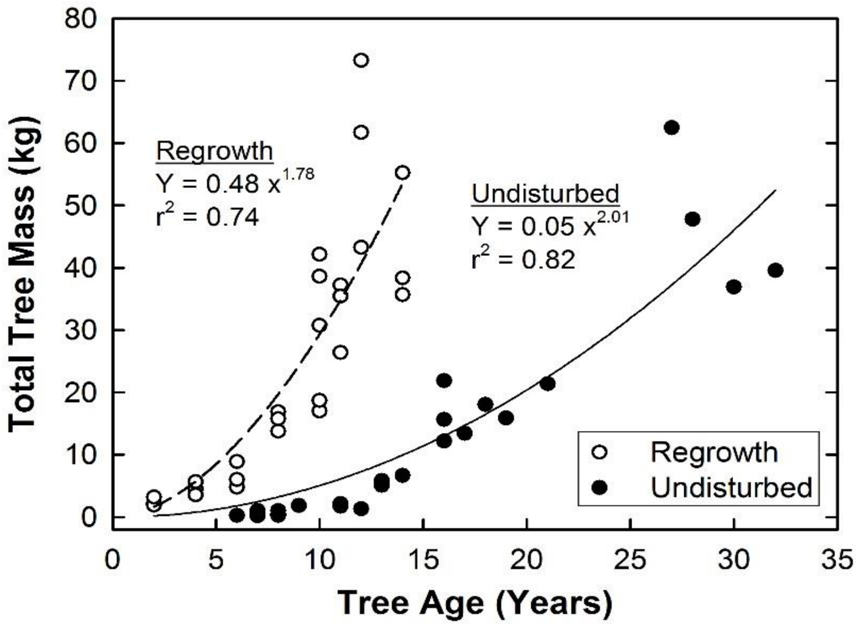

Figure 2. Total tree mass in regrowth and undisturbed mesquite trees (Adapted from (2). Copyright 2019 by John Wiley and Sons. Reprinted with permission).

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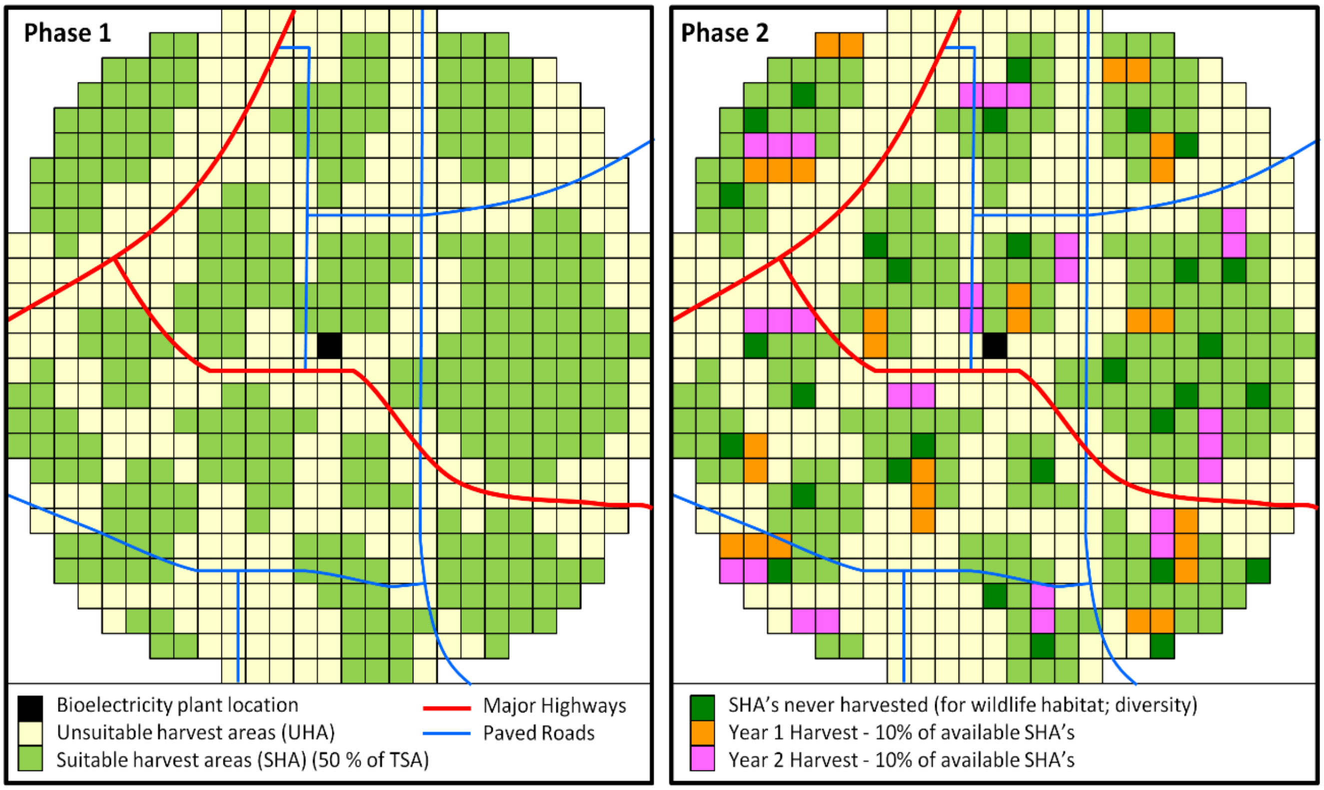

Figure 3. Phase 1 and 2 of a landscape harvest scenario for a mesquite bioenergy feedstock supply system with a central location for the bioelectricity plant. The left panel (Phase 1) illustrates the total system area (TSA) needed to supply the bioelectricity plant, based on a 10-year re-harvest cycle (the illustration assumes that the TSA is sufficient to supply the bioelectricity plant) and divided into equal sized cells. Cells with woody biomass densities suitable for harvest (suitable harvest areas; SHA's) are in green. Unsuitable harvest areas (UHA) are tan. Phase 2 (right panel) shows the development of the annual harvest plan where 10% of the SHA's are set aside initially for wildlife habitat considerations and are never harvested (dark green cells). Of the remaining SHA's, 10% are harvested each year, assuming a 10-yr re-harvest schedule. The harvest plans for the first two years are shown in orange and pink. Harvesting is distributed throughout the TSA in order to stabilize feedstock transport costs from year to year (Adapted from (6). Copyright 2019 by Springer Nature. Reprinted with permission).

Biodiversity and genetic resources of forage legumes in Brazil

M.A. Carvalho[1], A.K.B. Ramos[1], C. T. Karia[1], F. D. Fernandes[1], G.J. Braga[1]

Abstract: The use of forage legumes in tropical areas, besides the biological fixation capacity of atmospheric nitrogen, contributes to improve the nutritive value of animal diets. Despite its importance in various production systems, the adoption of new tropical legume germplasm has been inexpressive in several Latin American countries, even when germplasm lines and improved cultivars are available, as the case of Brazil, where more than 2500 germplasm accessions were tested and 50 cultivars are registered for commercialization. Regarding the tree legumes, much of the work that was developed was concentrated in only four genera: *Cratylia*, *Leucaena*, *Gliricidia* and *Sesbania*, which resulted in 10 cultivars releases. However, the level of adoption of these cultivars is very low.

Biodiversity can be defined as the total variability found within all living organisms and their habitats. It can be accessed at three different levels: communities (environment), species, and genes. When accessing biodiversity at the species level, we are interested in observing differences among individuals or populations of that particular species.

Since very early in the history of the world, humans have exploited the genetic diversity of plants, primarily as sources of food, and then to improve their landraces and cultivars. With the advance of modern agriculture, plant breeders around the world began to collect genetic diversity of the most important food crops and to store these materials at national research institutes and local institutions. Because of these efforts, FAO estimated that 6.2 million accessions of 80 different crop species were stored in 1,320 genebanks and related facilities in 131 countries (1).

Studies of genetic diversity are important because they are a tool for genetic improvement allowing the efficient use of the available germplasm of a species. Germplasm characterization consists of studies of eco-geographic and demographic adaptation, and involves mostly the parameters of the vital cycle of the organism, genetic and physiological studies, plant pathology, and yield evaluation, among other studies. Breeding programs should begin only after appropriate germplasm characterization (2).

In summary, characterization is the best way to understand the variability contained in a germplasm collection and to increase the use of the germplasm by plant breeders. It is also important in monitoring the genetic stability of the germplasm storage processes. Characterization of germplasm can be based on molecular, biochemical, morphological, and agronomic features.

Despite the importance of the forage legumes in various production systems, the adoption of new tropical legume germplasm has been inexpressive in several Latin American countries (3). However, according to Kretschmer (4), there are about 18,000 species of forage legumes and at least 1000 to 2000 species with potential for cultivation.

The use of legumes in tropical areas, besides the biological fixation capacity of

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atmospheric nitrogen, contributes to improve nutritive value of the animal diet. In general, its use is more widespread in temperate regions.

Spain (5) pointed out some barriers to the adoption of forage legumes, including the lack of adapted germplasm, insufficient knowledge on grazing management, and lack of credibility among specialists (extensionists, researchers and professors) and users (cattle ranchers and entrepreneurs in the field of seed production and marketing), mainly due to failures in the recent past.

Paradoxically, the reduced use of forage legumes in the Brazilian production system does not reflect the great genetic variability available and evaluated in national research institutions. Thousands of introductions have been tested in the last 30 years.

At Embrapa Cerrados, in Planaltina, DF, more than two thousand accessions of legumes with forage potential were introduced and evaluated. In Table 1 there is information about the number of available accessions and level of characterization of the germplasm stored at the Embrapa Cerrados Genebank. Most of the germplasm was agronomically characterized, focusing on herbage accumulation, pests and disease occurrence and general adaptation to the edaphoclimatic conditions to the Cerrado region.

Tree legume available germplasm is much more restricted than the herbaceous legumes species. For this reason, much of the work that was developed in Brazil concentrated on only four genera: *Cratylia*, *Leucaena*, *Gliricidia* and *Sesbania*.

Cratylia argentea is a leguminous species that occurs in the Cerrados and semi-arid regions of Brazil. It grows as a small shrub, ranging from 1.5 to 3 meter, presenting numerous branches emerging from the base of the plant with persistent leaves during periods of drought.

In research conducted in Minas Gerais State in areas of the Atlantic forest, the dry matter yield of the *Cratylia argentea* cultivar Ceci, with 10 months of age was 4.90 Mg/ha. After this first cut, with 3 and 6 months, this legume produced 4 Mg/ha and 14.9 Mg/ha of dry matter, respectively. It is important to note that the later occurred during the dry season when the growth of tropical forages cease, thus confirming its drought tolerance. Crude protein values were high, ranging from 25 to 28%. The estimated value for DM digestibility was 56.7% (6).

Pizarro *et al.* (7), working with 88 accessions from a collection of 10 genera of shrub legumes in the Cerrado, observed annual dry matter yields ranging from 500 to 2500 Mg/ha. The results obtained during 5 years concluded that the genera *Cratylia, Gliricidia* and *Mimosa* are the most promising.

The genus *Leucaena* is pointed as one of the most important tropical forage legumes being evaluated and tested in Australia, Asia, Central and North America. In Brazil, nine cultivars of *L. leucocephala* were registered for commercialization. Most of them are cultivars selected in Australia, USA and other countries, including cultivars Cunningham, Peru, El Salvador, Gigante, K4, K8, K29, K67 and K132. Although some of them are adapted, they are not used widely.

In Brazil, a breeding program implemented by CIAT and Embrapa focused on cultivars with tolerance to acid soils and quick establishment. To achieve this goal, the strategy implemented was based in the use of the interbreeding among the *Leucaena* species: *L. leucocephala* crossed with *L. esculenta*, *L. shannoni*, *L. pallida* and *L.*

Table 1. Information about the number of available accessions and characterization from germplasm stored at the Embrapa Cerrados Genebank.

Genus	# Accessions	Characterization		
		Morphological	Molecular	Agronomical
Bauhinia	20			20
Cajanus	19			19
Calliandra	12			12
Cratylia spp.	59	47	3	59
Flemingia	15			15
Gliricidia	1			1
Leucaena	123			123
Sesbania	44			44
Herbaceous legumes	2519	615	45	1965
TOTAL	**2812**	**662**	**48**	**2258**

Figure 1. *Cratylia argentea* plants

Figure 2. ***Cratylia argentea*** **plants**

Figure 3. ***Cratylia argentea*** **plants**

diversifolia. After several years of work, about 90 bulks and families were selected that showed good growth in acid soils with low Ca. A selection line of the crossing between *L. leucocephala* and *L. diversifolia* is in the final evaluation process for registration and protection.

Although there are thousands of forage legume germplasm accessions available, as January 2019, there were only 53 cultivars registered at the Ministry of Agriculture, Livestock and Supply (MAPA), for commercialization and use for the Brazilian producers. These cultivars belong to the genera *Arachis* (7), *Cajanus* (14), *Calopogonium* (3), *Centrosema* (5), *Cratylia* (1), *Leucaena* (9), *Macroptilium* (1), *Macrotyloma* (1), *Neonotonia* (5), *Pueraria* (1) and *Stylosanthes* (6). Of these 53 cultivars, seeds of only 10 to 15 are currently produced and traded - mostly for use as green manure.

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Figure 4. *Cratylia argentea* plants

Figure 5. *Gliricidia sepium* plants

Figure 6. ***Gliricia sepium*** **plants**

Arboreal legumes with potential for Texas silvopastoral systems

John E. Montoya, Jr.[1]*, Michael H. Eichman[1], Addison L. Singleton[1]

Abstract: Silvopasture is a form of multi-crop agriculture specifically designed to incorporate the production of trees, forage, and livestock within a single agricultural system. Legumes, specifically arboreal legumes, have a high level of potential for use within silvopastural systems. There is a need to further investigate the advantages and disadvantages of various arboreal legumes present in Texas for silvopastural use. Arboreal legumes in genera *Acacia, Cercis, Gledistia, Leucaena, Parkinsonia, Prosopis, Robinia, Sophora,* and *Styphnolobium* present in Texas are discussed for potential in silvopastural systems.

Introduction

Silvopasture is a form of multi-crop agriculture designed to incorporate the production of trees, forage, and livestock within the same agricultural system (1). Silvopastural systems often focus on using arbor to improve a forage crop, or using forages to improve an arboreal crop. Livestock generally are a key component in the system, providing short-term economic flow between harvests of the primary crop (1). Evaluation of arboreal legumes present in Texas for silvopastoral systems have not been examined, however several arboreal legumes are present in Texas that should be considered for further investigation.

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Arboreal legumes of Texas

Acacia farnesiana (L.) Willd. is a small to medium size tree to shrub generally growing 5 to 6 m tall with a multi-stemmed growth habit (2). *A. farnesiana* leaves improve soil organic matter and soil nitrogen content in arid and semi-arid ecosystems in Mexico (3). Leaves of *A. farnesiana* have also been investigated in Mexico as an economical supplementary feed for sheep and goats as the utilization of nitrogen and dry matter intake were comparable to the standard alfalfa hay diet (4). *A. farnesiana* has an aggressive growth habit, combined with sizable thorns, resulting in a negative perception by land-owners of the southern United States of America (2). However, this aggressive growth pattern could prove to be beneficial in a properly designed silvopasture system.

Cercis canadensis (Dickson), is a small deciduous tree, with heights ranging from 5 to 9 m (2). Its bark has been used for medicinal purposes, while the flowers, fruits, and seeds are frequently consumed by wildlife. Due to its tolerance of shading and low-input requirements, *C. canadensis* is recommended for use in the timber industry as a trainer tree inter-planted with timber species to cause side limb shading, thereby causing the timber tree to grow vertically and straighter (5). *C. canadensis* leaves (Figure 1) have high levels of protein precipitable phenolics (PPP) when compared to other leguminous shrubs of Texas, which could be utilized in a silvopastoral system; however, leaves contain lower amounts of nitrogen when compared to other arboreal legumes of Texas (6).

Gledistia triacanthos (L.) is a medium- to large-sized deciduous tree that typically reaches heights of 9 to 15 m, but can reach 30 m in optimal conditions (2). *G. triacanthos* is very resistant to saline soils and has high quality wood (2), making it a good candidate for silvopasture. However, with very large thorns (Figure 2), easily reaching 10 cm on its leaves and trunk (Figure 2), *G. triacanthos* may prove difficult to manage in a silvopasture system. However, a naturally occurring thornless variety exists, *G. triacanthos* var. *inermis* and should be investigated for use in a silvopastoral system although regionally adapted selections are needed (2). Although *G. triacanthos* contains high levels of nitrogen in its leaves when compared to other arboreal legumes of Texas (6), it does not have the ability to fix atmospheric nitrogen.

Leucaena retusa (Benth.), is a fast-growing tree, reaching heights of 5 to 8 m (2), typically reaching 4 m in height from seed in 150 days. The *Leucaena* genus is known for its usefulness as a forage and in silvopasture systems; however, *L. retusa* needs more investigation. Preliminary investigation has shown that *L. retusa* leaves (Figure 3) contain the highest amount of nitrogen when compared with other prominent arboreal legumes of Texas (6). In silvopastoral systems that implement forage plants susceptible to cotton root rot, such as alfalfa, *L. retusa* may be assistive in preventing pathological damage to these forage plants, as it has a natural resistance to cotton root rot (2).

Parkinsonia aculeata (L.), is a 5 to 6 m tall deciduous tree widely used as an ornamental tree, in addition to providing wind breaks, firewood, and fencing (2). The seeds and seed pods of *P. aculeata* are edible, with the potential for human and livestock consumption, as most anti-nutritional factors are eliminated by heat treatment (7). *P. aculeata* is an alternative protein crop in India due to its high nutritional content (7). These traits make *P. aculeata* a promising candidate for silvopastoral investigation.

Prosopis glandulosa (Torr.) is a medium-sized tree, typically reaching heights of 6 to 9 m (2). It has historically been consumed by humans and still holds the potential for human consumption in addition to the numerous uses for its wood (2). *P. glandulosa* has been investigated in Oregon for use in silvopastoral systems; however, due to transplant difficulties, a detailed investigation is still needed (8). *P. glandulosa* is often not highly favored by ranchers due to its large thorns and resistance to eradication; however, thornless varieties exist and should be investigated as an alternative to the armed variety in silvopasture systems.

Figure 1. *Cercis canadensis* (Dickson) leaves have high levels of PPP.

Robinia pseudocacia (L.) is an arboreal legume that can reach heights of up to 30 m but typically is a medium to large tree reaching 12 to 15 m tall (2). It is versatile and can be used for a multitude of agroeconomic products, ranging from fence posts to honey production from its flowers and increases phosphorus in surrounding areas (9). Species in the genus *Robinia* are among the most commonly planted trees worldwide, as they are fast growing, drought and heat tolerant, site adaptable, fix nitrogen, and have desirable ornamental qualities. *R. pseudocacia* has been investigated in a silvopastoral system in West Virginia where it was found that forages under its canopy experienced less variation in photosynthetically active radiation and temperature, resulting in a reduction of metabolic input to adapt (9). Leaf nutritive value had greater crude protein digestibility levels, resulting in a recommendation for *R. pseudocacia* over *G. triacanthos* for livestock browse (10).

Styphnolobium affine (*Sophora affinis*) (Torrey & Gray) is a small- to medium-sized deciduous tree that typically ranges in height from 5 to 8 m tall (2). It has drought tolerant properties, does well in full to partial sun, and fixes nitrogen. Further investigation of *S. affine* within silvopastoral systems is recommended since its leaves contain desirable nutritive qualities (6).

Sophora secundiflora (Ortega) is a small, 2.5 to 4 m tall, evergreen shrub or tree (2). Wide-spread contemporary use is limited to the ornamental trade, and widely reported to be poisonous when consumed by livestock, and therefore is not recommended for further investigation for use in silvopastoral systems.

Figure 2. ***Gledistia triacanthos*** **(L.) tree bark is armed with substantial thorns.**

Future considerations

Texas contains several arboreal legumes (Table 1), many of which are suited for silvopastoral systems and should be investigated further. Several species, such as *G. triacanthos*, *P. glandulosa*, and *A. farnesiana* have been negatively viewed by ranchers of Texas for generations, therefore an education campaign is suggested in conjunction with the recommendation of any of these species for silvopastoral systems. Of the arboreal legumes discussed, *L. retusa* contains the most desirable traits for silvopasture; however, all legumes with the exception of *S. secundiflora* are recommended for further investigation.

Figure 3. ***Leucaena retusa*** **(Benth.) leaves contain higher amounts of nitrogen than** ***S. affine*****,** ***G. triacanthos*****, and** ***C. canadensis*****.**

Table 1. Arboreal legumes of Texas

Latin Binomial	Uses	Usable Parts	Reference
Acacia farnesiana	Ethnobotany, Ornamental, Wind break, Hardwood Production	Timber, Tree gum, Bark pulp	(2, 3, 4)
Cercis canadensis	Ethnobotany, Ornamental, Browsing, Hardwood Production, Honey production	Timber, Edible leaves and seed pods	(2, 5, 6)
Gleditsia triacanthos	Ethnobotany, Hardy ornamental, Hardwood Production, Pioneer species	Timber, Blooms attract pollinators, Edible seed pods	(2, 6)
Leucaena retusa	Browsing, Ornamental	Edible leaves and seed pods	(2, 6)
Parkinsonia aculeata	Ornamental, Wind break, Hardwood Production	Timber, Edible seed pods	(2, 7)
Prosopis glandulosa	Ethnobotany, Hardwood Production	Timber, Edible leaves and seed pods	(2, 8)
Robinia pseudocacia	Landscaping, Soil protectant, Ornamental, Hardwood Production	Timber	(2, 8, 9, 10, 11)
Sophora secundaflora	Ornamental, pollinator attractor	Blooms attract pollinators	(2)
Styphnolobium affine (Sophora affinis)	Pollinator attractor	Blooms attract pollinators	(2, 6)

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Pasture nutrient cycling under leguminous trees

Suellen B. M. Costa[1], Barbara C. Bellows[2] and Valéria X. O. Apolinário[3]

Abstract: Nutrient movement within grazing ecosystems with leguminous trees is driven by complex soil-plant-animal-atmosphere nutrient cycles. Nutrient uptake is influenced by symbiotic microbial processes of nitrogen fixation and mycorrhizae-enhanced phosphorus and water uptake, recovery of leached nutrients by deep root systems, and the application of exogenous nutrients from fertilizers and manure. Nutrient uptake influences leaf nitrogen concentration and lignin + polyphenol:N ratio; factors that affect leaf decomposition rate and leaf digestibility by foraging ruminants. The inclusion of arboreal legumes in pastures also enhances carbon sequestration, both within tree biomass and in soil aggregates and other soil microbial structures.

Keywords: tree legumes, nutrient cycling, decomposition, carbon sequestration

Nutrient (N, P, K, etc.) movement within pasture and rangeland ecosystems with leguminous trees is driven by a complex soil-plant-animal-atmosphere nutrient cycle. While leguminous systems are characterized by biological N fixation (BNF), nutrient cycles in pasture systems with tree legumes are also affected by exogenous fertilizer applications, animal feed supplements, leaf chemistry, animal feeding habits, manure chemistry, organic matter decomposition rates, nutrient and water percolation, nutrient and water uptake by deep root systems, mycorrhizal activity, nutrient immobilization, vitalization, and animal product export (1).

Under moist tropical conditions, soil organic matter turns over rapidly and is highly affected by plant type, land management practices, and animal excreta. Introducing arboreal legumes sabiá (*Mimosa caesalpiniifolia*) and gliricídia (*Gliricidia sepium*) in a degraded *Brachiaria decumbens* pasture in northeastern Brazil increased soil N content and reduced C:N ratios (2). Litter C:N under the legume trees was 50% less compared to adjacent grass monocultures. In a follow-up litter bag decomposition study involving the same tree legumes, higher contribution from BFN and leaf N concentration resulted in more rapid decomposition and N mineralization from gliricídia compared to sabiá (3).

In addition to BNF, tree legumes deep root systems facilitate recycling leached potassium and nitrate. Enhanced P uptake due to mycorrhizal inoculation of *Erythrina berteroana* Urban in Costa Rica (4) resulted in increased biomass production and leaf N concentration. Using leaves from seven leguminous tree species (5) demonstrated that decomposition and N mineralization was negatively correlated with lignin + polyphenol:N ratio. By providing fertilizer to manipulate N uptake by *Calliandra calothyrsus* and *Gliricidia sepium*, leaf N concentration increased, leaf polyphenol:N ratio decreased, and leaf decomposition rate increased for both species (6).

Seasonal moisture conditions can also increase leaf N content. *Mimosa caesalpiniaefolia* leaves exhibited 7% higher N content during the wet season compared to the dry season (7). In contrast, leaves from *Acacia* spp. with high concentrations of polyphenols immobilized both soil N and P. However, when these leaves were fed to goats, the resultant manure exhibited higher P contents and mineralization rates than the leaf residues (8).

Arboreal legume leaf chemistry also affects digestibility by foraging livestock. High concentrations of condensed tannin and phenolics in *Calliandra calothyrsus* limited in-vitro digestibility while high crude protein and P content and low condensed tannins resulted in high in-vitro digestibility for *Gliricidia sepium* leaves (9). During the dry season, the relatively high protein concentration of tree legumes leaves can

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enhance forage digestibility and animal growth by compensating for the relatively low protein of grasses (10).

Grazing ruminants can concentrate or distribute nutrients across pastures through their browsing habits and feces dispersion. Ruminant fecal and urine excretion can contribute significant nutrient returns to the soil system. Examining the effect of stubble heights following cattle grazing in a *Pennisetum purpureum* pasture measured 506 g N ha^{-1} d^{-1}, 53% from feces and 47% from urine, equating to 185 kg N ha^{-1} yr^{-1} (11). Shade provided by tree legumes can reduce understory forage yield and nutritive value while enhancing accumulation of manure nutrients from animals congregating and lounging under the trees (12).

While early studies on nutrient cycling in grazing systems focused primarily on decomposition rates and nutrient availability either for plant uptake or in digestible forages, current studies increasingly examine the importance of processes that sequester C to both enhance soil health and mitigate against global climate change. Arboreal legumes can sequester C both directly in their aboveground and belowground biomass as well as indirectly through mycorrhizal-facilitated soil aggregate formation and other microbially-facilitated processes. Estimates of C stored in agroforestry systems range from 0.29 to 15.21 Mg ha^{-1} yr^{-1} in aboveground biomass and 30 to 300 M C ha^{-1} in the top 1 m of soil (13).

Carbon can be sequestered within the soil system through the formation of soil aggregates, biochemical recalcitrance of plant material to decomposition due to the presence of aromatic polymers, and organo-mineral stabilization or the conversion and binding of soil organic matter with minerals to form complexes (13). Tree legume root systems can directly sequester C as well as enhance nutrient uptake and aboveground biomass formation. In addition, soil climate and chemical modification through shading and leaf fall can modify soil microbial communities under tree legumes, resulting in increased C sequestration (14).

In summary, understanding tree legume nutrient uptake, leaf chemistry, and leaf decomposition processes in conjunction with grazing animal nutritional needs and feeding behavior allows for the effective management of grazing systems with tree legumes to provide both high feed quality and C sequestration and increased N cycling (Figure 1).

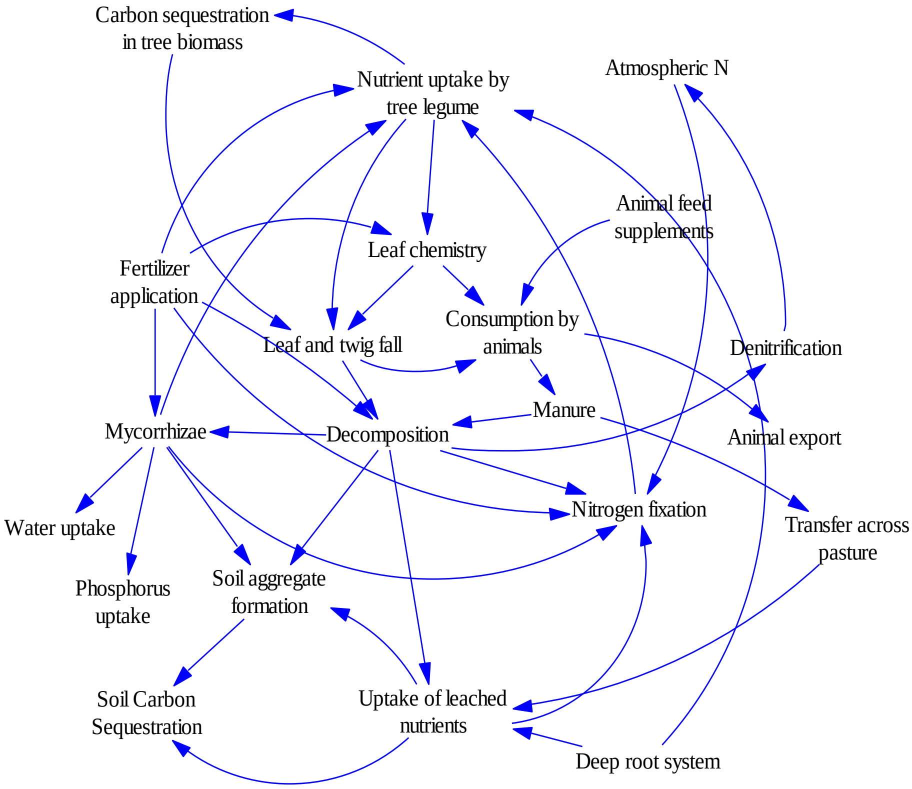

Figure 1. A diagram of potential nutrient cycling interactions within a grazing system with leguminous trees.

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