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This issue is dedicated to the memory of Professor **Albert E. Kretschmer, Jr. (1925−2014),** US American pasture agronomist, who made outstanding contributions to the science of tropical pastures and forages, mainly in Florida, USA. His friends and colleagues will not forget his infectious enthusiasm for pasture plant improvement. Al was a Fellow of the Tropical Grassland Society of Australia Inc. and member (1988-1991) of the Editorial Advisory Board of *Tropical Grasslands*.

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LivestockPlus – The sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics*

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Keywords: Eco-efficiency, environmental benefits, livestock and environment, mixed farming, pastures, smallholders.

Abstract

As global demand for livestock products (such as meat, milk and eggs) is expected to double by 2050, necessary increases to future production must be reconciled with negative environmental impacts that livestock cause. This paper describes the LivestockPlus concept and demonstrates how the sowing of improved forages can lead to the sustainable intensification of mixed crop-forage-livestock-tree systems in the tropics by producing multiple social, economic and environmental benefits. Sustainable intensification not only improves the productivity of tropical forage-based systems but also reduces the ecological footprint of livestock production and generates a diversity of ecosystem services (ES) such as improved soil quality and reduced erosion, sedimentation and greenhouse gas (GHG) emissions. Integrating improved grass and legume forages into mixed production systems (crop-livestock, tree-livestock, crop-tree-livestock) can restore degraded lands and enhance system resilience to drought and waterlogging associated with climate change. When properly managed tropical forages accumulate large amounts of carbon in soil, fix atmospheric nitrogen (legumes), inhibit nitrification in soil and reduce nitrous oxide emissions (grasses), and reduce GHG emissions per unit livestock product.

The LivestockPlus concept is defined as the sustainable intensification of forage-based systems, which is based on 3 interrelated intensification processes: *genetic intensification* - the development and use of superior grass and legume

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cultivars for increased livestock productivity; *ecological intensification* - the development and application of improved farm and natural resource management practices; and *socio-economic intensification* - the improvement of local and national institutions and policies, which enable refinements of technologies and support their enduring use. Increases in livestock productivity will require coordinated efforts to develop supportive government, non-government organization and private sector policies that foster investments and fair market compensation for both the products and ES provided. Effective research-for-development efforts that promote agricultural and environmental benefits of forage-based systems can contribute towards implemention of LivestockPlus across a variety of geographic, political and socio-economic contexts.

Resumen

De la misma manera que la demanda global de productos pecuarios (carne, leche, huevos) se duplicará para 2050, se espera que las producciones futuras tengan en cuenta los efectos ambientales negativos ocasionados por este sector. En este documento se describe el concepto *LivestockPlus* y se demuestra cómo en el trópico los forrajes mejorados pueden llevar a la intensificación sostenible de sistemas de producción mixta que integran forrajes/ganadería y cultivos y/o árboles, produciendo múltiples beneficios sociales, económicos y ambientales. La intensificación sostenible no sólo incrementa la productividad de los sistemas tropicales basados en forrajes, sino también reduce la huella ecológica de la producción pecuaria y genera una diversidad de servicios de ecosistema (ES, por sus siglas en inglés), como son el mejoramiento de la calidad del suelo, la reducción de la erosión y la sedimentación, y la mitigación de las emisiones de gases de efecto invernadero (GEI). La integración de gramíneas y leguminosas forrajeras mejoradas en los sistemas de producción mixta (agropastoril, silvopastoril y agrosilvopastoril) puede restaurar las tierras degradadas y aumentar la resiliencia de los sistemas a la sequía y el anegamiento asociados con el cambio climático. Si las prácticas de manejo son apropiadas, los forrajes tropicales acumulan grandes cantidades de carbono en el suelo, fijan el nitrógeno atmosférico (leguminosas), inhiben la nitrificación en el suelo y reducen las emisiones de óxido nitroso (gramíneas), y finalmente reducen las emisiones de GEI por unidad de producto pecuario.

El concepto *LivestockPlus* se define como la intensificación sostenible de los sistemas de producción basados en forrajes, con 3 procesos de intensificación interrelacionados como pilares: *intensificación genética* −el desarrollo y el uso de cultivares superiores de gramíneas y leguminosas para aumentar la productividad pecuaria; *intensificación ecológica* −el desarrollo y la aplicación de mejores prácticas agrícolas y de manejo de recursos naturales; e *intensificación socioeconómica* –el mejoramiento de las instituciones y políticas locales y nacionales, que permiten refinar las tecnologías y facilitan su uso duradero. Los aumentos en la productividad ganadera requerirán esfuerzos coordinados para desarrollar políticas de apoyo de los gobiernos, organizaciones no-gubernamentales y el sector privado para estimular inversiones y una compensación justa del mercado, tanto para los productos pecuarios como los servicios ecosistémicos proporcionados. Los esfuerzos efectivos de investigación para el desarrollo que promuevan los beneficios que los sistemas de producción basados en forrajes proporcionan para la producción agropecuaria y el medioambiente, pueden ampliar la aplicación de *LivestockPlus* a través de una variedad de contextos geográficos, políticos y socioeconómicos.

Introduction

The need to increase livestock production

The world population is expected to be 9.6 billion by 2050 (UNDESA 2012). Thus, 70% more food will be required in 2050 than in 2000 (Bruinsma 2009). Increasing yields per unit area in current agricultural zones is expected to achieve 90% of the required gains, with expanded areas in sub-Saharan Africa and Latin America providing the remainder (FAO 2010). Globally, livestock derive fodder from two-thirds (4.9 Bha) of all agricultural areas, comprising 3.4 Bha of grazing land and one-quarter of the area sown to crops (Foley et al. 2011). The world has 17 billion livestock (mainly cattle including buffaloes, sheep, goats, pigs and chickens, but also including lesser-known species such as guinea fowl, yaks and camels, which are important in some areas). Livestock, especially ruminants, have the ability to convert low-quality biomass into high-quality nutrient-dense foods (Smith et al. 2013a), and currently contribute 15% of total food energy, 25% of dietary protein and some micronutrients not readily available from plants for human consumption (FAO 2009).

Table 1. Actual demand for livestock products in developing and developed countries in 2002 and projections for 2050 (adapted from Rosegrant et al. 2009).

Livestock product	Developing countries			Developed countries		
	2002	2050	Difference (%)	2002	2050	Difference (%)
Meat						
Consumption per capita (kg)	28	44	57	78	94	21
Total consumption (Mt)	137	326	138	102	126	24
Milk						
Consumption per capita (kg)	44	78	77	202	216	7
Total consumption (Mt)	222	585	167	265	295	11

Global demand for meat, milk and eggs is expected to double by 2050, with the largest increases occurring in developing countries (Delgado et al. 2001; Herrero et al. 2009) (Table 1). Meat and milk consumption in developing countries has increased 3 times faster over the last 30 years than in developed countries (FAO 2009), with the largest increases occurring in East and Southeast Asia, along with Latin America and the Caribbean (LAC). Although greatest changes have occurred in developing countries with large populations and fast-growing economies such as China, India, Indonesia and Brazil (Pica-Ciamarra and Otte 2011), consumption of livestock products is expected to increase significantly in countries with smaller populations and economies (ILRI et al. 2011).

Of the 5 agricultural commodities with the highest global economic value, 4 (milk, beef, pork and chicken) come from livestock, which are an important global asset with an estimated value of at least USD 1.4 trillion. Further, the livestock sector and associated market chains employ 1.3 billion people worldwide and contribute to the livelihoods of some 600 million smallholder farmers (Thornton 2010). Despite substantial investment in agricultural technology and farm management, yield increases from the Green Revolution have slowed during the last 4 decades (Ray et al. 2012). Many productivity increases came with high environmental costs such as nutrient and pesticide contamination, soil salinization and water pollution, and future increases must be achieved by reducing agriculture's environmental footprint (Godfray et al. 2010). To meet these multiple and urgent challenges, a more comprehensive and coordinated research and development approach is needed.

Diverse crop-forage-livestock systems

Livestock production systems in developing countries involve varying degrees of grazing and/or feeding of cut forages and grain concentrates (Seré and Steinfeld 1996). The main focus of this paper is on forage-based crop-livestock-tree[1] systems in developing countries in the tropics. Most of the meat and milk produced in the developing world and almost half of the global cereal output come from mixed crop-livestock systems (Herrero et al. 2010). Improved performance of both crops and animals is essential for sustainable intensification (McDermott et al. 2010). Integration of forage systems with cropping systems should help mitigate negative environmental impacts resulting from intensification of cropping systems and improve the quality of forage systems through periodic restoration (Lemaire et al. 2014).

Tropical forage-based livestock production systems differ regionally (Peters et al. 2013a). In LAC, cattle are raised largely on sown pastures with increasing attention to crop components, while in West Africa cattle, sheep and goats graze native pastures and crop residues. In tropical Asia, cut-and-carry systems and crop residues predominate. In Eastern, Central and Southern Africa, native and sown forages are often combined with crop residues for both grazing and cut-and-carry to feed cattle and small ruminants. We class all such systems (grazing, cut-and-carry, agropastoral and silvopastoral systems) that utilize tropical grasses and legumes for feeding livestock as "tropical forage-based systems".

The majority of tropical forage-based systems face challenging production conditions. Soils are mostly infertile with low soil organic matter, very low pH, high aluminum (Al) saturation and phosphorus (P) deficiency. Rainfall is often markedly seasonal with prolonged (4–6 months) dry seasons, followed by unreliable wet seasons, that can be accompanied by waterlogging. These abiotic stresses, together with some major pests and diseases, affect both the quantity and quality of feed produced, and thus limit livestock productivity, particularly in prolonged dry seasons. Given such challenging biophysical conditions, coupled with lack of, or unapplied government policies, poorly performing markets and few

[1]When using this simplifying term we refer to integrated agricultural production systems that involve forage-based livestock, crops and/or trees (agropastoral, silvopastoral and agrosilvopastoral systems).

investment incentives, land used for livestock production is in varying stages of degradation (Macedo 1997; Miles et al. 2004). As pastures degrade, productivity and organic matter inputs decrease, non-palatable plant species invade, vegetative cover is reduced (thus increasing susceptibility to erosion), soils become compacted and more acidic, and microbial biomass decreases (Macedo 1997; Oliveira et al. 2004). Losses in soil organic matter could be associated with reduced soil aggregation, leading to a possible corresponding decline of organic P, with potentially significant implications for the efficient cycling of P in tropical soils (Fonte et al. 2014). Despite these limitations, developing countries have greater potential to increase livestock production through restoration of degraded lands than developed countries (Smith et al. 2008; Murgueitio et al. 2011). Thus, we focus on grasses and legumes selected because of their superior biomass production, nutritional quality and persistence relative to native or naturalized species, mainly grasses.

Livestock production and the environment

Livestock production is the world's largest system of land use (de Fraiture et al. 2007) and livestock consume about two-thirds of all dry matter produced by terrestrial plants in the food system (Wirsenius 2003). As a consequence, livestock production can have substantial negative effects on the environment, including global warming (Steinfeld et al. 2006a, 2006b; Herrero et al. 2013b), nitrogen (N) pollution (Bouwman et al. 2013), high water use and contamination of water resources (Herrero et al. 2012). In addition, reduction in biodiversity occurs when lands supporting native vegetation are converted to pastures (Alkemade et al. 2013).

It is recognized that forage-based systems provide a number of ecosystem services (ES) such as regulating water flows, reducing erosion and greenhouse gas (GHG) emissions (Cárdenas et al. 2007; Peters et al. 2013a, 2013b), and improving soil biota and quality (Velásquez et al. 2012; Rousseau et al. 2013; Lavelle et al. 2014), as well as cultural services by promoting traditional lifestyles. The relative importance of these diverse ES depends on priorities of landowners and other stakeholders affected by agricultural activities, which are ecosystem-specific.

It is well documented that livestock are a major contributor to GHG emissions, estimated at 7.1 Gt (billion metric tons) carbon dioxide (CO_2)-equivalent/yr (Ripple et al. 2014), representing 14.5% of all anthropogenic GHG emissions (Gerber et al. 2013). Beef and milk cattle account for 41% and 21%, respectively, of livestock's emissions, including: methane (CH_4) from enteric fermentation and animal manures; CO_2 from land use and land-use changes; and nitrous oxide (N_2O) from manure and slurry management and emissions associated with agricultural activities, mainly N fertilization, to produce animal feed (Scholes et al. 2014). Intensity of GHG emissions differs among geographical regions and production systems, including the animal species and the products in question. These differences are mostly driven by feed conversion efficiency (the amount of feed consumed per unit of product), which improves with dietary quality in terms of digestibility and protein content (Herrero et al. 2013a). Sub-Saharan Africa (SSA) produces a high intensity of emissions by livestock (Herrero et al. 2013b), owing to low animal productivity from large areas of arid lands, where animals have low productive potential, and feed available is of low quality and often scarce (Hristov et al. 2013).

Improving the quantity and quality of forage produced will improve animal production and feed efficiency and reduce GHG emissions (particularly CH_4) per unit of animal product (Hristov et al. 2013), but may result in increased emissions at the farm level, if animal numbers are not kept constant or are not reduced (Latawiec et al. 2014). Sustainable intensification of forage-based agricultural systems should result in release of land for other environmentally-friendly uses (such as tree plantations, reconversion to forest vegetation).

About 39% of the total water used for agriculture is associated with livestock production (de Fraiture et al. 2007), most being used in growing feed (Herrero et al. 2012). Consequently, water scarcity is a major limitation to livestock production in the seasonally-dry tropics (Rockström et al. 2007). Climate change can further aggravate water shortage problems, adversely affecting a high proportion of smallholder crop-livestock systems in marginal environments.

Opinions differ on how best to address the negative environmental effects of livestock production. While Pelletier and Tyedmers (2010) argue that growth of the livestock sector should be curbed, Steinfeld and Gerber (2010) suggest that production technologies (land intensification) with low ecological footprint should be developed for the benefit of poor smallholder producers in developing countries. Despite these contrasting views, there is general agreement on the importance of reducing the environmental footprint of livestock. This poses development challenges to improve food security and alleviate poverty. As crop and livestock farming complement each other (Herrero et al. 2010), the use of both improved forages and improved animal breeds can yield the same amount of food from a smaller area or more food from a similar area (Eisler et al. 2014).

Eco-efficiency and sustainable intensification

Coordinated research, development and policy initiatives are needed to improve the productivity of crop-forage-livestock-tree systems. Two related paradigms in the development literature, *eco-efficiency* and *sustainable intensification*, can be used to describe general approaches that aim to optimize social, economic and environmental objectives. *Eco-efficiency* aims to achieve highly-productive agro-ecological systems, which have a small environmental footprint, while being economically viable and socially equitable (CIAT 2009; Keating et al. 2013). *Sustainable intensification* produces increased outputs with more efficient use of inputs, while reducing environmental damage and building resilience, natural capital and ES (The Montpellier Panel 2013). Although social equity is not an explicit aim of sustainable intensification, it occurs within the context of sustainable development.

Three related processes lie at the heart of sustainable intensification (The Montpellier Panel 2013): *Genetic intensification* is the development and use of superior grass and legume cultivars for increased livestock productivity. This should be coupled with the development and use of superior animal breeds (not considered in the context of this concept and review paper). *Ecological intensification* is the application of improved farm and natural resource management (NRM) practices. *Socio-economic intensification* involves the improvement of local and national institutions and policies, which enable technology adoption, and supports their enduring use. In addition, fair and efficient market access for goods and services associated with both inputs and outputs is essential (Figure 1).

LivestockPlus: Concept and principles

The LivestockPlus concept (Figure 2) was formulated to demonstrate how improved forages, when and if properly managed, could lead to the sustainable intensification of mixed crop-forage-livestock systems in the tropics, while recognizing the multiple social, economic and environmental objectives. While minimizing trade-offs, LivestockPlus emphasizes the synergism between soils, plants, animals, people and the environment. The aim is to produce additional meat and milk based on 4 principles:

1) Selected sown grasses and legumes are more productive per unit land area than native or naturalized forages, and produce higher quality feed and thus may contribute to releasing land for alternative uses;
2) Sown grasses and legumes in combination with crop residues improve resource-use efficiency at farm level and produce more milk and meat, particularly during the dry season;
3) Sown grasses and legumes, especially when integrated with crops and trees, enhance system productivity and resilience and improve livelihoods. They also generate ES, thereby reducing the environmental footprint per unit livestock product; and
4) Multiple actions are needed to create conditions that are essential for the adoption and widespread use of improved forage-based systems, including: genetic improvement of livestock to match improved feeding; changes to regional and national policies; and increases in human and social capital.

We consider that increasing consumer demands for livestock products can and should be met by increasing productivity within the same region, particularly in the tropics. Although productivity could be increased using grain-based diets, we favor intensifying forage-based systems, based on goals of economic viability, environmental sustainability and social equity, associated with eco-efficiency (Rao et al. 2014). To spark greater interest and adoption of improved forages, the concepts and benefits of LivestockPlus need to be communicated to the global community. This paper is an initial step in that process.

LivestockPlus: Sustainable intensification of forage-based systems

Genetic intensification to provide a wide range of forage/feed options

Forage grasses. Domestication of forage grasses started when livestock producers began to collect and intentionally sow elsewhere seeds of plants that they considered improved livestock performance. As with crop plants, most useful forage plants were domesticated long before they were studied scientifically (Boonman 1993), being selected for different purposes according to user needs and the plants' characteristics. Many tropical grass species are useful as sown forages, and some are widely commercialized (Cook et al. 2005). Over the last 50 years, many thousands of accessions of grasses were evaluated in agronomic trials in the tropics and subtropics, resulting in the release of a number of cultivars for use as forages to improve livestock production (Table 2).

A number of cultivars are widely used as pastures. For the semi-arid tropics and subtropics, more than 30 cultivars of *Cenchrus ciliaris* (now *Pennisetum ciliare*) are available; some are extensively used. While

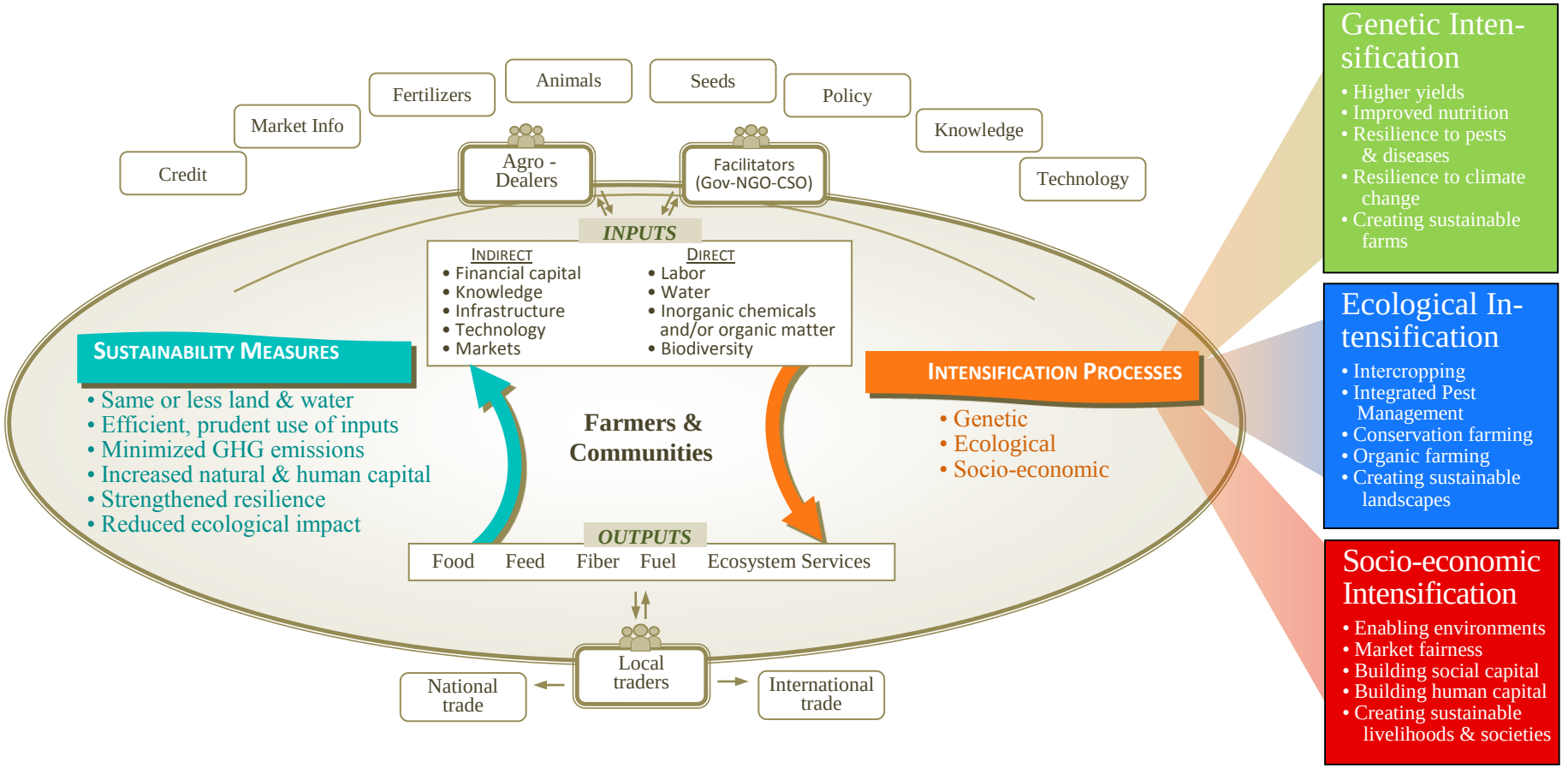

Figure 1. A sustainable intensification approach for improved forages to realize widespread social, economic and environmental benefits (modified from The Montpellier Panel 2013).

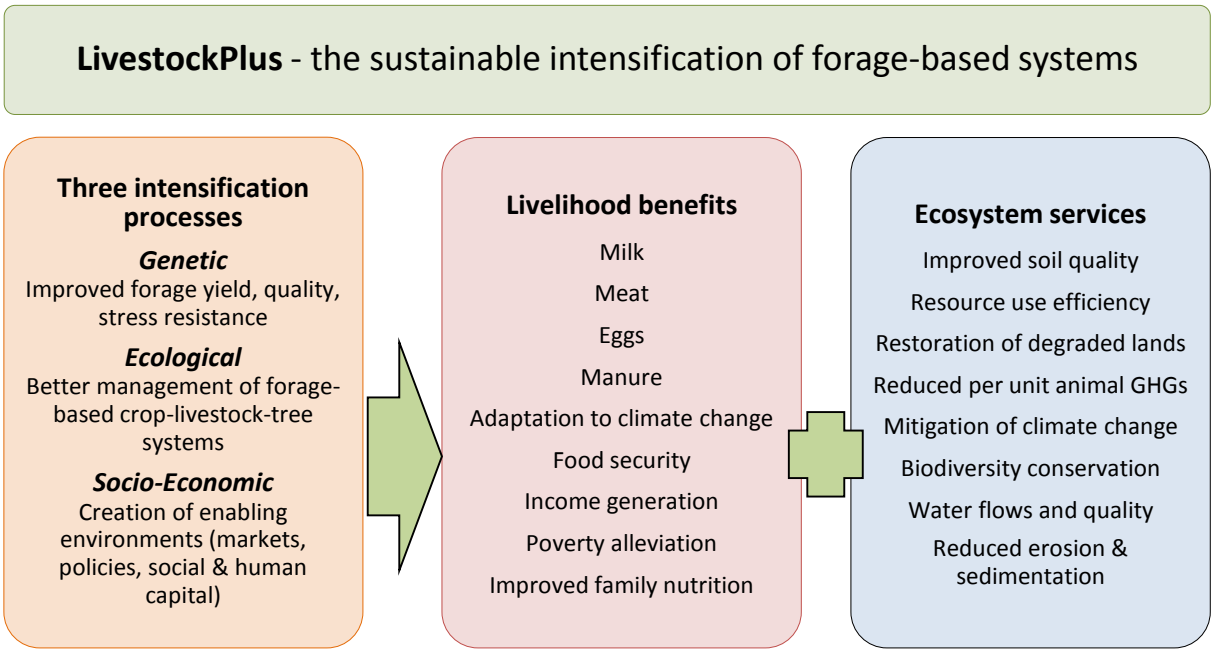

Figure 2. LivestockPlus: A concept to improve livelihoods and ecosystem services via the sustainable intensification of forage-based crop-livestock-tree systems.

Glenn Burton and colleagues achieved major genetic improvement in nutritive quality of bermudagrass (*Cynodon dactylon* and interspecific hybrids) at Tifton, GA, USA (Hill et al. 2001), the resulting cultivars are not widely grown in the lower-latitude tropics. Various cultivars of *Brachiaria* species, many of which are now accepted as *Urochloa* spp., have made an impressive contribution to animal production throughout the tropics, such as *B. brizantha* cvv. Marandu and Toledo; *B. humidicola* cvv. Tully and Llanero; *B. decumbens* cv. Basilisk; and *B. ruziziensis* cv. Kennedy (Miles et al. 2004). *Brachiaria* breeding at CIAT has produced the commercial cvv. Mulato, Mulato II, Cayman and Cobra. Guinea grass (*Panicum maximum*; now *Megathyrsus maximus*) is very productive on fertile soils in the humid and subhumid tropics and subtropics. Several accessions of *Paspalum* are adapted to wet sites. *Pennisetum purpureum* (napier grass or elephant grass) is widely used in cut-and-carry systems but available cultivars require fertilizer to sustain high yields and are subject to disease pressures (i.e. stunt disease) in Eastern Africa.

Breeding programs to improve temperate forage grasses began almost 100 years ago; in contrast, breeding of tropical forage grasses did not start until about 1960. The objectives of both plant breeding and germplasm selection were to identify or produce plants that were persistent and resistant to pests and diseases, with high yields of forage, high nutritive value and good seed yields and quality. Tolerance of acid soils, drought and waterlogging were also important; deep-rootedness was included to increase drought tolerance and the ability to scavenge for soil nutrients in infertile soils. Characteristics that contribute to ES received little attention (Miles et al. 2004; Rao 2014), although deep-rootedness has now been shown to contribute to accumulation of C at depth in the soil (Fisher et al. 1994; 2007). In addition, feeding ruminants with high quality forage reduces the amount of methane emitted per unit of animal product (Herrero et al. 2013b), and some tropical forage grasses inhibit biological nitrification, which reduces N_2O emissions from the soil (Subbarao et al. 2009). Breeding and selection can increase the ES that forages provide only if there is genetic variation for the desired traits in the available germplasm.

Forage legumes. Forage legumes have: (1) symbiotic nitrogen fixation, contributing N to the system and having high protein concentrations; (2) deep taproots, which contribute to drought tolerance and increase the ability to scavenge for nutrients in infertile soils; (3) a diversity of chemical compounds, many of them anti-nutritive substances; and (4) great genetic, morphological, taxonomic and ecological diversity. Tropical forage legumes not only provide high-quality animal feed but also enhance soil fertility, improve soil structure and water infiltration, increase soil C accumulation and contribute to weed control and soil conservation (Thomas and Lascano 1995). In addition, most forage legumes contain phenols that can favorably modulate processes of biohydrogenation and methanogenesis (Waghorn et al. 2002; Jayanegara et al. 2011).

Table 2. A selection of important commercial forage grasses and legumes used in tropical livestock production systems (including crop-tree-livestock systems) and natural resource management.

Species	Cultivar examples or (common name)	Current use					
		Livestock production			Livestock & NRM	Natural resource management (erosion and weed control, soil enhancement)	
		Grazing	Cut & carry	Processing (e.g. hay & leaf meal/ pellets)	Fodder banks, leys, improved fallows	Soil cover, green manure	Contour hedgerows
Grasses							
Brachiaria brizantha	Marandu, Toledo	X[1]	(x)	(x)			(x)
Brachiaria decumbens	Basilisk	X	(x)	(x)			
Brachiaria humidicola	Tully, Llanero	X		(x)		X	
Brachiaria hybrids	Mulato, Mulato II	X	(x)	(x)			
Cenchrus ciliaris	Biloela, Gayndah	X					
Chloris gayana	Callide, Katambora	X		X	X		
Cynodon nlemfuensis	(African Star grass)	X		X			
Digitaria eriantha	(Pangola)	X		X			
Panicum maximum	Mombasa, Tanzania	X	X	(x)			(x)
Paspalum atratum	Pojuca, Ubon	X	(x)				X
Pennisetum purpureum	(Napier)		X				X
Pennisetum hybrids	(King grass)		X				X
Herbaceous legumes							
Arachis pintoi	Amarillo	X				X	
Calopogonium mucunoides	(Calopo)	(x)				X	
Centrosema molle	Common centro	X				X	
Centrosema pascuorum	Cavalcade	X		X	X		
Desmodium heterocarpon subsp. *ovalifolium*	(Ovalifolium)	X				X	
Desmodium uncinatum	(Silverleaf desmodium)	(x)	(x)			(x)	
Lablab purpureus	Rongai	(x)	X	X		(x)	
Macroptilium atropurpureum	Siratro	X		(x)		(x)	
Mucuna pruriens	(Mucuna)		(x)		(x)	X	
Pueraria phaseoloides	(Tropical kudzu)	X				X	
Stylosanthes capitata + *S. macrocephala* (mixture)	Estilosantes Campo Grande	X			(x)		
Stylosanthes guianensis	CIAT 184, Cook	X	(x)	X	(x)	X	
Stylosanthes hamata	Verano	X				X	
Stylosanthes scabra	Seca	X	(x)		X		
Shrub and tree legumes							
Calliandra calothyrsus	(Calliandra)		X			X	X
Cratylia argentea	(Cratylia)	X	X	(x)			
Flemingia macrophylla	(Flemingia)					X	X
Gliricidia sepium	(Gliricidia)	(x)	X			(x)	X
Leucaena leucocephala	Cunningham, Tarramba	X	X	(x)			X

[1]X indicates major use; (x) indicates minor use.

In the 1930s in North Queensland, Australia, the presence of naturalized *Stylosanthes humilis* (then *S. sundaica*, "Townsville lucerne") in natural pastures was observed to boost animal growth rates (McTaggart 1937), resulting in extensive research on the benefits of including adapted legumes in tropical grass pastures. The technology was subsequently taken up elsewhere in the tropics (Table 3). Selection from within large collections of germplasm identified cultivars of species in the genera *Centrosema*, *Desmodium*, *Leucaena* and *Stylosanthes* for use in tropical and subtropical Australia (Table 2). Only few cultivars were bred, e.g. *Macroptilium*

atropurpureum cv. Siratro (Hutton 1962) and *Centrosema pascuorum* cv. Cavalcade (Clements et al. 1986) in Australia and psyllid-tolerant *Leucaena* hybrids in Hawaii (Austin et al. 1998).

In tropical America, the focus was on legumes adapted to acid, infertile soils and biotic constraints. The most promising species identified were (Tables 2 and 3): *Arachis pintoi*, *Cratylia argentea*, *Desmodium heterocarpon* ssp. *ovalifolium* ("*D. ovalifolium*"), *Stylosanthes capitata* and *S. macrocephala*; the latter two were also released as a mixture in "Estilosantes Campo Grande" (Fernandes et al. 2005). Other species in the genera *Centrosema*, *Desmodium* and *Stylosanthes* also show promise but as yet there is little adoption by producers.

In general, the main constraints to increased use and impact of forage legumes are considered to be:

1) diseases and insect pests, e.g. anthracnose (caused by *Colletotrichum gloeosporioides*) in *Stylosanthes* and psyllids in *Leucaena leucocephala*;
2) anti-nutritive compounds, e.g. mimosine in *L. leucocephala* and tannins in *Flemingia macrophylla*;
3) lack of clear management guidelines that ensure persistence of an adequate proportion of legume in grass-legume associations; and
4) failure to meet, in some cases, farmer expectations of increased animal production due to low genetic potential of animals used.

In addition to improving livestock production (Table 3), forage legumes can have important impacts on the environment (see overview by Schultze-Kraft et al. 2014). As a consequence of N fixation, grass-legume pastures need no N fertilizer and so offer both economic and environmental benefits. Furthermore forage legumes improve soil quality and can increase the yield of subsequent crops, which is particularly important in smallholder crop-livestock systems. Deep-rooted legumes scavenge nutrients from deep in the soil and redistribute them at the soil surface in litter. Cover legumes reduce weed pressure, can control pests and protect soil from erosion (including loss of soil organic matter) by water and wind (see also Section "Ecological intensification to generate multi-dimensional benefits and to minimize trade-offs" below).

Crop residues as feed. Crop residues (CR) are an important strategic feed resource (Blümmel et al. 2012), totaling 3.8 Bt DM/yr worldwide, of which cereals contribute 74%, sugar crops 10%, legumes 8%, tubers 5% and oil crops 3% (Lal 2005). Cereal CR have low nutritive quality, but leguminous CR can be very nutritious. In contrast with forages, production costs for the CR are charged to the crop that produces them (Blümmel et al. 2009). While the nutritive quality of cereal CR for use as fodder can be improved by chemical, physical or biological treatments, there has been little uptake of these technologies.

The second generation of processes to produce biofuels focuses on hydrolyzing plant ligno-celluloses to sugars, which are then fermented to ethanol. If the process can be made cheap and efficient, hydrolyzing low-quality straw, stover and woody material for use as animal feed may be a viable option. The trade-offs would be whether to use the hydrolyzed material as animal feed or to make ethanol (Dixon et al. 2010).

Ecological intensification to generate multi-dimensional benefits and to minimize trade-offs

Benefits. Improved forage-based systems can produce a wide range of benefits (Figure 3). White et al. (2013) conducted a meta-analysis of 98 studies on the effects of improved forages and their management, using a "triple bottom-line" approach (Elkington 1997) to analyze social, economic and environmental changes along a generic forage-livestock value chain with links of input, production, transformation and marketing.

Improved forages provide *social benefits* by improving the welfare of individuals, households, communities and entire countries. Intermediate outcomes include increases or decreases in labor use of family members depending on the system. Increases in livestock production can improve food and nutritional security (Rosegrant et al. 2009). Other social benefits include enhanced capacity to participate in community organizations, which can lead to institutional and policy changes, with possible improved well-being and equity. Resilience of both the farm and the community is likely, particularly in integrated systems with diverse production and market risks.

Improved forages can generate a variety of *economic benefits*. At the farm level, changes in soil physical, chemical and biological properties can result in improved soil quality, increased water infiltration and reduced fertilizer requirements (Ayarza et al. 2007). Forages can allow higher land and animal productivity, resulting in a shift from subsistence-orientation to market-orientation. Traditional livestock products may give way to new value chains for special market niches, such as sale of fresh forage in Thailand (Nakamanee et al. 2008), pasture seed in Bolivia (Pizarro and Sauma 2007), cheese in Central America (Holmann et al. 2004), concentrates from legume grains in Zimbabwe (Murungweni et al. 2004) and organic livestock products (Rahmann 2009).

Table 3. Effects of tropical legumes on cattle liveweight gain and milk yield.

Pasture type	Country/ region	Climate/ ecosystem	Legume species	Grass alone	Grass with legume	Reference
A. Liveweight gain						
Native (*Heteropogon contortus*)	Australia, Central Queensland	Dry subtropics	*Stylosanthes humilis*	83 kg/an/yr	121 kg/an/yr	Shaw and Mannetje (1970)
Native	Australia, Northern Territory	Dry tropics	*Centrosema pascuorum*[1]	-183 g/an/d	489 g/an/d	McCown et al. (1986)
Urochloa mosambicensis	Australia, Northern Queensland	Dry tropics	*Leucaena leucocephala* cv. Cunningham *L. diversifolia*	381 g/an/d[2]	723 g/an/d[2] 532 g/an/d[2]	Jones et al. (1998)
Brachiaria humidicola	Venezuela	Humid tropics	*Desmodium ovalifolium*[3]	336 g/an/d	385 g/an/d	Chacón (2005)
B. decumbens	Colombia, Llanos	Subhumid (savanna)	*Pueraria phaseoloides*	124 kg/an/yr	174 kg/an/yr	Lascano and Estrada (1989)
B. humidicola *B. dictyoneura*[4]	Colombia, Llanos	Subhumid (savanna)	*Arachis pintoi*	61−115 kg/an/yr 230−288 kg/ha/yr 106−124 kg/an/yr 248−369 kg/ha/yr	89−151 kg/an/yr 302−390 kg/ha/yr 124−166 kg/an/yr 332−459 kg/ha/yr	Lascano (1994)
B. dictyoneura[4]	Colombia, Llanos	Subhumid (savanna)	*Centrosema acutifolium* cv. Vichada *Stylosanthes capitata*	191 g/an/d[5]	456 g/an/d[5] 446 g/an/d[5]	Thomas and Lascano (1995)
B. brizantha	Mexico, Veracruz	Wet-dry tropics	*Cratylia argentea*	580 g/an/d	839 g/an/d	González-Arcia et al. (2012)
B. Milk yield (per cow/day)						
Mixture of *B. humidicola*, *Hyparrhenia rufa* and *Cynodon dactylon*	Rwanda, Bugesera	Dry-subhumid (savanna), medium altitude	*Stylosanthes scabra* (leaf meal)	0.98 L	1.27 L (10% meal) 1.40 L (20% meal) 1.52 L (30% meal)	Mupenzi et al. (2009)
B. decumbens	Colombia, Cauca	Subhumid tropics (forest margin)	*Cratylia argentea*	6.1 kg (cut & carry) 6.1 kg (grazing)	6.7 kg (cut & carry) 7.5 kg (grazing)	Lascano et al. (2001)
B. dictyoneura[4] cv. Llanero *Andropogon gayanus*	Colombia, Cauca	Subhumid tropics (forest margin)	*Centrosema macrocarpum* *C. acutifolium* (CIAT 5568) *C. macrocarpum* *C. acutifolium* (CIAT 5568)	8.1 kg 7.8 kg 	9.5 kg 10.0 kg 9.0 kg 8.1 kg	Lascano and Avila (1991)
Cynodon nlemfuensis	Costa Rica, Turrialba	Humid tropics (forest margin)	*Arachis pintoi* *Desmodium ovalifolium*[3]	9.5 kg	10.8 kg 9.4 kg	González et al. (1996)

[1]Supplementation as ley during the main dry season.
[2]192 grazing days.
[3]Now classified as *D. heterocarpon* subsp. *ovalifolium.*
[4]Now classified as *B. humidicola.*
[5]Means of 3 grazing cycles totalling 385 days; newly established pastures.

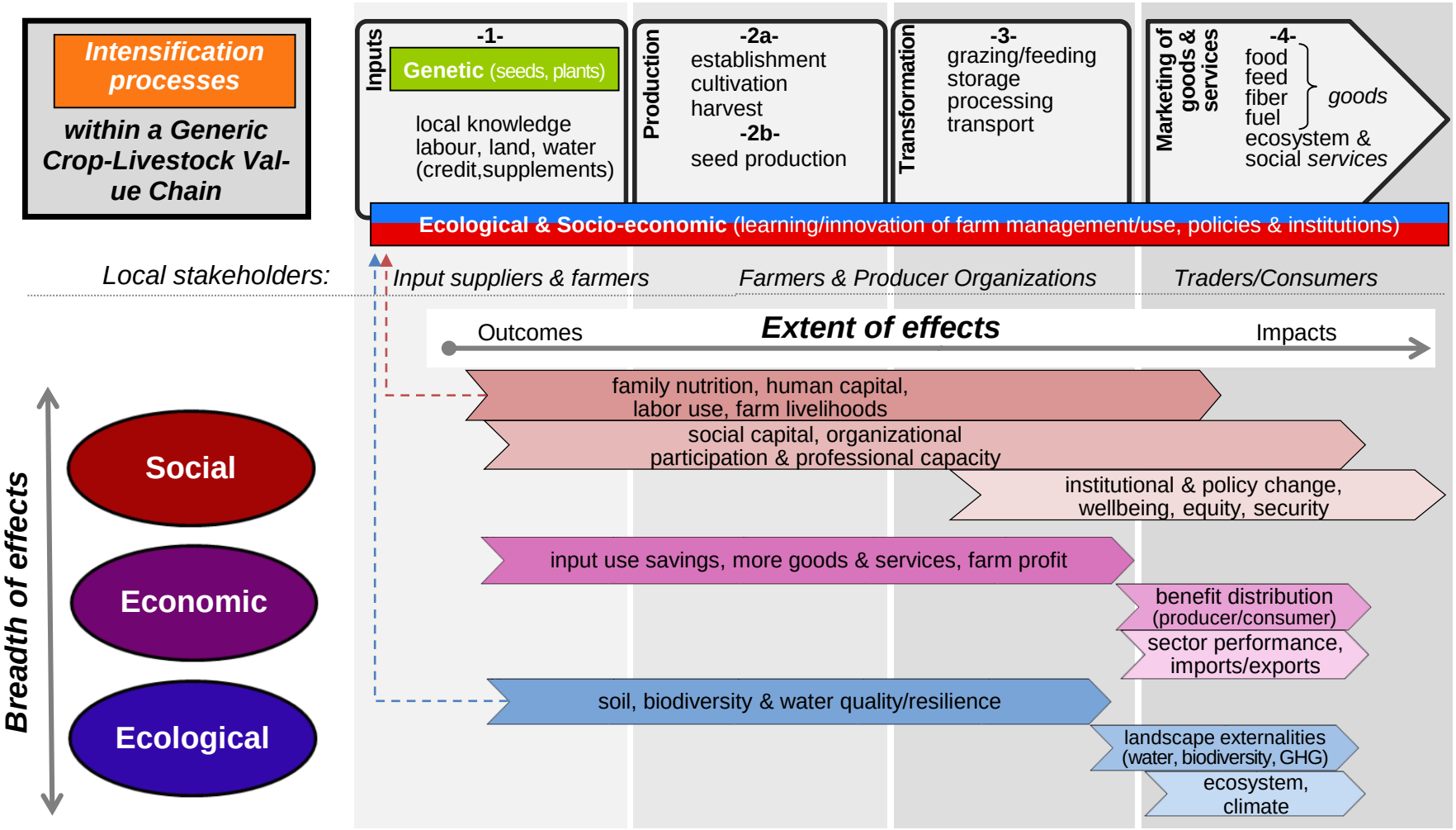

Figure 3. An array of effects generated by sustainable intensification processes of forages within a generic crop-livestock value chain (adapted from White et al. 2013).

Improved tropical forages can provide *environmental benefits* (Humphreys 1981; Schultze-Kraft and Peters 1997). At the farm level, forages adapted to biotic and abiotic stresses provide fast and complete soil cover that results in reduced erosion and weed infestation. Overall, plant production is more stable so that farms are more resilient to weather shocks.

Peters et al. (2013a) reviewed the potential of well-managed improved forages to mitigate GHG emissions, contrasting forage-based systems with feedlot systems, and concluded that the ecological footprint of forage-based systems was lower than that of feedlots. Livestock-related interventions, including better management of crops and grassland and the restoration of degraded land and soils, can mitigate as much as 3.5 Bt CO_2-eq/yr. This represents about 75% of the global potential biophysical mitigation (Smith et al. 2008). The potential of improved forages to accumulate C under adequate pasture and animal management is second only to forests (Fisher et al. 2007; Blanfort et al. 2012). A plausible 30% adoption rate of improved deep-rooted *Brachiaria* pastures in the Cerrados of Brazil would represent a mitigation potential of 29.8 Mt CO_2-eq/yr (Thornton and Herrero 2010).

The private sector is aware of these opportunities and is beginning to increase investments in both carbon credits and direct interventions in the supply chains, which provides scope for smallholders to trade mitigation credits to offset the costs of adapting their production systems and generate livelihood benefits. While credits are commonly traded in forestry systems, efforts are expanding to increase similar opportunities for silvopastoral systems (Banerjee et al. 2013; Nepstad et al. 2013).

Comparative analysis of GHG emissions from diverse production systems must include the environmental costs of feed production, including transport. Feedlot cattle produce fewer GHG emissions than forage-fed cattle per unit of beef produced, mainly due to better feed conversion (Casey and Holden 2006; Gerber et al. 2010). However, when we consider the GHG footprint of the grain they consume, forage cattle produce 15% lower total emissions per unit of beef (Pelletier et al. 2010).

Methane emissions. Although some compounds in forages such as tannins can reduce methane emissions by ruminants (Woodward et al. 2004), the most efficient strategy to achieve reduction in emissions is to increase productivity, which reduces methane emissions per unit livestock product. In this context, feeds with higher digestibility and nutrient content produce less methane per unit of feed ingested (Oliveira et al. 2007). As an adjunct, the deep and vigorous root systems of forage grasses and legumes improve soil structure and aeration. In doing so, they create suitable environments for aerobic methanotrophs, which oxidize methane as a source of C and energy, making soils of forage-based systems important sinks for methane (Mosier et al. 2004).

Carbon accumulation. Well-managed grass and grass-legume pastures have a huge potential to accumulate C, with values comparable with forest systems (Peters et al. 2013b). However, pasture degradation can substantially reduce the carbon stored by forage-based systems (Amézquita et al. 2010). Including legumes with the grass (Fisher et al. 1994; Soussana et al. 2010) or including trees in agroforestry systems (Smith et al. 2008) can increase the C accumulated by forage-based systems. Moreover, forages that are well-adapted to edaphic and climatic stresses have a higher potential to accumulate C than field crops, which have lower net primary productivity, particularly in marginal conditions. Assad et al. (2013) estimated changes in soil C stocks in 3 major Brazilian biomes (Cerrado, Atlantic Forest and Pampa) due to land use change and found soil C stocks under pasture were 15% greater than under the native vegetation.

Nitrous oxide. JIRCAS, CIAT, Corpoica and the University of Hohenheim are researching mechanisms of biological nitrification inhibition (BNI) in forage grasses (Rao et al. 2014; Subbarao et al. 2015). Forages with high BNI capacity enhance N utilization, and reduce N_2O emissions to the atmosphere and nitrate leached to ground water. Research is in progress to quantify the residual effects of BNI on subsequent crop production (Moreta et al. 2014). *Brachiaria humidicola* has high BNI activity, and a few germplasm accessions of *B. humidicola* are also more suitable for temporarily waterlogged environments than the commercial cultivars (Cardoso et al. 2013).

Limitations. Negative impacts of improved forages include soil acidification by legume-only swards (Haynes 1983) and the potential invasiveness of exotic species (Richardson and Pysek 2012). At larger scales, the cumulative effects of increased farm productivity can reduce water flows and quality downstream. Whether off-farm environmental effects are beneficial or detrimental depends on the site-specific context and management practices (Quintero et al. 2009). A serious environmental concern is the potential destruction of

natural ecosystems, such as rainforests, by replacing them with improved pastures, with the concurrent loss of biodiversity at all levels (mainly when monospecific grass pastures replace native multi-species vegetation).

Life cycle assessment. Life cycle assessment (LCA) examines all processes of a production system to estimate all environmental impacts such as GHG emissions, land and energy use, or eutrophication and acidification of water bodies. The growing concern over the environmental footprint of livestock has led to the increased use of LCA, relating environmental impact to a unit of production such as kilograms of meat or milk (de Vries and de Boer 2010). The analysis covers on-farm (C accumulation and GHG emissions) and off-farm stages (fertilizer production, transport, processing and delivery, etc.) related to livestock production. For example, beef production in USA requires 28, 11 and 6 times more land, irrigation water and reactive nitrogen, respectively, and produces 5 times more GHG than the average of the other livestock categories of dairy, poultry, pork and eggs (Eshel et al. 2014). Correct analysis of LCA depends on: (1) boundary conditions; (2) use of the appropriate functional unit (e.g. liters milk corrected for protein and fat contents as opposed to liters fresh milk); and (3) accurate allocation of emissions between different products (e.g. dairy milk, other dairy products or dairy beef) (O'Mara 2012). Furthermore, since such results are highly dependent upon management practices and biophysical conditions, examples of LCA within developing country contexts are likely to reveal different estimates.

LCAs have given insights on environmental impacts of livestock production. For example, a study on milk production in Peru found that the environmental costs of growing crops to make feed concentrates were significant (Bartl et al. 2011). While examples from the tropics are lacking, a study of beef production in Canada concluded that mitigation practices to reduce GHG emissions should focus on reducing enteric CH_4 production from mature beef cows (Beauchemin et al. 2010). In a comparison of conventional and organic milk production in the Netherlands, conventional farms used more energy and caused more eutrophication, while organic farms had higher soil acidification and produced more ammonia, CH_4 and N_2O emissions (Thomassen et al. 2008). Some researchers have called for improvements in LCA methodology to account for indirect second-order effects. These include opportunity costs of livestock production relative to other uses, and further analysis of the competition for land between humans and animals (Garnett 2009; de Vries and de Boer 2010).

Trade-offs. Trade-offs occur when 2 or more competing objectives cannot be simultaneously satisfied in full, thereby resulting in conflict or compromise. The multi-scale and multi-dimensional nature of agro-ecosystems creates a variety of both trade-offs and synergies between production, livelihoods and environmental objectives. Trade-offs influence the potential acceptability, impact and sustainability of interventions. They must be carefully assessed to achieve the goals of balancing livestock production, livelihoods and environmental protection (Herrero et al. 2009; Smith et al. 2013b).

In many aspects of pasture management, farmers are faced with trade-offs, some of which are subtle, but nevertheless important. For example, removal of biomass from forages by grazing and cut-and-carry represents an export of nutrients from the soil to the animal. In grazed systems, losses are small, although redistribution of N within pure grass pastures becomes important at high stocking rates (Boddey et al. 2004). Where the forage is physically removed, nutrient balance can be negative, if manure is not returned or the loss is not compensated for by applying mineral fertilizers (Rufino et al. 2007). This is especially the case for grasses that have high nutrient demand.

In intercropped systems, forages compete with the main crops for nutrients and water (Zhiping et al. 2004), but give the farmer more options. Thus, intercropping with multi-purpose forages (e.g. for livestock feed and/or soil conservation/improvement) allows farmers to choose between options that generate different benefits. For example, the intercropped forages might be grazed by dairy cows to produce milk during the dry season, when price is highest. The forage legume *Canavalia brasiliensis* can be intercropped with maize to improve the productivity of the smallholder maize-bean-livestock system. A comparison of using *C. brasiliensis* as forage or green manure showed that the forage option generated more income in the short term, and in the longer term avoided the costs of feed supplements and leasing pasture land (Douxchamps et al. 2014).

Prudent management balances trade-offs in using a pasture resource by avoiding overgrazing or complete biomass removal and maintaining sufficient residue to ensure soil cover and rapid regrowth. In addition, livestock excrete about 80% of the N ingested (Rufino et al. 2007), so managing animal manure is a key issue (Douxchamps et al. 2014). In summary, managing the trade-offs with multi-purpose forages can help restore degraded lands and improve crop and livestock production.

Socio-economic intensification to promote wide-spread use of improved forages

Although many farmers and ranchers have adopted improved forages in countries throughout the tropics (White et al. 2013), substantial geographic areas continue to perform below their potential. Adoption of improved forages, much like other agricultural technologies, occurs when a series of conditions exist. These include: (1) superior performance benefits, with greater and more resilient forage yields, energy and nutrient production; (2) low training costs for extensionists and farmers; (3) low financial inputs for establishment and management; (4) effective communication/extension capacities available (public or private); and (5) access to markets for livestock products (Feder and Umali 1993; Shelton et al. 2005).

For areas with little adoption of improved forages, at least one of these conditions remains inadequate. In order to achieve widespread improvement in livelihoods and ES with improved forages, conditions 3−5 above must be met. Since local contexts and associated biophysical and socio-economic conditions differ greatly across the tropics, efforts to increase adoption of forages require different priority actions in different situations. While some situations may require relatively straightforward genetic and ecological (i.e. management) intensification, others will need substantial multi-faceted partnership efforts, including training, marketing and advocacy to change policy. Continued demonstration of the social, economic and environmental benefits of improved forages (Figure 3) can help achieve institutional change. It is important, however, to note that the contribution of improved forages is only one of many coordinated actions essential to achieve sustainable intensification of forage-based crop-livestock-tree systems.

In order for forages to realize their maximum contribution to livelihoods and ES throughout the tropics, 3 actions are needed: (1) changing mindsets and attitudes; (2) increasing opportunities for technology and market co-development amongst farmers, researchers and extensionists; and (3) improving coordination across public and private organizations for enabling vital policies and investments.

Action 1: Change mindsets and attitudes. Altering personal and professional behaviors is a complex undertaking and requires innovative policies and practical solutions at every level of society (Darnton et al. 2005). Sustainability implies new lifestyle choices, with changes to both production and consumption systems. Thus, sustainable intensification is inherently about social transformation. Simple approaches that merely raise awareness need to expand into efforts that remove complex obstacles, which prevent changes in behavior (Robinson 2012). For example, some farmers in the tropics consider that forage plants are provided by nature and do not require active management, including the application of fertilizer (Peters et al. 2003). These attitudes may slowly change as extensive grazing lands become scarcer and consumer demands for livestock products increase incentives to invest in inputs that improve production. Nevertheless, efforts to publicize the multiple benefits of sustainably-intensified systems can help spur the adoption of improved forage management practices, both directly and indirectly.

Indirect effects occur by raising concerns and expectations of the general public, thereby influencing consumer preferences for sustainably-produced livestock products and associated ES. Social marketing strategies can promote sustainable behavior by making knowledge gained from psychological research relevant and accessible to those who design environmental programs (McKenzie-Mohr 2000). Analysis of social practices can provide better understanding of the underlying norms, values, identity, politics and consumption patterns, thereby revealing complex processes that lead to prevailing environmental practices (Barr et al. 2011). By going beyond advertising and publications, social marketing efforts extend into areas of community development, recruitment, training, and institution and infrastructure planning to achieve change (Robinson 2012).

Action 2: Increase opportunities for co-developing technologies and markets. Although the potential benefits from many improved forages may be known (Figure 3), their performance within specific farm contexts may not be. Scarce land, labor and rainfall are specific constraints that can limit the viability of forage options. Furthermore, crop-livestock systems in the tropics are diverse and dynamic, based on distinct agro-ecological and market conditons, resource endowments, land use, farm management and livelihood strategies. Thus, fitting the "most appropriate" improved forage into a particular context remains a persistent challenge (Byerlee and Collinson 1988; Giller et al. 2010).

Dialogue between farmers, extensionists, researchers and policymakers is needed to integrate forages into crop-livestock-tree systems. Processes of co-discovering and co-developing multiple benefits of forages reduce the gaps between research, development and implementation. For example, the Feed Assessment Tool (FEAST)

assists in formulating site-specific strategies and interventions for improved livestock feeding and production. It offers a systematic and rapid methodology to assess existing feed resources, constraints and opportunities (Duncan et al. 2012; Wassena et al. 2013).

The use of new organizational partnerships (public-public and public-private) and participatory research approaches helps farmers accumulate experience in inter-relating and negotiating with agro-dealers, local traders, consumers and government officials and increases trust and collaboration (Figure 1). Such activities, coupled with monitoring and evaluation and knowledge management and sharing can strengthen performance of both the links and associated connections along value chains (Peters et al. 2013a).

Action 3: Improve coordination across organizations for enabling vital policies and investments. Adoption of forage technology depends on the priorities and associated activities of a wide variety of organizations, including multiple levels of government (national-state-local), international bilateral agencies, non-government organizations (NGOs) with development and/or conservation objectives, producer and trade associations and community-based organizations. With so many types of stakeholders involved directly and indirectly in crop-forage-livestock activities, coordination is needed to avoid conflicting efforts and to achieve efficient, effective and equitable provision of services. Although past and current forage-livestock improvement programs often use an integrated approach (i.e. market development, improved feeding and management), attention is rarely paid to the genetic improvement of animals. To enhance adoption of improved high quality forages, there is a need to characterize and determine the most appropriate animal genotypes that will maximize economic benefits, and coordinate programs and policies. Three general types of government policy instruments (promotional, restrictive and supportive) can influence the adoption of crop-livestock-tree systems:

- Government incentives such as subsidized loans, subsidized credit, tax benefits and price subsidies can have a positive impact. Depending on the structuring and effectiveness of repayment mechanisms, the costs to the public can be minimal or neutral. For example, the state government of Mato Grosso do Sul in Brazil provides tax breaks to change livestock management practices (Bungenstab 2012). The Central American Bank for Economic Integration, funded by the Global Environment Facility, has developed green credits for supporting biodiversity, which take the form of loans to promote sustainable land use and good manure management, both of which protect water sources (Guerrero Pineda 2012).
- Coercive or punitive measures by governments such as taxes, penalties and land use planning regulations can restrict farming and land use practices. Although these measures have long been a popular tool of the public sector to control environmental damage in developed countries, they have proven to be inefficient and ineffective in developing countries (Blackman 2010).
- Private-sector incentives, including payment for ecosystem services (PES) for C accumulation and storage, biodiversity conservation and watershed protection, are alternative approaches. While enabling both adaptation to, and mitigation of, climate change, improved livestock feeding can improve food security (Bryan et al. 2013). The value of these services can be made directly to providers, through PES or associated with the agricultural product via marketing and certification schemes (Pagiola et al. 2004; Wunder 2005; Van Noordwijk and Leimona 2010). Future opportunities to increase ES via improved forages are substantial, yet are predicated upon legal rights to land and resources, which require support of governments.

Since US$21 billion was paid to developing countries by international sources in 2010 to generate ES (Sander and Cranford 2010), participating farmers and countries can generate substantial income by reducing emissions through livestock land use change (Havlik et al. 2014). For example, initiatives to reduce emissions from deforestation and forest degradation (REDD+), led by national governments, conservation NGOs and bilateral donors, focus on improved performance, sustainability and resilience of farms near forests. Economic analyses confirm that policies can encourage intensification of cattle ranching in Brazil and abate GHG emissions by sparing land from deforestation. A combination of revenue-neutral taxes and subsidies can help achieve these elements of sustainable intensification (Cohn et al. 2014; Strassburg et al. 2014).

Even without PES, farmers can increase incomes by differentiating their livestock products according to specific attributes such as animal breed, feed type, farm location or farm management practice. Formal certification assures consumers of the product quality, production attributes and validity of the associated price premium. The down-side is that establishing and implementing grades and standards increases producer costs and usually requires public and private sector involvement to support equitable participation in differentiated markets and monitor their performance (Alves-Pinto et al. 2013).

In the face of declining public funding for national agricultural research and extension agencies in many developing countries (Pardey et al. 1999), other organizations, including NGOs that specifically promote animal husbandry (e.g. Heifer International) and general rural development (e.g. CARE International, Catholic Relief Services, SNV-Netherlands), have assumed this role. As a result a blending of institutional responsibilities, while maintaining accountability, e.g. the mapping of expected outcomes from research and development (Earl et al. 2001) and the identification of impact pathways (Douthwaite et al. 2007), is needed to create inter-organizational dialogue.

Conclusions and future perspectives

LivestockPlus abides by the premises of sustainable intensification proposed by Garnett et al. (2013) of increasing food production through higher yields, while emphasizing food security and environmental sustainability. This concept proposes a practical pathway towards the goal of producing more livestock and crop products, with attention to livelihoods and ES for current and future generations.

The following questions are key to making the LivestockPlus concept operational:

- Can we reverse land degradation and improve GHG balance with well-managed forage-based landscapes in the subhumid and humid tropics?
- Is it possible to increase C accumulation and water use efficiency, while reducing GHG emissions per unit of livestock product?
- Are there synergies between crop and livestock production as they vary across regions?
- Where these synergies exist, how can they be exploited?
- How do market dynamics alter the magnitude of these synergies?
- How can LivestockPlus be implemented to promote inclusiveness and social equity and decrease existing gender gaps?

The LivestockPlus concept prioritizes the following action points for research-for-development topics:

Genetic intensification

- Develop stress-adapted and climate-resilient forage grasses and legumes.
- Develop forage grasses and legumes that contribute to reduced methanogenesis and increased polyunsaturated fatty acids with health implications for humans.
- Develop species and cultivar mixtures to improve functional biodiversity and to reduce land degradation.
- Improve interaction between forage researchers and livestock breeders and geneticists.

Ecological intensification

- Analyze the synergistic benefits and trade-offs from using crop residues with improved forages to overcome feed limitations, particularly in the dry season.
- Co-develop forage interventions for different farming systems, from extensive to semi-intensive, identifying suitable entry points for each system.
- Reduce yield gaps in milk and meat production by diversifying feed options.
- Contribute to reversing land degradation and mitigating GHG emissions.
- Assess in detail the potential of forage-based systems to accumulate C.
- Quantify differences between well-managed and degraded pastures in their capacity to accumulate C and determine the role of legumes and trees in further improving the potential for C accumulation.
- Develop methods to quantify ES as a basis for PES.
- Analyze trade-offs between forage productivity, forage quality and GHG emissions.
- Analyze trade-offs between C accumulation in soil, N_2O emission from soil and improvement of soil quality using grass-alone, grass-legume and grass-legume-tree associations.
- Develop decision support tools for use by policy makers, extensionists and farmers.

Socio-economic intensification

- Estimate the impacts of forage-based crop-livestock-tree systems as either trade-offs or win-win-win options for productivity, food and nutritional security and environmental benefits at different scales (from plot to farm to landscape to globe) and compare them with alternative scenarios.
- Assess direct economic benefits for farmers through product differentiation of environmentally-friendly products.
- Identify opportunities for rewarding farmers for ES.
- Identify the different social contexts in which forages are used and adjust actions accordingly.
- Change mindsets and attitudes of both producers and consumers on the importance and potential of improved land management with forage-based systems.

- Increase opportunities for technology and market co-development.
- Improve coordination across public and private organizations for enabling vital policies and investments.

The major outcomes of these actions will be achieved through site-specific research for development. Its target is to double livestock production on less land in the next 10 years in some regions of a few countries, where policies are favorable for adoption, freeing land for sustainable crop production and providing ES, including reduction of colonization pressure on unmodified ecosystems. Applying these interventions in resilient crop and livestock value chains will ensure economic gain and reduce poverty. They are expected to markedly increase the share of smallholder production linked to formal markets. Concerted research on the mitigation potential of forage-based systems to effect climate change can create a functional system of LivestockPlus in at least 5 countries within 5 or 6 years.

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References

Alkemade R; Reid RS; Van den Berg M; de Leeuw J; Jeuken M. 2013. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. Proceedings of the National Academy of Sciences of the United States of America 110:20900−20905. DOI: 10.1073/pnas.1011013108

Alves-Pinto H; Newton P; Pinto L. 2013. Certifying sustainability: Opportunities and challenges for the cattle supply chain in Brazil. CCAFS Working Paper No. 57. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. http://goo.gl/8yD5wi

Amézquita MC; Murgueitio E; Ibrahim M; Ramírez B. 2010. Carbon sequestration in pasture and silvopastoral systems compared with native forests in ecosystems of tropical America. In: Abberton M; Conant R; Batello C, eds. Grassland carbon sequestration: Management, policy and economics. Proceedings of the workshop on the role of grassland carbon sequestration in the mitigation of climate change. Integrated Crop Management Vol. 11. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. p. 153–161. www.fao.org/3/a-i1880e.pdf

Assad ED; Pinto HS; Martins SC; Groppo JD; Salgado PR; Evangelista B; Vasconcellos E; Sano EE; Pavao E; Luna R; Camargo PB; Martinelli LA. 2013. Changes in soil carbon stocks in Brazil due to land use: Paired site comparisons and a regional pasture survey. Biogeosciences 10:6141−6160. DOI: 10.5194/bg-10-6141-2013

Austin MT; Sun W; Brewbaker JL; Schifino-Wittmann MT. 1998. Developing *Leucaena* hybrids for commercial use. In: Shelton HM; Gutteridge RC; Mullen BF; Bray RA, eds. Leucaena: Adaption, quality and farming systems. ACIAR Proceedings No. 86. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. p. 82–85.

Ayarza M; Barrios E; Rao IM; Amézquita E; Rondón M. 2007. Advances in improving agricultural profitability and overcoming land degradation in savanna and hillside agroecosystems of tropical America. In: Bationo A; Waswa B; Kihara J; Kimetu J, eds. Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. Springer, Dordrecht, Netherlands. p. 209–229. DOI: 10.1007/978-1-4020-5760-1_19

Banerjee A; Rahn E; Läderach P; Van der Hoek R. 2013. Shared value: Agricultural carbon insetting for sustainable, climate-smart supply chains and better rural livelihoods. CIAT Policy Brief No. 12. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. http://goo.gl/5gAzZm

Barr S; Gilg AW; Shaw G. 2011. Citizens, consumers and sustainability: (Re)framing environmental practice in an age of climate change. Global Environmental Change 21:1224−1233. DOI: 10.1016/j.gloenvcha.2011.07.009

Bartl K; Gómez CA; Nemecek T. 2011. Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. Journal of Cleaner Production 19:1494–1505. DOI: 10.1016/j.jclepro.2011.04.010

Beauchemin KA; Janzen HH; Little SM; McAllister TA; McGinn SM. 2010. Life cycle assessment of greenhouse gas emissions from beef production in Western Canada: A case study. Agricultural Systems 103:371–379. DOI: 10.1016/j.agsy.2010.03.008

Blackman A. 2010. Alternative pollution control policies in developing countries. Review of Environmental Economics and Policy 4:234–253. DOI: 10.1093/reep/req005

Blanfort V; Ponchant L; Dezecache C; Stahl C; Freycon V; Picon-Cochard C; Huguenin J; Blanc L; Fontaine S. 2012. Dynamique du carbone dans les sols de prairies issues de la déforestation de la forêt amazonienne: Étude d'une chronoséquence en Guyane française. Rencontres Recherches Ruminants 19. http://goo.gl/t6NlTC

Blümmel M; Samad M; Singh OP; Amede T. 2009. Opportunities and limitations of food-feed crops for livestock feeding and implications for livestock-water productivity. Rangeland Journal 31:207–213. DOI: 10.1071/rj09005

Blümmel M; Anandan S; Wright IA. 2012. Improvement of feed resources and livestock feeding in mixed cropping systems. In: Mehra UR; Singh P; Verma AK, eds. Animal Nutrition Advances and Development. Satish Serial Publishing House, New Delhi, India. p. 459−475.

Boddey RM; Macedo R; Tarré R; Ferreira E; Oliveira OCD; Rezende CDP; Cantarutti RB; Pereira JM; Alves BJR; Urquiaga S. 2004. Nitrogen cycling in *Brachiaria* pastures: The key to understanding the process of pasture decline? Agriculture, Ecosystems and Environment 103:389–403. DOI: 10.1016/j.agee.2003.12.010

Boonman JG. 1993. East Africa's grasses and fodders: Their ecology and husbandry. Kluwer Academic Publishers, Dordrecht, Netherlands. DOI: 10.1007/978-94-015-8224-7

Bouwman L; Goldewijk KK; Van der Hoek KW; Beusen AHW; Van Vuuren DP; Willems J; Rufino MC; Stehfest E. 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900−2050 period. Proceedings of the National Academy of Sciences of the United States of America 110:20882–20887. DOI: 10.1073/pnas.1012878108

Bruinsma J. 2009. By how much do land, water and crop yields need to increase by 2050? FAO Expert meeting on how to feed the world in 2050, 24–26 June 2009. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://goo.gl/64ZAI

Bryan E; Ringler C; Okoba B; Koo J; Herrero M; Silvestri S. 2013. Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? Insights from Kenya. Climatic Change 118:151–165. DOI: 10.1007/s10584-012-0640-0

Bungenstab DJ. 2012. Pecuária de corte brasileira: Redução do aquecimento global pela eficiência dos sistemas de produção. Documentos 192. Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Brasilia, DF, Brazil. http://goo.gl/39iXZG

Byerlee D; Collinson MP. 1988. Planning technologies appropriate to farmers: Concepts and procedures. Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT), Mexico, DF, Mexico. http://goo.gl/1nyEFM

Cárdenas A; Reyes B; Ríos N; Woo A; Ramírez E; Ibrahim M. 2007. Impacto de los sistemas silvopastoriles en la calidad del agua de dos microcuencas ganaderas de Matiguás, Nicaragua. Revista Encuentro 39:70−82.

Cardoso JA; Jiménez J; Rincón J; Guevara E; Van der Hoek R; Jarvis A; Peters M; Miles J; Ayarza M; Cajas S; Rincón A; Mateus H; Quiceno J; Barragán W; Lascano C; Argel P; Mena M; Hertentains L; Rao I. 2013. Advances in improving tolerance to waterlogging in *Brachiaria* grasses. Tropical Grasslands−Forrajes Tropicales 1:197−201. DOI: 10.17138/TGFT(1)197-201

Casey JW; Holden NM. 2006. Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units. Journal of Environmental Quality 35:231–239. DOI: 10.2134/jeq2005.0121

Chacón CA. 2005. Evaluación de pasturas de *Brachiaria humidicola* sola y en asociación con *Desmodium ovalifolium*, en sistema de pastoreo rotativo, al norte del estado de Táchira. IX Seminario 'Manejo y utilización de pastos y forrajes en los sistemas de producción animal'. San Cristóbal, Venezuela. p. 138−149. http://goo.gl/66WC9E

CIAT. 2009. Strategic directions. Eco-efficient agriculture for the poor. International Center for Tropical Agriculture (CIAT), Cali, Colombia. http://goo.gl/WfWVdT

Clements RJ; Winter WH; Thomson CJ. 1986. Breeding *Centrosema pascuorum* for northern Australia. Tropical Grasslands 20:59−65. http://goo.gl/IA8ULS

Cohn AS; Mosnier A; Havlik P; Valin H; Herrero M; Schmid E; O'Hare M; Obersteiner M. 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proceedings of the National Academy of Sciences of the United States of America 111:7236−7241. DOI: 10.1073/pnas.1307163111

Cook BG; Pengelly BC; Brown SD; Donnelly JL; Eagles DA; Franco MA; Hanson J; Mullen BF; Partridge IJ; Peters M; Schultze-Kraft R. 2005. Tropical forages: An interactive selection tool. [CD-ROM], CSIRO, DPI&F (Qld), CIAT and ILRI, Brisbane, Australia. www.tropicalforages.info

Darnton A; Elster-Jones J; Lucas K; Brooks M. 2005. Promoting pro-environmental behaviour: Existing evidence to inform better policy making: Summary report. A study for the Department for Environment, Food and Rural Affairs DEFRA UK. The Centre for Sustainable Development, University of Westminster, London, UK. http://goo.gl/hgwRzR

de Fraiture C; Wichelns D; Rockström J; Kemp-Benedict E. 2007. Looking ahead to 2050: Scenarios of alternative investment approaches. In: Molden D, ed. Water for food, water for life: A comprehensive assessment of water management in agriculture. Earthscan, London, UK and International Water Management Institute (IWMI), Colombo, Sri Lanka. http://goo.gl/TJH57s

Delgado C; Rosegrant M; Steinfeld H; Ehui S; Courbois C. 2001. Livestock to 2020: The next food revolution. Outlook on Agriculture 30:27−29. http://goo.gl/IxCTtY

de Vries M; de Boer IJM. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livestock Science 128:1–11. DOI: 10.1016/j.livsci.2009.11.007

Dixon J; Xiaoyun Li; Msangi S; Amede T; Bossio D; Ceballos H; Ospina B; Howeler R; Belum VS; Abaidoo R; Timsina J; Crissman C; Mares V; Quiroz R; Leon-Velarde C; Herrero H; Blümmel M; Holmann F; Peters M; White W; Qadir M; Szonyi J. 2010. Feed, food and fuel: Competition and potential impacts on small-scale crop-livestock-energy farming systems. An assessment commissioned by the CGIAR Systemwide Livestock Program. International Livestock Research Institute (ILRI), Addis Ababa, Ethiopia. https://goo.gl/nIDUru

Douthwaite B; Alvarez BS; Cook S; Davies R; George P; Howell J; Mackay R; Rubiano J. 2007. Participatory impact pathways analysis: A practical application of program theory in research-for-development. Canadian Journal of Program Evaluation 22:127–159. http://goo.gl/2UEIw1

Douxchamps S; Rao IM; Peters M; Van der Hoek R; Schmidt A; Martens S; Polania J; Mena M; Binder C; Scholl R; Mosimann A; Holman F; Quintero M; Kreuzer M; Frossard E; Oberson A. 2014. Farm-scale tradeoffs between legume use as forage versus green manure: The case of *Canavalia brasiliensis*. Agroecology and Sustainable Food Systems 38:25–45. DOI: 10.1080/21683565. 2013.828667

Duncan A; York L; Lukuyu B; Samaddar A; Stür W. 2012. Feed Assessment Tool (FEAST): A systematic method for assessing local feed resource availability and use with a view to designing intervention strategies aimed at optimizing feed utilization. Questionnaire for facilitators (Version 5.3). www.ilri.org/feast

Earl S; Carden F; Smutylo T. 2001. Outcome mapping: Building learning and reflection into development programs. International Development Research Centre (IDRC), Ottawa, Canada. http://goo.gl/mqYuUk

Eisler MC; Tarlton JF; Martin GB; Beddington J; Dungait JAJ; Greathead H; Liu J; Mathew S; Miller H; Misselbrook T; Murray P; Vinod VK; Van Saun R; Winter M. 2014. Steps to sustainable livestock. Nature 507:32–34. DOI: 10.1038/507032a

Elkington J. 1997. Cannibals with forks: The triple bottom line of 21st century business. New Society Publishers, Stony Creek, CT, USA. http://goo.gl/XcHi8C

Eshel G; Shepon A; Markov T; Milo R. 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proceedings of the National Academy of Sciences of the United States of America 111:11996–12001. DOI: 10.1073/pnas.1402183111

FAO. 2009. The state of food and agriculture: Livestock in the balance. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://goo.gl/RRpE5

FAO. 2010. An international consultation on integrated crop-livestock systems for development. The way forward for sustainable production intensification. Integrated Crop Management Vol. 13. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://goo.gl/7Gb9MS

Feder G; Umali DL. 1993. The adoption of agricultural innovations: A review. Technological Forecasting and Social Change 43:215−239. DOI: 10.1016/0040-1625(93)90053-a

Fernandes CD; Grof B; Chakraborty S; Verzignassi JR. 2005. Estilosantes Campo Grande in Brazil: A tropical forage legume success story. Tropical Grasslands 39:223. http://goo.gl/jkUdIQ

Fisher MJ; Rao IM; Ayarza MA; Lascano CE; Sanz JI; Thomas RJ; Vera RR. 1994. Carbon storage by introduced deep-rooted grasses in the south American savannas. Nature 371:236–238. DOI: 10.1038/371236a0

Fisher MJ; Braz SP; Santos RSM dos; Urquiaga S; Alves BJR; Boddey RM. 2007. Another dimension to grazing systems: Soil carbon. Tropical Grasslands 41:65–83. http://goo.gl/Krj1Q8

Foley JA; Ramankutty N; Brauman KA; Cassidy ES; Gerber JS; Johnston M; Mueller ND; O'Connell C; Ray DK; West PC; Balzer C; Bennett EM; Carpenter SR; Hill J; Monfreda C; Polasky S; Rockstrom J; Sheehan J; Siebert S; Tilman D; Zaks DPM. 2011. Solutions for a cultivated planet. Nature 478:337–342. DOI: 10.1038/nature10452

Fonte S; Nesper M; Hegglin D; Velásquez JE; Ramírez B; Rao IM; Bernasconi S; Bünemann EK; Frossard E; Oberson A. 2014. Pasture degradation impacts soil phosphorus dynamics via changes to aggregate-associated soil organic matter in highly weathered tropical soils of Caquetá, Colombia. Soil Biology and Biochemistry 68: 150−157. http://goo.gl/0Gy0sC

Garnett T. 2009. Livestock related greenhouse gas emissions: Impacts and options for policymakers. Environmental Science and Policy 12:491–503. DOI: 10.1016/j.envsci.2009.01.006

Garnett T; Appleby MC; Balmford A; Bateman IJ; Benton TG; Bloomer P; Burlingame B; Dawkins M; Dolan L; Fraser D; Herrero M; Hoffman I; Smith P; Thornton PK; Toulmin C; Vermeulen SJ; Godfray HC. 2013. Sustainable intensification in agriculture: Premises and policies. Science 341:33–34. DOI: 10.1126/science.1234485

Gerber P; Vellinga T; Opio C; Henderson H; Steinfeld H. 2010. Greenhouse gas emissions from the dairy sector: A life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://goo.gl/6Ydd

Gerber P; Steinfeld H; Henderson B; Mottet A; Opio C; Dijkman J; Falcucci A; Tempio G. 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. www.fao.org/docrep/018/i3437e/i3437e.pdf

Giller KE; Tittonell P; Rufino MC; Van Wijk MT; Zingore S; Mapfumo P; Adjei-Nsiah S; Herrero M; Chikowo R;

Corbeels M; Rowe EC; Baijukya F; Mwijage A; Smith J; Yeboah E; Van der Burg WJ; Sanogo AM; Misiko M; de Ridder N; Karanja S; Kaizzi C; K'ungu J; Mwale M; Nwaga D; Pacini C; Vanlauwe B. 2010. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within farming systems to support innovation and development. Agricultural Systems 104:191–203. DOI: 10.1016/j.agsy.2010.07.002

Godfray HCJ; Beddington JR; Crute IR; Haddad L; Lawrence D; Muir JF; Robinson R; Thomas S; Toulmin C. 2010. Food security: The challenge of feeding 9 billion people. Science 327:812–818. DOI: 10.1126/science.1185383

González-Arcia M; Valles-de la Mora B; Alonso-Díaz MA; Castillo-Gallegos E; Ocaña-Zavaleta E; Jarillo-Rodríguez J. 2012. Effect of grazing *Cratylia argentea* associated with *Brachiaria brizantha*-Toledo on pasture quality and weight gain in Holstein x Zebu heifers. Tropical and Subtropical Agroecosystems 15(Sup 2):S1–S11. http://goo.gl/PKDppL

González MS; Van Heurck LM; Romero F; Pezo DA; Argel PJ. 1996. Producción de leche en pasturas de estrella africana (*Cynodon nlemfuensis*) solo y asociado con *Arachis pintoi* o *Desmodium ovalifolium*. Pasturas Tropicales 18(1):2–12. http://goo.gl/kT92c2

Guerrero Pineda Y. 2012. Impacto de créditos verdes del proyecto CAMBIo, en el establecimiento de sistemas silvopastoriles en fincas ganaderas de la Zona Central Norte de Nicaragua. M.Sc. Thesis. Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica.

Havlik P; Valin H; Herrero M; Obersteiner M; Schmid E; Rufino MC; Mosnier A; Thornton PK; Bottcher H; Conant RT; Frank S; Fuss S; Kraxner F; Notenbaert A. 2014. Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences of the United States of America 111:3709–3714. DOI: 10.1073/pnas.1308044111

Haynes RJ. 1983. Soil acidification induced by leguminous crops. Grass and Forage Science 38:1−11. DOI: 10.1111/j.1365-2494.1983.tb01614.x

Herrero M; Thornton PK; Gerber P; Reid RS. 2009. Livestock, livelihoods and the environment: Understanding the trade-offs. Current Opinion in Environmental Sustainability 1:111–120. DOI: 10.1016/j.cosust.2009.10.003

Herrero M; Thornton PK; Notenbaert AM; Wood S; Msangi S; Freeman HA; Bossio D; Dixon J; Peters M; Van de Steeg J; Lynam J; Parthasarathy Rao P; Macmillan S; Gerard B; McDermott J; Seré C; Rosegrant M. 2010. Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. Science 327:822–825. DOI: 10.1126/science.1183725

Herrero M; Thornton PK; Notenbaert A; Msangi S; Wood S; Kruska R; Dixon J; Bossio D; Van de Steeg J; Freeman HA; Li X; Parthasarathy Rao P. 2012. Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human wellbeing to 2030: A study commissioned by the CGIAR Systemwide Livestock Programme. ILRI Project Report. International Livestock Research Institute (ILRI), Nairobi, Kenya. https://goo.gl/5koRZb

Herrero M; Grace D; Njuki J; Johnson N; Enahoro D; Silvestri S; Rufino MC. 2013a. The roles of livestock in developing countries. Animal 7:3–18. DOI: 10.1017/s1751731112001954

Herrero M; Havlik P; Valin H; Notenbaert A; Rufino MC; Thornton PK; Blümmel M; Weiss F; Grace D; Obersteiner M. 2013b. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences of the United States of America 110:20888−20893. DOI: 10.1073/pnas.1308149110

Hill GM; Gates RN; West JW. 2001. Advances in bermudagrass research involving new cultivars for beef and dairy production. Journal of Animal Science 79 (E. Suppl.):E48–E58. http://goo.gl/tdX6Q8

Holmann F; Rivas L; Argel P; Pérez E. 2004. Impacto de la adopción de pastos *Brachiaria*: Centroamerica y México. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Hristov AN; Oh J; Meinen R; Montes F; Ott T; Firkins J; Rotz A; Dell C; Adesogan A; Yang W; Tricarico J; Kebreab E; Waghorn G; Dijkstra J; Oosting S. 2013. Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO_2 emissions. In: Gerber P; Henderson B; Makkar H, eds. FAO Animal Production and Health Paper No. 177, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. www.fao.org/docrep/018/i3288e/i3288e.pdf

Humphreys LR. 1981. Environmental adaptation of tropical pasture plants. McMillan Publishers Ltd., London, UK.

Hutton EM. 1962. Siratro, a tropical pasture legume bred from *Phaseolus atropurpureus*. Australian Journal of Experimental Agriculture and Animal Husbandry 2:117–125. DOI: 10.1071/ea9620117

ILRI; CIAT; ICARDA; World Fish Centre. 2011. More meat, milk, and fish by and for the poor (CGIAR Research Program 3.7): A proposal submitted to the CGIAR Consortium Board by ILRI on behalf of CIAT, ICARDA and WorldFish Centre. International Livestock Research Institute (ILRI), Nairobi, Kenya. http://goo.gl/6TUi5X

Jayanegara A; Kreuzer M; Wina E; Leiber F. 2011. Significance of phenolic compounds in tropical forages for the ruminal bypass of polyunsaturated fatty acids and the appearance of biohydrogenation intermediates as examined *in vitro*. Animal Production Science 51:1127−1136. DOI: 10.1071/an11059

Jones RJ; Galgal KK; Castillo AC; Palmer B; Deocareza A; Bolam M. 1998. Animal production from five species of *Leucaena*. In: Shelton HM; Gutteridge RC; Mullen BF; Bray RA, eds. Leucaena – Adaptation, quality and farm-

ing systems. Proceedings of a workshop held in Hanoi, Vietnam, 9−14 February 1998. ACIAR Proceedings 86, Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. p. 247−252. http://goo.gl/XZ1Uor

Keating B; Carberry P; Thomas S; Clark J. 2013. Eco-efficient agriculture and climate change: Conceptual foundations and frameworks. In: Hershey CH; Neate P, eds. Eco-Efficiency: From vision to reality. International Center for Tropical Agriculture (CIAT), Cali, Colombia. p. 19–28. http://goo.gl/T68Vok

Lal R. 2005. World crop residues production and implications of its use as a biofuel. Environment International 31:575–584. DOI: 10.1016/j.envint.2004. 09.005

Lascano CE. 1994. Nutritive value and animal production of forage *Arachis*. In: Kerridge PC; Hardy B, eds. Biology and agronomy of forage *Arachis.* International Center for Tropical Agriculture (CIAT), Cali, Colombia. p. 109–121. http://goo.gl/UlyiEq

Lascano CE; Estrada J. 1989. Long-term productivity of legume-based and pure grass pastures in the Eastern Plains of Colombia. Proceedings of the XVI International Grassland Congress, Nice, France, 1989. p. 1179–1180.

Lascano CE; Avila P. 1991. Potencial de producción de leche en pasturas solas y asociadas con leguminosas adaptadas a suelos ácidos. Pasturas Tropicales 13(3):2–10. http://goo.gl/AF1uzV

Lascano C; Toro P; Avila P. 2001. Evaluación de sistemas de uso de *Cratylia argentea* para la producción de leche. In: Holmann F; Lascano CE, eds. Sistemas de alimentación con leguminosas para intensificar fincas lecheras. Un proyecto ejecutado por el Consorcio Tropileche. International Center for Tropical Agriculture (CIAT), Cali, Colombia. p. 11–12. http://goo.gl/8AQaXr

Latawiec AE; Strassburg BBN; Valentim JF; Ramos F; Alves-Pinto HM. 2014. Intensification of cattle ranching production systems: Socioeconomic and environmental synergies and risks in Brazil. Animal 8:1255−1263. DOI: 10.1017/s1751731114001566

Lavelle P; Rodríguez N; Arguello O; Bernal J; Botero C; Chaparro P; Gómez Y; Gutiérrez A; Hurtado MP; Loaiza S; Pullido SX; Rodríguez E; Sanabria C; Velásquez E; Fonte SJ. 2014. Soil ecosystem services and land use in the rapidly changing Orinoco river basin of Colombia. Agriculture, Ecosystems and Environment 185:106−117. DOI: 10.1016/j.agee.2013.12.020

Lemaire G; Franzluebbers A; Carvalho PCF; Dedieu B. 2014. Integrated crop-livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agriculture, Ecosystems and Environment 190:4−8. DOI: 10.1016/j.agee.2013.08.009

Macedo MCM. 1997. Sustainability of pasture production in the savannas of tropical America. Proceedings of the XVIII International Grassland Congress, Winnipeg and Saskatoon, Canada, 1997. Vol. 1:391–399.

McCown RL; Winter WH; Andrew MH; Jones RK; Peake DCI. 1986. A preliminary evaluation of legume ley farming in the Australian semi-arid tropics. Proceedings of a workshop on 'Potentials of forage legumes in farming systems of Sub-Saharan Africa', Addis Ababa, Ethiopia, 1985. p. 397–419. http://pdf.usaid.gov/pdf_docs/pnaaw654.pdf

McDermott JJ; Staal SJ; Freeman HA; Herrero M; Van de Steeg JA. 2010. Sustaining intensification of smallholder livestock systems in the tropics. Livestock Science 130:95–109. DOI: 10.1016/j.livsci.2010.02.014

McKenzie-Mohr D. 2000. New ways to promote pro-environmental behaviour: Promoting sustainable behaviour: An introduction to community-based social marketing. Journal of Social Issues 56:543–554. DOI: 10.1111/0022-4537.00183

McTaggart A. 1937. *Stylosanthes*. Journal of the Council of Scientific and Industrial Research 10:201–203.

Miles JW; Valle CB do; Rao IM; Euclides VPB. 2004. Brachiariagrasses. In: Moser L; Burson B; Sollenberger LE, eds. Warm-season (C4) grasses. ASA-CSSA-SSSA, Madison, WI, USA. p. 745–783. DOI: 10.2134/agronmonogr45.c22

Moreta DE; Arango J; Sotelo M; Vergara D; Rincón A; Ishitani N; Castro A; Miles J; Peters M; Tohme J; Subbarao GV; Rao IM. 2014. Biological nitrification inhibition (BNI) in *Brachiaria* pastures: A novel strategy to improve eco-efficiency of crop-livestock systems and to mitigate climate change. Tropical Grasslands–Forrajes Tropicales 2:88–91. DOI: 10.17138/TGFT(2)88-91

Mosier A; Wassmann R; Verchot L. 2004. Methane and nitrogen oxide fluxes in tropical agricultural soils: Sources, sinks and mechanisms. Environment, Development and Sustainability 6:11–49. DOI: 10.1023/b:envi.0000003627.43162.ae

Mupenzi M; Karenzi E; Kanani T; Lussa Burasa A. 2009. Uses of supplement levels of *Stylosanthes scabra* (Stylo) leaf meal on milk yield of Ankole cows. Livestock Research for Rural Development, Vol. 21, Article 63. www.lrrd.org/lrrd21/5/muti21063.htm

Murgueitio E; Calle Z; Uribe F; Calle A; Solorio B. 2011. Native trees and shrubs for the productive rehabilitation of cattle ranching lands. Forest Ecology and Management 261:1654–1663.

Murungweni C; Mabuku O; Manyawu GJ. 2004. Mucuna, Lablab and Paprika calyx as substitutes for commercial protein sources used in dairy and pen-fattening diets by smallholder farmers of Zimbabwe. In: Whitbread AM; Pengelly BC, eds. Tropical legumes for sustainable farming systems in southern Africa and Australia. ACIAR Proceedings No. 115, Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. p. 126−135. http://aciar.gov.au/files/node/555/proc115.pdf

Nakamanee G; Srisomporn W; Phengsavanh P; Samson J; Stür W. 2008. Sale of fresh forage − a new cash crop for smallholder farmers in Yasothon, Thailand. Tropical Grasslands 42:65–74. http://goo.gl/HwgCQ4

Nepstad D; Irwin S; Bezerra T; Boyd W; Stickler C; Shimada J; Carvalho Jr O; MacIntyre K; Dohong A; Alencar A;

Azevedo A; Tepper D; Lowery S. 2013. More food, more forests, fewer emissions, better livelihoods: Linking REDD+, sustainable supply chains and domestic policy in Brazil, Indonesia and Colombia. Carbon Management 2:639–658. DOI: 10.4155/cmt.13.65

Njarui DMG; Mureithi JG; Wandera FP; Muinga RW. 2003. Evaluation of four forage legumes as supplementary feed for Kenya dual-purpose goat in the semi-arid region of Eastern Kenya. Tropical and Subtropical Agroecosystems 3:65–71.

Oliveira OC; Oliveira IP de; Alves BJR; Urquiaga S; Boddey RM. 2004. Chemical and biological indicators of decline/degradation of *Brachiaria* pastures in the Brazilian Cerrado. Agriculture, Ecosystems and Environment 103:289−300. DOI: 10.1016/j.agee.2003.12.004

Oliveira SG; Berchielli TT; Pedreira MS; Primavesi O; Frighetto R; Lima MA. 2007. Effect of tannin levels in sorghum silage and concentrate supplementation on apparent digestibility and methane emission in beef cattle. Animal Feed Science and Technology 135:236–248. DOI: 10.1016/j.anifeedsci.2006.07.012

O'Mara FPO. 2012. The role of grasslands in food security and climate change. Annals of Botany 110:1263–1270. DOI: 10.1093/aob/mcs209

Pagiola S; Agostini P; Gobbi J; de Haan C; Ibrahim M; Murgueitio E; Ramírez E; Rosales M; Ruiz JP. 2004. Paying for biodiversity conservation services in agricultural landscapes. Environment Department Paper No. 96, The World Bank, Washington, DC, USA. https://goo.gl/olJnwZ

Pardey PG; Roseboom J; Beintema N; Chan-Kang C. 1999. Cost Aspects of African Agricultural Research. EPTD Discussion Paper No. 42. International Food Policy Research Institute (IFPRI), Washington, DC, USA and International Service for National Agricultural Research (ISNAR), The Hague, Netherlands. http://goo.gl/DXVxTO

Pelletier N; Tyedmers P. 2010. Forecasting potential global environmental costs of livestock production 2000–2050. Proceedings of the National Academy of Sciences of the United States of America 107:18371–18374. DOI: 10.1073/pnas.1004659107

Pelletier N; Pirog R; Rasmussen R. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems 103:380–389. DOI: 10.1016/j.agsy.2010.03.009

Peters M; Lascano CE; Roothaert R; de Haan NC; 2003. Linking research on forage germplasm to farmers: The pathway to increased adoption – a CIAT, ILRI and IITA perspective. Field Crops Research 84:179–188. DOI: 10.1016/s0378-4290(03)00149-7

Peters M; Rao I; Fisher M; Subbarao G; Martens S; Herrero M; Van der Hoek R; Schultze-Kraft R; Miles J; Castro A; Graefe S; Tiemann T; Ayarza M; Hyman G. 2013a. Tropical forage-based systems to mitigate greenhouse gas emissions. In: Hershey CH; Neate P, eds. Eco-efficiency: From vision to reality. International Center for Tropical Agriculture (CIAT), Cali, Colombia. p. 171–190. http://goo.gl/T68Vok

Peters M; Herrero M; Fisher M; Erb K-H; Rao I; Subbarao GV; Castro A; Arango J; Chara J; Murgueitio E; Van der Hoek R; Läderach P; Hyman G; Tapasco J; Strassburg B; Paul BK; Rincon A; Schultze-Kraft R; Fonte S; Searchinger T. 2013b. Challenges and opportunities for improving eco-efficiency of tropical forage-based systems to mitigate greenhouse gas emissions. Tropical Grasslands–Forrajes Tropicales 1:137–148. DOI: 10.17138/TGFT(1)156-167

Pica-Ciamarra U; Otte J. 2011. The 'livestock revolution': Rhetoric and reality. Outlook on Agriculture 40:7–19. DOI: 10.5367/oa.2011.0030

Pizarro E; Sauma G. 2007. A novel approach for seed forage production by small farmers in South America: SEFO story. In: Hare MD; Wongpichet K, eds. Forages: A pathway to prosperity for smallholder farmers. Proceedings of an International Forage Symposium, March 5–7, 2007. Faculty of Agriculture, Ubon Ratchathani University, Ubon Ratchathani, Thailand. p. 89–102.

Quintero M; Wunder S; Estrada RD. 2009. For services rendered? Modeling hydrology and livelihoods in Andean payments for environmental services schemes. Forest Ecology and Management 258:1871−1880. DOI: 10.1016/j.foreco.2009.04.032

Rahmann G. 2009. Goat milk production under organic farming standards. Tropical Subtropical Forest Ecosystems 11:105–108. http://goo.gl/4GGKFr

Rao IM. 2014. Advances in improving adaptation of common bean and *Brachiaria* forage grasses to abiotic stress in the tropics. In: Pessarakli M, ed. Handbook of plant and crop physiology. 3rd Edn. CRC Press, Boca Raton, FL, USA. p. 847–889.

Rao I; Ishitani M; Miles J; Peters M; Tohme J; Arango J; Moreta DE; López H; Castro A; Van der Hoek R; Martens S; Hyman G; Tapasco J; Duitama J; Suárez H; Borrero G; Núñez J; Hartmann K; Domínguez M; Sotelo M; Vergara D; Lavelle P; Subbarao GV; Rincón A; Plazas C; Mendoza R; Rathjen L; Karwat H; Cadisch G. 2014. Climate-smart crop-livestock systems for smallholders in the tropics: Integration of new forage hybrids to intensify agriculture and to mitigate climate change through regulation of nitrification in soil. Tropical Grasslands–Forrajes Tropicales 2:130–132. DOI: 10.17138/TGFT(2)130-132

Ray DK; Ramankutty N; Mueller ND; West PC; Foley JA. 2012. Recent patterns of crop yield growth and stagnation. Nature Communications 3:1293. DOI: 10.1038/ncomms2296

Richardson DM; Pysek P. 2012. Naturalization of introduced plants: Ecological drivers of biogeographical patterns. New Phytologist 196:383−396. DOI: 10.1111/j.1469-8137.2012.04292.x

Ripple WJ; Smith P; Haberl H; Montzka SA; McAlpine C; Boucher DH. 2014. Ruminants, climate change and

climate policy. Nature Climate Change 4:2–5. DOI: 10.1038/nclimate2081

Robinson L. 2012. Changeology: How to enable groups, communities and societies to do things they've never done before. UIT Cambridge Ltd, Cambridge, UK.

Rockström J; Lannerstad M; Falkenmark M. 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences of the United States of America 104:6253–6260. DOI: 10.1073/pnas.0605739104

Rosegrant MW; Fernandez M; Sinha A; Alder J; Ahammad H; de Fraiture C; Eickhout B; Fonseca J; Huang J; Koyama O; Omezzine AM; Pingali P; Ramirez R; Ringler C; Robinson S; Thornton P; Van Vuuren D; Yana-Shapiro H; Ebi K; Kruska R; Munjal P; Narrod C; Ray S; Sulser T; Tamagno C; Van Oorschot M; Zhu T. 2009. Looking into the future for agriculture and AKST (Agricultural Knowledge, Science and Technology). In: McIntyre BD; Herren HR; Wakhungu J; Watson RT, eds. Agriculture at a crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) global report. Island Press, Washington, DC, USA. p. 307–376. http://goo.gl/peyoYN

Rousseau L; Fonte SJ; Téllez O; Van der Hoek R; Lavelle P. 2013. Soil macrofauna as indicators of land use impacts and soil quality in agricultural landscapes of northern Nicaragua. Ecological Indicators 27:71–82. DOI: 10.1016/j.ecolind.2012.11.020

Rufino MC; Tittonell P; Van Wijk MT; Castellanos-Navarette A; Delve RJ; de Ridder N; Giller KE. 2007. Manure as a key resource within smallholder farming systems: Analyzing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livestock Science 112:273–287. DOI: 10.1016/j.livsci.2007.09.011

Sander K; Cranford M. 2010. Financing environmental services in developing countries. The World Bank, Washington, DC, USA. https://goo.gl/U6xYZb

Scholes RJ; Palm CA; Hickman JE. 2014. Agriculture and climate change mitigation in the developing world. Working Paper No. 61. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. http://goo.gl/bmhl4e

Schultze-Kraft R; Peters M. 1997. Tropical legumes in agricultural production and resource management: An overview. Giessener Beiträge zur Entwicklungsforschung 24:1−17.

Schultze-Kraft R; Rao I; Peters M. 2014. Tropical legumes and the environment. In: Rodrigues RC; Araújo JS; Parente MO, eds. Anais do 2º Simpósio Maranhense de produção de ruminantes a pasto (II SIMPRUPASTO): O conhecimento e a tecnologia visando à mitigação de impactos ambientais. Editora da Universidade Federal do Maranhão, São Luis, MA, Brazil. p. 31−53.

Seré C; Steinfeld S. 1996. World livestock production systems: Current status, issues and trends. FAO Animal Production and Health Paper 127. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. www.fao.org/3/a-w0027e.pdf

Shaw NH; Mannetje L't. 1970. Studies on a spear grass pasture in central coastal Queensland − The effect of fertilizer, stocking rate and oversowing with *Stylosanthes humilis* on beef production and botanical composition. Tropical Grasslands 4:43−56. http://goo.gl/DvLmQn

Shelton HM; Franzel S; Peters M. 2005. Adoption of tropical legume technology around the world: Analysis of success. Tropical Grasslands 39:198−209. http://goo.gl/JqdQCp

Smith J; Sones K; Grace D; MacMillan S; Tarawali S; Herrero M. 2013a. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers 3:6–13. DOI: 10.2527/af.2013-0002

Smith J; Tarawali S; Grace D; Sones K. 2013b. Feeding the world in 2050: Trade-offs, synergies and tough choices for the livestock sector. Tropical Grasslands–Forrajes Tropicales 1:125–136. DOI: 10.17138/TGFT(1)125-136

Smith P; Martino D; Cai Z; Gwary D; Janzen H; Kumar P; McCarl B; Ogle S; O'Mara F; Rice C; Scholes B; Sirotenko O; Howden M; McAllister T; Pan G; Romanekov V; Schneider U; Towprayon S; Wattenbach M; Smith J. 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B 363:789–813. DOI: 10.1098/rstb.2007.2184

Soussana JF; Tallec T; Blanfort V. 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4:334–350. DOI: 10.1017/s1751731109990784

Steinfeld H; Gerber P; Wassenaar T; Castel V; Rosales M; de Haan C. 2006a. Livestock's long shadow: Environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://goo.gl/MQIXE

Steinfeld H; Wassenaar T; Jutzi S. 2006b. Livestock production systems in developing countries: Status, drivers, trends. Revue Scientifique et Technique de L'office International des Epizooties 25:505–516. https://goo.gl/guKCLO

Steinfeld H; Gerber P. 2010. Livestock production and the global environment: Consume less or produce better. Proceedings of the National Academy of Sciences of the United States of America 107:18237–18238. DOI: 10.1073/pnas.1012541107

Strassburg BN; Latawiec AE; Barioni LG; Nobre CA; Silva VP da; Valentim JF; Vianna M; Assad ED. 2014. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Global Environmental Change 28:84−97. DOI: 10.1016/j.gloenvcha.2014.06.001

Subbarao GV; Nakahara K; Hurtado MP; Ono H; Moreta DE; Salcedo AF; Yoshihashi AT; Ishikawa T; Ishitani M; Ohnishi-Kameyama M; Yoshida M; Rondón M; Rao IM; Lascano CE; Berry WL; Ito O. 2009. Evidence for biological nitrification inhibition in *Brachiaria* pastures.

Proceedings of the National Academy of Sciences of the United States of America 106:17302–17307. DOI: 10.1073/pnas.0903694106

Subbarao GV; Yoshihashi T; Worthington M; Nakahara K; Ando Y; Sahrawat KL; Rao IM; Lata JC; Kishii M; Braun HJ. 2015. Suppression of soil nitrification by plants. Plant Science 233:155−164. http://goo.gl/jByZwg

The Montpellier Panel. 2013. Sustainable intensification: A new paradigm for African agriculture. Imperial College, London, UK. https://goo.gl/lnZ3yQ

Thomas RJ; Lascano CE. 1995. The benefits of forage legumes for livestock production and nutrient cycling in pasture and agropastoral systems of acid-soil savannahs of Latin America. In: Powell JM; Fernández-Rivera S; Williams TO; Renard C, eds. Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II: Technical papers. Proceedings of an International Conference held in Addis Ababa, Ethiopia, 22−26 November 1993. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia. p. 277–292. https://goo.gl/p5GPBh

Thomassen MA; Van Calker KJ; Smits MCJ; Iepema GL; de Boer IJM. 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. Agricultural Systems 96:95–107. DOI: 10.1016/j.agsy. 2007. 06.001

Thornton PK. 2010. Livestock production: Recent trends, future prospects. Philosophical Transactions of the Royal Society B 365:2853−2867. DOI: 10.1098/rstb.2010.0134

Thornton P; Herrero M. 2010. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proceedings of the National Academy of Sciences of the United States of America 107:19667–19672. DOI: 10.1073/pnas.0912890107

UNDESA. 2012. World population prospects: The 2012 revision, highlights and advance tables. Working Paper No. ESA/P/WP.228. Population Division, Department of Economic and Social Affairs of the United Nations, New York, USA. http://goo.gl/OeEFvm

Van Noordwijk M; Leimona B. 2010. Principles for fairness and efficiency in enhancing environmental services in Asia: Payments, compensation, or co-investment? Ecology and Society 15(4):17. http://goo.gl/lT1rYZ

Velásquez E; Fonte SJ; Barot S; Grimaldi M; Desjardins T; Lavelle P. 2012. Soil macrofauna-mediated impacts of plant species composition on soil functioning in Amazonian pastures. Applied Soil Ecology 56:43−50. DOI: 10.1016/j.apsoil.2012.01.008

Waghorn GC; Tavendale MH; Woodfield DR. 2002. Methanogenesis in forages fed to sheep. Proceedings of the New Zealand Grassland Association 64:167−171. http://goo.gl/VyOPDy

Wassena FJ; Lukuyu B; Mangesho WE; Laswai GH; Bwire JMN; Kimambo AE; Maass BL. 2013. Determining feed resources and feeding circumstances by applying FEAST: Usefulness and lessons learned in Tanzania. Tropentag 2013: Agricultural development within the rural-urban continuum. Hohenheim, Germany. Book of abstracts. p. 353. http://goo.gl/2YvRFD

White D; Peters M; Horne P. 2013. Global impacts from improved tropical forages: A meta-analysis revealing overlooked benefits and costs, evolving values and new priorities. Tropical Grasslands–Forrajes Tropicales 1:12–24. DOI: 10.17138/TGFT(1)12-24

Wirsenius S. 2003. The biomass metabolism of the food system: A model based survey of the global and regional turnover of food biomass. Journal of Industrial Ecology 7:47–80. DOI: 10.1162/108819803766729195

Woodward SL; Waghorn GC; Laboyrie P. 2004. Condensed tannins in birdsfoot trefoil (*Lotus corniculatus*) reduced methane emissions from dairy cows. Proceedings of the New Zealand Society of Animal Production 64:160–164. www.sciquest.org.nz/node/41496

Wunder S. 2005. Payments for environmental services: Some nuts and bolts. CIFOR Occasional Paper No. 42, Center for International Forestry Research (CIFOR), Bogor, Indonesia. http://goo.gl/chPAvO

Zhiping Q; Rao IM; Ricaurte J; Amézquita E; Sanz J; Kerridge P. 2004. Root distribution and nutrient uptake in crop-forage systems on Andean hillsides. Journal of Sustainable Agriculture 23:39–50. DOI: 10.1300/ j064v23n04_05

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Evaluation of new hybrid brachiaria lines in Thailand. 1. Forage production and quality

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Abstract

Forty-three new hybrid bracharia lines were evaluated for forage accumulation and nutritive value in Northeast Thailand from 2006 to 2011 in experiments at 2 sites, using Mulato II hybrid brachiaria as a standard for comparison. The parameters evaluated were wet and dry season dry matter (DM) accumulation, leaf:stem ratio, crude protein (CP) concentration and fiber level [acid detergent fiber (ADF) and neutral detergent fiber (NDF)]. No lines consistently displayed superior dry season forage accumulation and leaf:stem ratio over Mulato II. In the wet seasons, 14 lines produced more DM than Mulato II but in only one wet season each. Mulato II produced forage with high leaf:stem ratio in all seasons. Many lines did have significantly higher CP concentrations and lower levels of ADF and NDF than Mulato II, but their forage accumulation and leaf:stem ratio were inferior. Four lines (BR02/1718, BR02/1752, BR02/1794 and BR02/0465) were granted Plant Variety Rights in 2011.

Resumen

En el período 2006–2011 en 2 sitios del noreste de Tailandia (Ubon Ratchathani y Amnart Charoen) fueron evaluadas por su producción de forraje y calidad nutritiva 43 líneas nuevas de híbridos de *Brachiaria*, incluyendo el cultivar (cv.) Mulato II como testigo, procedentes del CIAT. Los parámetros evaluados fueron producción de materia seca (MS) en épocas lluviosa y seca, relación hoja:tallo, concentración de proteína cruda (PC) y niveles de fibra detergente ácido (FDA) y fibra detergente neutro (FDN)]. En la época seca, ninguna de las líneas mostró en forma consistente una producción de MS y relación hoja:tallo superiores que cv. Mulato II. En las épocas lluviosas, 14 líneas produjeron más MS que Mulato II, pero sólo en una época lluviosa cada una. El cultivar Mulato II produjo forraje con alta relación hoja:tallo en todas las épocas. Varias de las líneas presentaron concentraciones de PC significativamente mayores y menores niveles de FDA y FDN que cv. Mulato II, pero su producción de forraje y la relación hoja:tallo fueron inferiores. Las líneas BR02/1718, BR02/1752, BR02/1794 y BR02/0465 alcanzaron la protección de obtención vegetal (*Plant Variety Rights*) en 2011.

Introduction

In 1988 CIAT (Centro Internacional de Agricultura Tropical) in Colombia and EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) in Brazil began breeding programs on hybridization of brachiaria grasses (Miles et al. 2004). Mulato hybrid brachiaria [*Brachiaria ruziziensis* (now *Urochloa ruziziensis*) x *B. brizantha* (now *U. brizantha*)] was the first hybrid brachiaria cultivar released from the breeding program. Mulato was granted Plant Variety Rights in 2002 (Loch and Miles 2002) and released by the Mexican seed company Grupo Papalotla in 2004 (Miles et al. 2004). Mulato had high forage yields and forage nutritive value but produced very low seed yields (Hare et al. 2007a). Mulato II (*B. ruziziensis* x *B. decumbens* (now *U. decumbens*) x *B. brizantha*), the second hybrid brachiaria cultivar released, was granted Plant Variety Rights in 2004 (Loch and Miles 2004) and released by Grupo Papalotla

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in 2005 (Argel et al. 2007). Mulato II was similar to Mulato but demonstrated excellent drought tolerance and superior seed yields (Hare et al. 2007b; 2007c) and in 2005, Grupo Papalotla replaced Mulato with Mulato II.

From 2006 to 2011, further studies were conducted by Grupo Papalotla in Thailand on selected lines from the BR02 and BR06 hybrid brachiaria collections from CIAT, and 2 lines from the MX02 collection from Mexico, with the aim of identifying lines with overall superior forage attributes. BR02 and BR06 are the names of new hybrid progeny from the CIAT breeding program in spaced plant trials in Colombia between 2002 and 2006. MX02 is the name given to new hybrid progeny, from original BR0 progeny that were further evaluated by Grupo Papalotla in Mexico during 2002–2005. New cultivar selection in the Thailand experiments focused on dry matter yield, forage nutritive value, seed production, drought tolerance and persistence.

This paper describes these studies on forage accumulation and nutritive value of hybrid brachiaria lines. A second paper (Hare et al. 2015) describes research on the seed production of these same lines.

Materials and Methods

Experiment 1 – BR02 and MX02 collections

A field experiment was conducted at Ubon Ratchathani University, Thailand, (15° N, 104° E; 130 masl) from 2006 to 2008. The site was on an upland sandy low humic gley (Paleaquult) soil (Roi-et series) (Mitsuchi et al. 1986). Soil samples, taken at planting in May 2006, showed that the soil was acid (pH 4.6; water method), and low in organic matter (1.1%), N (0.04%), P (3.5 ppm; Bray II extraction method) and K (27.4 ppm). Prior to planting the experiment, the site had grown a mixture of native grasses and legumes for many years. Thirteen hybrid brachiaria lines from the BR02 collection, 2 from the MX02 collection and cv. Mulato II (Table 3) were planted in June 2006 in a randomized complete block design with 4 replications; details of field crop management are presented in Table 1. Seedlings were grown in a nursery and transplanted into the field plots with 50 x 50 cm spacings (60 plants per plot). At each sampling cut, the forage in six 0.25 m^2 quadrats per plot was cut 5 cm from ground level and weighed fresh. A 300 g subsample was sorted into leaves and stems and dried at 70 °C for 48 h to determine dry weight. The dried subsamples were analyzed for total N (Kjeldahl method) in order to calculate crude protein (CP, %N x 6.25), acid detergent fiber (ADF, Van Soest method) and neutral detergent fiber (NDF, Van Soest method) concentrations. After each sampling cut, the remaining herbage in the plots was cut to 5 cm from ground level and removed.

Experiment 2 – BR06 collection

This study was conducted at a site, 90 km north of Ubon Ratchathani University, at the Amnart Charoen Livestock Development Centre, Amnart Charoen province, Northeast Thailand (15.5° N, 104.4° E; elevation 168 masl) from 2008 to 2011. The site was on an upland sandy reddish brown earth (Haplustalf) soil (Chatturat series) (Mitsuchi et al. 1986). Soil samples taken at planting in July 2008 showed that the soil was acid (pH 4.6; water method), very sandy (75% sand), and low in organic matter (0.4%), N (0.04%) and K (31 ppm), and adequate for P (25.2 ppm; Bray II extraction method). Prior to cultivation, the site had been growing Tanzania guinea grass (*Panicum maximum*, now *Megathyrsus maximus*) for 5 years.

Twenty-eight hybrid brachiaria lines from the BR06 collection, 4 from the BR02 collection (Table 7), and

Table 1. Field crop management during evaluation of hybrid brachiaria lines (Experiment 1).

Field cultivation	Plowing x 2, disking x 1, harrowing x 1
Plot size	3 m x 5 m with 50 cm walkway around plots and 1 m between replications
Planting date	1–5 Jun 2006
Cleaning cut	3 Aug 2006; all plots cut to 5 cm above ground level
Sampling harvests	
First wet season	2006: 13 Sep & 2 Nov
First dry season	2007: 10 Jan, 21 Mar & 30 Apr
Second wet season	2007: 11 Jun, 26 Jul, 10 Sep & 29 Oct
Second dry season	2008: 2 Jan & 25 Apr
Harvest quadrats/plot	Six 0.25 m^2 random quadrats
Fertilizer	Nil at planting; 200 kg/ha NPK (15:15:15) after every harvest

cvv. Mulato II, Toledo (*B. brizantha*) and Marandu (*B. brizantha*) were planted in a randomized complete block design with 4 replications in July 2008. Seedlings were grown in a nursery and transplanted into the field plots in 50 x 50 cm spacings (48 plants per plot). Details of crop management are presented in Table 2. Sampling and laboratory analyses were the same as for Trial 1.

Data from the experiments were subjected to analysis of variance, using the IRRISTAT program from the International Rice Research Institute (IRRI). Entry means were compared by Fisher's protected LSD ($P \leq 0.05$).

Results

Rainfall

Experiment 1 – BR02 and MX02 collections. Rainfall at Ubon Ratchathani in 2006 and 2007 was 9 and 11%, respectively, below the 13-yr mean (Figure 1). Rainfall in the dry seasons (Nov–Apr) was above average in 2006/2007 (33%) but nearly 90% below average in 2007/2008, with only 26 mm falling from November to April.

Table 2. Field crop management during evaluation of hybrid brachiaria lines (Experiment 2).

Field cultivation	Plowing x 2, disking x 1, harrowing x 1
Plot size	3 m x 4 m with 50 cm walkway around plots and 1 m between replications
Planting date	26–28 Jul 2008
Cleaning cut	8 Sep 2008; all plots cut to 5 cm above ground level
Sampling harvests	
First wet season	2008: 20 Oct
First dry season	2008: 18 Dec
	2009: 28 Apr
Second wet season	2009: 16 Jun, 3 Aug, 15 Sep & 29 Oct
Second dry season	2010: 19 Jan & 27 Apr
Third wet season	2010: 9 Jun, 4 Aug, 14 Sept & 26 Oct
Third dry season	2011: 26 Apr
Harvest quadrats/plot	Six 0.25 m^2 random quadrats
Fertilizer	Nil at planting; 200 kg/ha NPK (15:15:15) after every harvest

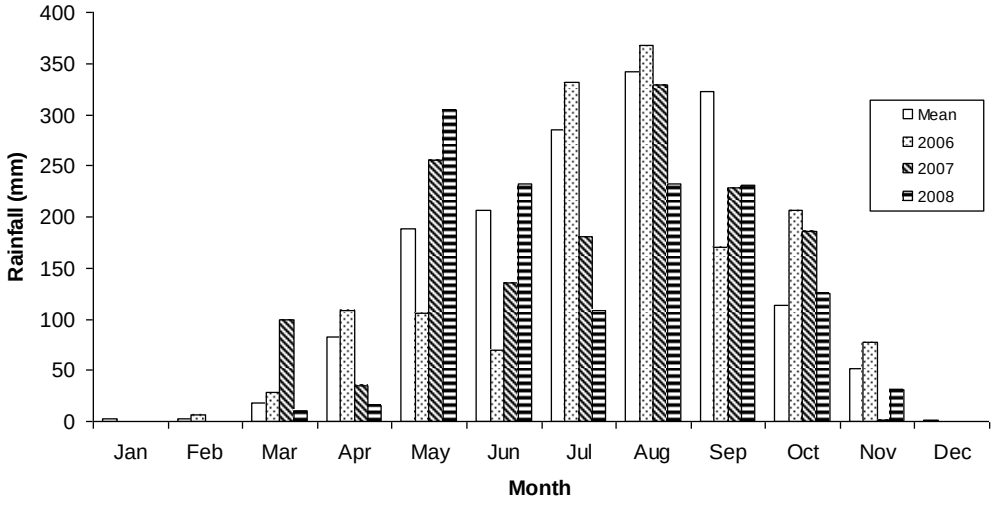

Figure 1. Rainfall at the Ubon Ratchathani University meteorological station, 1 km from the research site, during the experiment and the 13-yr mean (2000–2012).

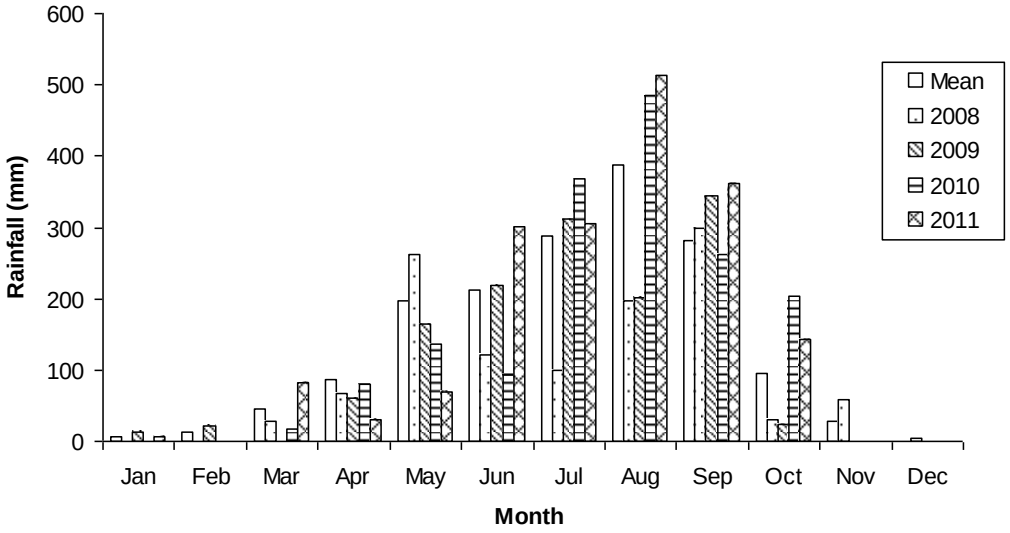

Figure 2. Rainfall at the Amnart Charoen meteorological station, 9 km from the research site, during the experiment and the 13-yr mean (2000–2012).

Experiment 2 – BR06 collection. Rainfall at Amnart Charoen in 2008 and 2009 was, respectively, 30 and 20% below the 13-yr mean, but 2010 rainfall was slightly above the mean (Figure 2). Rainfall in the dry seasons (Nov–Apr) during the experiment was 30% (2008/2009), 47% (2009/2010) and 74% (2010/2011) below the mean.

Forage accumulation and nutritive value

Experiment 1 – BR02 and MX02 collections. Only 2 lines accumulated more DM than Mulato II: BR02/1752 in the first dry season and second wet season and BR02/1718 in the second dry season (Table 3). BR02/0768 was the only line that produced a higher leaf proportion than Mulato II, which was in the second dry season.

Crude protein concentrations were higher in the dry season than in the wet season and higher in leaves than in stems (Table 4). BR02/1452 had higher CP concentrations than Mulato II in both seasons and plant parts.

ADF concentrations were lower in the dry season than in the wet season and in leaves than in stems (Table 4). BR02/1752, 1794 and 1452 had overall lower ADF concentrations than Mulato II, while BR02/0465 and MX02/1263 had higher ADF concentrations.

Lower NDF concentrations were found in the dry season than in the wet season and in leaves than in stems (Table 4). BR02/1752 had lower overall NDF concentrations, while BR02/0465 and MX02/1263 had higher NDF concentrations.

Experiment 2 – BR06 collection. Several BR06 lines accumulated significantly more DM than Mulato II: BR06/0206, 0387, 0423, 0850, 1348, 1366, 1388, 1454 and 2058 and Marandu in the first wet season; and BR06/0206, 1175, 1278, 1415 and 1454 in the third wet season (Table 5). In the second wet season, only Toledo accumulated more DM than Mulato II, while all BR06 lines, except for BR06/1000, 1278 and 1696, accumulated significantly less DM than Mulato II.

No lines or cultivars accumulated significantly more DM than Mulato II in the dry seasons (Table 5). In the first dry season, Mulato II accumulated significantly more DM than more than half the BR06 lines, BR02/1718 and BR02/1372. In the second dry season, DM accumulation was similar for all lines and cultivars, as it was in the third dry season, except for BR06/1433, 1567 and 1922, which produced significantly less DM than Mulato II.

No hybrid line or cultivar produced a higher leaf proportion than Mulato II throughout the trial at Amnart Charoen (Table 6). Mulato II produced a higher leaf proportion than all hybrids and other cultivars in all seasons, except: Marandu, BR06/1000, 1567, 1932 and 2020 in the first wet season; Toledo, BR02/1372, BR06/0012, 0387, 0531, 0584, 1000, 1175 and 1922 in the first dry season; BR06/0204 and 0423 and Toledo in the second wet season; and BR06/1922 in the second and third dry seasons.

Table 3. Dry matter accumulation and leaf percentages in forage DM of hybrid brachiaria lines in wet (May–October) and dry (November–April) seasons from 2006 to 2008 in Ubon Ratchathani, Thailand.

Hybrid line/ cultivar	Dry matter accumulation (kg/ha)				Leaf percentage (%)			
	First year		Second year		First year		Second year	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Mulato II	4,460	3,280	10,570	2,320	69	85	72	81
BR02/0465	3,720	3,240	11,590	2,480	66	77	66	78
BR02/0768	3,680	3,910	10,650	2,240	68	87	74	88
BR02/0771	3,770	3,580	10,870	2,330	70	80	71	83
BR02/0799	3,650	2,460	10,730	2,520	64	85	63	80
BR02/1245	3,900	3,370	10,400	2,170	62	78	64	80
BR02/1372	3,910	3,960	8,720	2,460	60	76	66	78
BR02/1452	2,680	2,320	7,670	1,930	70	80	67	80
BR02/1485	4,920	3,410	11,790	2,560	60	81	65	79
BR02/1718	4,790	3,710	10,390	2,930	51	77	67	76
BR02/1728	3,810	3,510	10,560	2,160	63	79	56	81
BR02/1747	4,230	3,220	10,540	2,280	51	77	56	76
BR02/1752	4,200	3,990	12,600	2,160	60	78	55	79
BR02/1794	3,700	3,300	11,150	2,500	61	78	55	77
MX02/1263	5,010	3,230	10,860	2,110	63	81	66	80
MX02/1423	4,150	3,190	10,570	2,050	56	77	56	73
Mean	4,040	3,360	10,640	2,230	62	80	64	79
LSD (P<0.05)	990	700	1,350	430	5.2	4.2	3.7	4.7
F ratio	2.78	3.48	5.73	2.62	10.06	5.39	22.56	4.11
Probability	0.004	<0.001	<0.001	0.006	<0.001	<0.001	<0.001	<0.001

Table 4. Average crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) concentrations in stem (S) and leaf (L) of hybrid brachiaria lines in wet (May–October) and dry (November–April) seasons from 2006 to 2008 in Ubon Ratchathani, Thailand.

Hybrid line/ cultivar	CP (%)				ADF (%)				NDF (%)			
	Wet		Dry		Wet		Dry		Wet		Dry	
	S	L	S	L	S	L	S	L	S	L	S	L
Mulato II	4.7	8.6	5.9	9.7	37.4	30.9	33.1	28.6	66.0	58.4	62.1	53.5
BR02/0465	4.5	9.1	6.2	10.1	39.5	33.7	34.3	30.5	67.0	61.3	63.2	57.4
BR02/0768	4.5	8.9	6.4	9.6	37.8	29.6	32.7	27.1	65.7	58.0	60.5	53.2
BR02/0771	5.5	9.9	7.2	9.8	38.3	29.7	33.9	27.0	65.3	56.8	61.7	52.6
BR02/0799	5.4	8.2	7.7	10.1	36.4	29.5	30.8	26.2	64.8	59.3	61.1	54.9
BR02/1245	4.3	8.1	6.0	9.3	40.1	30.4	34.2	27.1	68.7	58.3	63.6	54.8
BR02/1372	4.9	8.9	6.0	9.4	38.5	30.9	35.3	27.0	65.5	56.9	62.7	53.4
BR02/1452	5.4	9.6	7.3	10.2	37.3	29.4	33.4	26.0	66.3	56.6	61.7	51.9
BR02/1485	4.4	9.2	6.3	9.7	39.5	30.0	34.7	28.0	67.6	59.0	64.6	53.8
BR02/1718	5.2	9.4	7.0	9.4	37.5	32.3	31.6	27.6	63.2	56.6	59.4	53.0
BR02/1728	4.8	9.6	6.1	9.8	39.8	31.1	35.6	29.0	66.6	59.2	64.3	54.8
BR02/1747	4.4	8.7	5.7	8.9	38.2	32.3	32.5	29.5	66.9	57.3	62.3	54.4
BR02/1752	4.1	9.1	5.8	8.7	36.6	30.0	32.4	27.8	65.8	57.0	60.5	52.5
BR02/1794	4.4	8.6	6.3	8.8	38.2	30.8	32.8	27.2	66.3	58.6	61.9	52.6
MX02/1263	4.1	8.1	6.6	9.7	40.0	29.7	34.5	29.9	69.9	60.6	63.9	54.1
MX02/1423	4.4	8.8	6.4	9.9	39.8	29.1	34.1	27.0	66.9	57.2	61.9	52.6
Mean	4.7	8.9	6.4	9.6	38.4	30.6	33.5	27.8	66.4	58.2	62.2	53.7
LSD (P<0.05)	0.59	0.90	0.90	0.81	0.93	0.82	0.79	0.76	1.00	0.91	0.85	0.73
F ratio	7.17	15.47	21.7	5.1	23.1	58.9	24.6	22.7	61.5	31.0	48.3	51.5
Probability	<0.001	0.001	0.014	0.007	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 5. Dry matter accumulation (kg/ha) of hybrid brachiaria lines and cultivars in wet (May–October) and dry (November–April) seasons from 2008 to 2011 in Amnart Charoen, Thailand.

Hybrid line/	First year 2008/2009		Second year 2009/2010		Third year 2010/2011	
cultivar	Wet	Dry	Wet	Dry	Wet	Dry
Mulato II	1,990	4,390	9,770	1,280	5,940	1,070
BR02/1794	2,670	3,680	8,790	1,150	5,300	930
BR02/0465	1,490	4,030	10,730	1,540	5,870	1,180
BR02/1718	2,390	3,490	9,340	1,300	5,430	1,210
BR02/1372	2,370	3,140	7,390	1,410	5,330	1,170
Marandu	3,110	4,240	9,360	1,270	6,620	1,300
Toledo	2,800	4,340	11,690	940	5,970	1,140
BR06/0012	2,260	3,270	7,040	1,200	6,120	890
BR06/0204	2,290	3,110	6,930	1,160	6,000	650
BR06/0206	2,990	3,870	8,330	1,240	7,510	810
BR06/0387	2,870	3,070	6,560	1,300	6,260	850
BR06/0405	2,680	3,390	7,480	1,200	6,280	890
BR06/0423	3,290	3,740	7,710	1,450	6,580	1,280
BR06/0531	2,630	4,050	8,520	1,510	6,860	1,130
BR06/0584	2,610	3,660	7,640	1,160	6,190	790
BR06/0850	2,890	3,940	8,590	1,020	6,530	690
BR06/1000	2,330	3,210	8,730	1,630	7,690	780
BR06/1132	2,460	3,430	7,190	970	6,360	760
BR06/1175	2,480	3,330	7,680	1,270	7,180	860
BR06/1254	2,820	3,200	7,980	1,240	6,770	1,010
BR06/1278	2,860	3,910	8,820	1,880	7,650	1,440
BR06/1348	3,090	4,390	8,460	1,200	6,860	740
BR06/1366	3,030	3,410	8,040	1,180	6,700	990
BR06/1388	2,890	3,910	7,250	1,140	5,960	790
BR06/1415	2,760	3,430	7,460	1,050	7,790	810
BR06/1433	2,800	3,410	6,930	790	6,270	580
BR06/1454	2,960	3,480	8,150	1,230	7,870	900
BR06/1567	1,940	3,660	7,110	860	4,430	610
BR06/1696	2,750	3,660	8,820	1,740	6,320	1,090
BR06/1832	2,820	3,750	6,810	1,340	5,160	1,170
BR06/1922	2,740	2,970	6,710	880	4,090	540
BR06/1932	2,470	3,450	8,410	1,420	6,060	1,010
BR06/2020	2,380	3,740	8,190	1,260	6,100	810
BR06/2058	2,970	3,300	8,210	1,150	4,820	900
BR06/2204	2,420	3,240	7,280	1,280	4,910	1,040
Mean	2,640	3,610	8,120	1,250	6,220	940
LSD (P<0.05)	870	780	1,160	ns	1,190	420
F ratio	2.70	2.83	5.20	1.24	4.83	1.77
Probability	<0.001	<0.001	<0.001	0.202	<0.001	0.002

Crude protein concentrations in forage were higher in the dry season than the wet season and in leaves than in stems (Table 7). All BR06 lines had CP concentrations either significantly higher than or similar to those of Mulato II in both stems and leaves in the wet season and in stems in the dry season, while only BR06/1922 and 2058 had significantly higher dry season leaf CP levels than Mulato II.

ADF and NDF concentrations varied between seasons, plant parts and hybrid lines (Table 7). Dry season concentrations were lower than in the wet and leaf concentrations were lower than in stems. Most BR06 hybrid lines had significantly lower dry season leaf ADF and leaf and stem NDF concentrations than Mulato II, while some had lower leaf and stem ADF concentrations in the wet season. While leaf NDF concentrations in the wet season in the BR06 hybrid lines were generally lower than in Mulato II, stem NDF concentrations were generally higher in the hybrids.

Table 6. Leaf proportion (%) of forage DM of hybrid brachiaria lines and cultivars in wet (May–October) and dry (November–April) seasons from 2008 to 2011 in Amnart Charoen, Thailand.

Hybrid line/	First year 2008/2009		Second year 2009/2010		Third year 2010/2011	
cultivar	Wet	Dry	Wet	Dry	Wet	Dry
Mulato II	66	74	70	83	72	88
BR02/1794	52	70	54	75	56	81
BR02/0465	56	67	65	73	65	78
BR02/1718	38	69	64	73	67	76
BR02/1372	43	72	67	76	68	81
Marandu	60	74	63	77	64	80
Toledo	64	73	68	76	69	78
BR06/0012	58	75	64	76	65	77
BR06/0204	61	60	69	69	64	77
BR06/0206	49	67	63	71	64	75
BR06/0387	52	72	66	75	63	79
BR06/0405	33	69	55	73	61	78
BR06/0423	58	70	68	72	66	73
BR06/0531	58	72	66	76	67	76
BR06/0584	54	72	65	72	64	73
BR06/0850	52	62	51	65	54	68
BR06/1000	64	75	62	77	64	79
BR06/1132	40	61	61	68	63	76
BR06/1175	53	75	57	77	62	80
BR06/1254	57	68	65	74	65	80
BR06/1278	58	70	61	72	66	73
BR06/1348	50	65	64	68	62	71
BR06/1366	28	62	55	67	61	71
BR06/1388	40	66	54	66	57	67
BR06/1415	57	68	61	70	61	72
BR06/1433	45	69	59	72	64	74
BR06/1454	51	69	56	70	62	72
BR06/1567	62	69	65	72	63	76
BR06/1696	55	69	62	72	59	75
BR06/1832	52	65	60	67	58	68
BR06/1922	54	76	62	81	65	86
BR06/1932	60	72	65	74	63	75
BR06/2020	60	66	58	71	60	75
BR06/2058	41	70	66	74	64	78
BR06/2204	58	70	66	72	67	76
Mean	53	69	62	74	63	76
LSD (P<0.05)	7.2	3.8	2.9	4.3	2.6	4.8
F ratio	12.15	8.95	20.18	7.89	15.77	6.91
Probability	<0.001	<0.001	<0.001	<0.001	0.110	<0.001

Table 7. Average wet season (May–October) and dry season (November–April) crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) concentrations in stem (S) and leaf (L) of hybrid brachiaria lines and cultivars from 2008 to 2011 in Amnart Charoen, Thailand.

Hybrid line/ cultivar	CP (%)				ADF (%)				NDF (%)			
	Wet		Dry		Wet		Dry		Wet		Dry	
	S	L	S	L	S	L	S	L	S	L	S	L
Mulato II	6.2	8.3	7.0	11.8	36.9	31.2	33.7	28.0	64.6	59.8	60.4	52.1
BR02/1794	6.0	7.8	7.0	9.4	38.2	31.0	32.4	28.2	65.7	59.6	56.9	51.6
BR02/0465	5.5	8.5	7.7	11.9	39.9	34.3	36.3	30.9	66.8	64.7	63.3	56.5
BR02/1718	6.3	8.5	7.4	10.6	37.7	31.6	33.3	28.6	63.0	58.7	58.0	51.5
BR02/1372	7.1	8.8	7.1	9.8	38.5	30.9	35.5	28.2	64.3	58.7	61.9	50.2
Marandu	5.5	8.5	6.4	9.8	38.3	32.9	33.8	30.4	66.5	63.6	61.4	57.5
Toledo	4.4	6.8	5.5	8.4	39.3	34.5	35.0	32.	68.0	64.8	61.6	58.7
BR06/0012	7.4	9.0	8.9	9.7	39.6	33.1	34.0	31.0	65.7	60.2	59.6	53.1
BR06/0204	7.9	9.1	7.7	10.7	36.3	31.1	32.7	27.5	62.5	58.5	60.0	49.9
BR06/0206	7.0	9.1	8.2	11.3	39.0	31.5	33.7	27.2	65.9	60.2	59.6	50.9
BR06/0387	7.7	9.3	10.9	11.4	39.5	31.0	30.7	27.9	65.8	58.6	52.2	48.5
BR06/0405	7.2	8.8	8.2	11.1	39.5	31.7	33.7	27.8	66.3	58.5	56.5	49.1
BR06/0423	7.0	8.3	8.0	9.8	37.0	31.1	32.5	28.0	66.3	58.5	56.9	50.1
BR06/0531	6.3	8.6	7.0	10.7	38.0	30.4	33.9	27.6	65.5	57.9	56.6	47.9
BR06/0584	7.5	8.1	10.1	10.7	37.7	31.3	30.9	27.9	65.4	60.5	57.7	51.1
BR06/0850	6.0	8.3	7.5	10.8	39.6	30.5	34.2	26.7	69.0	60.7	62.9	51.2
BR06/1000	6.6	9.2	7.9	10.6	38.0	30.8	33.0	27.6	65.4	57.0	58.7	48.3
BR06/1132	6.5	8.6	6.8	10.5	37.7	31.3	33.2	28.1	65.4	59.8	61.1	51.0
BR06/1175	6.0	9.2	8.5	10.9	37.7	31.3	31.3	27.2	65.0	58.3	57.8	49.8
BR06/1254	7.2	8.1	10.9	12.0	37.8	30.6	31.8	26.1	64.4	59.1	57.4	49.1
BR06/1278	6.6	8.9	8.6	11.7	39.3	31.3	33.3	27.6	64.8	58.0	58.2	48.8
BR06/1348	7.3	8.5	7.1	10.8	38.1	30.5	34.2	27.2	64.5	58.4	60.2	49.3
BR06/1366	6.6	8.9	8.8	11.8	39.0	31.5	34.1	27.7	66.9	59.5	58.8	49.9
BR06/1388	6.6	8.8	8.6	10.5	40.1	31.3	34.2	27.5	67.5	58.8	59.5	51.0
BR06/1415	6.7	8.0	7.4	11.0	38.5	30.9	34.3	27.6	67.7	60.5	60.4	51.8
BR06/1433	8.5	9.3	8.3	11.8	38.9	30.7	33.5	26.2	65.3	57.4	55.8	49.0
BR06/1454	7.6	9.2	9.5	11.7	38.0	29.3	34.2	25.6	64.2	56.0	57.4	48.2
BR06/1567	7.2	7.9	8.2	10.6	38.8	32.6	32.5	27.7	65.5	60.1	58.2	51.9
BR06/1696	6.8	7.9	7.5	10.1	39.0	30.6	34.2	28.1	65.5	57.3	59.0	51.0
BR06/1832	7.2	8.1	8.8	11.4	38.1	30.3	34.1	28.0	66.0	59.4	60.3	51.5
BR06/1922	7.4	8.4	9.5	13.2	37.6	29.5	31.7	25.6	65.1	57.3	59.1	48.2
BR06/1932	7.0	8.4	7.5	10.8	38.0	30.1	32.4	26.3	65.3	58.8	58.8	50.7
BR06/2020	7.6	8.9	9.0	10.9	37.2	29.4	33.3	27.0	63.9	56.0	59.6	49.8
BR06/2058	7.1	8.8	7.6	13.1	37.0	29.3	31.8	24.3	65.0	57.1	58.7	47.6
BR06/2204	7.4	8.6	7.8	11.1	36.5	29.2	32.6	25.9	64.2	59.1	58.4	50.3
Mean	6.8	8.6	8.1	10.9	38.5	31.1	33.3	27.7	65.5	59.2	58.9	50.8
LSD (P<0.05)	0.41	0.42	0.62	0.60	0.31	0.23	0.32	0.27	0.35	0.25	0.66	0.46
F ratio	31.5	16.2	27.8	20.6	127.6	394.5	117.4	271.3	312.4	606.4	84.6	238.5
Probability	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Discussion

This study suggests that some of the hybrid lines tested might have advantages over Mulato II in terms of wet season DM accumulation, but there was little evidence of any superiority in terms of DM accumulation during the dry season, when extra forage might be most needed. While, in some seasons, some BR02 and BR06 hybrid lines produced more forage than Mulato II, particularly in the wet season, only 2 hybrid lines produced significantly more DM than Mulato II in the dry season; BR02/1752 and BR02/1718 in one dry season each at the Ubon Ratchathani site. At the Amnart Charoen site, none of the BR06 lines accumulated more DM than Mulato II in the dry, but several did accumulate significantly more DM than Mulato II in the first and third wet seasons.

Forage accumulation was inconsistent, as nine BR06 lines produced, on average, 50% more DM than Mulato II in the first wet season and 5 lines produced, on average, 28% more DM than Mulato II in the third wet season. By contrast, in the second wet season at the Amnart Charoen site, 25 of the twenty-eight BR06 lines produced significantly less DM (28% less) than Mulato II. The superior DM accumulation of BR02/1752 over Mulato II (12,600 vs. 10,600 kg/ha) in the second wet season at the Ubon Ratchathani site was at variance with other reports (Hare et al. 2013a; Vendramini et al. 2014), where BR02/1752 displayed no forage production advantages over Mulato II.

A distinct advantage of Mulato II in these experiments was the superior leaf proportion in forage compared with the other hybrid lines, averaging 66–72% in the wet season and 74–88% in the dry season. The high production of lush, soft green leaves and low stem DM has always made Mulato II an attractive forage for livestock (Argel et al. 2007; Hare et al. 2009).

Concentrations of CP in both leaves and stems were not high in both experiments, and were particularly low (4.3–5.5%) in stems in the wet season in Experiment 1 (Table 4). Interestingly, many of the BR06 lines had superior stem CP concentrations to Mulato II but similar leaf CP concentrations. Compared with other studies on hybrid brachiaria grasses, CP concentrations in these experiments were generally inferior. In Florida, CP concentrations in whole plants (leaf and stem) of Mulato II averaged 13% in one study, 10% in a second (Vendramini et al. 2012) and 11.4% in a third (Vendramini et al. 2014). In cutting trials in Thailand, Mulato II, BR02/1752 and BR02/1794 produced high CP concentrations (8.8–9.4% in stems and 12.6–13.2% in leaves), only when cut every 30 days (Hare et al. 2013a). However, occasionally, there have been instances of high CP concentrations in hybrid brachiarias. In seed-production trials in Thailand, Mulato and Mulato II forage cut at seed-crop closing produced leaf CP levels up to 17.5% (Hare et al. 2007b). In those trials 200 kg/ha NPK (15:15:15) was applied monthly. In Florida, Mulato pastures, that received 150 kg N/ha in 3 applications (April, June and August), contained CP levels up to 17.2% and averaged 13.8% over 2 years (Inyang et al. 2010). However, such results are not common, and hybrid brachiarias appear to average about 7–11% CP in leaves in Thailand.

Many BR06 lines and BR02/1752 had lower fiber (ADF and NDF) percentages than Mulato II, particularly in the wet season. All hybrid lines and cultivars tested in these trials produced far lower fiber levels than *Panicum maximum* cultivars grown in adjacent trials at the same site (Hare et al. 2013b).

The higher CP concentrations and lower fiber levels than Mulato II in many BR06 lines make them appear attractive, but none produced more dry season forage than Mulato II and they generally had poorer leaf:stem ratios than Mulato II. Several did produce more wet season forage than Mulato II in some seasons but this was not consistent. In addition, their seed yields tended to be erratic and low compared with Mulato II (Hare et al. 2015). More studies need to be conducted on these lines before they could be considered superior to Mulato II and likely to warrant release as a cultivar.

Two BR02 lines have already been released as cultivars. The first was BR02/1752, which was granted Plant Variety Rights in 2011 (Loch et al. 2011b) and released as cv. Cayman by Grupo Papalotla in 2012 (Pizarro et al. 2013). In the current studies Cayman produced more DM than Mulato II in only one wet season and one dry season, and had significantly lower leaf production than Mulato II. The superior leaf production of Mulato II compared with Cayman was also found in another study at Ubon Ratchathani University (Hare et al. 2013a). The nutritive value of Cayman compared with Mulato II was variable, with overall lower CP concentrations but also lower fiber levels. However, Cayman had higher stem CP concentrations and consistently lower fiber levels than Mulato II in a separate study at Ubon Ratchathani University (Hare et al. 2013a). The main factor that justified Cayman's release as a cultivar was its superior waterlogging tolerance compared with Mulato II (Pizarro et al. 2013). It produced a mass of adventitious roots (1,065/plant) following 55 days of waterlogging compared with only 4/plant for Mulato II (Pizarro and Hare 2014). While Cayman's tolerance of waterlogging is lower than that of *B. humidicola* (now *Urochloa*

humidicola), Cayman has superior nutritional value to *B. humidicola*. There is a strong demand for high quality waterlogging-tolerant forage cultivars.

BR02/1794 was granted Plant Variety Rights in 2011 (Loch et al. 2011c) and released by Grupo Papalotla as cv. Cobra in 2014 (E. Stern pers. comm.). In this study, while Cobra had similar DM production to Mulato II, it had significantly lower leaf proportion, particularly in the wet season, where leaf:stem ratio, averaged across both experiments, was 55:45 for Cobra and 70:30 for Mulato II (data not shown). Two main attributes have justified Cobra's release: The first is its strong upright nature, which is ideal for cut-and-carry forage systems. Secondly, its seed production is superior to that of Mulato II, as in 4 of 5 seed harvests, Cobra produced significantly more seed than Mulato II (Hare et al. 2015).

Two other lines, BR02/1718 and BR02/0465, have been granted Plant Variety Rights (Loch et al. 2011a; 2011d) but have not been released as cultivars. BR02/1718 had similar DM production to Mulato II in all seasons but lower leaf production. BR02/0465 produced more DM in the wet season than Mulato II but had lower leaf production. Both lines produced significantly higher seed yields than Mulato II in some seasons (Hare et al. 2015).

While 43 hybrid brachiaria lines were evaluated in this study from 2005 to 2011, only 2 lines, BR02/1752 (cv. Cayman) and BR02/1794 (cv. Cobra), had some attributes superior to those of Mulato II, i.e. upright habit and waterlogging tolerance, that warranted their release as named cultivars. They were not equal to Mulato II in terms of DM yield and nutritive value in this study. While some other lines showed greater DM production in some wet seasons, the superiority displayed in these studies would not justify their being considered for release. Further studies would need to be done before such a decision could be made.

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References

Argel PJ; Miles JW; Guiot JD; Cuadrado H; Lascano CE. 2007. Cultivar Mulato II (*Brachiaria* hybrid CIAT 36087): A high-quality forage grass, resistant to spittlebugs and adapted to well-drained, acid tropical soils. International Center for Tropical Agriculture (CIAT), Cali, Colombia. http://goo.gl/HQhH80

Hare MD; Tatsapong P; Saipraset K. 2007a. Seed production of two brachiaria hybrid cultivars in north-east Thailand. 1. Method and time of planting. Tropical Grasslands 41:26–34. http://goo.gl/Zfns2N

Hare MD; Tatsapong P; Saipraset K. 2007b. Seed production of two brachiaria hybrid cultivars in north-east Thailand. 2. Closing date. Tropical Grasslands 41:35–42. http://goo.gl/qlYfW9

Hare MD; Tatsapong P; Saipraset K. 2007c. Seed production of two brachiaria hybrid cultivars in north-east Thailand. 3. Harvesting method. Tropical Grasslands 41:43–49. http://goo.gl/0mhOao

Hare MD; Tatsapong P; Phengphet S. 2009. Herbage yield and quality of *Brachiaria* cultivars, *Paspalum atratum* and *Panicum maximum* in north-east Thailand. Tropical Grasslands 43:65–72. http://goo.gl/dJ0lDN

Hare MD; Phengphet S; Songsiri T; Sutin N; Stern E. 2013a. Effect of cutting interval on yield and quality of three brachiaria hybrids in Thailand. Tropical Grasslands-Forrajes Tropicales 1:84–86. DOI: 10.17138/TGFT(1)84-86

Hare MD; Phengphet S; Songsiri T; Sutin N; Stern E. 2013b. Effect of cutting interval on yield and quality of two *Panicum maximum* cultivars in Thailand. Tropical Grasslands-Forrajes Tropicales 1:87–89. DOI: 10.17138/TGFT(1)87-89

Hare MD; Pizarro E; Phengphet S; Songsiri T; Sutin N. 2015. Evaluation of new hybrid brachiaria lines. 2. Seed production. Tropical Grasslands-Forrajes Tropicales 3 (this issue). DOI: 10.17138/TGFT(3)94-103

Inyang U; Vendramini JMB; Sollenberger LE; Sellers B; Adesogan A; Paiva L; Lunpha A. 2010. Forage species and stocking rate effects on animal performance and herbage responses of 'Mulato' and bahiagrass pastures. Crop Science 50:1079–1085. DOI: 10.2135/cropsci2009.05.0267

Loch DS; Miles JW. 2002. *Brachiaria ruziziensis x Brachiaria brizantha* Brachiaria 'Mulato'. Plant Varieties Journal 15(3):20–21. http://goo.gl/IzUG9j

Loch DS; Miles JW. 2004. *Brachiaria ruziziensis x B. decumbens x B. brizantha* Brachiaria 'Mulato II'. Plant Varieties Journal 17(3):146–151. http://goo.gl/WoS0JT

Loch DS; Hare MD; Miles JW. 2011a. Brachiaria hybrid *(Brachiaria ruziziensis x decumbens x brizantha)* Variety CIAT BR02/1718. Plant Varieties Journal 24(1):48, 133–139. http://goo.gl/4XsFfb

Loch DS; Hare MD; Miles JW. 2011b. Brachiaria hybrid *(Brachiaria ruziziensis x decumbens x brizantha)* Variety CIAT BR02/1752. Plant Varieties Journal 24(1):49, 140–146. http://goo.gl/4XsFfb

Loch DS; Hare MD; Miles JW. 2011c. Brachiaria hybrid *(Brachiaria ruziziensis x decumbens x brizantha)* Variety CIAT BR02/1794. Plant Varieties Journal 24(1):50, 147–153. http://goo.gl/4XsFfb

Loch DS; Hare MD; Miles JW. 2011d. Brachiaria hybrid *(Brachiaria ruziziensis x decumbens x brizantha)* Variety

CIAT BR02/0465. Plant Varieties Journal 24(1):51, 154–160. http://goo.gl/4XsFfb

Miles JW; Valle CB do; Rao IM; Euclides VPB. 2004. Brachiariagrasses. In: Moser LE; Burson BL; Sollenberger LE, eds. Warm-season (C_4) grasses. Agronomy Monograph No. 45. ASA, CSSA, SSSA, Madison, WI, USA. p. 745–783. DOI: 10.2134/agronmonogr45.c22

Mitsuchi M; Wichaidit P; Jeungnijnirund S. 1986. Outline of soils of the northeast plateau, Thailand. Their characteristics and constraints. Technical paper No. 1. Agricultural Development Research Center in Northeast. Khon Kaen, Thailand.

Pizarro EA; Hare MD; Mutimura M; Bai Changjun. 2013. *Brachiaria* hybrids: Potential, forage use and seed yield. Tropical Grasslands-Forrajes Tropicales 1:31–35. DOI: 10.17138/TGFT(1)31-35

Pizarro EA; Hare MD. 2014. Brachiaria hybrids: New forage alternatives. Pasturas de América, August 2014. http://goo.gl/EC31h2

Vendramini JMB; Sollenberger LE; Lamb GC; Foster JL; Liu K; Maddox M. 2012. Forage accumulation, nutritive value, and persistence of "Mulato II" brachiariagrass in northern Florida. Crop Science 52:914–922. DOI: 10.2135/cropsci2011.06.0338

Vendramini JMB; Sollenberger LE; Soares AB; Silva da WL; Sanchez JMD; Valente AL; Aguiar AD; Mullenix MK. 2014. Harvest frequency affects herbage accumulation and nutritive value of brachiaria grasses in Florida. Tropical Grasslands-Forrajes Tropicales 2:197–206. DOI: 10.17138/TGFT(2)197-206

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Evaluation of new hybrid brachiaria lines in Thailand. 2. Seed production

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Abstract

Forty-three new hybrid bracharia lines bred at CIAT, Colombia, were evaluated for seed production in Northeast Thailand between 2006 and 2010 in 2 experiments at 2 sites, Ubon Ratchathani and Amnart Charoen. These lines were compared with Mulato II hybrid brachiaria. From the BR02 collection, 4 lines, BR02/1718, BR02/1752, BR02/1794 and BR02/0465, were granted Plant Variety Rights in 2011. BR02/1794 produced more seed than Mulato II on most occasions, including both harvests at Ubon Ratchathani and 2 of 3 harvests at Amnart Charoen. The next best yielding lines were BR02/1718 and BR02/0465, which produced more seed than Mulato II in 1 of 2 harvests at Ubon Ratchathani and 2 of 3 harvests at Amnart Charoen. Seed-set (percentage of cleaned seed to spikelets) was generally very low in all hybrid lines (1–12%). The reasons for low seed-set in hybrid brachiaria grasses are discussed, including: being a common defect in newly formed apomictic forage hybrids; previous selection for seed yield not being rigorous enough; and insufficient selection at latitudes and sites where commercial brachiaria seed production is practiced.

Resumen

En el período 2006–11 en 2 sitios del noreste de Tailandia (Ubon Ratchathani y Amnart Charoen) fueron evaluadas por su producción de semilla 43 líneas nuevas de híbridos de *Brachiaria*, incluyendo el cultivar (cv.) Mulato II como testigo, procedentes del CIAT. La línea BR02/1794 produjo más semilla que cv. Mulato II en 2 cosechas realizadas en Ubon Ratchathani y en 2 de las 3 cosechas en Amnart Charoen. Otras líneas con buenos rendimientos de semilla fueron BR02/1718 y BR02/0465 que produjeron más semilla que cv. Mulato II en una de las 2 cosechas en Ubon Ratchathani y 2 de 3 cosechas en Amnart Charoen. La formación de semilla (porcentaje del número de semillas limpias en relación con el número de espiguillas formadas) fue, en general, muy baja en todas las líneas, con un valor entre 1 y 12%. Se analizan las posibles razones de este bajo porcentaje en los híbridos de *Brachiaria* evaluados, entre ellas, un defecto común en híbridos apomícticos recién formados, falta de rigor en las etapas previas de selección para producción de semilla, y fallas en la selección de las latitudes y los sitios de producción comercial de semilla de *Brachiaria*. Las líneas BR02/1718, BR02/1752, BR02/1794 y BR02/0465 alcanzaron la protección de obtención vegetal (*Plant Variety Rights*) en 2011.

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Introduction

Mulato II [*Brachiaria ruziziensis* (now *Urochloa ruziziensis*) x *B. decumbens* (now *U. decumbens*) x *B. brizantha* (now *U. brizantha*)] was the second hybrid brachiaria cultivar released from the hybridization programs begun in 1988 at the Centro Internacional de Agricultura Tropical (CIAT) in Cali, Colombia (Argel et al. 2007). Even though Mulato II produced 60% higher seed yields than Mulato (*Brachiaria ruziziensis* x *B. brizantha*), which was the first hybrid brachiaria released (Hare et al. 2007a), Mulato II seed yields of 232–258 kg/ha were still very low compared with yields from other commercial brachiaria cultivars (not hybrids) elsewhere. In order to compete in price internationally with commercial brachiaria cultivars from Brazil and Australia, commercial seed yields from hybrid brachiarias must be at least 600–700 kg/ha. Commercial seed yields average 650–700 kg/ha in Brazil for cv. Marandu (*B. brizantha*) and cv. Basilisk (*B. decumbens*) (Souza 1999). In Australia, seed yields of Basilisk have reached 1,000 kg/ha (Hopkinson and Clifford 1993). Seed of these commercial brachiaria species is almost half the price of hybrid brachiaria seed. The high price of hybrid brachiaria seed is a reflection of low seed yields and represents a significant barrier to farmer uptake.

From 2006 to 2011, studies were conducted in Thailand on hybrid brachiaria collections from CIAT. The first paper of these studies reported on forage production and quality (Hare et al. 2015), while this paper focuses on seed production.

Materials and Methods

Two experiments were conducted with the aim of selecting lines that had higher seed yields than Mulato II.

Experiment 1. BR02 and MX02 collections

The first experiment was conducted at Ubon Ratchathani University, Thailand, (15° N, 104° E; 130 masl) during 2006 and 2007 alongside a forage biomass experiment. The site was on an upland sandy low humic gley soil that was acid (pH 4.6) and low in organic matter (1.1%), N (0.04%), P (3.5 ppm) and K (27.4 ppm). The mean rainfall was 1,620 mm, with a dominant dry season from November to April (Figure 1). The site is further described in the first paper on forage production (Hare et al. 2015). Thirteen hybrid brachiaria lines from the BR02 collection and 2 from the MX02 collection (Hare et al. 2015) were planted in a randomized complete block design with 3 replicates in June 2006. Seedlings were grown in a nursery and transplanted into the field plots using 50 x 50 cm spacings (48 plants per plot). Details of field crop management are presented in Table 1. Two seed harvests were conducted in 2006 and 2007.

Experiment 2. BR06 collection

This experiment was conducted at one site at the Amnart Charoen Livestock Development Centre, Amnart Charoen province, Northeast Thailand (15.5° N, 104.4° E; 168 masl) from 2008 to 2010 (3 harvests of each plot) alongside the forage trial. The site was on an upland sandy reddish brown earth with a mean rainfall of 1,640 mm, and a dominant dry season from November to April (Figure 2). Soil samples taken at planting in July 2008 showed that the soil was acid (pH 4.6), sandy (75%), and low in organic matter (0.4%), N (0.04%), and K (31 ppm), and adequate for P (25.2 ppm). The site is described further in the first paper on forage production (Hare et al. 2015).

Table 1. Field crop management of hybrid brachiaria lines during evaluation in Ubon Ratchathani, Thailand (Experiment 1).

Field cultivation	Plowing x 2, disking x 1, harrowing x 1
Plot size	3 m x 4 m with 50 cm walkway around plots and 1 m between replications
Sowing date	1–3 Jun 2006
Cleaning and closing cuts	2006: 3 Aug
	2007: 27 Apr & 24 Jul
	All plots cut to 5 cm above ground level
Fertilizer	2006: 3 Aug 200 kg/ha NPK (15:15:15); 7 Sep & 3 Oct 46 kg N/ha as urea
	2007: 24 Jul 46 kg N/ha as urea; 28 Aug urea (46 kg N/ha), double superphosphate (18 kg P/ha), potash (52 kg K/ha), gypsum (17 kg S/ha); 5 Oct urea (46 kg N/ha)

Twenty-eight hybrid brachiaria lines from the BR06 collection (Hare et al. 2015), 4 from the BR02 collection, Mulato II, Toledo (*B. brizantha*) and Marandu (*B. brizantha*) were planted in July 2008 in a randomized complete block design with 4 replications. Seedlings were grown in a nursery and transplanted during 26–28 July 2008 into the field plots in 80 x 50 cm spacings (32 plants per plot). Seed harvests were conducted in 2008, 2009 and 2010. Details of field crop management are presented in Table 2.

For both experiments all inflorescences in 3 m of the middle 2 rows were counted once a week. Twenty inflorescences were taken from just outside this area for reproductive analysis at peak anthesis (Table 3). All racemes were counted on each inflorescence and spikelets were counted on 3 racemes per inflorescence, selected from the top, middle and bottom of each inflorescence. At peak anthesis, nylon bags were tied over each seed head of 10 plants (5 plants/row in the above middle 2 rows) to collect the seed. The seed was allowed to fall naturally into the bags and collected once at the end of the season and cleaned through hand screens and a small seed blower to 99% pure seed. Settings were adjusted according to seed weights of each line. Following cleaning, seed yields were corrected to 10% seed moisture content. One thousand seed weights (TSW) were calculated by drying 4 lots of 100 seeds per plot and correcting to 10% seed moisture.

Data from the experiments were subjected to analysis of variance, using the IRRISTAT program from the International Rice Research Institute (IRRI). Entry means were compared using Fisher's protected LSD ($P \leq 0.05$) procedure.

Results

Rainfall

Experiment 1. BR02 and MX02 collections. Rainfall for the experimental period is shown in Figure 1. The critical period of rainfall for seed production in Thailand is the period from July to October, when the plants establish, develop, and initiate and elongate inflorescences and seed is set and matures. The medium-term mean (13 years) rainfall at Ubon Ratchathani for this period is 917 mm, and in 2007 rainfall closely approximated the mean, but in 2006, rainfall during this critical period was 17% higher. October and November are important months for seed maturity and harvest. In 2006 and 2007, rainfall during these months exceeded the mean, by a factor of 1 in 2006 and 0.5 in 2007.

Table 2. Field crop management of hybrid brachiaria lines during evaluation in Amnart Charoen, Thailand (Experiment 2).

Field cultivation	Plowing x 2, disking x 1, harrowing x 1
Plot size	3.2 m x 4 m with 50 cm walkway around plots and 1 m between replications
Sowing date	26–28 Jul 2008
Cleaning cuts	2008: No cuts before harvest 2009: 13 Jan & 13 May 2010: 28 Apr & 16 Jun All plots cut to 5 cm above ground level
Closing cuts[1]	2008 & 2009: No closing cuts from sowing 2 Jul (first group[2]), 28 Jul (second group), 8 Sep (third group) 2010: 20 Jul (first group), 10 Aug (second group)
Fertilizer (amounts of fertilizer applied based on experience of soils in the region)	2008: 8 Sep NPK (15:15:15) 200 kg/ha 2009: 13 May, 2 Jul (first group), 28 Jul (second group), 8 Sep (third group) NPK (15:15:15) 200 kg/ha 13 Aug (first group), 28 Sep(second group), 19 Oct (third group) 46 kg N/ha as urea 2010: 28 Apr, 16 Jun, 20 Jul (first group), 10 Aug (second group) NPK (15:15:15) 200 kg/ha 31 Aug (first group), 21 Sep (second group) 46 kg N/ha as urea

[1]Closing cuts, 5 cm above ground level, were implemented about 90 days before peak anthesis (recorded in the first year in 2008) to avoid seed head lodging prior to anthesis.
[2]Groups are recorded in Table 3.

Table 3. Dates for peak anthesis for hybrid brachiaria lines in Ubon Ratchathani (Experiment 1) and Amnart Charoen (Experiment 2), Thailand.

Experiment	Peak anthesis date and hybrid line/cultivar
Experiment 1	
2006	Oct 24: BR02/0779; MX02/1423; Nov 11: BR02/1372, 1794; Nov 20: BR02/1484, 1718, 1728, 1747, MX02/1263; Dec 12: BR02/0465, 0768, 0771, 1245, 1452, 1752, Mulato II
2007	Oct 10–17: BR02/0779, 1372, 1728, 1794, MX02/1423; Oct 24: BR02/0465, 1718, 1752; Nov 1: BR02/0768, 0771, 1452, 1485, 1747, 1752; Nov 8: MX02/1263, Mulato II; No flowering: BR02/1245
Experiment 2	
2008	Sep 25–Oct 3: BR06/0405, 1366, 1388, 1433, 1454, BR02/1372; Oct 24: BR06/0206, 0387, 0423, 1000, 1132, 1175, 1415, 1696, 1832, 2058, BR02/0465, 1718, 1794; Nov 1–8: Mulato II, Marandu; Nov 14–21: BR06/0012, 0204, 0584, 0850, 1278, 1348, 1567, 1922, 1932, 2020, 2204; Dec 4: Toledo; No flowering: BR06/0531, 1254
2009	[1]*Sep 15: BR06/0405, 1366, 1388, 1433, 1454, 1922, BR02/1794, 1372; **Sep 28–Oct 8: BR06/0206, 0387, 0423, 0531, 0850, 1175, 1278, 1415; **Oct 19: BR06/0012, 1000, 1132, 1567, 1696, 1832, 1932, 2020, 2058, BR02/0465, 1718; **Nov 15: BR06/0204, 1348, 1584, 2204, Mulato II, Marandu; No flowering: **BR06/1254, ***Toledo
2010	*Sep 21–28: BR06/0206, 0405, 0850, 1132, 1175, 1278, 1366, 1388, 1415, 1433, 1454, 1922, 1932, 2020, BR02/1794, 1372; **Oct 19: BR06/0204, 1000, 1348, 1696, 1832, 2058, 2204, BR02/0465, 1718; **Nov 2: BR06/0012, 0387, 0423, 0531, 1567; **Nov 23: BR06/0584, Mulato II, Marandu; **Dec 20: Toledo; No flowering: **BR06/1254

[1]Groups for closing cuts and fertilizer application: * First group, ** Second group, *** Third group.

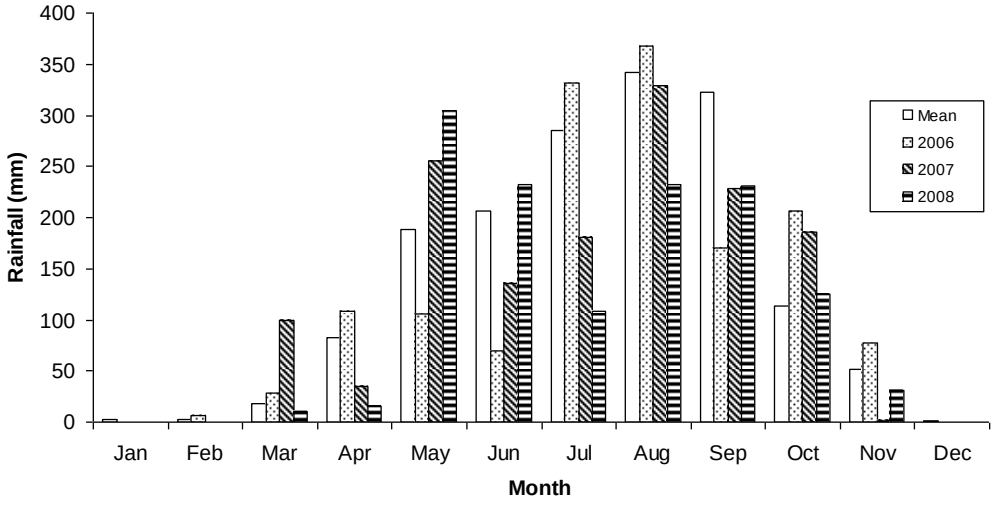

Figure 1. Rainfall at the Ubon Ratchathani University meteorological station, 1 km from the research site, during the experiment and the 13-yr mean (2000–2012).

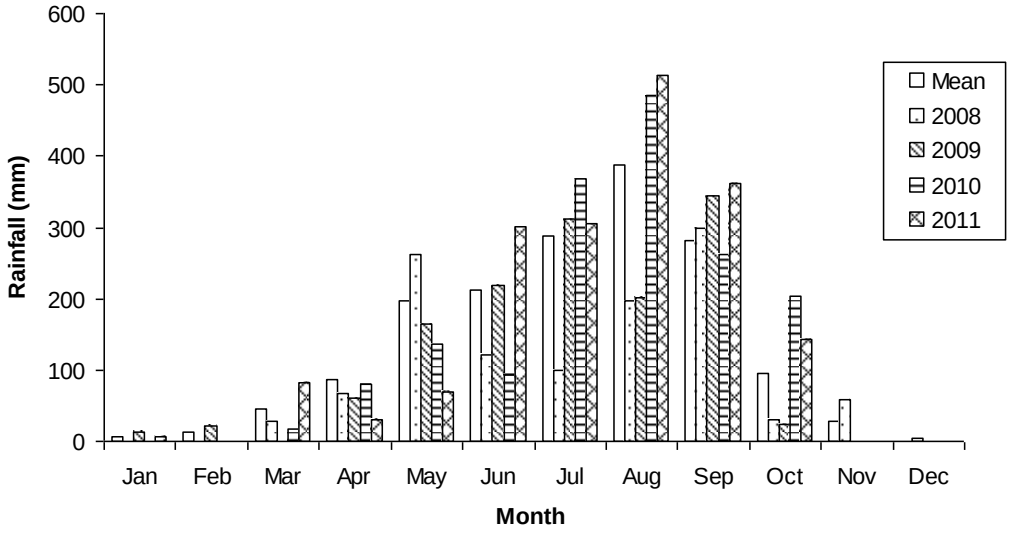

Figure 2. Rainfall at the Amnart Charoen meteorological station, 9 km from the research site, during the experiment and the 13-yr mean (2000–2012).

Experiment 2. BR06 collection. Rainfall for this experiment is shown in Figure 2. Rainfall for the July–September period in 2008 and 2009 was 38 and 22%, respectively, lower than the medium-term mean (13 years), while in 2010, it was 25% higher than the mean. For the October–November period, rainfall in 2008 and 2009 was 40 and 80%, respectively, lower than the medium-term mean. In 2010, rainfall for the same period was 62% higher than the mean but with no rain at all during November.

Seed production

Experiment 1. BR02 and MX02 collections. Seed yields ranged from 12 to 282 kg/ha and one line produced no seed at all in the second year. Hybrid brachiaria line BR06/1794 produced significantly higher seed yields than all other lines in both years, except for BR02/1718 and BR02/0465 in the second year (Table 4). BR02/1718 and BR02/0465 also produced higher seed yields than Mulato II in the second year but not in the first year. One line, BR02/1245, failed to produce any seed in the second year.

Mulato II produced significantly lower numbers of inflorescences per m^2 than many of the other hybrid lines, which were also significantly lower than the overall mean (Table 4). Lower numbers of inflorescences per m^2 were produced in the first year compared with the second year.

Racemes per inflorescence, spikelets per raceme and TSW were lower in the second year than in the first year (Table 4). There was large variability in spikelet numbers among the lines, ranging from 24 to 48. BR02/0465 produced significantly heavier seed (10.3–10.5 g per 1,000 seeds) than all other lines (Table 4). Three lines (BR02/1485, 1747 and 1794) had significantly higher TSW than Mulato II at both harvests.

Experiment 2. BR06 collection. Seed yields ranged from 6 to 659 kg/ha with 2 lines producing no seed in some years and 1 line producing no seed at any harvest (Table 5). In the first year (2008), BR02/1794 and Marandu produced significantly more seed than the other hybrid lines, including Mulato II. The majority of the BR06 lines had lower seed yields in 2008 than Mulato II, Marandu and Toledo and the BR02 lines, except for BR02/1372, which produced low seed yields at every harvest. In the second year (2009), BR02/0465 produced a significantly higher seed yield than the other hybrid lines and cultivars. Seed yields of many of the BR06 lines improved, with BR06/1278 producing similar seed yields to Mulato II, and BR06/0423 and BR06/1000 producing, respectively, 412 and 400 kg/ha. In the third year, seed yields of nearly all cultivars and

lines declined significantly, except for BR06/1000 and 2058, which produced a little over 200 kg/ha (Table 5). BR06/1254 failed to produce seed at any harvest.

The majority of the BR06 lines produced significantly higher numbers of inflorescences (300–400/m^2) in the first year than the cultivars and the BR02 lines (Table 5). In the second year, inflorescence numbers increased compared with numbers in the first year for most lines and cultivars, with a similar range (300–600/m^2) for BR02 and BR06 lines and Mulato II. In the third year, there was a substantial decrease in inflorescence numbers for all lines and cultivars, particularly for Mulato II and Marandu. Toledo produced very few inflorescences in Years 1 and 3, and no inflorescences at all in Year 2.

Racemes per inflorescence declined with age, averaging 4.7 in the first year, 3.8 in the second year and 3.4 in the third year (Table 5). Overall, the majority of the BR06 lines produced fewer racemes per inflorescence than Mulato II. Five BR06 lines (0204, 0584, 1132, 1348 and 1696) produced numbers of racemes similar to or higher than Mulato II at each harvest.

Spikelet numbers per raceme were similar in the first and second seed harvests, 38 and 39, respectively, but declined to 34.6 at the third seed harvest (Table 5). Several BR06 lines produced more than 40 spikelets per raceme at each seed harvest, significantly higher than Mulato II and most BR02 lines.

BR02/0465 produced significantly heavier seed than all other lines and cultivars at all harvests, except for Toledo at the first harvest (Table 5). BR02/1794 and BR02/1718 produced significantly heavier seed than Mulato II and all 3 produced significantly heavier seed than all BR06 lines, except for BR06/0531, at the second and third harvests (Table 5).

Table 4. Seed yield and components of seed yield at peak anthesis of hybrid brachiaria lines during 2006 and 2007 in Ubon Ratchathani, Thailand (Experiment 1).

Hybrid line/ cultivar	Seed yield (kg/ha)		Inflorescences[1] (no./m^2)		Racemes/ inflorescence[1] (no.)		Spikelets/ raceme[1] (no.)		TSW[3] (g)	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
Mulato II	116	166	128	280	5.1	4.3	35.4	32.8	8.2	8.3
BR02/0465	87	244	230	352	5.6	4.4	36.0	26.4	10.3	10.5
BR02/0768	124	121	628	886	3.7	3.2	28.1	20.2	7.1	7.1
BR02/0771	94	58	533	454	4.6	3.5	32.3	24.3	7.4	7.6
BR02/0799	49	130	423	776	3.1	3.3	35.3	32.9	6.8	7.8
BR02/1245	74	-[2]	173	-	4.1	-	31.1	-	9.6	-
BR02/1372	20	23	509	468	3.6	3.1	48.4	36.7	6.7	6.6
BR02/1452	161	65	282	343	3.6	3.3	35.2	24.1	8.3	8.2
BR02/1485	59	50	278	413	4.2	3.1	36.9	25.4	9.3	9.3
BR02/1718	94	249	352	721	5.8	4.0	38.2	39.2	8.9	8.6
BR02/1728	85	73	306	257	4.0	4.5	35.3	32.0	7.8	7.1
BR02/1747	87	89	306	458	5.1	4.8	42.3	27.8	9.3	9.2
BR02/1752	118	155	346	351	3.9	3.4	40.2	30.0	8.7	9.0
BR02/1794	282	272	380	488	4.7	4.2	45.7	30.6	8.9	9.1
MX02/1263	154	12	483	181	4.6	3.4	41.0	27.6	8.8	8.9
MX02/1423	18	30	435	682	3.0	2.9	45.8	33.4	6.7	7.6
Mean	103	109	362	444	4.3	3.5	37.9	27.7	8.3	7.8
LSD (P≤0.05)	74	54	199	133	0.5	0.4	2.5	2.2	0.6	0.5
F ratio	6.94	13.19	3.83	35.03	27.9	81.5	42.7	135.8	35.2	194.3
Probability	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[1]Counted at peak anthesis. [2]Failed to produce inflorescences. [3]One-thousand-seed weight.

Table 5. Seed yield and components of seed yield at peak anthesis of hybrid brachiaria lines during 2008–2010 in Amnart Charoen, Thailand (Experiment 2).

Hybrid line/ cultivar	Seed yield (kg/ha)			Inflorescences[1] (no./m^2)			Racemes/ inflorescence[1] (no.)			Spikelets/ raceme[1] (no.)			TSW[3] (g)		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
Mulato II	256	497	19	111	361	19	5.8	4.5	3.8	37.9	32.7	29.1	8.1	7.9	7.6
BR02/1794	370	206	95	231	348	132	5.7	3.7	3.9	36.7	42.5	36.6	9.4	8.4	8.8
BR02/0465	276	659	140	149	338	128	5.3	4.3	3.7	35.9	37.9	30.5	10.2	11.1	10.4
BR02/1718	309	492	151	221	528	105	6.0	3.1	4.3	37.5	36.7	34.2	8.8	8.3	8.0
BR02/1372	64	11	6	199	463	229	3.9	5.3	3.1	51.5	39.6	32.9	7.6	6.8	7.1
Marandu	344	334	103	94	152	23	4.8	3.9	3.3	47.0	38.3	32.7	9.0	8.4	8.4
Toledo	256	-[2]	36	48	-	23	6.5	-	4.0	35.5	-	29.2	11.4	-	9.6
BR06/0012	47	58	22	263	376	64	3.3	2.7	2.6	53.4	45.7	28.8	8.2	7.4	7.0
BR06/0204	18	67	51	64	185	126	6.7	6.0	3.7	31.8	35.3	53.2	6.7	6.7	7.3
BR06/0206	23	73	19	298	302	135	3.0	2.8	2.6	58.5	49.0	39.2	7.1	7.2	6.9
BR06/0387	176	264	143	407	575	271	4.7	3.1	2.8	41.8	41.7	27.2	6.9	7.1	7.1
BR06/0405	34	29	31	307	475	250	3.5	3.2	3.3	41.1	34.3	33.0	6.1	5.8	6.0
BR06/0423	218	412	58	266	356	41	5.8	4.6	4.2	38.5	37.8	36.3	7.1	7.1	6.6
BR06/0531	-[2]	141	54	-	280	137	-	3.2	2.9	-	38.4	30.6	-	8.2	8.1
BR06/0584	45	32	5	121	121	22	5.4	4.8	3.6	20.3	20.8	18.4	6.8	6.3	6.2
BR06/0850	148	204	42	188	275	95	4.5	3.8	3.0	24.9	48.3	44.6	6.0	5.6	5.2
BR06/1000	126	400	202	220	317	215	4.9	4.3	3.2	30.0	48.8	37.9	7.7	7.8	8.1
BR06/1132	114	220	41	281	421	102	6.6	4.9	4.3	30.6	31.7	31.7	6.8	6.9	6.6
BR06/1175	169	320	64	303	327	195	3.6	3.4	3.0	50.0	46.6	35.7	7.9	7.7	6.8
BR06/1254	-[2]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BR06/1278	137	483	72	223	262	100	3.3	3.2	3.0	57.5	55.0	46.4	7.8	7.6	6.9
BR06/1348	112	88	93	207	456	124	5.8	4.1	4.1	28.3	27.6	33.9	6.0	5.2	6.0
BR06/1366	172	71	65	339	324	216	3.5	3.4	3.1	58.7	50.7	43.8	6.8	6.0	6.3
BR06/1388	76	6	12	468	421	145	3.3	3.2	3.3	42.8	35.0	35.4	5.7	5.4	5.6
BR06/1415	90	134	29	462	416	136	3.7	4.2	4.0	50.3	40.3	35.3	6.7	5.7	5.5
BR06/1433	95	13	11	444	634	272	3.1	2.2	2.2	41.7	31.8	26.1	6.2	5.5	6.1
BR06/1454	164	28	17	367	447	231	3.3	3.2	2.9	53.8	50.6	43.7	6.9	6.4	6.5
BR06/1567	57	71	28	368	359	69	4.0	3.8	3.4	19.3	22.9	20.1	6.6	6.0	6.2
BR06/1696	200	228	106	388	394	265	7.2	5.8	4.2	47.3	37.2	28.6	7.8	7.5	6.7
BR06/1832	121	214	65	336	442	73	5.2	4.2	3.3	34.2	34.6	33.4	7.3	7.1	7.8
BR06/1922	140	59	38	379	316	131	3.7	3.4	3.1	25.4	35.1	33.2	6.6	6.0	6.5
BR06/1932	46	269	39	171	318	122	4.7	2.9	3.0	26.8	50.9	48.2	7.0	7.2	6.8
BR06/2020	58	161	56	220	333	176	4.2	3.6	3.4	31.7	44.5	41.4	7.0	6.9	6.1
BR06/2058	223	315	205	395	532	155	6.0	4.5	3.6	30.9	33.8	32.0	7.1	7.2	7.1
BR06/2204	52	99	85	234	342	117	3.8	3.5	3.0	32.7	33.9	34.5	7.2	6.6	7.6
Mean	135	191	63	251	349	133	4.4	3.6	3.3	37.0	36.9	33.7	7.0	6.6	6.8
LSD (P<0.05)	59	60	32	62.	69	42	0.4	0.3	0.3	2.5	3.6	3.0	0.4	0.3	0.4
F ratio	21.7	66.5	22.2	33.0	32.1	26.6	129.6	113.5	63.1	247.9	89.0	77.4	220.8	270.9	121.6
Probability	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[1]Counted at peak anthesis. [2]Failed to produce inflorescences. [3]One-thousand-seed weight.

Discussion

The main aims of the experiments were to identify hybrid brachiaria lines with seed yields higher than Mulato II and equal to or better than commercial seed yields of over 600 kg/ha produced by commercial brachiaria species in Australia and Brazil (Hopkinson and Clifford 1993; Souza 1999). These aims were partially achieved. While BR02/0465 was the only hybrid line that produced in excess of 600 kg/ha (659 kg/ha in the second harvest at Amnart Charoen), a number of lines produced more seed than Mulato II. The best overall seed producer, BR02/1794 (95−370 kg/ha), produced significantly more seed than Mulato II (19−497 kg/ha) in both harvests at Ubon Ratchathani and 2 of 3 harvests at Amnart Charoen. The next best lines (BR02/1718 and BR02/0465) produced more seed than Mulato II in 1 of 2 harvests at Ubon Ratchathani and 2 of 3 harvests at Amnart Charoen. BR02/1794 and BR02/0465 produced heavier seed (TSW) than Mulato II at every harvest.

The 3 lines above all reached peak flowering earlier than Mulato II (Table 3). BR02/1794 usually flowers earliest (late September–early October). Peak flowering of BR02/1718 and BR02/0465 is usually 2 to 3 weeks later in mid-October, while peak flowering of Mulato II is nearly always in the second week of November in Northeast Thailand.

Different flowering times can strongly influence seed production. If late October–early November is particularly dry, late-flowering species can fail to set seed on sandy soils with low soil moisture retention. This appeared to be the case with Mulato II in the third year at Amnart Charoen (2010). Heavy rainfall in the first half of October benefited the earlier-flowering lines, but with no rain falling from late October onwards, Mulato II produced only 19 inflorescences per m^2 and only 19 kg/ha of seed was harvested.

The seed yields from the BR06 lines overall were disappointing. It was only when Mulato II failed to produce a large number of inflorescences at the third seed harvest at Amnart Charoen, that the BR06 lines produced more seed than Mulato II. However, these third-harvest seed yields were also extremely low, averaging only 60 kg/ha.

Our experience with seed production of hybrid brachiaria grasses in Thailand is that seed yields decline with age, even though adequate levels of soil N are maintained by applying fertilizer. At the Ubon Ratchathani site seed yields from the first and second seed harvests were similar but at Amnart Charoen, seed yields were higher at the second harvest than at the first and very low for nearly all lines at the third harvest. The decline in seed yield over years in many tropical grass species is considered to be caused by larger tillers in older stands providing nutritional support for weaker tillers (low-yielding or sterile) to the detriment of their own seed development and the long-term productivity of the stand (Loch et al. 1999), though for the brachiaria lines we have no data to support this hypothesis. Farmers in Thailand have found that seed yields from second-year hybrid brachiaria grass seed crops were less than half those of first-year seed crops. In order to get satisfactory seed yields, (300−400 kg/ha of clean seed), they treat hybrid brachiaria grass seed crops as annuals and replant every year, as they do with all other tropical grass seed crops (Hare 2014).

We consider that cleaned seed yields from commercial operations must be above 600 kg/ha for the seed prices of the hybrid brachiaria cultivars to become competitive with other commercial cultivars of brachiaria species. Some farmers in Thailand can produce more than 600 kg/ha of Mulato II seed by ground-sweeping but the majority produce only about 385 kg/ha (Hare 2014). Farmers in Northern Laos currently average 250 kg/ha of Mulato II seed from hand-knocking seed from seedheads (Hare 2014). In our experiments, we have at times produced 500 kg/ha of clean seed (98–99% purity by weight) (Hare et al. 2007b) by catching the seed in bags tied over the seedheads, but these occasions have been extremely rare. Commercial seed production of Mulato II is still very erratic.

Another factor which adds to the cost of hybrid brachiaria seed production is acid-scarification. This results in a loss of seed weight of 15–20% from scarifying off the glume, lemma and palea around each seed, light and empty seed, and small amounts of viable seed. Even though some viable seed is lost, without acid-scarification, germination of the seed fails to exceed 30% (Hare 2014).

Nearly all hybrid lines produced sufficient numbers of inflorescences, racemes and spikelets to indicate a potential for useful seed yields. In the trials at Ubon Ratchathani, most hybrid lines produced 300–500 inflorescences/m^2 and at Amnart Charoen, the BR06 lines produced 300–500 inflorescences/m^2 in the first and second years. Mulato II produced fewer inflorescences than the new lines at both sites. Inflorescence numbers have nearly always been the main indicator of whether a forage plant has the potential to produce seed. However, with hybrid brachiaria grasses, it appears that seed-set is the most determining factor of seed yields. By seed harvest there seems to be a massive failure of seed-set,

caryopsis maturation or both, with the cleaned seed coming from fewer than 10% of spikelets. In other brachiaria species it is not uncommon for abscission to precede maturation in a high proportion of spikelets (Hopkinson et al. 1996), but in the hybrid brachiaria grasses it appears to be an extremely high proportion.

Previous studies have shown seed yields of Mulato II are generally very low, with fewer than 2% of the spikelets formed producing viable seed (Hare et al. 2007a). There is speculation that this low seed-set is caused by pollen sterility, as Risso-Pascotto et al. (2005) found that more than 65% of pollen grains in brachiaria interspecific hybrids (*B. ruziziensis* x *B. brizantha*) were sterile and this sterility was genetic. Miles and Hare (2007) suggested this poor seed-set may be a common defect of newly formed apomictic forage grass hybrids. They referred to failures of buffel grass hybrids, which produced erratic and usually poor seed yields, leading to high seed prices. A hybrid-derived apomictic bahiagrass clone was not released because of concerns of low seed yields (Miles and Hare 2007).

In these current studies, we did not examine the percentage of spikelets that formed a caryopsis to calculate biological seed-set, but rather calculated economical seed-set, which is the ratio between realized and potential seed yield (Elgersma 1985). Mulato II seed-set (percentage of the number of cleaned seed to formed spikelets) ranged from 1.6 to 3.8% at Ubon Ratchathani and from 11.8 to 12.9% at Amnart Charoen. BR02/1794, which had superior seed yields to Mulato II, averaged 4.3% seed-set across both sites and seed-set for BR02/1752 ranged from 1.1 to 3.6% across both sites. Values for BR02/1718 were 1.8–3.1% at Ubon Ratchathani, and 7.0–12.2% at Amnart Charoen. Similarly, BR02/0465 had seed-set of 1.6–3.8% at Ubon Ratchathani, rising to 9.3–10.8% at Amnart Charoen.

The superior seed-set at Amnart Charoen compared with Ubon Ratchathani is interesting. Amnart Charoen is farther north than Ubon Ratchathani (15.5° vs. 15° N) and at a slightly higher elevation (168 vs. 130 masl). Grof (1968) showed that Basilisk signalgrass could set good seed yields and these seed yields were enhanced in drier upland regions in tropical latitudes (Loch et al. 1999). Basilisk seed production in Australia is predominantly on the Atherton Tablelands at lower latitudes but at elevations of 600–900 masl. In Brazil, successful seed production of Basilisk signalgrass and cv. Marandu is in the higher tropical latitudes (20 and 22° S) and at elevations of 700–1,000 masl (Souza 1999). The slightly higher elevation at Amnart Charoen compared with Ubon Ratchathani may have compensated for insufficient latitude and encouraged greater seed-set. Ferguson et al. (1983) showed that, at similar latitudes in South America (15–19° S), the site with the highest elevation (1,000 masl) produced the highest seed yields of signalgrass, even though it had the lowest latitude (15° S).

Under commercial conditions in Thailand, we have produced hybrid brachiaria seed in Ubon Ratchathani, Amnart Charoen, Mukdahan and Roi-et provinces. It is only in the more northerly province, Roi-et (16.8° N; 160 masl), that farmers still continue with Mulato II seed production (Hare 2014). In the other provinces seed yields are too low and erratic to be economical and farmers have ceased production. Roi-et farmers, however, found that BR02/1752 seed yields (100–200 kg/ha) were too low to interest them; thus BR02/1752 seed production is limited to Northern Laos (19–21° N; 700–1,200 masl), where farmers find the seed yields satisfactory (200–300 kg/ha) under their low-input management (Hare 2014). We have also commenced seed production of BR02/1794 in these Northern Laos provinces.

While 43 hybrid Brachiaria lines were evaluated for seed yield between 2005 and 2010, only 3 lines, BR02/1794, BR02/1718 and BR02/0465, displayed a potential for seed yields greater than or equal to Mulato II. BR02/1752 had seed yields similar to or slightly lower than Mulato II, though in another study at Ubon Ratchathani, BR02/1752 and BR02/1794 produced significantly higher seed yields than Mulato II (Bouathong et al. 2011).

In considering the commercial release of hybrid brachiaria lines as named cultivars, forage production and quality (Hare et al. 2015) and seed production were important considerations, together with the waterlogging tolerance of BR02/1752, released as cv. Cayman (Pizarro et al. 2013), and the upright nature of BR02/1794 for cut-and-carry forage, released as cv. Cobra (E. Stern pers. comm.).

Further research is needed to verify the influence of elevation and latitude on flowering and seed-set in hybrid brachiaria grasses. In future breeding of new hybrids, there must be more rigorous selection for seed production characteristics at latitudes and sites typical of where commercial brachiaria seed production occurs.

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References

Argel PJ; Miles JW; Guiot JD; Cuadrado H; Lascano CE. 2007. Cultivar Mulato II (*Brachiaria* hybrid CIAT 36087): A high-quality forage grass, resistant to spittlebugs and adapted to well-drained, acid tropical soils. International Center for Tropical Agriculture (CIAT), Cali, Colombia. http://goo.gl/HQhH80

Bouathong C; Hare M; Losirikul M; Wongpichet W. 2011. Effect of nitrogen rates on plant growth, seed yield and seed quality of three lines of brachiaria hybrid grass. Khon Kaen Agricultural Journal 39:295–306. http://202.28.92.38/kaj/

Elgersma A. 1985. Floret site utilization in grasses: Definitions, breeding perspectives and methodology. Journal of Applied Seed Production 3:50–54.

Ferguson JE; Thomas D; Andrade RP de; Costa NS; Jutzi S. 1983. Seed production potentials of eight tropical species in regions of Latin America. Proceedings of the XIV International Grassland Congress, Lexington, KY, USA, 1981. p. 275–278.

Grof B. 1968. Viability of *Brachiaria decumbens.* Queensland Journal of Agricultural Science 25:149–152.

Hare MD. 2014. Village-based tropical pasture seed production in Thailand and Laos – a success story. Tropical Grasslands-Forrajes Tropicales 2:165–174. DOI: 10.17138/TGFT(2)165-174

Hare MD; Tatsapong P; Saipraset K. 2007a. Seed production of two brachiaria hybrid cultivars in north-east Thailand. 2. Closing date. Tropical Grasslands 41:35–42. http://goo.gl/qlYfW9

Hare MD; Tatsapong P; Saipraset K. 2007b. Seed production of two brachiaria hybrid cultivars in north-east Thailand. 3. Harvesting method. Tropical Grasslands 41:43–49. http://goo.gl/0mhOao

Hare MD; Pizarro E; Phengphet S; Songsiri T; Sutin N. 2015. Evaluation of new hybrid brachiaria lines. I. Forage production and quality. Tropical Grasslands-Forrajes Tropicales 3 (this issue). DOI: 10.17138/TGFT(3)83-93

Hopkinson JM; Clifford PTP. 1993. Mechanical harvesting and processing of temperate zone and tropical pasture seed. Proceedings of the XVII International Grassland Congress, Palmerston North, New Zealand and Rockhampton, Qld, Australia, 1993. p. 1815−1822.

Hopkinson JM; Souza FHD de; Diulgheroff S; Ortiz A; Sánchez M. 1996. Reproductive physiology, seed production, and seed quality of *Brachiaria.* In: Miles JW; Maass BL; Valle CB do, eds. Brachiaria: Biology, Agronomy and Improvement. CIAT, Cali, Colombia. p. 124–140. http://goo.gl/vDO7ny

Loch DS; Cook BG; Harvey GL. 1999. Location of seed crops: Grasses. In: Loch DS; Ferguson JE, eds. Forage Seed Production, Volume 2: Tropical and subtropical species. CAB International, Wallingford, UK. p. 113–128.

Miles JW; Hare MD. 2007. Plant breeding and seed production of apomictic tropical forage grasses. In: Aamlid TS; Havstad LT; Boelt B, eds. Seed production in the northern light. Proceedings of the Sixth International Herbage Seed Conference, Gjennestad, Norway, 18–20 June 2007. Bioforsk Fokus 2(12):74–81. http://goo.gl/aGBDiW

Pizarro EA; Hare MD; Mutimura M; Bai Changjun. 2013. *Brachiaria* hybrids: Potential, forage use and seed yield. Tropical Grasslands-Forrajes Tropicales 1:31–35. DOI: 10.17138/TGFT(1)31-35

Risso-Pascotto C; Pagliarini MS; Valle CB do. 2005. Meiotic behavior in interspecific hybrids between *Brachiaria ruziziensis* and *Brachiaria brizantha* (Poaceae). Euphytica 145:155–159. DOI: 10.1007/s10681-005-0893-z

Souza FHD de. 1999. *Brachiaria* spp. in Brazil. In: Loch DS; Ferguson JE, eds. Forage Seed Production, Volume 2: Tropical and subtropical species. CAB International, Wallingford, UK. p. 371–379.

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Productive performance of three tropical legumes for protein banks in the dry tropics of Colima, Mexico

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Abstract

The aim of this study was to evaluate the productive performance of mucuna (*Mucuna pruriens*), lablab (*Lablab purpureus*) and clitoria (*Clitoria ternatea*) for protein banks in Colima, Mexico, with irrigation used prior to the rainy season. Fifteen plots were allocated in a complete randomized block design with 5 replicates. Dry matter production, crude protein, calcium and phosphorus concentrations and leaf:steam ratio were evaluated. The highest dry matter production was recorded for clitoria and lablab (9.80 and 8.93 t/ha, respectively, over 240–260 days), while mucuna produced 5.5 t DM/ha in 120 days. Leaf production in clitoria (4.73 t/ha) exceeded that in lablab (3.23 t/ha) and mucuna (2.69 t/ha), while leaf:stem ratio was 0.94 for clitoria, 1.0 for mucuna and 0.58 for lablab. Crude protein concentrations in all species were high (21.7–27.8%) as were concentrations of Ca (1.17–1.64%) and P (0.38–0.67%). Use of the 3 forages is discussed. Studies in the absence of irrigation in a range of seasons would determine how relevant these findings are in those situations. Feeding studies with animals would provide additional information on which to decide the appropriate species to plant in different situations.

Resumen

El objetivo del estudio fue evaluar el desempeño productivo de las leguminosas frijol terciopelo (*Mucuna pruriens*), lablab (*Lablab purpureus*) y clitoria (*Clitoria ternatea*) cuando se utilizan como bancos de proteína con aplicación de riego controlado después de la época de lluvias en Colima, México. Las leguminosas fueron establecidas en un diseño experimental de bloques completos al azar con cinco repeticiones para un total de 15 parcelas. Se midieron la producción de materia seca (MS), los contenidos (%) de proteína cruda (PC), calcio (Ca) y fósforo (P), y la relación hoja:tallo. Clitoria, 240 días después de la siembra (dds), y lablab, 260 dds, mostraron las mayores producciones de MS (9.80 y 8.93 t/ha, respectivamente); mientras que mucuna, 120 dds, produjo 5.5 t/ha de MS. La producción de hoja de clitoria (4.73 t/ha) superó a la de lablab (3.23 t/ha) y a la de mucuna (2.69 t/ha). La relación hoja:tallo fue 0.94 en clitoria, 1.0 en mucuna y 0.58 en lablab. Las especies mostraron un alto contenido de PC entre 21.7 y 27.8%, Ca (1.17 y 1.64%) y P (0.38 y 0.67%). Se discute el uso de las 3 especies y se sugieren estudios adicionales sin aplicación de riego.

Introduction

The state of Colima is located in the seasonally dry tropical region of Mexico, which is characterized by frost-free temperatures and rainfall of about 900 mm/yr, but also a pronounced seasonal arid pattern. This region provides a challenging environment for beef production owing to heat, disease and pest factors common to tropical areas, plus the added burden of a 7- to 8-month dry season, when forage quantity and quality are low (Peel et al. 2010).

Smallholder livestock production in the seasonally dry tropical areas is based on traditional dual-purpose systems (Macedo et al. 2003; Guevara et al. 2013),

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which provide only about 80 and 68% of the dry matter and protein requirements, respectively, of cattle. These systems have traditionally been based on feeding low-quality roughage sources and/or crop residues, mainly maize stover, during the dry season (Macedo et al. 2008; Guevara et al. 2013). The low protein concentration in these forages limits microbial activity in the rumen, resulting in depressed feed intake, low dry matter digestibility and suboptimal animal production, whether measured in terms of milk yield, draught power or growth rate (McDonald et al. 1996).

The integration of well-adapted protein bank legumes to supplement crop residues and grasses in animal production systems has the potential to improve forage quality in the dry season, and this strategy is being adopted much more widely by smallholders in many tropical countries (Pengelly et al. 2004; Rootman et al. 2004). In Zimbabwe, supplementing maize stover with lablab hay has significantly increased milk yields from 4–6 L/day to 6–17 L/day (Thorpe 1999). Milk yield and protein, lactose and non-fat solids from cows fed a ration with mucuna hay were similar to those from cows eating commercial feed concentrates (Murungweni et al. 2004).

Among the legume species being used or with potential as forage, lablab (*Lablab purpureus*) and mucuna (*Mucuna pruriens*) are annual legumes capable of producing large quantities of high-quality, above-ground biomass for livestock feed (Murungweni et al. 2004; Peters et al. 2010). In addition, clitoria (*Clitoria ternatea*) is a perennial climbing, strongly persistent, herbaceous legume with good potential under irrigation, yielding good quality forage (Villanueva et al. 2004; Cabrera et al. 2010). These 3 legumes are some of those recommended for the seasonally dry tropical areas of Mexico. Since the rainy season is so short, irrigation is normally used either before or after the rainy season to ensure that crops grow satisfactorily.

This study aimed to evaluate the productive potential of the above legumes for protein banks in Colima, Mexico, when irrigation was used prior to onset of the rainy season.

Materials and Methods

The trial was carried out in Armería, Colima, Mexico (19°00'56'' N, 104°00'05'' W; 91 masl), where the climate is warm, subhumid with summer rains (Figure 1). The average annual temperature and rainfall are 26.5 ºC and 790.8 mm, respectively (SEFOME 2012).

A complete randomized block design with 5 replications was used. Legumes were sown on 2 March 2007 in 9.60 m^2 plots, on a Eutric Regosol, at sowing rates of 15 kg/ha for mucuna (González 2007), 30 kg/ha for lablab (Martínez et al. 1987) and 20 kg/ha for clitoria (Villanueva et al. 2004). The area was irrigated prior to sowing, with drip irrigation applied every 10 days after sowing until the rains began (30 June 2007). Seeds were immersed for 5 minutes in water at 80 °C before sowing and urea, superphosphate and potassium chloride fertilizers were applied to the experimental plots to provide 100 kg N/ha, 80 kg P/ha and 80 kg K/ha. Weed control was done manually.

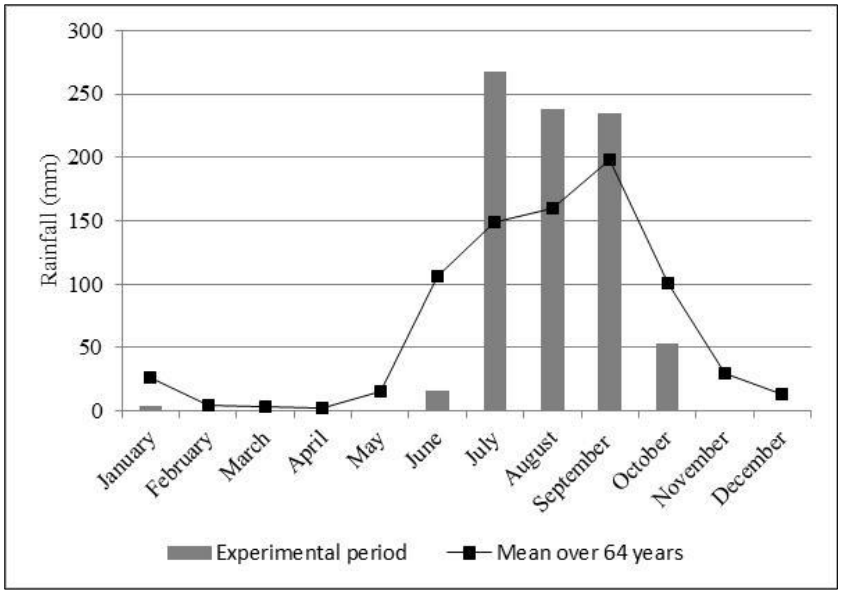

Figure 1. Rainfall during the study and the average of the last 64 years.

The legumes were harvested from an area of 4.80 m^2 in the center of the plot at a uniform height of 10 cm above ground. Mucuna (first harvest) and lablab (first and second harvests), were cut at 120 d of age, while clitoria was harvested at early flowering (10%), which occurred at 70 d for the first cut and at 47 d average for the 4 subsequent cuts.

At each harvest, an 800 g sample of fresh forage from each plot was selected, bagged and dried at 60 ºC for 48 h for estimating dry matter production. Following drying, leaves and stems were separated and weighed. Leaf and stem yields and leaf:stem ratio were calculated. The dried samples were bulked over all harvests and mean crude protein, calcium and phosphorus concentrations were determined (Goering and Van Soest 1970; AOAC 1990). In the case of clitoria, the only one that behaved as a perennial, plant height, stem length and cover were evaluated before each harvest. To assess plant cover, a 1 m^2 metal frame was used, with a single sample per plot. Plant height and length of stem were measured with a 1 m ruler on 5 randomly selected plants per plot.

The effects of legume and harvest on dependent variables were analyzed with ANOVA and Tukey´s test (P=0.05) using the SAS general model procedure (SAS Institute Inc. 2009).

Results

Dry matter (DM) production of mucuna and lablab at the first harvest was greater than that of clitoria, while lablab and clitoria had greater total production than mucuna (P<0.05) (Table 1). Dry matter production of lablab decreased significantly from the first to the second harvest, while production of clitoria remained unchanged over the 5 harvests (Table 1).

Table 1. Dry matter production (t/ha) and leaf:steam ratio of 3 legumes in Colima, Mexico.

	Harvest							
	1	2	3	4	5	Total	s.e.	Sig. level
Whole plant								
Mucuna pruriens	5.50A†					5.50B		
Lablab purpureus	5.89Aa†	3.04Ab‡				8.93A	0.59	0.00
Clitoria ternatea	1.40Ba†	2.15Aa†	1.92a§	2.12a§	2.21a§	9.80A	0.11	0.11
s.e.	0.65	0.21				0.68		
Sig. level	0.00	0.09				0.01		
Leaf								
Mucuna pruriens	2.69A†					2.69B		
Lablab purpureus	2.39Aa†	0.84Ab‡				3.23B	0.28	0.00
Clitoria ternatea	0.71Ba†	1.08Aa†	0.84a§	1.03a§	1.07a§	4.73A	0.05	0.07
s.e.	0.27	0.07				0.30		
Sig. level	0.00	0.24				0.01		
Stem								
Mucuna pruriens	2.81A†					2.81B		
Lablab purpureus	3.50Aa†	2.21Aa‡				5.71A	0.37	0.17
Clitoria ternatea	0.69Ba†	1.08Ba†	1.08a§	1.09a§	1.14a§	5.08 A	0.06	0.16
s.e.	0.40	0.21				0.45		
Sig. level	0.00	0.14				0.00		
Leaf:stem ratio								
Mucuna pruriens	1.00AB†					1.00 A		
Lablab purpureus	0.75Ba†	0.38Bb‡				0.58 B	0.08	0.01
Clitoria ternatea	1.05Aa†	1.07Aa†	0.79a§	0.95a§	0.95a§	0.94 A	0.04	0.10
s.e.	0.06	0.13				0.06		
Sig. level	0.04	0.01				0.00		

Values within columns and parameters followed by different upper-case letters and within rows followed by different lower-case letters are significantly different according to Tukey's test (P≤0.05).
†Irrigation; ‡Irrigation−rainy season; §Rainy season.

Table 2. Crude protein, calcium and phosphorus concentrations (%) of 3 legumes in Colima, Mexico.

Species	Crude protein	Calcium	Phosphorus
Mucuna pruriens	27.8	1.48	0.38
Lablab purpureus	21.6	1.64	0.67
Clitoria ternatea	22.1	1.17	0.41

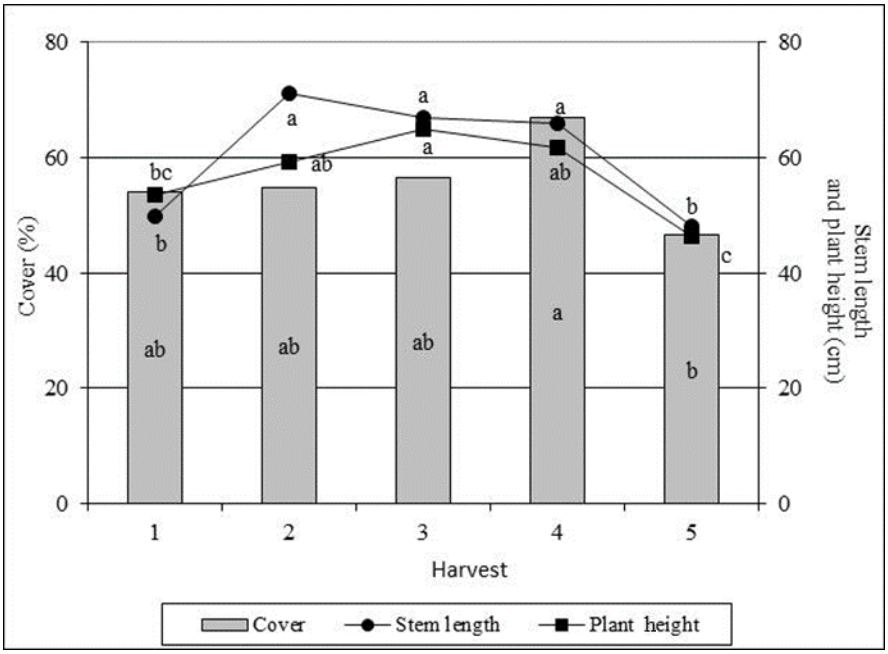

Figure 2. Evolution of cover, stem length and plant height of clitoria (*Clitoria ternatea*) in Colima, Mexico. Different letters in columns or on lines denote significant differences (P<0.05).

The production of leaf and stem of mucuna and lablab at the first harvest and stem production of lablab at the second harvest were greater than those from clitoria (P<0.05) (Table 1). While total leaf production for clitoria was greater than for mucuna and lablab, lablab and clitoria produced more stem than mucuna (P<0.05). As a result, leaf:stem ratio for mucuna and clitoria was greater than for lablab (P<0.05). Leaf production and leaf:stem ratio of lablab decreased significantly from the first to the second harvest, while these parameters did not vary over the 5 harvests for clitoria (Table 1).

At 120 days of age, mucuna and lablab had average crude protein concentrations of 27.8 and 21.6%, respectively. Average concentrations of calcium and phosphorus in mucuna and lablab were 1.48 and 1.64%, and 0.38 and 0.67%, respectively. At 47 days of age, average concentrations of crude protein, calcium and phosphorus in clitoria were 22.1, 1.17 and 0.41%, respectively (Table 2).

Ground cover of clitoria was similar at the first 4 harvests, decreasing significantly at the final harvest, while height peaked at the 4th harvest. The stems showed maximum length from the second to the fourth harvest, and decreased towards the end of the study (Figure 2).

Discussion

This study has provided useful information on the potential of mucuna, lablab and clitoria as legumes for use as protein banks in the seasonally dry tropics of Mexico. All 3 legumes produced good yields of forage of high quality and could have a role in improving nutritional levels for ruminants, especially during the dry season. It is important to realize that the data in this study are for 1 year only and seedlings were irrigated for the 4 months until the rains started to ensure survival. Harvesting of mucuna, the first harvest of lablab and the first 2 harvests of clitoria occurred before the wet season started,

so the growth was produced by drip irrigation. Rainfall during the rainy season was well above the long-term mean, so yields obtained and survival of the species, especially clitoria, might be better than would be obtained under non-irrigated situations and in average or below average rainfall conditions.

The total DM yield of clitoria over the 5 harvests compared favorably with yields reported by Bakhashwain and Elfeel (2012) in Saudi Arabia, when it was drip-irrigated and heavily fertilized. Average DM production of clitoria under irrigation per harvest was lower than that reported in Sudan (2.95 t/ha) by Mohamed-Osman et al. (2013). While in our study DM production of clitoria remained unchanged over the 5 harvests, other authors in Mexico found that, owing to low rainfall and no irrigation, the greatest DM production occurred at the first harvest, with significant decreases subsequently (Carvajal and Lara 2005). A similar trend was observed in clitoria under irrigation (Bakhashwain and Elfeel 2012). In the present study, irrigation followed by adequate rainfall favored vigorous regrowth, while in other studies in the absence of irrigation, DM production varied significantly between the rainy and dry seasons (Sosa et al. 2008).

DM yield of the primary growth (first harvest) of lablab in this study was greater than the yields reported by Barnes (1996) in Ghana, who harvested less than 2.89 t/ha at 2 sites in consecutive years. In addition, total DM yield of lablab was greater than the 5.9 t/ha reported by Jingura et al. (2001) in Zimbabwe. However, Nworgu and Ajayi (2005) reported DM yields of 19.98–20.82 and 44.58–48.66 t/ha/yr in Nigeria[1], harvesting at 8 and 12 weeks, respectively. The DM yield of mucuna in this study was lower than the 8.2–11.6 t/ha reported by Kaizzi et al. (2004), but greater than the 2.61 t/ha of Jara (1997). Factors like soil moisture (rainfall), temperature, soil type, plant density, cutting height, cutting interval and fertilizer application affect DM production of legumes (Jingura et al. 2001; Njarui et al. 2004; Sosa et al. 2008; Ogedegbe et al. 2011).

The leaf fraction of forages generally has better nutritional value than more fibrous stems (Van Soest 1994). Since cattle select for the leaf fraction, the leaf:stem ratio is a very important parameter in determining the nutritional value of forages, including legumes (Hendricksen et al. 1981; Wood 1983). Legumes with high leaf:stem ratios would seem to be those of highest nutritional value (Norton and Poppi 1995). Clitoria maintained the same leaf:stem ratio throughout, in contrast with the results of Ramírez et al. (2003), who observed a decline in this parameter with progressive harvests. Leaf:stem ratio of clitoria was significantly lower than values of up to 7.3 reported by Abusuwar and Omer (2011), who suggested that leaf:stem ratio increased with the addition of 50 kg triple superphosphate/ha before planting. At the first harvest, leaf:steam ratio for lablab was similar to that found by Murphy et al. (1999) in Honduras (0.76) in plants of similar age (117 days), but the overall value (0.58) was slightly lower than the bottom of the range (0.63–6.0) reported by Abusuwar and Omer (2011). As normally occurs in most forages, with maturity lablab showed a decrease in leafiness, resulting in a decrease in leaf:stem ratio. With regard to mucuna, leaf:stem ratio was significantly lower than that indicated (2.94) in a previous study (Nyambati and Sollenberger 2003).

The crude protein concentrations in clitoria, lablab and mucuna were much higher than the minimum requirement (7%) for maintenance of beef cattle (NRC 1984). Juma et al. (2006) reported crude protein concentrations in clitoria and mucuna of 21.8 and 18.0%, respectively, while Aganga and Autlwetse (2000) reported a crude protein concentration in lablab of 16.4%.

Calcium and phosphorus concentrations in the 3 legumes were higher than the suggested critical levels of 0.30% Ca and 0.25% P, necessary to meet ruminant requirements in the tropics (McDowell and Arthington 2005). Legumes are good sources of Ca, and are higher in Ca content than grasses.

In clitoria, length of stem was higher than that reported for 2 genotypes, blue (28.2 cm) and white (31.7 cm) in Venezuela by Suárez et al. (2012). The coverage and height of clitoria were better than observed in another Mexican study, in which plant coverage decreased from 63 to 11% and the height from 67 to 41 cm, from first to fourth harvest (Carvajal and Lara 2005). Meanwhile, Adjei and Fianu (1985) mentioned that clitoria coverage declined during the first year after planting, from almost 60% to less than 15%. These studies show that, despite clitoria being a perennial plant which could be expected to remain productive for perhaps 5 years (Pengelly and Conway 2000), it often performs as an annual. Its lack of persistence is often due to grazing management, soil type, weed competition, drought and cutting interval (Adjei and Fianu 1985; Peck et al. 2012). The fact that our crops were irrigated from before planting until the start of the rainy season and the rainy season was wetter than normal could indicate that the results obtained were the best that might be expected on this soil type in this region.

While all 3 species grew well and produced high yields of high quality forage, their various attributes make them suitable for use in different situations. One

[1]Data presented without major methodological details.

needs to consider how the protein bank would function, i.e. would forage be harvested and stored for feeding livestock later in the year or would it be left to stand in the field for grazing off during the dry season? Issues like how well the species retain their leaves post maturity become important for stand-over forage. Owing to its perennial growth pattern, clitoria is more flexible in how the forage might be used. It could be used as green forage for several cuts, which could eliminate costs of hay making and storage. Some authors, e.g. Abreu et al. (2014), recommend feeding the forage fresh, either in a cut-and-carry system or under grazing. Annual legumes such as lablab and mucuna can provide a large quantity of forage within a short period, which can be conserved and used as hay for dry season livestock feeding. While this incurs additional costs for labor and storage, the area is freed up for growing other crops, especially under the conditions of our study, where growth of mucuna and most of the growth of lablab occurred before the start of the wet season. A major limitation for some producers with these annuals is that they might need replanting each year (Pengelly and Conway 2000).

Currently, it has been shown that using legume protein banks increases milk yield and weight gain, and improves household short-term income in tropical countries (Kabirizi et al. 2013; Nulik et al. 2013; Douxchamps et al. 2014).

Studies over a range of years in the absence of irrigation would provide a better understanding of how these legumes would perform under strictly rain-fed conditions.

Feeding studies with the forage produced by the 3 species would provide a sounder basis for decision making on which species to plant in different situations.

References

Abreu MLC; Vieira RAM; Rocha NS; Araujo RP; Glória LS; Fernandes AM; Lacerda PD de; Gesualdi Júnior A. 2014. *Clitoria ternatea* L. as a potential high quality forage legume. Asian-Australasian Journal of Animal Science 27:169–178. DOI: 10.5713/ajas.2013.13343

Abusuwar AO; Omer EA. 2011. Effect of intercropping, phosphorus fertilization and rhizobium inoculation on the growth and nodulation of some leguminous and cereal forages. Agriculture and Biological Journal of North America 2:109–124. DOI: 10.5251/abjna.2011.2.1.109.124

Adjei MB; Fianu FK. 1985. The effect of cutting interval on the yield and nutritive value of some tropical legumes on the coastal grassland of Ghana. Tropical Grasslands 19:164–171. http://goo.gl/gM5VDR

Aganga AA; Autlwetse MN. 2000. Utilization of sorghum forage, millet forage, veldt grass and buffel grass by Tswana sheep and goats when fed *Lablab purpureus* L. as protein supplement. Asian-Australasian Journal of Animal Science 13:1127-1132. DOI: 10.5713/ajas.2000.1127

AOAC. 1990. Official methods of analysis. 15th Edn. Association of Official Analytical Chemists (AOAC), Arlington, VA, USA. http://goo.gl/gawF2Y

Bakhashwain AA; Elfeel AA. 2012. Foliage productivity and quality of valuable medicinal plant (*Clitoria ternatea* L.) as affected by different fertilizers. Journal of Medicinal Plants Research 6:4225–4230. DOI: 10.5897/JMPR12.321

Barnes P. 1996. Dry matter production and chemical composition of introduced forages at two moist savanna sites in Ghana. Tropical Grasslands 30:418–421. http://goo.gl/OtLOvP

Cabrera TEJ; Sosa REE; Pérez RJD. 2010. *Clitoria ternatea*, suplemento alimenticio para vacas doble propósito. Folleto Técnico No. 6. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) – Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Chetumal, Quintana Roo, Mexico. http://goo.gl/vaACqv

Carvajal AJJ; Lara RM. 2005. Producción de heno de gramíneas y leguminosas forrajeras. Proceedings of the XXIX Congreso Nacional de Buiatría, Puebla, Mexico, 2005. p. 228.

Douxchamps S; Rao IM; Peters M; Van der Hoek R; Schmidt A; Martens S; Polania J; Mena M; Binder CR; Schöll R; Quintero M; Kreuzer M; Frossard E; Oberson A. 2014. Farm-scale tradeoffs between legume use as forage versus green manure: The case of *Canavalia brasiliensis*. Agroecology and Sustainable Food Systems 38:25–45. DOI: 10.1080/21683565.2013.828667

Goering HK; Van Soest PJ. 1970. Forage fiber analysis. Agriculture Handbook No. 379. Agriculture Research Service, USDA, Washington, DC, USA. http://goo.gl/bQHJt6

González SA. 2007. Asociación de frijol terciopelo con forrajes de corte en el trópico semiárido de Colima. Proceedings of the XLIII Reunión Nacional de Investigación Pecuaria, Sinaloa, Mexico, 2007. p. 156.

Guevara F; Rodríguez LA; Saraoz V; La OM; Gómez H; Pinto R; Fonseca M; Ruiz B; Nahed J. 2013. Energy balance of the local system of fattening bovine production in Tecpatán, Chiapas, México. Cuban Journal of Agricultural Science 47:359–365. http://goo.gl/2D68Uf

Hendricksen RE; Poppi DP; Minson DJ. 1981. The voluntary intake, digestibility and retention time by cattle and sheep of stem and leaf fractions of a tropical legume (*Lablab purpureus*). Australian Journal of Agricultural Research 32:389–398. DOI: 10.1071/ar9810389

Jara FAF. 1997. Evaluación del aporte de tres leguminosas (*Canavalia ensiformis*, *Mucuna pruriens*, *Dolichos lablab*) usadas como abono verde sobre la recuperación de suelos degradados de ladera. Bachelor Thesis. Escuela Agrícola Panamericana, Zamorano, Honduras.

Jingura RM; Sibanda S; Hamudikuwanda H. 2001. Yield and nutritive value of tropical forage legumes grown in semi-arid parts of Zimbabwe. Tropical Grasslands 35:168–174. http://goo.gl/Ee4Ez2

Juma HK; Abdulrazak SA; Muinga RW; Ambula MK. 2006. Effects of supplementing maize stover with clitoria, gliricidia and mucuna on performance of lactating jersey cows in coastal lowland Kenya. Tropical and Subtropical Agroecosystems 6:1–7. http://goo.gl/9mwD3y

Kabirizi J; Ziiwa E; Mugerwa S; Ndikumana J; Nanyennya W. 2013. Dry season forages for improving dairy production in smallholder systems in Uganda. Tropical Grasslands–Forrajes Tropicales 1:212−214. DOI: 10.17138/TGFT(1)212-214

Kaizzi CK; Ssali H; Vleck PLG. 2004. The potential of Velvet bean (*Mucuna pruriens*) and N fertilizers in maize production on contrasting soils and agro-ecological zones of East Uganda. Nutrient Cycling in Agroecosystems 68:59–72. DOI: 10.1023/b:fres.0000012233.27360.60

Macedo R; Galina MA; Zorrilla JM; Palma JM; Pérez-Guerrero J. 2003. Análisis de un sistema agropecuario tradicional en Colima, México. Archivos de Zootecnia 52:463–474. http://goo.gl/dsy8Mx

Macedo R; Galina MA; Zorrilla JM. 2008. Balance forrajero, energético y proteico de un sistema de producción tradicional de doble propósito en Colima, México. Zootecnia Tropical 26:455–463.

Martínez J; Milera M; Remy VA. 1987. Estimación del tamaño de parcela experimental de dolichos (*Lablab purpureus* cv. Rongai). Pastos y Forrajes 10:274–278.

McDonald P; Edwards RA; Greenhalgh JFD. 1996. Animal nutrition. Longman Scientific and Technical, London, UK.

McDowell LR; Arthington JD. 2005 Minerals for grazing ruminants in tropical regions. 4th Edn. Institute of Food and Agricultural Sciences (IFAS), University of Florida, Gainesville, FL, USA.

Mohamed-Osman AA; Hag-Babiker FS; Abdel-Aziz AAH. 2013. Evaluation of Rhodes grass (*Chloris gayana* Kunth) with local forage legumes in the Sudan. Advances in Environmental Biology 7:164–169. http://goo.gl/5tN4sx

Murphy AM; Colucci PE; Padilla MR. 1999. Analysis of growth and nutritional characteristics of *Lablab purpureus*. Livestock Research for Rural Development 11, article #3. www.cipav.org.co/lrrd/lrrd11/3/colu113.htm

Murungweni C; Mabuku O; Manyawu GJ. 2004. Mucuna, lablab and paprika calyx as substitutes for commercial protein sources used in dairy and pen-fattening diets by smallholder farmers of Zimbabwe. In: Whitbread MA; Pengelly BC, eds. Tropical legumes for sustainable farming systems in southern Africa and Australia. ACIAR Proceedings No. 115. Australian Centre for International Agricultural Research, Canberra, Australia. p. 126–135. http://goo.gl/mdNg71

Njarui DMG; Keating BA; Jones RK; Beattie WM. 2004. Evaluation of forage legumes in the semi-arid region of eastern Kenya. 2: Persistence and dry matter production of selected forage legumes. Tropical and Subtropical Agroecosystems 4:57–68. http://goo.gl/KUBNrZ

Norton BW; Poppi DP. 1995. Composition and nutritional attributes of pasture legumes. In: D'Mello JPF; Devendra C, eds. Tropical legumes in animal nutrition. CAB International, Wallingford, UK. p. 23–47.

NRC. 1984. Nutrient requirements of beef cattle. 6th Edn. National Research Council (NRC), National Academic Press, Washington, DC, USA.

Nulik J; Dalgliesh N; Cox K; Gabb S, eds. 2013. Integrating herbaceous legumes into crop and livestock systems in eastern Indonesia. Monograph No. 154. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. http://goo.gl/5Ckmov

Nworgu FC; Ajayi FT. 2005. Biomass, dry matter yield, proximate and mineral composition of forage legumes grown as early dry season feeds. Livestock Research for Rural Development 17, article # 11. http://goo.gl/pWnmqG

Nyambati EM; Sollenberger LE. 2003. Nutritive value of top-canopy herbage of mucuna and lablab relay cropped in maize in the sub-humid highlands of northwestern Kenya. Tropical and Subtropical Agroecosystems 1:81–86.

Ogedegbe SA; Ogunlela VB; Olufajo OO; Odion EC. 2011. Herbage yield of lablab (*Lablab purpureus* L. Sweet) as influenced by phosphorus application, cutting height and age in a semi-arid environment, Nigeria. International Journal of Agricultural Research 6:789–797. DOI: 10.3923/ijar.2011.789.797

Peck G; Hall T; Silcock R; Clem B; Buck S; Kedzlie G. 2012. Persistence of pasture legumes in southern and central Queensland. In: Yunusa I, ed. Proceedings of the 16th Australian Agronomy Conference 2012, Armidale, NSW, Australia. http://goo.gl/LSiiEl

Peel DS; Johnson RJ, Mathews KH. 2010. Cow-calf beef production in Mexico. USDA, Economic Research Service LDP-M-196-01. http://goo.gl/lNq1EB

Pengelly BC; Conway MJ. 2000. Pastures on cropping soils: Which tropical pasture legume to use? Tropical Grasslands 34:162–168. http://goo.gl/mmQImK

Pengelly BC; Whitbread A; Mazaiwana PR; Mukombe N. 2004. Tropical forage research for the future – Better use of research resources to deliver adoption and benefits to farmers. In: Whitbread MA; Pengelly BC, eds. Tropical legumes for sustainable farming systems in southern Africa and Australia. ACIAR Proceedings No. 115. Australian Centre for International Agricultural Research, Canberra, Australia. p. 28–37. http://goo.gl/mdNg71

Peters M; Franco LH; Schmidt A; Hincapié B. 2010. Especies forrajeras multipropósito. Opciones para productores del trópico americano. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. http://goo.gl/892LAV

Ramírez RO; Pérez PJ; Hernández GA; Herrera HJG; Martínez HPA. 2003. Evaluación del rendimiento y la utilización de la asociación estrella-Clitoria cosechada a diferente asignación de forraje. Técnica Pecuaria en México 41:219–230.

Rootman G; Mabistela M; Pengelly B. 2004. Selecting potential fodder bank legumes in semi-arid northern South Africa. In: Whitbread MA; Pengelly BC, eds. Tropical legumes for sustainable farming systems in southern Africa and

Australia. ACIAR Proceedings No. 115. Australian Centre for International Agricultural Research, Canberra, Australia. p. 38–43. http://aciar.gov.au/files/node/555/proc115.pdf

SAS Institute Inc. 2009. SAS/SAT user's guide. Release version 9. SAS Institute Inc, Cary, NC, USA.

SEFOME. 2012. Armería. Cédula para la promoción municipal. Secretaría de Fomento Económico (SEFOME), Colima, México. http://goo.gl/MULQid

Sosa REE; Cabrera TE; Pérez RD; Ortega RL. 2008. Producción estacional de materia seca de gramíneas y leguminosas forrajeras con cortes en el estado de Quintana Roo. Técnica Pecuaria en México 46:413–426.

Suárez H; Mercado W; Ramírez M; Bracho B; Rivero J; García DE. 2012. Caracterización morfoagronómica y evaluación del contenido proteínico en dos genotipos de *Clitoria ternatea* L. cultivados en un sistema de espalderas. Pastos y Forrajes 35:365–380.

Thorpe W. 1999. ILRI's smallholder dairy systems research: Experiences and lessons from collaborative R&D in eastern Africa. Proceedings of the Workshop on Ecoregional Research at International Livestock Research Institute, Addis Ababa, Ethiopia, 1998. p. 69–82. http://goo.gl/NyTfOZ

Villanueva JF; Bonilla JA; Rubio JV; Bustamante JJ. 2004. Agrotecnia y utilización de *Clitoria ternatea* en sistemas de producción de carne y leche. Técnica Pecuaria en México 42:79–96. www.redalyc.org/articulo.oa?id=61342107

Van Soest PJ. 1994. Nutritional Ecology of the Ruminant. 2nd Edn. Comstock Publishing Association, Cornell University Press, Ithaca, NY, USA.

Wood IM. 1983. Lablab bean (*Lablab purpureus*) for grain and forage production in the Ord River irrigation area. Australian Journal of Experimental Agriculture and Animal Husbandry 23:162–171. DOI: 10.1071/ea9830162

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Variations in soil properties, species composition, diversity and biomass of herbaceous species due to ruminant dung residue in a seasonally dry tropical environment of India

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Abstract

Ruminants directly or indirectly influence nutrient cycling and vegetation structure in grassland ecosystems. We assessed the impact of natural cattle dung deposition on soil attributes and the resulting effects on species composition, species diversity and biomass of herbaceous vegetation in a natural grassland in the seasonally dry tropical environment of Banaras Hindu University, India. For this 72 plots of 1 × 1 m [12 locations × 2 treatments (dung residue and control) × 3 replicates] were selected in January 2013 and soil and vegetation samples collected. A total of 74 species belonging to 66 genera and 25 families were recorded. Principal Component Analysis (PCA) ordination revealed that the dung residue (DP) and control (CP) plots were distinctly different in terms of soil attributes and species composition. The *k*-dominance plot showed greater species diversity in DPs than CPs, with higher soil nutrients and moisture and lower soil pH in DPs than CPs. Similarly, DPs showed more herbaceous species and greater biomass than CPs. This trend can be explained by the positive responses of forbs, erect plants, annuals, large-statured, non-native and non-leguminous species to dung residue, while increased biomass can be partly due to cattle preferentially not grazing areas adjacent to a dung pat. Overall, the study showed that deposition of dung during grazing by cattle stimulates growth of pasture species and increases species diversity. Therefore cattle dung could be used as a sustainable alternative to chemical fertilizers to manage soil pH, species composition and diversity, and forage production in the seasonally dry tropical grasslands of India, which are nutrient- and moisture-limited.

Resumen

Los rumiantes directa o indirectamente influyen en el ciclo de nutrientes y en la estructura de la vegetación en los ecosistemas de pastizales. En el estudio se evaluó el impacto de la deposición natural de heces de bovinos en las características del suelo, la composición y diversidad de especies y en la biomasa de la vegetación herbácea de un pastizal nativo en ambiente tropical seco estacional de Banaras Hindu University, India. Para el efecto fueron seleccionadas 72 parcelas de 1 × 1 m [12 sitios x 2 tratamientos (residuo de heces y control) x 3 repeticiones]. Al comienzo del ensayo, en enero de 2013, se recolectaron muestras de suelo y vegetación. Se registraron un total de 74 especies pertenecientes a 66 géneros y 25 familias. Los Análisis de Componentes Principales (PCA) mostraron que las características de suelo y la composición de especies fueron diferentes entre los sitios con residuo de heces (DP) y el control (CP). La curva *k*-dominancia mostró una mayor diversidad de especies en las DPs que en las CPs, con niveles más altos de nutrientes y humedad en el suelo, y pH más bajo en DPs que en CPs. Del mismo modo, los DPs mostraron mayor número de especies herbáceas y mayor biomasa que los CPs. Esta tendencia se explica por las respuestas positivas de las especies herbáceas, erectas, anuales, de porte alto, no nativas y no leguminosas, a residuo de heces, mientras que el aumento de la biomasa puede deberse, en parte, a que el ganado prefiere no pastar en áreas adyacentes a residuos de heces. En general, el estudio mostró que la deposición de heces durante el pastoreo por el ganado bovino estimula el crecimiento de las especies y aumenta su diversidad. Por tanto las heces podrían ser utilizadas como una alternativa sostenible a los fertilizantes químicos para manejar el pH del suelo, la composición y diversidad de las especies y la producción de forraje en los pastizales tropicales en ecosistemas estacionales secos de la India, que presentan limitaciones de fertilidad y escasa humedad.

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Introduction

Grasslands occupy roughly 25% (33×10^6 km^2) of the total land surface of the Earth (Shantz 1954) and about 18% of the total land area in India (Singh et al. 2006), the second most populous country globally. With the continuously growing human population, agricultural production per unit area has increased to fulfill the greater food requirements by increased use of N-based chemical fertilizers (Shukla et al. 1998). Usage of N-fertilizer has increased from 0.06 million tonnes in 1952 to 9.5 million tonnes in 1995, increasing the release of global warming gases into the atmosphere (Galloway et al. 2008; Zhou et al. 2010) and causing changes in soil, water and vegetation (Giles 2005). Therefore, an alternative to chemical N-fertilizer, which has the capacity to enhance forage production and species diversity with little or no negative effect on the environment, is needed.

The effects of dung on pasture ecosystems have been studied extensively with respect to nutrient cycling (Dickinson and Craig 1990) and species composition in temperate grasslands (MacDiarmid and Watkin 1971; Castle and MacDaid 1972). Such studies, with particular emphasis on biodiversity and biomass of plants, are lacking in tropical grasslands. We assumed that plants with different traits will respond differentially to dung residue and competitive interactions may be changed. Further, we hypothesized that dung residue may promote herbaceous biomass production and species diversity of certain plant species (Steinauer and Collins 1995), because moist dung is a nutrient-rich microhabitat that facilitates seed germination and seedling establishment of competitively superior species (Brown and Archer 1987).

The objectives of the present studies were to assess the effects of deposition of ruminant dung on soil and vegetation attributes in a seasonally dry tropical environment in India. Specifically, we examined the effects of ruminant dung deposition on: (1) community composition; (2) species diversity and biomass; and (3) diversity of plant functional groups in natural grasslands of Banaras Hindu University, Varanasi, India.

Material and Methods

Study sites

The study was conducted at 12 locations (INH - International Hostel; SUK - Sukanya; KAS - Kasturba; SNPG - Sarojani Nayadu; MMV - Mahila Maha Vidhyalay; BG - Botanical Garden; MB - Madhuban; MC - Meera Colony; AG-1 - Agriculture Farm-1; AG-2 - Agriculture Farm-2; AG-3 - Agriculture Farm-3; and GB - Gandhi Bhawan) at the Banaras Hindu University (24°18′ N, 83°03′ E; 76 masl), Varanasi, India, during January–March 2013. The grassland studied is representative of the unmanaged rangelands in the region. The area is a part of the Indo-Gangetic Plains characterized by a tropical monsoon climate. The year is made up of a cold winter (November–February), a hot summer (April–June) and a warm rainy season (July–September). October and March are transitional months between rainy and winter, and winter and summer seasons, respectively. During the study period, mean maximum temperature was 25.9 °C (range 18–34.4 °C), while mean minimum temperature was 11.2 °C (range 4.9–16.6 °C). The soil is characterized as Banaras Type III, which is a well-drained, pale brown, silty loam (Buol et al. 2003). In general, the soil is moderately fertile, being low in available nitrogen and medium in available phosphorus and potassium with neutral to alkaline pH (Sagar et al. 2008).

Study design

For sampling, 12 locations were selected visually to represent the entire range of variations in terms of soil, vegetation and ruminant dung residue. Within each location, 3 homogeneous dung residue (DP) pats of one month age (because in the dry season dung completely disappears within 2 months; Holter 1979) and 3 adjacent control (CP) spots with no dung were selected. Around each pat and control spot, a plot of 1 × 1 m in size was established, because a single release of cattle excrement on soil roughly occupies this area (Haynes and Williams 1993). Cow and buffalo dung pats are easily decomposed and scattered by the activity of dung beetles to cover 1 m^2 area within a month (R. Sagar personal observation). Thus, a total of 72 plots (12 locations × 2 treatments × 3 replicates) were sampled.

Soil sampling and analysis

From each plot, 3 soil samples (0–10 cm depth) were randomly collected, using a corer of 100 cm^3 capacity. These samples were mixed and gently homogenized. Large roots, fine roots, wood and litter were removed from the composite soil samples carefully and the soil sieved through a 2 mm mesh screen. One part of each sample was weighed and oven-dried at 105 °C to determine soil moisture content, bulk density and porosity, while a second portion was air-dried for analysis of soil

pH, total soil carbon (total-C), total soil phosphorus (total-P), total soil nitrogen (total-N: inorganic-N + organic-N), ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N). The sum of NH_4^+-N and NO_3^--N is referred to as mineral-N or inorganic-N.

Soil moisture was measured by the gravimetric method. Soil bulk density (g/cm^3) was determined by using the corer method (stainless steel cylinders with a volume of 100 cm^3) (Piper 1944) and was calculated as the dry weight of soil divided by the soil volume (Su and Zhao 2003). Soil porosity was calculated by subtracting the ratio of soil bulk density and particle density (ca. 2.65) from its maximum value of 1 (Sagar and Verma 2010). Soil pH was determined by using a glass electrode (1:2, soil:water ratio). Total soil-C was analyzed by the Walkley (1947) and total soil-N by the Jackson (1958) methods. NH_4^+-N was determined by the phenate method (APHA 1985), NO_3^--N by the PDSA method (Jackson 1958) and organic-N by the Jackson (1958) method. Soil phosphorus was analyzed by Allen's method (Allen et al. 1974).

The nutrient concentration (kg/ha) at each location was calculated by multiplying soil bulk density (g/cm^3) by the determined nutrient value (mg/kg). Inputs of soil moisture, pH and nutrients at each location due to ruminant dung were calculated by subtracting the values of control plots (CPs) from the values of the dung residue plots (DPs).

Vegetation sampling and analyses

For each established 1 × 1 m plot, the numbers of individual plants were recorded by species and aboveground live biomass of each species was clipped at the soil surface. All samples were oven-dried at 80 °C to constant mass and weighed.

Six plant functional attributes pertaining to the various life forms (grasses, sedges and forbs), growth forms (erect, prostrate, procumbent and decumbent), life span (annual, biennial and perennial), relative height (tall, medium and short), N-fixing ability (leguminous forbs and non-leguminous forbs) and origin and distribution (native, non-native and cosmopolitan) were selected. We selected these traits because of their differentiating role of morphology, phenology, competitive ability and taxonomy (Diekmann and Falkengren-Grerup 2002). Species were classed as medium height if 45–90 cm tall, while those below and above this range were grouped as short and tall categories, respectively. Other traits were determined with the help of Flora of Raipur, Durg and Rajnandangaon (Verma et al. 1985) and Flora of the upper Gangetic plain (Duthie 1903). The biomass of each functional attribute was computed by summing the biomass of all species in each category.

The Importance Value Index (IVI) of each herbaceous species for each location was calculated by summing the relative frequency, relative density and relative biomass (Mueller-Dombois and Ellenberg 1974). The alpha-diversity (H') and its components, i.e. species richness (number of species/m^2), evenness (E; distribution of importance values among the species), and beta diversity in terms of habitat heterogeneity (β) were calculated for each location. The following equations were used to calculate the species diversity indices:

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \quad \text{(Shannon and Weaver 1949)}$$

$$E = \frac{H'}{\ln S} \quad \text{(Pielou 1966)}$$

$$\beta = \frac{Sc}{\bar{S}} \quad \text{(Whittaker 1972)}$$

where:

p_i = the proportion of importance value belonging to species 'i'; S = number of species; Sc = total number of species in the pooled sample; and $\bar{S}$ = average number of species per sample. The diversities of DPs and CPs were compared using the k-dominance plots in which percent cumulative importance values were plotted against log species rank (Platt et al. 1984).

Statistical analyses

Analysis of variance (ANOVA) procedures of SPSS package (SPSS 1997) were used to examine the effects of trait, treatment and location on the soil and vegetation parameters. Paired 't'-test was used to understand the notable variations in the means of soil and vegetation parameters between the treatments. A Tukey's HSD (honestly significant difference) test was used to determine the significance of differences in the soil and vegetation variables among the locations and the traits. The locations of DPs and CPs were ordinated by PCA, using PC-ORD software (McCune and Mefford 1999). Pearson correlation coefficient was established between the soil variables with the help of SPSS package (SPSS 1997). In addition, stepwise regression was used to find out the main soil variables to explain the variability in species and biomass in DPs and CPs with the help of SPSS software (SPSS 1997).

Results

Soil moisture, porosity, pH and nutrient concentrations

Across DP and CP locations, soil moisture, porosity, pH, NH_4^+-N, NO_3^--N, mineral-N, organic-N and total-N ranged from 3.7 to 21%, 48 to 76%, 7.4 to 7.8, 0.9 to 5.4 kg/ha, 0.6 to 3.0 kg/ha, 1.6 to 8.4 kg/ha, 527 to 1,059 kg/ha and 529 to 1,064 kg/ha, respectively. The mean values for soil moisture (t = 18.33, P≤0.0001), porosity (t = 12.86, P≤0.0001), NH_4^+-N, NO_3^--N, mineral-N, organic-N and total-N were significantly higher in DPs than in CPs (Tables 1−3). Contrastingly, the mean values for soil pH (t = 17.44, P≤0.0001) were higher in CPs than in DPs (Tables 1−3). ANOVA showed significant differences in these variables due to locations, treat-ments and location × treatment (Table 3). Similarly, total-C, total-P and C:N ratio varied significantly due to location, treatment and location × treatment (Table 3), with values approximately 2-fold greater in DPs than CPs (Tables 1 and 2). PCA ordination based on component soil attributes distinctly categorized DPs and CPs (Figure 1).

Pearson correlation analysis showed significant relationships between C:N ratio and NH_4^+-N (r = -0.58, P≤0.05), NO_3^--N (r = -0.59, P≤0.05), mineral-N (r = -0.68, P≤0.05), organic-N (r = -0.67, P≤0.05), total-N (r = -0.66, P≤0.05), total-C (r = 0.91, P≤0.001) and total-P (r = 0.67, P≤0.05) in DPs, while in CPs, only total-C (r = 0.97, P≤0.001) and total-P (r = -0.59, P≤0.05) were significantly related with C:N ratio.

Nutrient inputs due to dung deposition

The subtraction of nutrient concentration of CPs from that of DPs is referred to here as nutrient input due to ruminant dung. ANOVA suggested that soil NH_4^+-N, NO_3^--N, mineral-N, organic-N, total-N, total-C, total-P and C:N ratio contributed by ruminant dung varied substantially due to location (Table 3). Across the locations, the changes of these nutrients displayed the following ranges: 1.3–3.0, 0.9–1.9, 2.2–4.5, 124–502, 127–506, 3,928–10,718, 27–60 kg/ha and 0.1–12.2, respectively (Tables 1 and 2). Similarly, soil moisture (5.3–12.9%), porosity (0.0–14%) and pH (-0.09 to -0.33) inputs or outputs (depending on a particular case) also varied with the location (Table 3).

Table 1. Mean soil physico-chemical characteristics (± s.e.) of different off dung pat locations (CPs).

Location	Moisture (%)	Porosity (%)	pH	NH_4^+-N	NO_3^--N	Mineral-N	Organic-N	Total-N	Total-C	C:N ratio	Total-P (kg/ha)
						(kg/ha)					
INH	3.7a	48a	7.8e	2.1b	1.3g	3.4c	719c	722cd	949a	1.3a	73ab
	(0.1)	(2.2)	(0.0)	(0.1)	(0.0)	(0.2)	(33)	(33)	(33)	(0.0)	(3)
KAS	4.1ab	52ab	7.8de	1.9b	1.3e	3.1bc	744c	747cd	989a	1.3a	76ab
	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(4)	(4)	(2)	(0.0)	(1)
SUK	4.7cd	57bc	7.8bcd	1.8b	1.2e	2.9bc	684bc	687bcd	922a	1.3a	77b
	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(3)	(3)	(3)	(0.0)	(0.15)
SNPG	3.9a	51a	7.7e	1.9b	1.4fg	3.3c	731c	734cd	997a	1.4a	74ab
	(0.1)	(0.2)	(0.0)	(0.0)	(0.0)	(0.0)	(17)	(17)	(11)	(0.0)	(0.95)
MMV	5.1def	62cd	7.7cde	3.0c	1.2e	4.2d	762c	766d	5,934d	7.7b	74ab
	(0.1)	(2.3)	(0.0)	(0.2)	(0.1)	(0.3)	(43)	(43)	(365)	(0.1)	(4.48)
BG	5.5f	65de	7.7bcd	1.9b	0.8bc	2.7b	744c	747cd	5,549cd	7.4b	74ab
	(0.0)	(0.2)	(0.0)	(0.0)	(0.0)	(0.1)	(9)	(9)	(33)	(0.1)	(0.9)
MB	5.3ef	64d	7.7bcd	2.9c	1.1de	4.0d	696bc	700bcd	4,999bc	7.2b	70ab
	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(12)	(12)	(30)	(0.2)	(0.2)
MC	4.9de	63d	7.7bcd	2.9c	1.1efg	4.1d	761c	765cd	5,770d	7.6b	74ab
	(0.1)	(1.3)	(0.0)	(0.1)	(0.0)	(0.2)	(29)	(29)	(190)	(0.1)	(2.9)
AG-1	5.3ef	69ef	7.6ab	1.3a	0.7ab	2.0a	527a	529a	6,022d	11.4cd	66ab
	(0.1)	(0.2)	(0.0)	(0.0)	(0.0)	(0.0)	(25)	(25)	(255)	(0.1)	(1.0)
AG-2	6.1g	70f	7.5a	0.9a	0.6a	1.6a	557bc	558ab	4,706b	8.4b	65a
	(0.1)	0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(5)	(5)	(55)	(0.1)	(0.8)
AG-3	5.3ef	65de	7.7bcd	2.1b	0.9cd	3.0bc	610abc	613abc	5,661cd	9.2bc	66ab
	(0.2)	(0.2)	(0.1)	(0.0)	(0.0)	(0.0)	(3)	(3)	(25)	(0.1)	(0.4)
GB	4.4bc	48a	7.8de	3.1c	1.4g	4.5d	661abc	666abcd	8,519e	13.2d	73ab
	(0.2)	(1.1)	(0.0)	(0.1)	(0.0)	(0.1)	(75)	(75)	(180)	(1.6)	(3.68)

INH = International Hostel, KAS = Kasturba, SUK = Sukanya, SNPG = Sarojani Nayadu, MMV = Mahila Maha Vidhyalay, BG = Botanical Garden, MB = Madhuban, MC = Meera Colony, AG-1 = Agriculture Farm-1, AG-2 = Agriculture Farm-2 AG-3 = Agriculture Farm-3 and GB = Gandhi Bhawan.

Table 2. Mean soil physico-chemical characteristics (± s.e.) of different dung pat locations (DPs).

Location	Moisture (%)	Porosity (%)	pH	NH_4^+-N	NO_3^--N	Mineral-N	Organic-N	Total-N	Total-C	C:N ratio	Total-P (kg/ha)
						(kg/ha)					
INH	9.0a	53a	7.6d	3.8ab	2.8de	6.5abc	843a	849a	9,632ab	11.4b	133f
	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(13)	(13)	(38)	(0.2)	(0.6)
KAS	10.1a	55a	7.6d	3.8abc	2.5bcd	6.3abc	906a	912a	11,226bcd	12.3bc	131f
	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(13)	(13)	(10)	(0.2)	(0.6)
SUK	12.2b	58ab	7.6d	3.8ab	2.5abcd	6.2ab	907a	913a	10,941abc	12.0bc	123cdef
	(0.1)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(11)	(11)	(78)	(0.2)	(1)
SNPG	9.3a	54a	7.6d	3.8abcd	2.7cde	6.5abc	860a	867a	11,715cd	13.5bc	133f
	(0.0)	(0.2)	(0.0)	(0.0)	(0.0)	(0.1)	(16)	(16)	(71)	(0.3)	(0.8)
MMV	14.7c	62bc	7.5c	5.4g	3.0e	8.4e	909a	917a	12,315cd	13.4bc	138f
	(0.3)	(2.0)	(0.0)	(0.3)	(0.2)	(0.4)	(44)	(45)	(644)	(0.1)	(7)
BG	18.4fg	71ef	7.4a	4.4de	2.3ab	6.7bc	917ab	924ab	10,963bcd	11.9bc	106abc
	(0.6)	(0.5)	(0.0)	(0.1)	(0.0)	(0.1)	(12)	(12)	(167)	(0.1)	(1)
MB	16.3de	68de	7.4ab	4.8efg	2.5abcd	7.3cd	916ab	923ab	11,126bcd	12.1bc	114cde
	(0.3)	(0.7)	(0.0)	(0.1)	(0.1)	(0.2)	(28)	(28)	(203)	(0.6)	(2)
MC	15.8cd	65cd	7.5bc	5.3fg	2.7cde	8.0de	889a	897a	12,548d	14.0c	127def
	(0.2)	(1.2)	(0.0)	(0.2)	(0.1)	(0.3)	(32)	(32)	(429)	(0.8)	(4)
AG-1	19.5gh	74fg	7.4ab	4.3bcde	2.2a	6.4abc	892a	899a	10,785bcd	12.1bc	95ab
	(0.3)	(0.2)	(0.0)	(0.0)	(0.0)	(0.0)	(51)	(51)	(369)	(0.7)	(1)
AG-2	21.0h	76g	7.4a	3.6a	2.1a	5.7a	1,059b	1,064b	8,913a	8.4a	92a
	(0.6)	(0.3)	(0.0)	(0.1)	(0.0)	(0.0)	(21)	(21)	(91)	(0.3)	(2)
AG-3	17.5ef	69def	7.4ab	4.6ef	2.4abc	7.0bcd	883a	890a	10,726bc	12.1bc	110bcd
	(0.3)	(1.1)	(0.0)	(0.2)	(0.1)	(0.3)	(34)	(34)	(366)	(0.6)	(3)
GB	14.5c	62bc	7.5bc	4.4cde	2.3ab	6.7bc	961ab	967ab	12,447cd	12.9bc	132f
	(0.3)	(2.2)	(0.0)	(0.2)	(0.1)	(0.3)	(31)	(31)	(690)	(0.8)	(6)

Means within columns followed by different letters are significantly different at P≤0.05. INH = International Hostel, KAS = Kasturba, SUK = Sukanya, SNPG = Sarojani Nayadu, MMV = Mahila Maha Vidhyalay, BG = Botanical Garden, MB = Madhuban, MC = Meera Colony, AG-1 = Agriculture Farm-1, AG-2 = Agriculture Farm-2 AG-3 = Agriculture Farm-3 and GB = Gandhi Bhawan.

Table 3. Summary of ANOVA (*F*-values and degrees of freedom) of different soil and vegetation parameters due to location and treatment (DP and CP).

Variable	Location	Treatment	Location × Treatment
	$F_{11,48}$ =	$F_{1,48}$ =	$F_{11,48}$ =
Soil moisture	215***	1,177***	109***
Porosity	111***	107***	5.97***
pH	49***	1,021***	8.46***
NH_4^+-N	74***	2,768***	11.36***
NO_3^--N	40***	4,175***	8.63***
Mineral-N	50***	3,345***	9.38***
Organic-N	3.19**	367***	7.73***
Total-N	3.25**	377***	7.74***
Total-C	69***	3,965***	41.94***
C:N ratio	43.3***	902***	45.60***
Total-P	21.7***	1,636***	9.91***
Richness	26.48***	1,718***	5.37***
Evenness	3.42**	22***	5.85***
Shannon index	23.17***	1,080***	7.35***
Beta diversity	8.5***	253***	2.91**
Biomass	139***	761***	46.15***

** = P≤0.001; *** = P≤0.0001.

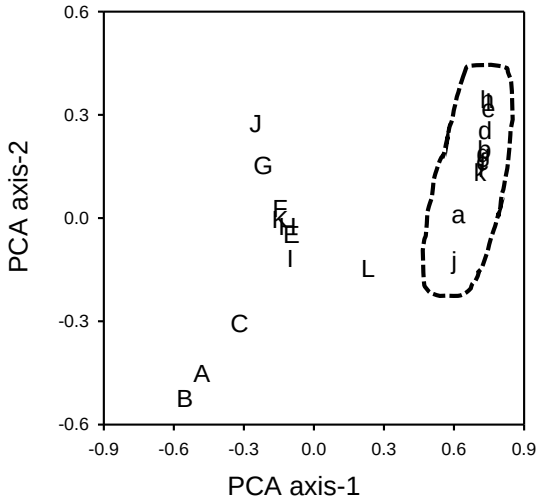

Figure 1. PCA ordination of different off dung pat (capital letters) and dung pat (small letters) locations (CPs resp. DPs) on the basis of nutrient concentrations. The letters within the dotted line represent the dung pat locations. In the ordination diagram A and a = International Hostel, B and b = Sukanya, C and c = Kasturba, D and d = Sarojani Nayadu, E and e = Mahila MahaVidhyalay, F and f = Botanical Garden, G and g = Gandhi Bhawan, H and h = Madhuban, I and i = Meera Colony, J and j = Agriculture Farm-1, K and k = Agriculture Farm-2, L and l = Agriculture Farm-3.

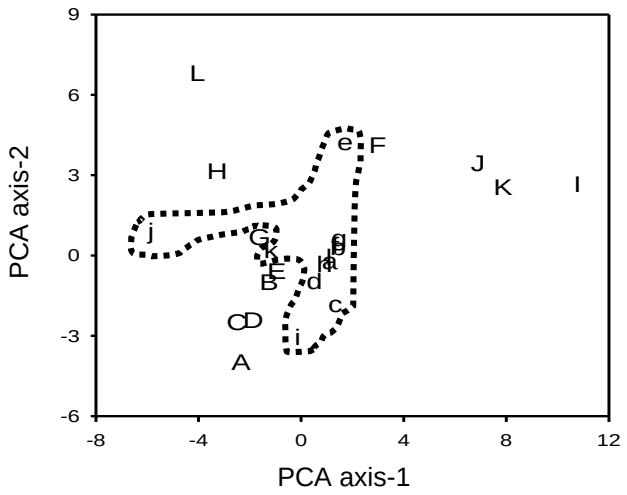

Figure 2. PCA ordination of different dung (capital letters) and off dung pat (small letters) locations (CPs resp. DPs) on the basis of relative biomass of herbaceous species. The letters within the dotted line represent the off dung pat locations. Stepwise regression showed that the soil phosphorus explained PCA axis-1 in CPs, while soil phosphorus and soil pH, respectively, explained PCA axes-1 and -2 in DPs. In the ordination diagram A and a = International Hostel, B and b = Sukanya, C and c = Kasturba, D and d = Sarojani Nayadu, E and e = Mahila MahaVidhyalay, F and f = Botanical Garden, G and g = Gandhi Bhawan, H and h = Madhuban, I and i = Meera Colony, J and j = Agriculture Farm-1, K and k = Agriculture Farm-2, L and l = Agriculture Farm-3.

Species composition

A total of 74 species belonging to 66 genera and 25 families was recorded from seventy-two 1 × 1 m plots (Table 4). The families Asteraceae and Poaceae had the highest number of species (10), followed by Fabaceae (7) and Amaranthaceae (6), with 12 families being represented by a single species. The DPs had 72 species and CPs had 52 species. Twenty-three species were exclusively present in DPs, while only 2 species were restricted to CPs, and 49 species were common to both DPs and CPs (Table 4).

On the basis of biomass, *Cynodon dactylon* was the dominant species for both DPs and CPs. The second and third most common species in DPs were *Echinochloa crus-galli* and *Urena lobata*, respectively, while *Malvastrum tricuspidatum* was the second and *Oxalis corniculata* the third most common species in CPs (Table 4). PCA ordination based on component species of these 2 treatments also showed differences in species composition of DPs and CPs (Figure 2).

Species diversity and biomass

Across locations, the mean species number, evenness, Shannon index and beta diversity per plot varied from 3 to 17, 0.70 to 0.97, 1.05 to 2.62 and 1.07 to 3.14, respectively (Tables 5 and 6). ANOVA suggested that these diversity indices differed substantially due to location, treatment and location × treatment (Table 3). Mean values for species number and Shannon index were higher in DPs than in CPs. On the other hand, mean values for evenness and beta diversity were lower in DPs than in CPs (Tables 5 and 6). Thus, dung inputs by ruminants promoted species diversity and restricted the distribution of individuals among the species. The *k*-dominance plots for DPs and CPs are illustrated in Figure 3, in which the uppermost line (DPs) represented greater diversity than the bottom line (CPs).

On the basis of stepwise regression analysis, soil moisture explained 97% of the variation in species number and soil porosity explained 85% of the variation in Shannon index and 69% of the variation in beta diversity in CPs, while none of the soil variables explained the variability in species evenness. In contrast with these patterns, soil pH independently accounted for 85% of the variation in species number and, together with NO_3^--N, explained 91% of the variation in species number in DPs. Similarly, soil pH also accounted for variation in Shannon index, while soil moisture accounted for variation in species evenness and beta diversity (Table 7). Linear regression analysis showed significant negative relationships between soil pH and species number in both DPs and CPs (Figure 4). Further, the higher determination coefficient (R^2) in DPs than in CPs (0.92 vs. 0.55) suggested that soil pH had a greater influence on species number in areas where dung was deposited.

Table 4. Species and biomass (g DM/ha) of herbaceous species of different dung pat and off dung pat locations (CPs resp. DPs).

Species[1]	Family	Dung pat (DP)		Off dung pat (CP)	
		Biomass	Sites occupied	Biomass	Sites occupied
Abutilon indicum (L.) Sweet E,L,Pe,NLF,N	Malvaceae	46	BG, MC, AG-1, AG-2, AG-3	13	MB
Acalypha indica L. E,M,A,NLF,N	Euphorbiaceae	17	INH, SUK, MMV, BG, MB	4	SNPG
Achyranthes aspera L. E,L,Bi,NLF,N	Amaranthaceae	38	INH, SUK, BG, MB, MC, GB	8	KAS, MB
Aerva sanguinolenta (L.) Blume E,L,Pe,NLF,N	Amaranthaceae	13	INH, SUK, MMV, MB,	14	MMV, BG, GB
Aeschynomene indica L. E,M,Bi,LF,NN	Fabaceae	9	AG-1,AG-2	0	
Ageratum conyzoides L. E,L,A,NLF,NN	Asteraceae	35	SUK, MMV, BG, MB, MC, GB	10	AG-2
Alternanthera sessilis (L.) R. Br. ex DC. P,L,A,NLF,NN	Amaranthaceae	17	BG, MB, MC, AG-1	24	MMV, BG, GB
Alysicarpus vaginalis (L.) DC. De,L,Pe,LF,N	Fabaceae	16	AG-2, AG-3	4	AG-2
Amaranthus spinosus L. E,L,A,NLF,NN	Amaranthaceae	33	BG, AG-1, AG-2, AG-3	0	
Amaranthus viridis L. E,M,A,NLF,NN	Amaranthaceae	16	BG, MB, MC, GB	14	BG, MB
Ammannia baccifera L. E,L,A,NLF,N	Lythraceae	12	GB	54	KAS, SUK, SNPG, MC, AG-1
Anagallis arvensis L. E,M,A,NLF,NN	Primulaceae	12	AG-1, AG-3	0	
Argemone mexicana L. E,L,A,NLF,NN	Papaveraceae	22	BG, MC, AG-1, AG-3	0	
Atylosia marmorata R. Br. ex Benth. P,L,A,LF,NN	Fabaceae	3	MMV, BG, MB	34	BG, MB, AG-2, AG-3, GB
Biophytum sensitivum (L.) DC. E,L,A,NLF,NN	Oxalidaceae	16	AG-3	0	
Caesulia axillaris Roxb. De,L,A,NLF,N	Asteraceae	12	MC, GB	0	
Chenopodium album L. E,L,A,NLF,NN	Amaranthaceae	33	BG, AG-1, AG-2, AG-3	0	
Commelina benghalensis L. Pro,L,A,NLF,NN	Commelinaceae	53	MMV, BG, AG-1	0	
Convolvulus prostratus Forssk. P,S,Pe,NLF,N	Convolvulaceae	11	INH, SUK, MMV, MB	1	MC
Croton bonplandianus Baill. E,M,Pe,NLF,NN	Euphorbiaceae	12	MC	6	MC
Cynodon dactylon (L.) Pers. P,S,Pe,G,COS	Poaceae	194	INH, SUK, SNPG, MMV, BG, MB, MC, AG-AG-2, AG-3, GB	105	INH, KAS, SUK, SNPG, MMV, BG, MB, MC
Cyperus cyperoides (L.) Kuntze P,M,Pe,Se,NN	Cyperaceae	29	KAS, SNPG, MB, MC, GB	1	MB
Cyperus rotundus L. P,M,Pe,Se,COS	Cyperaceae	43	INH, SUK, SNPG, MB, MC	28	INH, KAS, MMV, MC
Dactyloctenium aegyptium (L.) Willd. De,S,A,G,NN	Poaceae	56	INH, SUK, SNPG, MMV, BG, MB, MC, GB	2	MMV, MB
Desmodium triflorum (L.) DC. E,L,Pe,LF,NN	Fabaceae	0		34	MMV, BG, MB, AG-1
Dichanthium annulatum (Forssk.) Stapf E,S,Pe,G,NN	Poaceae	77	INH, SUK, SNPG, MMV, BG, AG-1, AG-2, AG-3, GB	9	MB
Digitaria ciliaris (Retz.) Koeler De,S,A,G,NN	Poaceae	48	INH, KAS, SUK, SNPG, MMV, MC	14	AG-1, AG-3
Echinochloa colona (L.) Link De,M,A,G,NN	Poaceae	50	INH, KAS, SNPG, AG-AG-2, AG-3	8	AG-2
Echinochloa crus-galli (L.) Beauv. De,L,A,G,NN	Poaceae	134	SNPG, MMV, BG, MB, MC, AG-1, AG-2, AG-3, GB	0	

Continued

Species[1]	Family	Dung pat (DP)		Off dung pat (CP)	
		Biomass	Sites occupied	Biomass	Sites occupied
Eclipta alba (L.) Hassk. P,S,A,NLF,NN	Asteraceae	28	INH, SUK, SNPG, MB, MC, GB	10	GB
Eleusine indica (L.) Gaertn. E,M,A,G,NN	Poaceae	19	INH, KAS, SUK, SNPG	2	MMV
Eragrostis tenella (L.) P. Beauv. ex Roem. & Schult. E,L,Pe,G,NN	Poaceae	53	INH, KAS, SUK, SNPG, MMV, MB, MC, AG-1, AG-2, AG-3	10	SUK, AG-1
Euphorbia dracunculoides Lam. E,L,Bi,NLF,NN	Euphorbiaceae	34	AG-1, AG-3	16	AG-1, AG-2
Euphorbia hirta L. Pr,L,A,NLF,NN	Euphorbiaceae	62	INH, KAS, SUK, SNPG, MMV, BG, MB, AG-1, AG-2, AG-3	5	MMV
Evolvulus nummularius (L.) L. P,S,Pe,NLF,NN	Convolvulaceae	22	INH, MMV, BG, MB, GB	7	KAS, SUK, GB
Evolvulus alsinoides (L.) L. Pr,S,A,NLF,NN	Convolvulaceae	42	INH, KAS, SNPG, MMV	1	AG-2
Gomphrena celosioides Mart. E,M,A,NLF,NN	Amaranthaceae	49	KAS, SNPG, MMV, MB, MC	0	
Gnaphalium luteoalbum L. De,M,A,NLF,NN	Asteraceae	31	KAS, SNPG, MMV,	0	
Heliotropium indicum L. E,M,A,NLF,NN	Boraginaceae	16	MB, MC, GB	0	
Herpestis monnieri (L.) Kunth E,M,Pe,NLF,N	Plantaginaceae	20	AG-1, AG-2, AG-3, GB	8	SUK, MC
Hyptis suaveolens (L.) Poit. P,L,A,NLF,NN	Lamiaceae	19	AG-1, AG-3, GB	5	GB
Imperata cylindrica (L.) P. Beauv. E,L,Pe,G,NN	Poaceae	36	AG-1, AG-2, AG-3	5	BG
Indigofera linifolia (L. f.) Retz. Pr,M,A,LF,NN	Fabaceae	13	SNPG, AG-1, AG-2, AG-3	6	AG-1
Lathyrus aphaca L. E,M,A,LF,NN	Fabaceae	8	AG-2	3	AG-2
Launaea procumbens (Roxb.) Ramayya & Rajagopal P,S,Pe,NLF,N	Asteraceae	38	KAS, SNPG, MMV, BG, MB	16	MMV, AG-1, AG-2
Leucas aspera (Willd.) Link E,M,A,NLF,NN	Lamiaceae	33	BG, MB, MC, GB	1	AG-1
Lindenbergia indica (L.) Vatke E,L,A,NLF,N	Orobanchaceae	12	GB	15	MMV, BG
Malvastrum tricuspidatum (R. Br.) A. Gray E,L,Pe,NLF,NN	Malvaceae	55	SUK, SNPG, BG, MB, MC, AG-1, AG-2, AG-3	62	INH, BG, MC, AG-1, 1GB
Melilotus albus Medik. E,L,Bi,LF,NN	Fabaceae	28	AG-1, AG-2	13	AG-1, AG-2
Nicotiana alata Link & Otto E,M,Pe,NLF,NN	Solanaceae	2	GB	3	MB
Oldenlandia corymbosa L. P,M,A,NLF,NN	Rubiaceae	2	KAS, SUK, SNPG	12	SNPG, AG-1, AG-2
Oplismenus compositus (L.) P. Beauv. P,S,Pe,G,NN	Poaceae	32	KAS, SUK, SNPG, MMV, BG, AG-1, AG-2, AG-3	19	KAS, MMV, AG-3, GB
Oxalis corniculata L. Pr,S,Pe,NLF,NN	Oxalidaceae	12	AG-1, AG-3	55	INH, KAS, SUK, SNPG, BG, MB, AG-1
Parthenium hysterophorus L. E,L,Pe,NLF,NN	Asteraceae	66	MC, AG-2, AG-3, GB	0	
Paspalidium flavidum (Retz.) A. Camus P,L,Pe,G,NN	Poaceae	0		4	AG-2
Peristrophe bicalyculata (Retz.) Nees. E,L,Pe,NLF,NN	Acanthaceae	6	GB	0	
Phyla nodiflora (L.) Greene P,L,A,NLF,NN	Verbenaceae	2	MC	0	

Continued

Species[1]	Family	Dung pat (DP)		Off dung pat (CP)	
		Biomass	Sites occupied	Biomass	Sites occupied
Portulaca oleracea L. P,S,A,NLF,NN	Portulacaceae	66	INH, KAS, SUK, SNPG, MMV, MB	0	
Ranunculus sceleratus L. E,L,A,NLF,NN	Ranunculaceae	32	AG-1, AG-2, AG-3	0	
Rorippa dubia (Pers.) H. Hara E,M,A,NLF,N	Brassicaceae	28	AG-1, AG-2, AG-3	14	INH, SUK
Ruellia tuberos L. E,M,Bi,NLF,NN	Acanthaceae	4	GB	1	MC
Rumex dentatus L. E,L,Bi,NLF,N	Polygonaceae	25	AG-1, AG-2, AG-3	0	
Rungia pectinata (L.) Nees Pr,M,A,NLF,N	Acanthaceae	4	GB	21	INH, SUK, BG, AG-3
Rungia parviflora Nees Pr,M,A,NLF,NN	Acanthaceae	26	KAS, SUK, SNPG, BG, MB, AG-1, AG-2, AG-3	0	
Scoparia dulcis L. E,M,Pe,NLF,NN	Plantaginaceae	22	SUK, SNPG, MMV AG-3, GB	1	AG-3
Sida acuta Burm. f. E,L,Bi,NLF,NN	Malvaceae	57	KAS, SUK, SNPG, GB	47	INH, KAS, SNPG, BG, MC, AG-3
Sida cordifolia L. E,S,Pe,NLF,NN	Malvaceae	121	INH, KAS, SUK, SNPG, MMV, BG, MB, MC, GB	0	
Solanum nigrum L. E,L,A,NLF,NN	Solanaceae	22	MC, AG-2	17	MC, AG-2, AG-3
Sonchus oleraceus L. E,L,A,NLF,NN	Asteraceae	47	AG-1, AG-2, AG-3	21	AG-1, AG-2, AG-3
Spilanthes acmella (L.) L. E,M,Pe,NLF,NN	Asteraceae	21	BG, MB, MC, GB	0	
Tridax procumbens L. Pr,M,Pe,NLF,NN	Asteraceae	16	SUK, SNPG, MB, MC	15	SUK, SNPG
Uraria picta (Jacq.) Desv. ex DC. E,L,Pe,LF, N	Fabaceae	20	AG-2, AG-3	0	
Urena lobata L. E,L,Pe,NLF,NN	Malvaceae	162	KAS, SNPG, MMV, BG, MB, MC, AG-1, AG-2, AG-3, GB	0	
Vernonia cinerea (L.) Less. E,M,A,NLF,NN	Asteraceae	9	SUK, MB, GB	6	MMV

[1]Nomenclature according to the Tropicos taxonomic database (www.tropicos.org).
Abbreviations used: E = Erect, P = Prostrate, De = Decumbent, Pr = Procumbent; L = Tall, M = Medium, S = Short height; A = Annual, Bi = Biennial, Pe = Perennial; G = Grasses, Se = Sedges, NLF = Non-leguminous forb, LF = leguminous forb; N = Native, NN = Non-native, COS = Cosmopolitan; INH = International Hostel, SUK= Sukanya, KAS= Kasturba, SNPG = Sarojani Nayadu, MMV = Mahila MahaVidhyalay, BG= Botanical Garden, GB = Gandhi Bhawan, MB = Madhuban, MC = Meera Colony, AG-1 = Agriculture Farm-1, AG-2 = Agriculture Farm-2 and AG-3 = Agriculture Farm-3.

Across species, locations and treatments, herbaceous biomass varied between 0.4 and 194 g/m^2 (Table 4) and from 14.6 to 93 g/m^2 across locations and treatments (Tables 5 and 6). ANOVA showed substantial variation in herbaceous biomass owing to location, treatment and coupling of location and treatment (Table 3). Stepwise regression suggested that soil moisture explained much of the variation in herbaceous biomass in both treatments (DP and CP), with greater values in DP than in CP (Tables 5−7). Thus, greater soil moisture availability together with soil nutrients provided greater biomass accumulation in this dry tropical grassland.

Plant functional attributes

ANOVA revealed significant variation in species number and biomass of plants with different functional attributes due to trait, location and treatment and their interactions (Table 8). The differences in mean species number and biomass among plants with different traits in DPs and CPs, analyzed by the HSD test, are presented in Table 9. Forbs plus erect, annual, tall, non-native and non-leguminous plants predominated in both DPs and CPs, while mean values for species number and biomass for plants with different traits were greater in DPs than in CPs (Table 9).

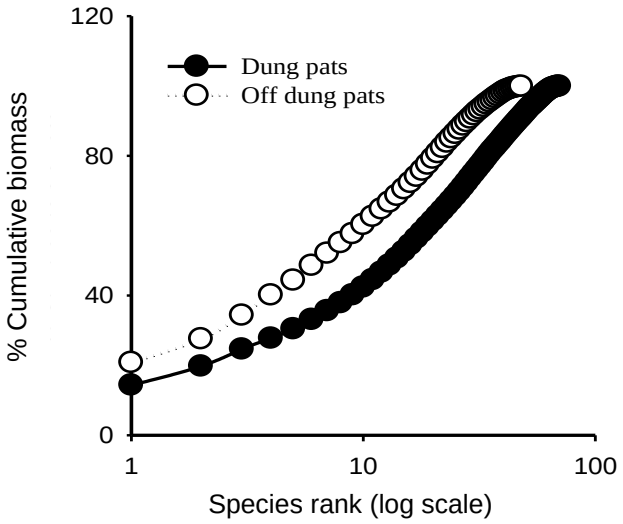

Figure 3. The k-dominance plot in which total percentage cumulative biomass is plotted against log species rank for dung and off dung pats (DPs resp. CPs).

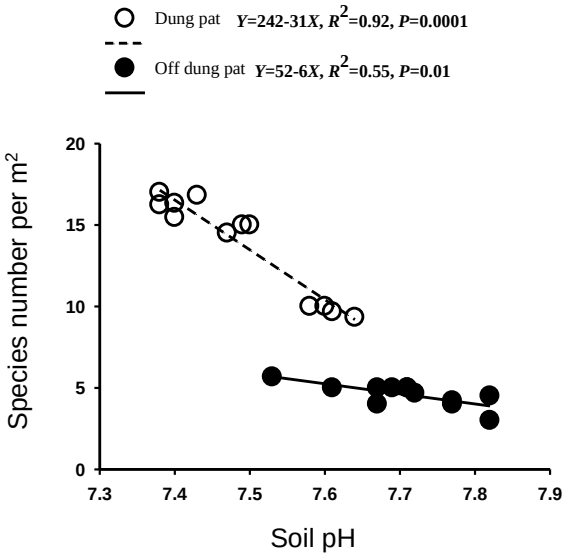

Figure 4. Linear relationships between soil pH (*X*) and species number (*Y*) at dung and off dung pat locations (CP resp. DP).

Table 5. Mean values for vegetation parameters (± s.e.) at different off dung pat locations (CPs).

Location	Species number	Evenness	Shannon index	Beta diversity	Biomass (g DM/m^2)
INH	4.5ab	0.96ab	1.05a	1.76a	14.7a
	(0.00)	(0.03)	(0.04)	(0.19)	(0.13)
KAS	4.2ab	0.89ab	1.14ab	1.80ab	17.0a
	(0.33)	(0.04)	(0.06)	(0.10)	(0.58)
SUK	4.0ab	0.90ab	1.24abc	2.11ab	22.5bc
	(0.00)	(0.03)	(0.05)	(0.06)	(0.29)
SNPG	3.0a	0.97b	1.07a	2.51abc	14.6a
	(0.00)	(0.00)	(0.00)	(0.09)	(0.15)
MMV	4.7bc	0.96ab	1.40bc	2.32abc	24.8d
	(0.33)	(0.01)	(0.07)	(0.05)	(0.17)
BG	5.0c	0.93ab	1.49c	2.63abc	28.3d
	(0.00)	(0.01)	(0.02)	(0.13)	(0.88)
MB	5.0c	0.89ab	1.44bc	2.69abc	24.5c
	(0.00)	(0.01)	(0.02)	(0.27)	(0.29)
MC	5.00c	0.78a	1.26abc	2.77bc	23.0bc
	(0.00)	(0.08)	(0.12)	(0.26)	(0.29)
AG-1	5.00c	0.92ab	1.48c	3.09c	29.0d
	(0.00)	(0.02)	(0.03)	(0.31)	(0.58)
AG-2	5.67d	0.79a	1.41bc	3.14c	30.0d
	(0.33)	(0.02)	(0.04)	(0.14)	(0.58)
AG-3	5.00c	0.91ab	1.46c	3.13c	24.0c
	(0.00)	(0.04)	(0.07)	(0.32)	(0.58)
GB	4.00abc	0.85ab	1.14ab	2.27abc	21.2b
	(0.58)	(0.05)	(0.08)	(0.08)	(0.44)

INH = International Hostel, KAS = Kasturba, SUK = Sukanya, SNPG = Sarojani Nayadu, MMV = Mahila Maha Vidhyalay, BG = Botanical Garden, MB = Madhuban, MC = Meera Colony, AG-1 = Agriculture Farm-1, AG-2 = Agriculture Farm-2 AG-3 = Agriculture Farm-3 and GB = Gandhi Bhawan.

Table 6. Mean values for vegetation parameters (± s.e.) at different dung pat locations (DPs).

Location	Species number	Evenness	Shannon index	Beta diversity	Biomass (g DM/m^2)
INH	9.3a	0.75ab	1.69a	1.18ab	44a
	(0.33)	(0.01)	(0.04)	(0.10)	(1.4)
KAS	10.0a	0.70a	1.63a	1.46abc	50a
	(0.00)	(0.02)	(0.05)	(0.08)	(0.3)
SUK	10.0a	0.82abcd	1.90ab	1.39abc	53a
	(0.00)	(0.04)	(0.10)	(0.11)	(1.3)
SNPG	9. 7a	0.84bcd	1.92abc	1.07a	48a
	(0.33)	(0.00)	(0.04)	(0.07)	(0.3)
MMV	15.0b	0.83abcd	2.25cd	1.53abc	68b
	(0.58)	(0.05)	(0.13)	(0.20)	(2.7)
BG	17.0c	0.81abcd	2.27cde	1.65abc	88de
	(0.33)	(0.01)	(0.01)	(0.13)	(3.1)
MB	16.33bc	0.82abcd	2.22bcd	1.21ab	77c
	(0.88)	(0.04)	(0.11)	(0.07)	(1.8)
MC	15.00b	0.80abcd	2.16bcd	1.29ab	74bc
	(0.58)	(0.01)	(0.03)	(0.26)	(1.1)
AG-1	15.46b	0.91cd	2.49de	1.59abc	93e
	(1.00)	(0.01)	(0.05)	(0.08)	(2.7)
AG-2	16.24bc	0.93d	2.44de	2.01c	93e
	(1.45)	(0.01)	(0.08)	(0.10)	(1.6)
AG-3	16.82bc	0.89cd	2.33de	1.79bc	79cd
	(0.88)	(0.01)	(0.04)	(0.13)	(2.2)
GB	14.50b	0.92cd	2.62e	1.27ab	74bc
	(0.58)	(0.01)	(0.05)	(0.11)	(1.1)

Means within columns followed by different letters are significantly different at P≤0.05. INH = International Hostel, KAS = Kasturba, SUK = Sukanya, SNPG = Sarojani Nayadu, MMV = Mahila Maha Vidhyalay, BG = Botanical Garden, MB = Madhuban, MC = Meera Colony, AG-1 = Agriculture Farm-1, AG-2 = Agriculture Farm-2 AG-3 = Agriculture Farm-3 and GB = Gandhi Bhawan.

Table 7. Products of stepwise regressions between different soil and vegetation variables in off dung (CP) and dung pats (DP) for herbaceous vegetation.

Off dung pat (CP)				Dung pat (DP)			
Models	Regression equations	R^2	P	Models	Regression equations	R^2	P
1	$SR = -0.58 + 0.31M$	0.97	≤0.0001	1	$SR = 38 - 4.7pH$	0.85	≤0.0001
				2	$SR = 44 - 5.7pH + 0.6Ni$	0.91	≤0.0001
1	No relation	-	-	1	$E = 0.67 + 0.01M$	0.46	≤0.02
1	$Sh = 0.15 + 0.02Por$	0.85	≤0.0001	1	$Sh = 22.06 - 2.7pH$	0.70	≤0.001
1	$\beta = -0.47 + 0.05Por$	0.69	≤0.001	1	$\beta = 0.69 + 0.05M$	0.56	≤0.005
2	$\beta = 4.45 + 0.03Por - 0.05P$	0.81	≤0.001				
1	$B = -11.07 + 7.0M$	0.82	≤0.0001	1	$B = 5.87 + 4.32M$	0.97	≤0.0001

In the equations, *S*, *E*, *Sh*, *β*, *B*, *M*, *Por*, *P*, *pH* and *Ni* represent species number, evenness, Shannon index, beta diversity, biomass, soil moisture, soil porosity, soil phosphorus, soil pH and soil nitrate nitrogen, respectively.

Table 8. Summary of ANOVA on herbaceous species number and biomass of different trait categories.

Sources	Dependent variables	*Df*	*F*	
			Species	Biomass
Trait	Life form	2	525***	324***
	Growth form	3	303***	97***
	Life span	2	172***	105***
	Height	2	40***	34***
	Nativity	2	664***	339***
	N-fixing ability	1	231***	179***
Location	Life form	11	4.20***	4.71***
	Growth form	11	4.59***	2.97**
	Life span	11	4.19***	4.77***
	Height	11	4.17***	3.59***
	Nativity	11	4.60***	5.32***
	N-fixing ability	11	3.02**	2.41*
Treatment	Life form	1	365***	236***
	Growth form	1	425***	143***
	Life span	1	299***	203***
	Height	1	364***	144***
	Nativity	1	427***	244***
	N-fixing ability	1	92***	70***
Trait × Location	Life form	22	7.15***	5.16***
	Growth form	33	6.90***	3.74***
	Life span	22	2.73***	2.41**
	Height	22	10.85***	6.01***
	Nativity	22	6.00***	8.04***
	N-fixing ability	11	2.32*	1.45^{NS}
Location × Treatment	Life form	11	1.69^{NS}	1.86*
	Growth form	11	1.75^{NS}	1.44^{NS}
	Life span	11	1.94*	2.49**
	Height	11	1.82*	1.31^{NS}
	Nativity	11	2.00*	2.28*
	N-fixing activity	11	1.26^{NS}	0.95^{NS}
Trait × Treatment	Life form	2	111***	71***
	Growth form	3	97***	32***
	Life span	2	49***	29***
	Height	2	5.96**	9.01***
	Nativity	2	270***	146***
	N-fixing activity	1	77***	49***
Trait × Location × Treatment	Life form	22	4.11***	2.63***
	Growth form	33	5.34***	2.42***
	Life span	22	1.97*	0.86^{NS}
	Height	22	4.48***	3.00***
	Nativity	22	2.39**	2.59***
	N-fixing activity	11	1.90*	1.64^{NS}
Error	Life form	143		
	Growth form	192		
	Life span	143		
	Height	144		
	Nativity	144		
	N-fixing activity	96		

* = P≤0.01, ** = P≤0.001, *** = P≤0.0001 and ^{NS} = non-significant.

Table 9. Mean species number (per m^2) and biomass (g DM/m^2) (± s.e.) of plants with different functional traits in dung pat (DP) and off dung pat (CP) locations.

Plant functional attribute	Trait	Off dung pats		Dung pats		% Increase/decrease	
		Species	Biomass	Species	Biomass	Species	Biomass
Life form	Grasses	1.00b (0.12)	6.19b (0.75)	3.93b (0.28)	24.10b (2)	293	289
	Sedges	0.12a (0.06)	0.61a (0.31)	0.26a (0.11)	1.13a (0.53)	117	85
	Forbs	3.30c (0.21)	16.00c (1.31)	9.26c (0.55)	44.85c (2)	181	180
Growth form	Erect	2.12b (0.20)	11.00b (1.25)	8.00c (0.47)	37.50c (3)	277	241
	Prostrate	1.58b (0.19)	7.09b (1.00)	3.73b (0.24)	22.00b (2)	136	210
	Procumbent	0.47a (0.10)	2.78a (0.62)	1.08a (0.16)	8.08a (1)	130	191
	Decumbent	0.25a (0.07)	1.93a (0.33)	1.58a (0.15)	3.50ab (1)	132	81
Life span	Annual	1.81b (0.21)	9.80b (1.21)	7.19c (0.38)	35.08b (2)	297	257
	Biennial	0.36a (0.10)	1.97a (0.61)	0.80a (0.16)	4.00a (1)	122	103
	Perennial	2.25b (0.22)	11.00b (1.29)	5.40b (0.26)	31.00b (2)	140	182
Height	Tall	2.08c (0.20)	10.80b (1.31)	7.60b (0.54)	45.00b (4)	265	317
	Medium	0.97a (0.11)	5.00a (0.9)	3.02a (0.24)	19.02a (1)	211	280
	Short	1.37b (0.13)	7.00a (1.20)	2.77a (0.38)	15.06a (2)	102	115
Nativity	Native	0.94a (0.14)	4.55a (0.72)	1.42a (0.22)	10.50a (1)	51	131
	Non-native	2.90b (0.26)	14.72b (1.40)	11.00b (0.50)	54.00b (4)	279	267
	Cosmopolitan	0.58a (0.12)	3.53a (0.76)	0.97a (0.10)	7.30a (2)	67	107
N-fixing activity	Leguminous forbs	0.81a (0.12)	6.00a (0.66)	0.36a (0.37)	4.90a (2)	-56	-17
	Non-leguminous forbs	2.49b (0.18)	10.00b (1.27)	8.64b (0.58)	39.95b (3)	247	300

Within parameters, means within columns followed by different letters are significantly different ($P \leq 0.05$).

Discussion

Soil properties

While ruminants depend on grasslands, they control their structure and cycling of energy and nutrients (Augustine and McNaughton 1998) through foraging, trampling and dung and urine inputs, which are important sources of moisture and nutrients for plant establishment and growth on drier locations (Bakker et al. 2004; Williams and Haynes 2006). The greater soil moisture and porosity in DPs compared with CPs in this study may be due to increased physical mixing of soil by micro- and macro-organisms (dung beetles, earthworms, termites, bacteria and fungi) in DPs (Lovell and Jarvis 1996; Williams and Haynes 2006). The study suggests that dung inputs to the soil by ruminants may improve physical properties, water infiltration and water holding capacity of the soil (Brouwer and Powell 1998).

The lower soil pH in DPs than in CPs may be due to the release of carbonic acids during decomposition of dung residues in the presence of adequate soil moisture and temperature (Rao et al. 2009; Verma et al. 2013). Williams and Haynes (2006) suggest that dung with suf-

ficient soil moisture absorbs greater solar heat, which raises the temperature of underlying soil, and accelerates the decomposition process of dung residue (Stanford et al. 1973), resulting in increased release of carbonic acids. Other studies have also suggested that application of ruminant manure to acidic soils increases the level of acidity (Bussink and Oenema 1998; Whalen et al. 2000).

The negative relationships of C:N ratio with NH_4^+-N, NO_3^--N, mineral-N, total-N and total-C suggested greater rates of N and C mineralization in DPs compared with CPs. High levels of nutrients in dung residue (undigested food with lignified plant tissues and cell wall, gut microorganisms, secretions and cellular debris from the gut mucosa; Church 1969) might have determined the rates of C- and N-mineralization. It has been suggested that organic matter rich in N (low C:N ratio) has greater C- and N-mineralization than organic matter with low N concentration (Vourlitis et al. 2007; Rao et al. 2009; Verma et al. 2013). In temperate grazed grassland, the return of animal dung can contribute 260 kg N/ha (Schnyder et al. 2010) and 22,500 kg C/ha (Whitehead 1986) and in intensively managed systems may boost concentrations of these elements to a much higher level than in unmanaged grasslands (Lovell and Jarvis 1996). In the present study, the total-N (232 kg/ha) and total-C (6,860 kg/ha) contributed by ruminant dung residue to the soil were lower than the values reported by Schnyder et al. (2010) for N and by Whitehead (1986) for C. It reflected lower nutrient mineralization and C:N ratio in the tropics than in temperate grasslands. Differences in forage quality in the 2 different climates could explain the differences.

Composition, diversity and biomass of plant functional traits

Based on the diversity indices and *k*-dominance analyses, the study showed comparatively higher species diversity in DPs than in CPs. In different situations, other studies have also emphasized that diversity can be unequivocally compared only when the *k*-dominance plots from the locations to be compared do not overlap. In this circumstance, the lowest line will correspond to the most diverse community and the uppermost line will represent the least diversity (Sagar and Singh 2005; Sagar et al. 2012; Verma et al. 2013). This pattern can be explained because of cumulative effects of 2 mechanisms: (1) grazers might have added viable seeds of grasses, forbs and woody species via their digestive tracts to the soil; and (2) the dung might have provided sufficient moisture and nutrients for the germination and establishment of the deposited as well as remaining seeds at the respective microsites. Seeds of grasses, forbs and woody species can remain viable even after passing through the digestive tracts of ruminants (Thomson et al. 1990; Gardener et al. 1993). It appears that the dung residue created favorable environmental conditions to the microsites for the germination of seeds and subsequent seedling establishment due to increased soil fertility, increased water holding capacity and reduced competition with existing species (Ocumpaugh et al. 1996). Further, nutrients from dung residue may either suppress or destroy some existing species and create gaps and resource availability for other species (Watt 1947; Coffin and Lauenroth 1988). Our experience and observations indicate that livestock preferentially graze areas with no dung in a pasture and avoid pasture adjacent to dung pats. Consequently, areas where dung is deposited carry a much higher biomass of pasture because of differential grazing pressure on dung and non-dung areas. Therefore, the apparent difference between the two plots (DPs and CPs) would over-estimate the increase in growth as a result of dung deposition.

Soil pH is an important attribute affecting species diversity because of its relationship with the availability of nutrients and toxic elements (Pausas and Austin 2001). In unmanaged grassland, Grime (1973) reported maximum species diversity at a range of soil pH of 6.1–6.5; species diversity declined as soils became more acidic or alkaline because few species were adapted to highly acidic or alkaline soils. Both low and high soil pH and nutrients can limit seed germination and plant performance (Van den Berg et al. 2005). In this alkaline soil, dung residue lowered soil pH and resulted in the accumulation of a larger number of species. Evidently, the negative relationships between soil pH and the parameters of species diversity in DPs promoted species diversity due to decreased soil pH as reported by Verma et al. (2013) in a nitrogen-amendment experiment.

In an N-deposition study, Lauenroth et al. (1978) reported variation in community structure mainly due to changes in several dominant groups. While factors like rooting depth, N-use efficiency and association with mycorrhizae can affect responses of plants to changed nutrient conditions (Ren et al. 2011), soil water and annual rainfall are vital factors which can interact with N to influence ecosystem functioning (Chen et al. 2011). When water and N were added separately to shortgrass steppe in North America, above-ground biomass increased by 250 and 100%, respectively, but the increase was 700% when water and N were added together (Lauenroth et al. 2008). In the present study, dung deposits increased the tall, erect, annual, non-native and non-leguminous forbs. This is not surprising as the native vegetation would

have evolved largely in the absence of additional nutrients. It has been reported that weedy and ruderal species are successful invaders in N-rich environments (Sharma et al. 2005; Gaertner et al. 2012); hence they dominated in DPs compared with CPs. According to Diekmann and Falkengren-Grerup (2002), tall species are typically favored by N-deposition at the cost of short species, and can overgrow and shade the short-statured species. Short-statured species are excluded due to light limitation (Stevens et al. 2006). In this study, most forbs were erect in growth habit and hence, adapted to compete for light, which may be a reason for the greater increment in species number and biomass of forbs in DPs than CPs. Nevertheless, N-fixing species normally compete for light less effectively than non-N-fixing species (Haynes 1980). Thus, the study suggests that the natural attributes of forbs allowed them to take advantage of the higher nutrient levels due to dung deposition. Similarly, with the help of a meta-analysis including data from 304 studies and 456 terrestrial plant species, Xia and Wan (2008) also reported 54% increase in the herbaceous biomass due to fertilizing with N.

Overall, the study revealed that the seasonally dry tropical grasslands, which experience relatively high soil pH and low soil moisture and nutrients, benefit from ruminant dung deposition, through reduction in soil pH, and increase in soil moisture and nutrients. These conditions favored seed germination and seedling establishment of opportunistic plants, which led to increased diversity and biomass of herbaceous species in the dry tropical pasture studies. While it is well known that application of ruminant dung can benefit a pasture by increasing dry matter yields, this study has shown that the species composition in available forage can be changed as well, which can also affect nutritional value, depending on the species' palatability. It is important to return dung to pastures or croplands, where animals are housed or placed in corrals at night, to ensure the sustainable use of the pastures/grasslands. The study suggested that dung could be a substitute for chemical fertilizers to increase soil nutrients and herbaceous species diversity. However, further study of diversity-productivity relationships is vital before a clear understanding of full benefits of fertilizing with dung is available to make recommendations for the sustainable management of seasonally dry tropical ecosystems.

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References

Allen SE; Grimshaw HM; Parkinson JA; Quarnby C. 1974. Chemical analysis of ecological materials. Blackwell, Oxford, UK.

APHA. 1985. Standard methods for the examination of water and wastewater. American Public Health Association (APHA), Washington, DC, USA.

Augustine DJ; McNaughton SJ. 1998. Ungulate effects on the functional species composition of plant communities: Herbivore selectivity and plant tolerance. Journal of Wildlife Management 62:1165–1183. DOI: 10.2307/3801981

Bakker ES; Olff H; Boekhoff M; Gleichman JM; Berendse F. 2004. Impact of herbivores on nitrogen cycling: Contrasting effects of small and large species. Oecologia 138:91–101. DOI: 10.1007/s00442-003-1402-5

Brouwer J; Powell JM. 1998. Micro-topography; water balance; millet yield and nutrient leaching in a manuring experiment on sandy soil in south-west Niger. In: Renard G; Neef A; Becker K; Oppen M von, eds. Soil fertility management in West African land use systems. Workshop Proceedings, Niamey, Niger, 4–8 March 1997. Margraf, Weikersheim, Germany. p. 349–360.

Brown JR; Archer S. 1987. Woody plant seed dispersal and gap formation in a North American subtropical savanna woodland: The role of domestic herbivores. Vegetation 73:73–80. DOI: 10.1007/bf00031854

Buol SW; Southard RJ; Graham RC; McDaniel PA. 2003. Soil Genesis and Classification. 5th Edn. Iowa State Press, Blackwell, Ames, IA, USA.

Bussink DW; Oenema O. 1998. Ammonia volatilization from dairy farming systems in temperate areas: A review. Nutrient Cycling in Agroecosystems 51:19–33. DOI: 10.1023/A:1009747109538

Castle ME; MacDaid E. 1972. The decomposition of cattle dung and its effect on pasture. Journal of the British Grassland Society 27:133–137. DOI: 10.1111/j.1365-2494.1972.tb00700.x

Chen Q; Hooper DU; Lin S. 2011. Shifts in species composition constrain restoration of overgrazed grassland using nitrogen fertilization in Inner Mongolian steppe, China. PLoS One 6: e16909. DOI: 10.1371/journal.pone.0016909

Church DC. 1969. Digestive Physiology and Nutrition of Ruminants. Oregon State University, Corvallis, OR, USA.

Coffin DP; Lauenroth WK. 1988. The effect of disturbance size and frequency on a shortgrass plant community. Ecology 69:1609–1617. DOI: 10.2307/1941658

Dickinson CH; Craig G. 1990. Effect of water on the composition and release of nutrients from cow pats. New Phytologist 115:139–147.

Diekmann M; Falkengren-Grerup U. 2002. Prediction of species response to atmospheric nitrogen deposition by means of ecological measures and life history traits. Journal of Ecology 90:108–120. DOI: 10.1046/j.0022-0477.2001.00639.x

Duthie JF. 1903. Flora of the upper Gangetic plain, and of the adjacent Siwalik and sub-Himalayan tracts. Office of the

Superintendent of Government Printing, Calcutta, India. DOI: 10.5962/bhl.title.21629

Gaertner M; Holmes PM; Richardson DM. 2012. Biological invasions: Resilience and restoration. In: Van Andel J; Aronson J, eds. Restoration Ecology: The New Frontier. 2nd Edn. Wiley-Blackwell, Oxford, UK. p. 265–280.

Galloway JN; Townsend AR; Erisman JW; Bekunda M; Cai ZC; Freney JR; Martinelli LA; Seitzinger SP; Sutton MA. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science 320:889–892. DOI: 10.1126/science.1136674

Gardener CJ; McIvor JG; Jansen A. 1993. Passage of legume and grass seeds through the digestive tract of cattle and their survival in faeces. Journal of Applied Ecology 30:63–74. DOI: 10.2307/2404271

Giles J. 2005. Nitrogen study fertilizes fears of pollution. Nature 433:791. DOI: 10.1038/433791a

Grime JP. 1973. Competitive exclusion in herbaceous vegetation. Nature 242:344–347. DOI: 10.1038/242344a0

Schnyder H; Locher F; Auerswald K. 2010. Nutrient redistribution by grazing cattle drives patterns of topsoil N and P stocks in a low-input pasture ecosystem. Nutrient Cycling in Agroecosystems 88:183–195. DOI: 10.1007/s10705-009-9334-z

Haynes RJ. 1980. Competitive aspects of the grass-legume association. Advances in Agronomy 33:227–261. DOI: 10.1016/s0065-2113(08)60168-6

Haynes RJ; Williams PH. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49:119–199. DOI: 10.1016/s0065-2113(08)60794-4

Holter P. 1979. Effect of dung beetles and earthworms on the disappearance of cattle dung. Oikos 32:393–402. DOI: 10.2307/3544751

Jackson M. 1958. Soil Chemical Analysis. Prentice Hall, Englewood Cliffs, NJ, USA.

Lauenroth WK; Dodd JL; Sims PL. 1978. The effects of water and nitrogen-induced stresses on plant community structure in a semiarid grassland. Oecologia 36:211–222. DOI: 10.1007/bf00349810

Lauenroth WK; Milchunas DG; Sala OE; Burke IC; Morgan JA. 2008. Net primary production in the shortgrass steppe. In: Lauenroth WK; Burke IC, eds. Ecology of the shortgrass steppe: A long-term perspective. LTER Research Network Series. Oxford University Press, Oxford, UK. p. 270–305.

Lovell RD; Jarvis SC. 1996. Effect of cattle dung on soil microbial biomass C and N in a permanent pasture soil. Soil Biology and Biochemistry 28:291–299. DOI: 10.1016/0038-0717(95)00140-9

MacDiarmid BN; Watkin BR. 1971. The cattle dung patch. 1. Effect of dung patches on yield and botanical composition of surrounding and underlying pasture. Journal of the British Grassland Society 26:239–245. DOI: 10.1111/j.1365-2494.1971.tb00670.x

McCune B; Mefford MJ. 1999. PC-ORD. Multivariate analysis of ecological data. Version 4.0. MjM Software Design, Gleneden Beach, OR, USA.

Mueller-Dombois D; Ellenberg H. 1974. Aims and methods of vegetation ecology. John Wiley and Sons, New York, USA.

Ocumpaugh WR; Archer S; Stuth JW. 1996. Switchgrass recruitment from broadcast seed vs. seed fed to cattle. Journal of Range Management 49:368–371. DOI: 10.2307/4002599

Pausas JG; Austin MP. 2001. Patterns of plant species richness in relation to different environments: An appraisal. Journal of Vegetation Science 12:153–166. DOI: 10.2307/3236601

Pielou EC. 1966. The measurement of diversity in different types of biological collections. Journal of Theoretical Biology 13:131–144. DOI: 10.1016/0022-5193(66)90013-0

Piper CS. 1944. Soil and plant analysis. Interscience, New York, USA.

Platt HM; Shaw KM; Lambshead PJD. 1984. Nematode species abundance patterns and their use in the detection of environmental perturbations. Hydrobiologia 118:59–66. DOI: 10.1007/bf00031788

Rao LE; Parker DR; Bytnerowicz A; Allen EB. 2009. Nitrogen mineralization across an atmospheric nitrogen deposition gradient in Southern California deserts. Journal of Arid Environments 73:920–930. DOI: 10.1016/j.jaridenv.2009.04.007

Ren HY; Xu ZW; Huang JH; Clark C; Chen SP; Han XG. 2011. Nitrogen and water addition reduce leaf longevity of steppe species. Annals of Botany 107:145–155. DOI: 10.1093/aob/mcq219

Sagar R; Singh JS. 2005. Structure, diversity and regeneration of tropical dry deciduous forest of northern India. Biodiversity and Conservation 14:935–959. DOI: 10.1007/s10531-004-0671-6

Sagar R; Singh A; Singh JS. 2008. Differential effect of woody plant canopies on species composition and diversity of ground vegetation: A case study. Tropical Ecology 49:189–197. http://goo.gl/7fx4AC

Sagar R; Verma P. 2010. Effects of soil physical characteristics and biotic interferences on the herbaceous community composition and species diversity in the campus of Banaras Hindu University, India. Environmentalist 30:289–298. DOI: 10.1007/s10669-010-9276-7

Sagar R; Pandey A; Singh JS. 2012. Composition, species diversity, and biomass of the herbaceous community in dry tropical forest of northern India in relation to soil moisture and light intensity. Environmentalist 32:485–493. DOI: 10.1007/s10669-012-9414-5

Schnyder H; Locher F; Auerswald K. 2010. Nutrient redistribution by grazing cattle drives patterns of topsoil N and P stocks in a low-input pasture ecosystem. Nutrient Cycling in Agroecosystems 88:183–195. DOI: 10.1007/s10705-009-9334-z

Shannon CE; Weaver W. 1949. The mathematical theory of communication. University of Illinois Press, Urbana, IL, USA.

Shantz HL. 1954. The place of grassland in the earth's cover of vegetation. Ecology 35:143–145. DOI: 10.2307/1931110

Sharma GP; Raghubanshi AS; Singh JS. 2005. *Lantana* invasion: An overview. Weed Biology and Management 5:157–165. DOI: 10.1111/j.1445-6664.2005.00178.x

Shukla BD; Misra AK; Gupta RK. 1998. Application of nitrogen in production and post-production systems of agriculture and its effect on environment in India. Environmental Pollution 102:115–122. DOI: 10.1016/s0269-7491(98)80023-7

Singh JS; Singh SP; Gupta SR. 2006. Ecology, Environment and Resource Conservation. Anamaya Publishers, New Delhi, India.

SPSS. 1997. SPSS Base 7.5 Application Guide. SPSS, Chicago, IL, USA.

Stanford G; Frere MH; Schwaninger DH. 1973. Temperature coefficient of soil nitrogen mineralization. Soil Science 115:321–323. DOI: 10.1097/00010694-197304000-00009

Steinauer EM; Collins SL. 1995. Effects of urine deposition on small-scale patch structure in prairie vegetation. Ecology 76:1195–1205. DOI: 10.2307/1940926

Stevens CJ; Dise NB; Gowing DJG; Mountford JO. 2006. Loss of forb diversity in relation to nitrogen deposition in the UK: Regional trends and potential controls. Global Change Biology 12:1823–1833. DOI: 10.1111/j.1365-2486.2006.01217.x

Su YZ; Zhao HL. 2003. Soil properties and plant species in an age sequence of *Caragana microphylla* plantations in the Horqin Sandy Land, north China. Ecological Engineering 20:223–235. DOI: 10.1016/s0925-8574(03)00042-9

Thomson EF; Rihawi S; Cocks PS; Osman AE; Russi L. 1990. Recovery and germination rates of seeds of Mediterranean medics and clovers offered to sheep at a single meal or continuously. Journal of Agricultural Research 114:295–299. DOI: 10.1017/s0021859600072683

Van den Berg L; Dorland E; Vergeer P; Hart MAC; Bobbink R; Roelofs JGM. 2005. Decline of acid-sensitive plant species in heathland can be attributed to ammonium toxicity in combination with low pH. New Phytologist 166:551–564. DOI: 10.1111/j.1469-8137.2005.01338.x

Verma DM; Pant PC; Hanfi MI. 1985. Flora of Raipur, Durg and Rajnandgaon. Flora of India. Series 3. Botanical Survey of India, Howrah, India.

Verma P; Verma P; Sagar R. 2013. Variations in N mineralization and herbaceous species diversity due to sites, seasons, and N treatments in a seasonally dry tropical environment of India. Forest Ecology and Management 297:15–26. DOI:10.1016/j.foreco.2013.02.006

Vourlitis GL; Zorba G; Pasquini SC; Mustard R. 2007. Chronic nitrogen deposition enhances nitrogen mineralization potential of semiarid shrubland soils. Soil Science Society of America Journal 71:836–842. DOI: 10.2136/sssaj2006.0339

Walkley A. 1947. A critical examination of a rapid method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. Soil Science 63:251–264. DOI: 10.1097/00010694-194704000-00001

Watt AS. 1947. Pattern and process in the plant community. Journal of Ecology 35:1–22. DOI: 10.2307/2256497

Whalen JK; Chang C; Clayton GW; Carefoot JP. 2000. Cattle manure amendments can increase the pH of acid soils. Soil Science Society of America Journal 64:962–966. DOI: 10.2136/sssaj2000.643962x

Whitehead DC. 1986. Organic nitrogen in intensively managed grassland soils. In: Van der Meer HG; Ryden JC; Ennik GC, eds. Nitrogen fluxes in intensive grassland systems. Martinus Nijhoff Publishers, Dordrecht, The Netherlands. p. 47–58.

Whittaker RH. 1972. Evolution and measurement of species diversity. Taxon 21:213–231. DOI: 10.2307/1218190

Williams PH; Haynes RJ. 2006. Effect of sheep, deer and cattle dung on herbage production and soil nutrient content. Grass and Forage Science 50:263–271. DOI: 10.1111/j.1365-2494.1995.tb02322.x

Xia J; Wan S. 2008. Global response patterns of terrestrial plant species to nitrogen addition. New Phytologist 179:428–439. DOI: 10.1111/j.1469-8137.2008.02488.x

Zhou J; Cui J; Fan J; Liang J; Wang T. 2010. Dry deposition velocity of atmospheric nitrogen in a typical red soil agroecosystem in Southeastern China. Environmental Monitoring and Assessment 167:105–113. DOI: 10.1007/s10661-009-1034-2

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