Silvopasture for Food Security in a Changing Climate

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Abbreviations

ADF	Acid detergent fiber
ADG	Average daily gain
AU	Animal units
C	Carbon
CAFO	Concentrated agricultural feeding operation
CP	Crude protein
DM	Dry matter
ISPS	Intensive silvopastoral systems
LWG	Live weight gain
N	Nitrogen
NDF	Neutral detergent fiber
P	Phosphorus
PAR	Photosynthetically active radiation
PES	Payment for environmental services
THI	Temperature humidity index
TNC	Total nonstructural carbohydrates

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Introduction

The Food-Climate Crisis

Agroforestry is often praised for the many environmental benefits it provides, such as carbon sequestration, reduction of toxic runoff into waterways, and wildlife enhancement (Udawatta et al. 2011; Udawatta and Jose 2012; McDermott and Rodewald 2014). However, there remains an important and often overlooked value of the ecosystem services provided by agroforestry: food security. In a time when monocultures and chemical inputs of conventional agriculture prevail, there is growing concern about the future of food production, particularly in regard to soil loss and degradation, indiscriminate use of agrochemicals, and environmental and ethical challenges of industrial animal agriculture. Globally, the human population is exploding and is expected to reach 9.1 billion by 2050, urbanization is increasing, and incomes are rising. This has resulted in a rapidly growing demand for animal products and continued natural resource degradation, all of which have profound effects on food security (Delgado et al. 1999).

Although global grain production has more than doubled and global meat production has more than tripled over the last half-century (FAOSTAT 2010), food yield may need to increase by 50% or more in the next half-century to keep up with demands (Godfray et al. 2010). Projected demands for meat and milk production were expected to grow at respective rates of 2.8 and 3.2% annually up to 2020 (Delgado et al. 1999). All the while, food producers are experiencing greater competition for land, water, and energy.

Climate change is exacerbating consequences for animal production through its effects on forage productivity and heat-related stress on the animal. Under climate change scenarios, water will become the main limiting factor to all livestock systems (Steinfeld et al. 2006; de Fraiture et al. 2010) and extended droughts will become the norm. In the face of climate change, producing more food for a growing population while diminishing poverty and hunger is a daunting task, but a challenge that must be heeded. An even greater challenge is not only to increase productivity, but also to do so while treading more lightly on the land (Cribb 2010).

Sustainable Livestock Production

Many decades of research have demonstrated that livestock management is critical for maintaining healthy pastures and optimal productivity (Gerrish 2004; Rayburn 2007). In 1959, farmer and scientist André Voisin coined the term *rational grazing* (Voisin 1988), where he described the basic guidelines necessary for good grazing management: short periods of occupation followed by an ample recovery period. More recently, authors have built on these management guidelines with the introduction of terms such as *prescribed grazing* (USDA-NRCS 2010), *management* *intensive grazing* (Gerrish 2004), holistic planned grazing (HPG), and mob grazing (Savory and Butterfield 2016). All these terms apply to the same key grazing principles proposed by Voisin, ultimately favoring important pasture species, improving soil health, and increasing forage productivity and nutritional quality (Flack 2016).

These sustainable livestock production methods can be implemented in open pasture or alternatively under dispersed tree cover in a silvopastoral setting. Silvopasture is an agroforestry practice where trees and livestock are combined with improved pasture plants and managed intensively, effectively integrating intensive animal husbandry, silviculture, and forage agronomy practices (Sharrow et al. 2009; Jose and Dollinger 2019). The simultaneous production of timber and livestock can increase the diversity of on-farm products, improve land-use efficiency, and provide better welfare for animals (Murgueitio et al. 2011; Calle et al. 2012b; Broom et al. 2013). Despite numerous accounts of silvopasture's ability to strike an optimal balance between production and conservation (Ibrahim et al. 2010; Galindo et al. 2013; Jose et al. 2019), many producers remain skeptical, arguing that productivity is too greatly reduced under tree cover.

In this chapter, we review a number of studies from various regions of the world that highlight silvopasture's contribution to achieving food security. We focus on the production of forage, meat, and milk in silvopastoral systems as direct indicators of food supply as well as indirect indicators such as thermal stress in livestock, animal health, and habitat provisioning for pollinators. We conclude by addressing some of the problems of modern-day animal agriculture and how silvopasture could play a critical role in the sustainable intensification of livestock production systems.

Silvopasture: A Contribution to Food Security

Forage Production

It is well established that trees have both competitive (negative) and facilitative (positive) effects on the microenvironments beneath them (Jose et al. 2004; Jose et al. 2019). Canopy solar interception results in lower light transmittance, decreasing the photosynthetic rate of understory vegetation. Trees have been shown to compete vigorously for water and nutrients and can even emit allelopathic chemicals that impede the growth of surrounding vegetation. However, canopy interception can also provide protection from desiccating winds and reduce soil surface temperature and soil evapotranspiration (Belsky et al. 1989; Belesky 2005), which can increase overall soil moisture content (Vetaas 1992). Some trees can fix atmospheric nitrogen (N) and provide up to 650 kg N $yr.^{-1}$, more than enough to fulfill crop N needs for sustained yield (Nygren et al. 2012). Leaf litter under trees has been shown to improve the physical properties of the surface soil and increase chemical properties including soil nutrients and organic matter (Belsky 1994). As a result, the content of carbon (C), phosphorus (P), and N has been shown to gradually decline as a function from the distance of the trunk, resulting in significantly lower levels in the open ground than in sub-canopy soil (Belsky et al. 1989; Tiedemann and Klemmedson 2008).

Elevated nutrient levels can improve the forage quality of sub-canopy grasses, attracting grazers that return nutrients to the soil. This, combined with the trapping of wind and waterborne sediments by trees, can contribute to an "island of fertility" effect (Belsky et al. 1989; Dohn et al. 2013). Tree roots can also decrease the bulk density of the soil, creating the macroporosity favorable to the infiltration of water, increasing water-holding capacity (Malmer et al. 2010). Additionally, integrated perennial systems have better soil thermal properties that can help improve C storage and microenvironment (Adhikari et al. 2014). These benefits, combined with the selection of appropriate tree and forage species, can sometimes result in increased levels of productivity when compared with monocultures.

Tree canopy effects on the growth and nutritive value of understory forages depend on many factors, including forage type, local climate and topography, season, soil fertility and structure, and amount of photosynthetically active radiation (PAR). It is well known that shading has a more detrimental effect on warm-season (C4) grasses than it does on cool-season (C3) grasses (Kephart and Buxton 1993; Lin et al. 1998; Buergler et al. 2005; Pang et al. 2019a). This is because the physiology of C4 grasses allows for greater biomass accumulation per unit of PAR—or radiation-use efficiency—than does the physiology of C3 species. The amount of rainfall appears to be important in determining forage production under shade. In xeric environments where water is the limiting factor, growth and development of many herbaceous species are facilitated by tree canopies through the improvement in moisture regimes (Joffre and Rambal 1993), soil nutrients, and organic matter (Kellman 1979). Several studies have demonstrated that under certain conditions, moderate shading can provide the optimal environment for grass growth and quality (Belsky 1994; Ibrahim et al. 2007; DeBruyne et al. 2011; Orefice et al. 2016b). Hernández and Guenni (2008) concluded that guinea grass [*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.l. Jacobs] benefited from a compensatory effect from trees that increased soil humidity and improved total forage biomass. Andrade et al. (2004) found that guinea grass var. *Massai* growing under artificial shade reached its highest dry matter (DM) accumulation rate under 30% shade cover in both the rainy and dry seasons. Moustakas et al. (2013) demonstrated that tree effects on grass biomass across a precipitation gradient in a subtropical savanna were facilitative in drier sites, with greater grass biomass observed beneath tree canopies than outside.

Conversely, many studies in temperate environments with more rainfall have shown that canopy coverage either maintains (DeBruyne et al. 2011) or reduces the quantity of understory forage (Feldhake et al. 2010; Orefice et al. 2016b). In a study conducted in the Appalachian Mountains, USA, Neel and Belesky (2015) showed that hardwood silvopasture DM production was 60–70% that of open pasture in the spring and equal to only 40–60% of it in summer. Studying an alder (*Alnus spp.*) and willow (*Salix spp.*) silvopasture in New Zealand, Devkota et al. (2001) concluded

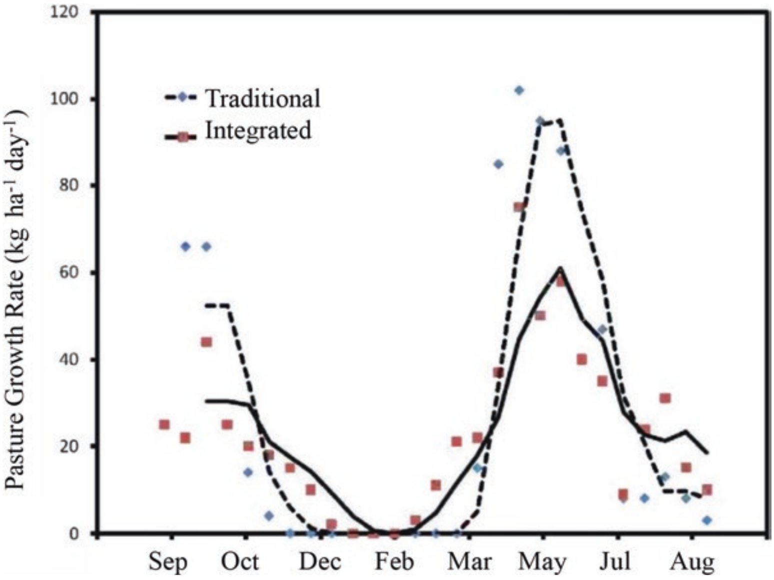

Fig. 1 Pasture growth rates in traditional (open) and integrated (25% of land area under silvopasture) pasture systems at the Horticulture and Agroforestry Research Center near New Franklin, Missouri, USA (source: Kallenbach 2009)

that a 40–50% canopy closure would maintain pasture production at approximately two-thirds of that in unshaded pasture.

However, research in both temperate and tropical environments has suggested that silvopasture may extend forage longevity and provide more forage than conventional pastures during certain times of the year. Kallenbach (2009) compared the growth of cool season grasses in traditional open pastures to that of integrated pastures where silvopasture was used on only 25% of the total land area. Forage growth on integrated pastures outperformed that of traditional pastures early in the spring, midsummer, and late fall, all times when cool season grasses likely benefit from more moderate microclimates in the understory (Fig. 1).

Similarly, a study examining the growth of guinea grass in the understory of native tree plantations in Panama found that forage DM accumulation early in the dry season was greatest under moderate tree coverage but was greater in open pasture throughout the rainy season (Dibala et al. 2021). In the driest month of February, pooled mean DM grass production was 38% greater under moderate canopy when compared to open pasture. These studies indicate that producers may achieve maximum gains by integrating silvopastures into larger open pasture operations and using them only during periods of relative scarcity.

Forage Nutritive Value

A plethora of research indicates that forage nutritive value may increase when grown under tree canopies (Lin et al. 1998, 2001; Buergler et al. 2006; Feldhake et al. 2010; Neel and Belesky 2017; Orefice et al. 2017). Specifically, increases in crude protein (CP) content are commonly observed. A shade tolerance screening trial in Missouri showed that all 22 tested forages (16 grasses and 6 legumes) had equal or higher percent CP and CP yield (g pot^{-1}) under moderate shade than in the control (Pang et al. 2019a, b). Percent CP of forages grown in dense shade was 4.5, 6.1, and 6.11% higher than that of forages grown in full sun for "benchmark" orchardgrass (*Dactylis glomerata* L.), smooth brome (*Bromus inermis* Leyss.), and timothy (*Phleum pretense* L.), respectively. In Veracruz, Mexico, Medinilla-Salinas et al. (2013) found that guinea grass growing under a 12-year-old canopy of [*Gliricidia sepium* (Jacq.) Kunth ex Walp.] trees contained 1.9% greater CP than those growing in the open during the windy season. This is likely due to adaptive mechanisms and changes in plant physiology such as elongation of the cell wall (Kephart and Buxton 1993) and increases in the specific leaf area and shoot:root ratio (Paciullo et al. 2017). The presence of N-fixing trees may also indirectly increase CP content in forages through leaf decomposition, root exudation, and direct nutrient exchange (Sierra and Nygren 2006; Sierra et al. 2007; Jalonen et al. 2009). Xavier et al. (2014) found that N recycled via the litter pathway in a silvopastoral system exceeded that in a monoculture by 34 kg ha^{-1}, concluding that the extra N recycled in the system—along with biological N fixation—would confer increases in quality and longevity of forage when compared to grass monocultures.

Typically, the structural carbohydrate metrics acid detergent fiber (ADF) and neutral detergent fiber (NDF) are either increased or unaffected by shade for most forage species (Ladyman et al. 2003; Kallenbach et al. 2006; Sousa et al. 2010; Paciullo and de Castro 2011; Neel and Belesky 2015). However, there are a number of studies that report decreasing values with increased levels of shade (Kephart and Buxton 1993; Obispo et al. 2008; Medinilla-Salinas et al. 2013), indicating lower levels of lignification and overall higher digestibility.

It is well known that the nutritive value of a plant changes throughout its growth stages of maturity, containing greater contents of total nonstructural carbohydrates (TNC) in the early stages of growth and developing larger quantities of lignin and cellulose later in the season (Ball et al. 2001; Pang et al. 2019b). This increase in lignification reduces digestibility and palatability of the plant, resulting in decreased animal intake. Thus, it is important for producers to manage livestock dynamically in response to temporal changes in both the quantity and quality of forages. Silvopasture has been shown to improve the quality of forage at specific times of the year when the quality of open-grown forages declines. Kallenbach et al. (2006) reported that the forage quality of an annual ryegrass (*Lolium perenne* L.) and cereal rye (*Secale cereale* L.) mixture growing in moderate shade frequently outperformed that of open pasture, particularly late in the summer grazing season when ambient temperatures were too high for cool-season grasses.

Tree Fodder Production and Nutritive Value

One way producers can respond to loss of forage productivity and quality is to rely on trees and shrubs to provide alternative and highly nutritious forage sources during critical periods. In the tropics, fodder shrubs can be a strategic resource for farmers during the worst drought periods that often occur during the dry season. For example, in the Yucatán Peninsula of Mexico, mixed stands of the fodder shrubs [*Leucaena leucocephala* (Lam.) de Wit.] and [*Guazuma ulmifolia* Lam.] have been shown to produce up to 5.18 Mg of edible DM ha^{-1}, with no statistical differences in yield between dry and wet seasons (Casanova-Lugo et al. 2015). This is a substantial contribution to forage availability, particularly during the dry season, when herbaceous forage yields may be reduced by 5–6 times relative to yields attained during the rainy season (Santiago-Hernández et al. 2016). Fodder shrubs like *Calliandra calothyrsus* Meisn., *G. ulmifolia* Lam., *L. leucocephala* (Lam.) de Wit., and *Tithonia diversifolia* (Hemsl.) A. Gray retain green foliage amidst even the harshest droughts. As the dry season progresses, forage shrubs have been shown to lose nutritive value, digestibility, and palatability at a slower rate than herbaceous forages (Talamuci and Pardini 1999), providing relatively high-quality supplemental forage to both ruminants and nonruminants during times of scarcity.

A widely touted silvopasture model that includes the use of native and non-native trees, shrubs, and herbaceous forages is known as intensive silvopasture (Fig. 2). Intensive silvopastoral systems (ISPS) include the planting of timber trees that are intercropped with high-density (~10,000 plants ha^{-1}) plantings of fodder shrubs and highly productive pasture grasses in a system that can be directly grazed by livestock (Murgueitio et al. 2011).

Shrubs are periodically coppiced to encourage low, dense growth of the foliage. Cattle are provided permanent supplies of drinking water and rotated periodically with the use of electric fences to prevent overgrazing and to allow time for pastures to recover. ISPS first began in Australia more than 40 years ago, but it is now becoming the technology of choice in Colombian and regional livestock sectors because they can help reduce the seasonality of production and therefore help to mitigate and adapt to climate change (Cardona et al. 2013).

There is compelling evidence that demonstrates how ISPS can increase overall forage production when compared to open pastures. An ISPS using the shrubs *L. leucocephala* and *G. sepium* combined with guinea grass in the humid tropics of West Africa produced over 20 Mg of DM ha^{-1} of mixed tree-grass fodder (Atta-Krah and Reynolds 1989). Bacab-Pérez and Solorio-Sánchez (2011) compared forage availability and voluntary intake on two ISPS ranches with a conventional ranch in Michoacán, Mexico, and found that the available forage in both ISPS ranches was at least 2.6 times greater than that in the conventional ranch (17,290 and 18,851 versus 6636 kg DM $yr.^{-1}$). Furthermore, only 9% of the available *L. leucocephala* forage was rejected by cattle on both ISPS farms (Table 1). Shelton and Dalzell (2007) reported that *L. leucocephala*-grass pastures are the most productive, profitable, and sustainable beef production systems in northern Australia.

Fig. 2 Intensive silvopastoral system (ISPS) in Colombia, South America, where it has been widely promoted and implemented (source: Zoraida Calle Diaz/CIPAV)

Table 1 Forage availability, refusal, and utilization efficiency (kg DM ha^{-1}) at three farms in Michoacán, Mexico (Bacab-Peréz and Solorio-Sánchez 2011)

Farm	*Forage*	Edible forage	Rejection	Use	Use (%)
Los Huarinches	*L. leucocephala*	8386	826	7560	91
	Guinea grass	8904	4655	4249	48
	Total	17,290	5481	11,809	68
El Aviador	*L. leucocephala*	9156	826	8330	91
	Guinea grass	9695	3542	6153	63
	Total	18,851	4368	14,483	77
Conventional	*Cynodon plectostachyus*	6636	2660	3976	60

The use of woody trees and shrubs for livestock fodder in temperate regions has been limited primarily due to a relatively limited plant selection and existing cultural and behavioral norms. Temperate regions lack the diversity of nutritious, N-fixing woody plants capable of coppicing that exists in the tropics. Trees of temperate regions produce palatable fodder during the growing season when highly preferred herbaceous forage is available, unless compromised by extreme weather. Cultural norms such as stockpiling and hay-baling are used instead of the cut-and-carry systems more commonplace in the tropics. However, researchers in temperate regions have explored the production and intake of densely planted forage shrubs and some species have shown particular promise (Papachristou and Papanastasis 1994; Papanastasis et al. 1998, 2008). In North Carolina, black locust (*Robinia pseudoacacia* L.) fodder banks were highly preferred by meat goats with a mean

DM yield of 3213 kg ha^{-1} when planted on a 50 cm spacing and coppiced at 50 cm (Addlestone et al. 1999). In New Zealand, full access to willow (*Salix* spp.) fodder banks was beneficial for ewe reproductive rates (Pitta et al. 2005). Other promising species for temperate ISPS include *Paulownia* (Mueller et al. 2001) and mulberry (*Morus* spp.) (Sánchez 2000). When planted with subterranean clover (*Trifolium subterraneum* L.) in a silvopasture in central Italy, white mulberry (*Morus alba* L.) produced between 4.2 and 5.3 Mg DM ha^{-1} (Talamuci and Pardini 1999). Armand and Meuret (1993) demonstrated that the Japanese white mulberry cultivar Kokuso 21 produced up to 2.2 Mg DM ha^{-1} on good sites in France, but on poorer sites production was much lower at 444 kg DM ha^{-1}.

Silvopastoral systems containing forage shrubs are effective at improving animal production because tree foliage is often of higher nutritional quality than grasses (Mueller et al. 2001). Sosa Rubio and others (2004) analyzed the nutritive value of 30 perennial woody species and found that 70% of them contained 12% or more CP. In the case of tropical legumes, even seeds are browsed, which provide nutrients in excess of that required for digestion and metabolism, potentially correcting nutritional deficiencies in mature roughage (Aganga and Tshwenyane 2003).

The overall nutritive value of woody perennial forage can often be hindered by the presence of anti-nutritional compounds that have the ability to severely restrict nutrient utilization (Papanastasis et al. 2008). Secondary compounds such as condensed tannins, alkaloids, saponins, and oxalates are known to occur in many woody perennials and can have detrimental effects to the animal if consumed in high quantities. However, diets containing herbaceous forage with a high level of digestible CP have been shown to counteract the negative effects of tannins (Yiakoulaki 1995). Furthermore, tannins in low to moderate concentrations (20–40 g kg^{-1} DM) can induce beneficial effects, which are associated with suppression of bloat in ruminants (Jones et al. 1973). Research has shown that feeding tannin- and saponin-containing compounds to cattle can increase intake of endophyte-infected tall fescue (*S. arundinacea* L.) and reduce its overall toxicity (Provenza et al. 2009). With the endophyte infecting a large percentage of the estimated 14 million ha of tall fescue in the United States (Ball et al. 2015), the incorporation of woody fodder to animal diets could help mitigate damages and have an enormous economic impact on the beef industry.

Tree Fruit Production

The more obvious food product of perennial trees and shrubs is fruit. In 1929, author J. Russell Smith exposed the masses to the agricultural wealth of trees in his seminal work *Tree Crops: A Permanent Agriculture*. In this masterpiece, Smith expounds on the overlooked abundance of food for both humans and animals produced by woody perennials. He describes the fruiting patterns and yields of common trees like oak (*Quercus* spp.), hickory and pecan (*Carya* spp.), walnut (*Juglans* spp.), chestnut (*Castanea* spp.), persimmon (*Diospyros* spp.), carob (*Ceratonia siliqua* L.), mulberry, and honey locust (*Gleditsia triacanthos* L.). Many anecdotes from producers are found throughout the book, with statements like:

"I never weighed my pigs at the beginning and close of the mulberry season, but I think I can safely say that a pig weighing 100 pounds at the start would weight 200 pounds at the close" and

"I let the cattle pick them (honeylocust pods) up where they can; and where they cannot graze, the beans are gathered and fed to them. My herd of heifers get a great part of their winter pasture from the honeylocust pods."

Since then, accounts like these have been corroborated with empirical evidence. Gold and Hanover (1993) noted that the edible seedpods from honey locust trees can serve as supplemental feed for livestock over several months in autumn and winter when cool-season grass production is limited or negligible. In Virginia, whole-ground honey locust seedpods from the "Millwood" cultivar had a nutritional profile comparable to that of ground whole-ear dent corn (*Zea mays* L.) or oat (*Avena sativa* L.) grain (Johnson et al. 2013). In that same study, mean DM yields of pod-bearing trees were 15.8, 4.8, and 14.7 kg tree^{-1} in 2008, 2009, and 2010, respectively. In good years, a honey locust crop can easily exceed 66 kg of cleaned seed per tree (Gold and Hanover 1993).

In the Mediterranean oak woodland known as the *dehesa*, Iberian pigs are raised extensively on acorns and grass during a 2-month fattening period that coincides with the fruiting period of surrounding holm oak (*Quercus ilex* Lam. spp. *ballota*) and cork oak (*Quercus suber* L.; Fig. 3). In the managed *dehesa*, where mean tree

Fig. 3 Iberian, acorn-finished pigs under the canopy of holm oak (*Quercus ilex* Lam. spp. *ballota*) in the Mediterranean *dehesa* (source: https://foodism.co.uk/features/long-reads/origins/cinco-jotas-iberico-pork/)

density ranges between 30 and 50 trees ha^{-1}, the productivity of acorns is reported to be ten times higher than a dense *Quercus ilex* forest (Pulido 1999; Pulido et al. 2001). Although extremely variable, mean acorn yield was estimated to be 300–700 kg ha^{-1}, with yields of 8–14 kg tree^{-1} for *Q. ilex* and 5–10 kg tree^{-1} for *Q. suber* (Rodríguez-Estévez et al. 2007). Individual pigs can consume 7–10 kg of acorns day^{-1}, and generally will increase their weight from 100 to 160 kg during the finishing period (Nieto et al. 2002). In Spain, conventional pork finishing operations have resulted in average daily gains (ADG) of 0.66 kg (Agostini et al. 2013), while acorn-finished operations have resulted in ADGs of 0.76 kg (Rodríguez-Estévez et al. 2011).

In Southeast Asia, the presence of livestock has been shown to increase yields of commercially important tree crops like coconut (*Cocos nucifera* L.), palm oil (*Elaeis guineensis* Jacq.), and rubber [*Hevea brasiliensis* (Willd. Ex A. Juss.) Mull. Arg.] (Alexandratos 1995). The establishment of mixed pastures under coconuts in Sri Lanka resulted in increases of 17% and 11% in nut and copra yields, respectively (Liyanage et al. 1993). Moreover, the nutrients from 73 kg of fresh manure and 30 L of urine palm^{-1} year^{-1} reduced the cost of fertilizing the coconuts by 69% (Devendra and Ibrahim 1999). Livestock can also help reduce the cost of weed maintenance, as is the case with Chee and Faiz (1991), who reported a reduction of 20–40% in weeding costs due to regular grazing by cattle.

Animal Performance

Several important measurements of silvopasture's sustainable contribution to food security are livestock ADG, conception rate, reproductive rate, and stocking rate (animal units (AU) ha^{-1}). An increase in any of these metrics can translate into income generation for ranchers. Historically, most studies on silvopastoral systems in temperate regions have demonstrated either decreased or equal animal performance when compared to open pastures (Teklehaimanot et al. 2002; Kallenbach et al. 2006, 2010; Sharrow et al. 2009; Neel and Belesky 2015). More recently, Pent and Fike (2018) compared ADGs of lambs in black walnut (*J. nigra*) and honey locust (*G. triacanthos*) silvopastures with open pasture of stockpiled tall fescue (*S. arundinaceus*) during the winter in Virginia. During the first three weeks of the trial, lambs did not consume honey locust pods due to naivety, but after the fourth week, consumption of pods was so high that lamb ADG was significantly greater than that in plots without honey locust. Future study is needed to determine whether honey locust supports even greater lamb weight gains when there has been previous exposure to pods and higher quality herbaceous forages are available (Pent and Fike 2018). In a study previously described evaluating integrated silvopastures—rotational stocking with a combination of open pasture and silvopasture—Kallenbach (2009) reported that cows in integrated silvopastures lost approximately 10% less weight over winter, reducing the need for supplementation by about 12%.

Table 2 Performance of cow-calf pairs in a traditional (open) pasture system compared to those in an integrated (a combination of open pasture and silvopasture) system (adapted from Kallenbach 2009)

Treatment	Winter weight loss (kg)	Calving difficulty (%)	Calf weaning weight (kg)
Traditional	*105*	15.00	270
Integrated	*93*	3.00	295
P-value	0.02	0.04	<0.01

Table 3 Average daily gain (ADG; g animal^{-1}) and gain per area (kg ha^{-1}), according to rearing systems and experimental year, in the rainy and dry seasons (source: Paciullo and de Castro 2011)

Experimental year	Rainy season		Dry season	
	Silvopasture	Monoculture	Silvopasture	Monoculture
ADG				
2004/2005	722Aa	624Ba	348ab	387a
2005/2006	647ab	563ab	298b	274b
2006/2007	628Ab	515Bb	420a	352ab
Gain per area				
2004/2005	298Aa	256Ba	88	97
2005/2006	242ab	230ab	75	68
2006/2007	258Ab	211Bb	105	89

Means followed by different letters, for each season of the year, capital in the row and lowercase in the column, are different at $p < 0.05$

Additionally, cows that gave birth in integrated silvopastures were 12% less likely to experience calving difficulty (Table 2).

More examples of silvopasture's positive influence on animal performance can be found from the tropics. A silvopastoral system in Brazil including signal grass [*Brachiaria decumbens* (Staph) R.D. Webster] and leguminous shrubs *G. sepium* and [*Mimosa caesalpiniifolia* Benth.] planted at a density of 2500 plants ha^{-1} yielded similar livestock production per unit land area compared with signal grass in monoculture (de M. Costa et al. 2016). Furthermore, additional income and ecosystem services provided by the woody components demonstrate the overall beneficial contributions of this system.

Paciullo and de Castro (2011) evaluated dairy heifer performance in Brazilian silvopastures planted in signal grass with four species of 105 dispersed mature trees ha^{-1} and drew comparisons with performance in similar signal grass open pasture. The authors concluded that a 13% increase in the CP content of signal grass in silvopasture compared with open pasture was sufficient to increase live weight gain of dairy heifers by 17% during the rainy season (Table 3). They posited that this increase in annual average gain could contribute to a reduction in the age at first conception and, consequently, of the first calving event.

A study at the Embrapa Dairy Cattle Center in Brazil concluded that Zebu-Friesian heifers grazing in a silvopasture planted in signal grass accompanied by *Acacia mangium* Willd., *Mimosa artemisiana* Heringer and Paula, and *Eucalyptus*

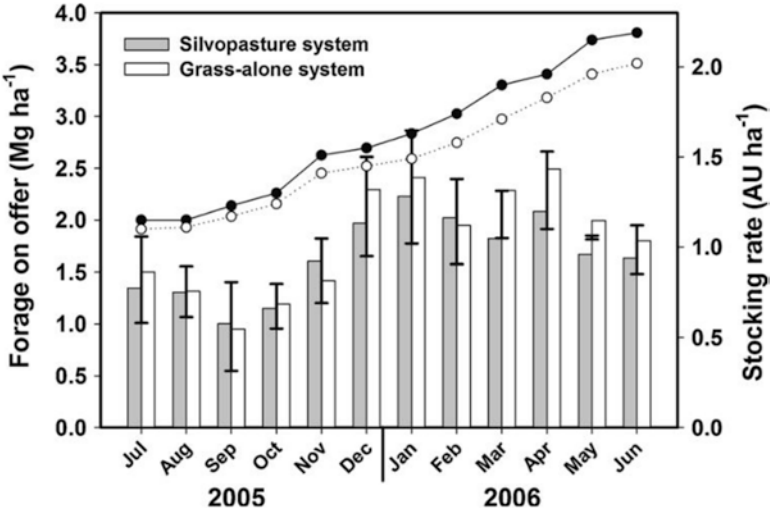

Fig. 4 Total dry matter yield of forage on offer (Mg ha^{-1}; bars) and stocking rate of heifers (AU ha^{-1}; lines) from July 2005 to June 2006 in the silvopasture system and the signal grass monoculture. Values are means of 20 replicate samples. Error bars represent least significant differences between means. One AU is equivalent to 450 kg of live weight (source: Xavier et al. 2014)

grandis Hill ex Maiden at a density of 198 trees ha^{-1} had significantly greater live weight gain (LWG) five years after system establishment than those grazing signal grass monocultures (Xavier et al. 2014). Silvopasture-raised cattle averaged annual LWGs of 205 kg head^{-1} while those in monocultures averaged 177 kg head^{-1} year^{-1}. This equates to a 16% increase in silvopasture-raised heifer annual LWG. The total annual animal intake was estimated to be 4.0 Mg ha^{-1} in the silvopasture compared to 3.5 Mg ha^{-1} in the signal grass monoculture. Forage DM annual mean in the monoculture was marginally greater than that in the silvopasture, but the authors could not determine whether this was due to shading or higher forage intake by heifers in the silvopasture (Fig. 4).

A study on sheep performance in Quintana Roo State, Mexico, analyzed five different feeding rations made up of various percentages of grasses and tree fodders and found that diets consisting of 75% or 100% tree fodder resulted in the greatest weight gains (Sosa Rubio et al. 2004). Similarly, sheep fed *G. sepium* (Chadhocar and Kantharaju 1980) and *Brosimum alicastrum* SW. leaves gained more weight than sheep grazing grass monocultures alone (Pérez et al. 1995). In Bali, Indonesia, the development of a shrub layer creates a three-strata forage system that has resulted in an increase in stocking rates by one animal ha^{-1} and an increase in LWG by 153 kg ha^{-1} year^{-1} (Devendra 2012).

Yamamoto et al. (2007) used data on herd, milk production, and land use from 74 farms in central Nicaragua to quantify the effects of silvopastoral systems on milk production. The data indicated that silvopastoral areas, especially pasturelands with moderate tree density (tree cover approximately 20%), have significant positive

Table 4 Production parameters of conventional and ISPS farming systems in Australia, Mexico, and Colombia (source: Cardona et al. 2013)

		Parameter			Reference
System	Country	Stocking rate (AU ha^{-1})	Live weight gain (g animal^{-1} day^{-1})	Meat production (kg ha^{-1} year^{-1})	
Conventional	Australia	1.5	411	225	Dalzell et al. (2006)
	Mexico	1 to 2.5	500	182,456	Solorio-Sanchez et al. (2011)
	Colombia	1.2	130	56.9	Cordoba et al. (2010)
ISPS	Australia	3	822	910	Dalzell et al. (2006)
	Mexico	6	900	1971	Solorio-Sanchez et al. (2011)
	Colombia	3.5 to 4.7	651–790	827–1341	Cordoba et al. (2010)
		3.5	793–863	1013–1103	Mahecha et al. (2011)

impacts on annual milk production when overgrazing was avoided. The authors suggested that changing land use from low-density trees with natural pasture to moderate-density trees with conventional pasture using palisade grass [*Brachiaria brizantha* (A.Rich.) Stapf] could result in greatest improvements in yield.

Research has shown that when installed and managed effectively, ISPS can increase carrying capacity by as much as fourfold per hectare (4.3 heads ha^{-1}), milk production by as much as 130% to 16,000 liters ha^{-1} year^{-1}, and meat production by as much as tenfold (Table 4). These gains, largely due to better distributions of biomass throughout the year, have been shown to increase farm income by at least $440 USD ha^{-1} year^{-1} while sustaining long-term system resiliency (Murgueitio et al. 2011; Calle et al. 2012a; Cardona et al. 2013). Meat quality of ISPS stock rivals the quality of those fed in feedlots, in terms of slaughtering weight and age, fat thickness and color, meat color, and marbling score (Dalzell et al. 2006). Additionally, ISPS has been shown to completely eliminate the use of chemical fertilizers from operations that once relied on inputs of 400 kg urea ha^{-1} year^{-1} (Murgueitio et al. 2011).

The main reason for greater productivity in ISPS is that a diversity of forages is offered to the animal. Evidence indicates that the contribution of legumes to the ruminant diet results in higher performance on mixed forages compared with those grazing grass only (Tudsri and Prasanpanich 2001). This may be due to synergistic effects between grasses and roughage within the animal's gut. Carbohydrates are needed to supply energy for rumen microbial activity to efficiently digest and synthesize proteins. Thus, synchronous availability of TNC and CP has been shown to be critical in the improvement of animal nutrition (Neel and Belesky 2015).

Another way to increase overall system productivity and output of silvopasture is to integrate a variety of livestock, either simultaneously or via the leader-follower grazing system. Manríquez-Mendoza et al. (2011) observed significantly greater annual meat production in a mixed-species silvopasture including both cattle and sheep than for silvopastures grazed by cattle or sheep alone. Leader-follower systems can often outproduce other grazing systems for total animal weight gain because each animal tends to consume its optimal foods first (Shepard 2013).

Thermal Stress

Thermal stress has been shown to be responsible for reductions in feed intake, ADG, and milk production in dairy cows and can be caused by changes in air temperature, relative humidity, wind speed, and solar radiation (Kendall et al. 2006). Symptoms of heat stress, such as increased respiration rate and body temperature, begin to occur at 30 °C and shade typically becomes beneficial to livestock when the temperature-humidity index (THI) is over 72° Fahrenheit (Blackshaw and Blackshaw 1994). Thermal comfort is especially important for European or mixed European × Zebu cattle breeds, which are more sensitive to the high temperatures of the tropics than pure Zebu breeds (Kendall et al. 2006). A study conducted in Alabama demonstrated that even when artificial shade was made available, cattle preferred the shade provided by trees (Zuo and Goodman 2004).

Several studies have shown that trees modify understory microclimates, creating environments that can mitigate heat stress in animals (Tucker et al. 2008; Karki and Goodman 2015), increasing overall grazing time, ADG, lactation, and reproductive rates (Mitlöhner et al. 2001; Kallenbach 2009; Galindo et al. 2013). Kallenbach (2009) reported that cows using silvopastures experienced less difficulty calving (3% compared to 15%) and weaned heavier calves (295 kg compared to 270 kg) than those using traditional pastures. A study in New Zealand comparing four groups of cattle reported that milk production was significantly higher in cattle that had access to shade (Kendall et al. 2006). In turn, livestock have been shown to modify their behavior in the presence of trees, leading to more consistent and uniform grazing across the landscape (McIlvain and Shoop 1971; Karki and Goodman 2010). It has also been suggested that trees can protect animals against the dangers of extreme cold temperatures (Webster 1970; McArthur 1991).

Animal Health

Managed intensive rotational grazing and silvopasture can have direct impacts on animal health, helping to prevent the spread of parasites and disease. One of the most economically damaging and widespread ectoparasites affecting livestock production is the horn fly (*Hydrotaea irritans* Fall.), a Eurasian fly that relies on feces or vegetative refuse for reproduction, often causing irritation and transmitting disease in livestock (Giraldo et al. 2011; Broom et al. 2013). The continual animal movement seen in rotational grazing lowers the rate at which livestock return to paddocks where dung patties have yet to fully decompose, reducing host-parasite interactions. Additionally, multispecies leader-follower systems can be used, where free-range poultry follow livestock and actively forage on horn fly larvae developing in dung patties (Greg Judy, personal communication).

Silvopastures provide environments that are conducive to the establishment of beneficial insects, including many that help rapidly degrade cattle manure, further inhibiting the spread of the horn fly. In Colombia, Giraldo et al. (2011) documented significantly greater numbers of dung beetles in ISPS than in conventional pasture. The authors observed an inverse relationship between dung beetle and horn fly abundance in the two cattle-raising systems, which they attributed to both plant cover and contribution of plant litter provided by *L. leucocephala*. Plant litter favors the establishment of not only dung beetles, but also other beneficial fauna that can control pest populations and predatorial beetles (Giraldo et al. 2011). Silvopastures have been shown to support increased numbers of birds (McDermott and Rodewald 2014), ants (Rivera et al. 2013), and other beneficial predators that can lower the populations of ticks and reduce the incidence of diseases such as anaplasmosis, which has been shown to drop from 25 to <5% (Yadav et al. 2019).

ISPS contributes ample amounts of tree foliage to the diet, much of which contains condensed tannins, phenols, saponins, and other anti-nutritive secondary compounds that may have anti-parasitic effects. *T. diversifolia*, a widely planted forage shrub in ISPS throughout the tropics, appears to have promising effects on ruminal microbial ecology, reducing the methanogen and protozoa population and increasing the population of cellulolytic bacteria (Ruíz et al. 2014).

Still, there is some concern that silvopastoral environments could increase the presence of parasitic helminths. In southeastern Brazil, Costa et al. (2013) tested this hypothesis throughout a six-month period and found no significant differences in overall weight, weight gain, or helminth infestation between crossbred Holstein and Gir heifers grazed in silvopasture environments and traditional open pasture environments. In contrast, Francisco et al. (2009) studied two groups of wild horses in Spain and concluded that silvopasture increased the presence of infection by gastrointestinal nematodes.

A relatively new area of research has examined livestock social interactions in silvopastoral systems as a diagnostic for social welfare. Améndola et al. (2015) reported that heifers in an ISPS maintained more stable social hierarchies and expressed more socio-positive behaviors, suggesting that animal welfare was enhanced.

Habitat for Pollinators

Pollinator richness and density have been declining in recent years on a global scale (Thomann et al. 2013). Declines in wild bees and butterflies are linked to historical landscape modification (Burkle et al. 2013) and loss of key nesting and foraging sites (Baude et al. 2016). Pollinator decline not only threatens food security, but could also lead to the extinction of pollinator-dependent plants and ultimately the collapse of modern-day agriculture (Dubeux Junior et al. 2017). A report published by the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services identified agriculture as both a threat to pollinators and a potential solution to support them (Duvic-Paoli 2017). One key way to achieve this is through "ecological intensification," or the process of maintaining or enhancing agricultural productivity through the cultivation and management of beneficial biodiversity—a process achieved with silvopasture.

A study examining pollinator presence on two silvoarable and four silvopastoral systems in the UK found that butterfly diversity was significantly higher on the agroforestry plots when compared to conventional pasture (Brosi et al. 2008). However, hoverfly and bumblebee abundance was higher in the silvoarable treatments, but not for the silvopastoral treatments. The authors attributed this to strips of forbs and grasses retained in tree rows within the silvoarable plots. These so-called pollination reservoirs have been shown to be crucial—even in small strips—to the provisioning of adequate pollinator habitat (Brosi et al. 2008). Moreover, planting insect-pollinated tree species may make silvopastures more attractive to pollinators (Varah et al. 2013).

Conclusion

Silvopasture has been shown to be an effective strategy to ecologically intensify and increase food supply in livestock production systems, but it should not be promoted in isolation of other important food security considerations. In an eye-opening report, Steinfeld et al. (2006) claimed that the livestock sector emerges as one of the top two or three most significant contributors to the most serious environmental problems. With more than 20 billion domestic farm animals on the planet, they may be even more of a burden for the Earth's biosphere than the current 7.7 billion humans (Hahlbrock 2009). It is time we took a careful look at where and how livestock is being produced and whether or not they hinder or advance our aims to sustain the land in perpetuity (Janzen 2011).

Much of the world's increase in livestock production is occurring through intensive concentrated animal feeding operations (CAFOs), using feed produced on arable lands that could be growing food crops for humans (Pollen 2006). A large portion of food energy in plant biomass is lost when it passes through animals, so that the number of people fed ha^{-1} of cropland declines when grain is diverted through livestock (Godfray et al. 2010). Stresses in which livestock are implicated include land-use change, excretion of pollutants (nutrients, antibiotics, pathogens), overuse of freshwater, inefficient use of energy, diverting food for use as feed, and emission of greenhouse gasses (Janzen 2011). Thus, a worthy and prudent goal would be to decrease livestock product consumption and increase awareness of the origin of livestock products, if they are to be consumed.

With that said, many authors make cogent arguments for the role of animal agriculture (Janzen 2011; Hahn Niman 2014; Savory and Butterfield 2016). Livestock may compete with humans for food, but they also create protein from resources we cannot use directly—namely cellulose, from vast grasslands that cannot, or at least should not, be cultivated (Garnett 2009). Most grasslands have coevolved with large ungulates and have even been shown to thrive best under periodic animal impact, restorative disturbances that naturally aerate and return nutrients to soils. Unlike arable cropland, perennial grasses are not regularly tilled, reducing erosion and sequestering large amounts of carbon to help mitigate climate change (Janzen 2004; Mbow et al. 2014). Carbon sequestration can be enhanced even further when combined with trees in silvopastoral systems (Udawatta and Jose 2012). One study found that long-term storage of soil carbon in silvopasture was up to five times greater than traditionally grazed systems, and that did not take into account the carbon sequestered by trees (Toensmeier 2017).

Animal agriculture is now widely engrained in the fabric of many cultures and societies. In fact, meat, milk, and other animal products account for about a third of the protein consumed by humans globally and account for 40% of the global agricultural gross domestic product (Steinfeld et al. 2006). This, combined with the growing stigma of affluence surrounding the consumption of meat, is reason to believe that animal agriculture is here to stay. Silvopasture is an age-old practice that could augment the benefits and minimize the stresses of livestock production if adopted more widely.

Establishing agroforestry on land that currently has low tree cover has been identified as one of the most promising strategies to raise food production without additional deforestation (Garrity et al. 2010). Creating silvopastures from existing monocultures is the low-hanging fruit for the sustainable intensification of livestock production systems. Some have also proposed the thinning, seeding, and management of private woodlots currently under no form of management (Orefice et al. 2016a). In the Central Hardwood Region of the United States, there is an estimated 2.3 million ha of forest being pastured without the benefit of intensive management (Garrett et al. 2004). Managing this acreage under silvopasture would help prevent damages caused by extensive grazing and increase the overall pasture area available.

The establishment of silvopasture is often easier said than done. In many developing countries, a lack of land tenure makes farmers reluctant to invest in the long-term endeavor of establishing trees that may ultimately benefit others than themselves. Where landholdings are small, farmers are often unwilling or unable to spare land for agroforestry establishment, even if it promises higher long-term returns (Mbow et al. 2014). In the case of ISPS, start-up costs can be relatively expensive—with return on investment taking as long as 3–4 years—and may be entirely prohibitive without the availability of subsidies (Murgueitio et al. 2011; Calle 2013) or incentive programs like payment for environmental services (PES) (Pagiola et al. 2005). ISPS is also inherently complex, often requiring extensive capacity building, training, and deployment of new technologies through outreach and extension programs (Calle 2013).

National and regional policy makers across the globe would be wise to support and promote the multiple benefits of silvopasture: sound pasture management, simultaneous timber and livestock production, seasonal increases in meat and milk production, increased biodiversity and forage diversity, better welfare for animals, and carbon sequestration are all advantages of this land-use practice. There is a strong need for programs connecting producers who have successfully implemented silvopasture with others who have not. Policy makers should also address the obstacles faced by landholding producers and create programs to incentivize the adoption and utilization of silvopasture. Prohibitive start-up costs, lack of access to technical information, and poor understanding of existing government-subsidized programs are all issues that need to be addressed. As climate change continues to intensify and jeopardize global food security, silvopasture should no longer be treated as an anomaly, practiced by the few; it should be widely recognized, supported, and promulgated for the effective food provisioning tool that it is, expanding and facilitating green ranching opportunities to farmers around the world.

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