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

LivestockPlus

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

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Preface

LivestockPlus is one of three strategic initiatives created under CIAT's new strategy for the period 2014–2020. These forward-looking and collaborative endeavors are aimed at opening new avenues for enhancing the impacts of CGIAR research for agricultural development. CIAT and its partners formulated the LivestockPlus concept to demonstrate how improved forages, when properly managed, can lead to sustainable intensification of mixed crop–forage–livestock systems in the tropics, contributing to multiple social, economic, and environmental objectives. LivestockPlus attempts to minimize the trade-offs between these objectives through synergies between soils, plants, animals, people, and the environment.

Forage grasses and legumes, used as key components of sustainable crop–livestock–tree systems in the tropics, offer significant benefits in terms of improving food security, alleviating poverty, restoring degraded lands, and mitigating climate change. Climate-smart tropical forage-based agricultural systems can improve the livestock productivity of smallholder farming systems and break the cycle of poverty and resource degradation. Sustainable intensification of tropical forage-based systems contributes to better human nutrition, increases farm incomes, raises soil carbon accumulation, and reduces greenhouse gas emissions.

This publication consists of two parts. Part 1 is an article published recently in the open-access journal *Tropical Grasslands–Forrages Tropicales* (DOI: [10.17138/TGFT\(3\)59-82](https://doi.org/10.17138/TGFT(3)59-82)), while part 2 consists of an annex describing the progress of long-term research carried out by CIAT and its partners on variations of the LivestockPlus concept developed in different parts of the tropics, with a particular focus on its implementation in Colombia and Brazil.

The purpose of this monograph is not only to share current scientific knowledge on tropical forage-based agricultural systems but also to send a proactive call for action to agricultural researchers and educators, while at the same time providing useful information for policy makers and development practitioners.

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

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 three interrelated intensification processes: *genetic intensification* – the development and use of superior grass and legume 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 implementation 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 solo 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 ecosistémicos (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.

* This concept and review paper was developed from active participation by and contributions from a large number of co-authors during an international workshop entitled "Pastures, climate change and sustainable intensification" held at CIAT, Cali, Colombia, during 28–29 May 2013.

El concepto *LivestockPlus* se define como la intensificación sostenible de los sistemas de producción basados en forrajes, con tres 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 para 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 medio ambiente 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).

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 three 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).



Table 1. Actual demand for livestock products in developing and developed countries in 2002 and projections for 2050.

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

Source: Adapted from Rosegrant et al. (2009).



Of the five agricultural commodities with the highest global economic value, four (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–tree¹ 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

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).

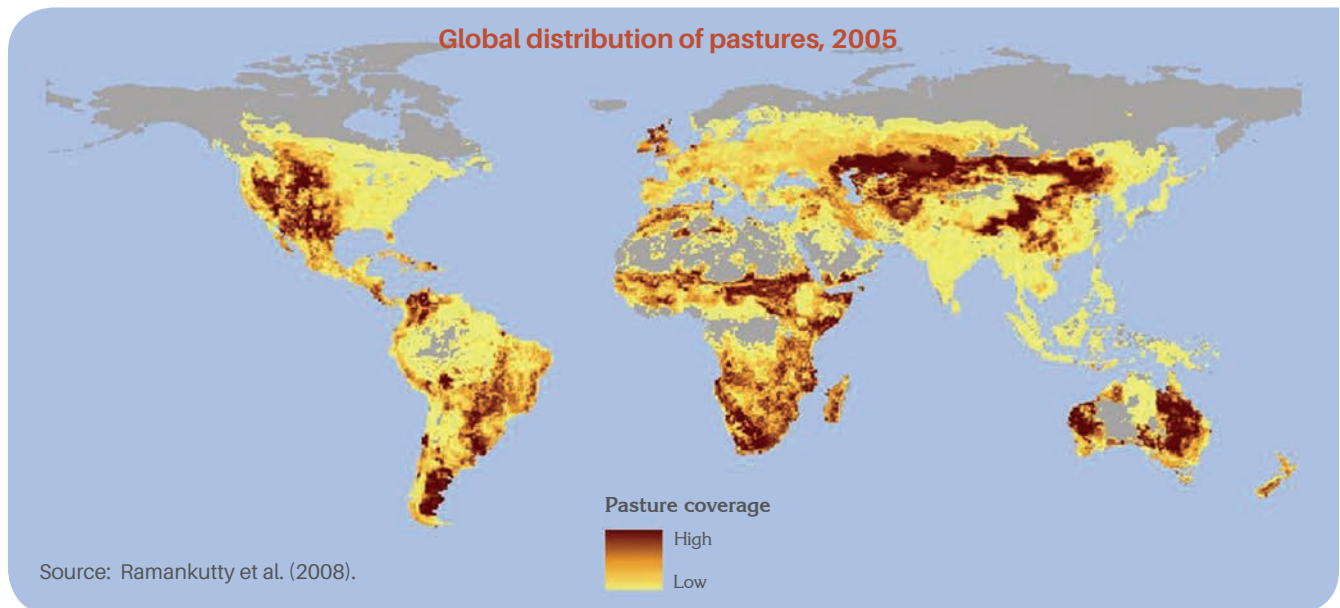


Given such challenging biophysical conditions, coupled with lack of, or unapplied government policies, poorly performing markets, and few investment incentives, land used for livestock production is in varying stages of degradation (Macedo 1997; Miles et al. 2004). As pastures degrade, productivity and 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 (see the Annex for details on experiences from different regions and countries).

(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.

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 (CO₂)-eq/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 (CH₄) from enteric fermentation and animal manures; CO₂ from land use and land-use changes; and nitrous oxide (N₂O) 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 CH₄) 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 four 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.
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.



Grazing association of hybrid *Brachiaria* cv. Cayman with *Leucaena diversifolia*

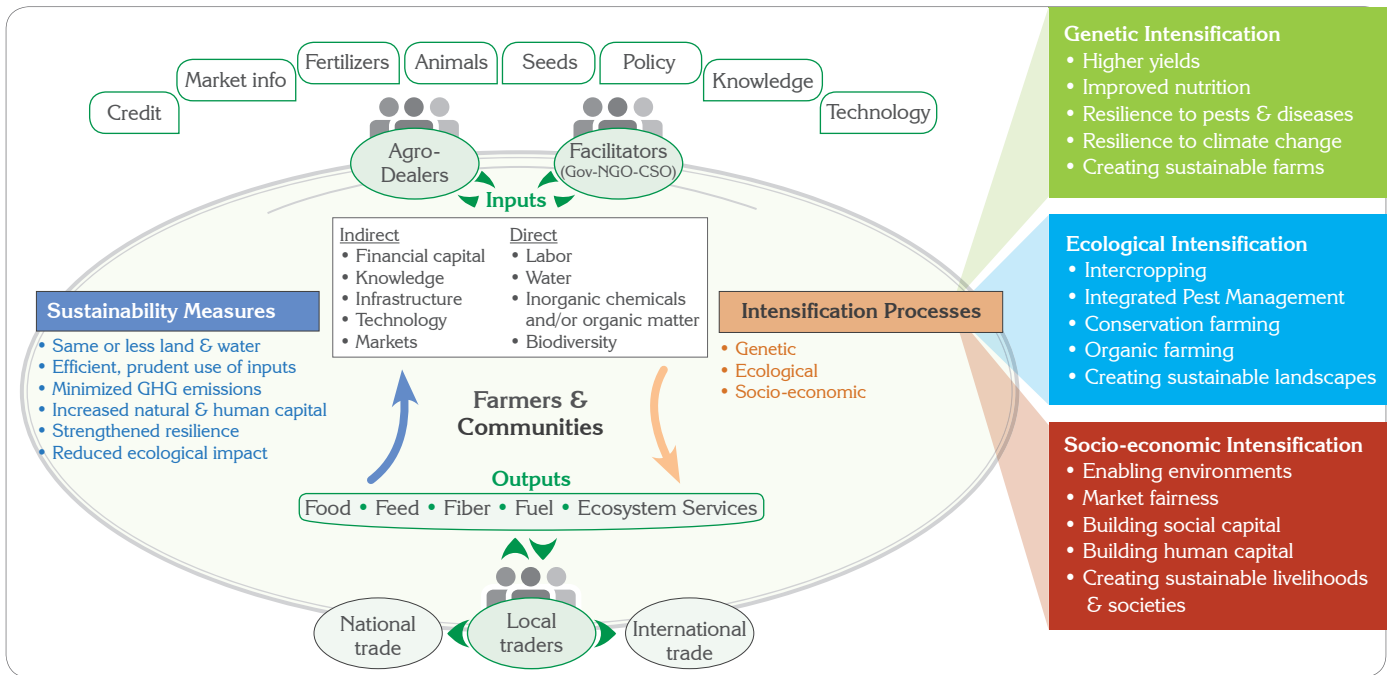


Figure 1. A sustainable intensification approach for improved forages to realize widespread social, economic, and environmental benefits. Source: Modified from The Montpellier Panel (2013).

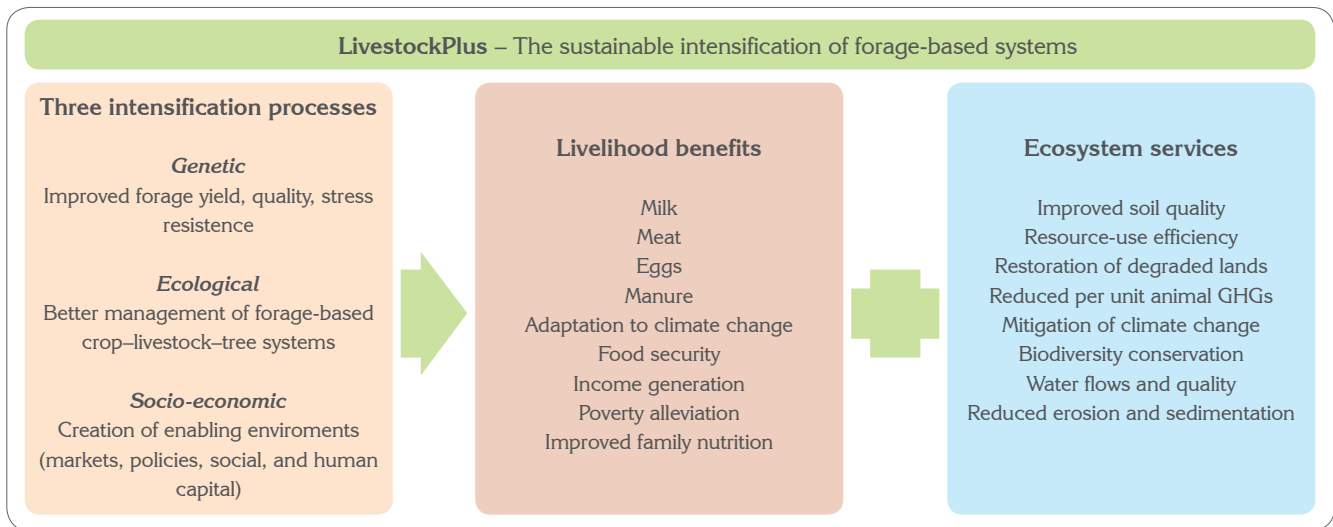


Figure 2. LivestockPlus: A concept to improve livelihoods and ecosystem services via the sustainable intensification of forage-based crop–livestock–tree systems.

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 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* cv. Marandu and Toledo; *B. humidicola* cv. Tully and Llanero; *B. decumbens* cv. Basilisk; and *B. ruziziensis* cv. Kennedy (Miles et al. 2004). *Brachiaria* breeding at CIAT has produced the commercial cv. 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 N₂O 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,



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

^a X indicates major use; (x) indicates minor use.

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).

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 pintoii*, *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.
4. Failure to meet, in some cases, farmer expectations of increased animal production due to low genetic potential of animals used.



Drought-resistant *Cratylia argentea* in Honduras



Association of *Brachiaria decumbens* with *Arachis pintoii*

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

^a Supplementation as ley during the main dry season.

^b 192 grazing days.

^c Now classified as *D. heterocarpon* subsp. *ovalifolium*.

^d Now classified as *B. humidicola*.

^e Means of three grazing cycles totaling 385 days; newly established pastures.

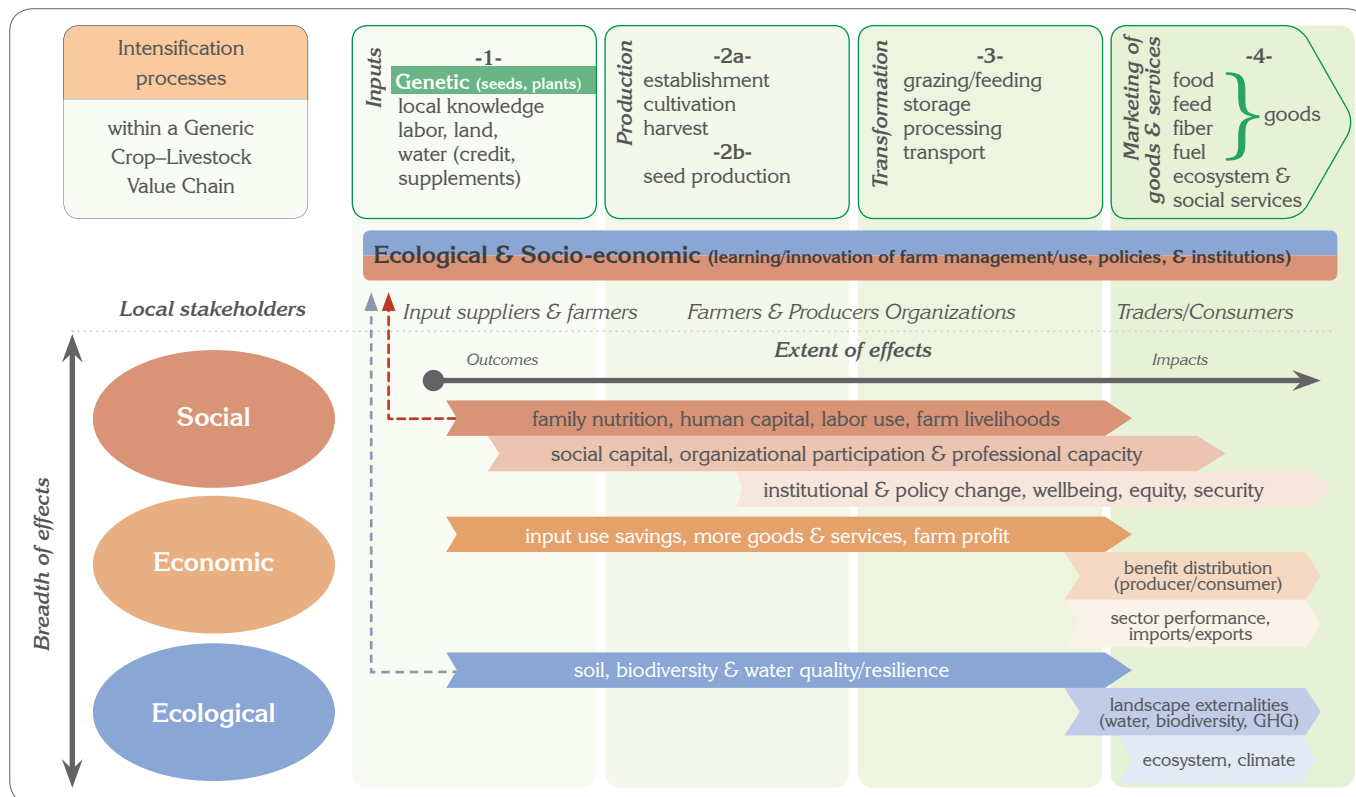


Figure 3. An array of effects generated by sustainable intensification processes of forages within a generic crop-livestock value chain. Source: Adapted from White et al. (2013).

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 CO₂-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 CO₂-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 three 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 N₂O 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, 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.

LCA has 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 CH₄ 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, CH₄ and N₂O 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 agroecosystems 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, three 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 conditions, 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 climate change adaptation and mitigation, 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 USD 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 downside 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, N₂O 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 affect climate change can create a functional system of LivestockPlus in at least five countries within 5 or 6 years.

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Annex

Experiences from different regions and countries

We now describe interregional variations in the LivestockPlus concept within the tropics, with particular focus on the implementation of LivestockPlus in Colombia and Brazil.

Regional comparisons

South America



Colombia's Eastern Plains

Meat and milk are major agricultural products in tropical South America, and demand for both is increasing with population growth and increasing incomes. Animal production is largely based on grazed pastures, including both native savannas of the Llanos of Colombia and Venezuela and the Cerrados of Brazil, and improved grasslands developed from these savannas and from formerly forested areas. The majority of these grasslands are on acid, infertile soils (mainly Oxisols and Ultisols), where the native species are mostly of low productivity and quality (Lascano 1991). It is generally accepted that the best option for increasing cattle productivity in these areas is the use of improved grasses and legumes adapted to infertile acid soils high in Al and P deficient and to prolonged dry seasons.

The main strategy of CIAT and its partners for the past four decades was to identify and generate adapted germplasm coupled with technology to establish, manage, and utilize pastures (Lascano 1991; Fisher et al. 1996; Guimarães et al. 2004; Rao 2014). CIAT's forage germplasm bank holds 23,140 accessions (21,460 legumes; 1,680 grasses) (<http://goo.gl/6HvQj0>). Much of this material was screened for adaptation to acid, high Al soils with low P availability, and tolerance of diseases and insect pests through the RIEPT Network (Rao et al. 1993). Accessions that passed this initial screening were then characterized in terms of tolerance of grazing, minimum nutrient

requirements, nutritive value, dry season performance, and compatibility in grass/legume mixtures.

Subsequently, promising accessions were assembled as pastures, the technology for their establishment was developed, and cattle liveweight performance was measured (Lascano 1991). The most promising pasture combinations underwent long-term productivity and economic evaluation, prior to release as cultivars.

Improved *Brachiaria*-based pastures are the most extensively used to replace native vegetation, with over 99 Mha sown in Brazil alone (Jank et al. 2014). During the past two decades, development of cultivars based on screening the natural variation within the collection has been complemented by plant breeding (Miles et al. 2004). Although improved cultivars have been shown to stabilize farm productivity, the effect of their adoption on forest cover is largely debatable, since factors such as population growth, market access and government land tenure policies influence forest conservation and reforestation activities (White et al. 2001).

There is increasing demand for new forage components to improve the efficiency of animal production and sustainability in tropical South America. For example, in the savannas there is a need to increase production efficiency as more land is used for cropping and as capital and labor costs increase. A major challenge is to develop and implement locally adapted agropastoral and agrosilvopastoral systems based on improved forages, shrubs or trees, and livestock (Rao et al. 2012). These integrated systems would appear to be less vulnerable to pasture degradation caused by poor management and lack of maintenance fertilizer.

Many forage-based livestock systems in South America are confronted with long periods of seasonal drought and temporary or seasonal waterlogging. Livestock production is, therefore, strongly influenced by climate variability, which is expected to increase in the future due to climate change. Strategies to cope with climate variability include producing forage plants, including trees, that are adapted to drought and waterlogging, and the use of crop residues in

integrated production systems. A further option is to preserve biomass surpluses from the wet season to meet animal requirements during the dry season. Forage conservation, such as hay or silage, however, is not used much in the tropics and must be adapted to local conditions, including socioeconomics, mainly for smallholders (Heinritz et al. 2012; Reiber et al. 2013).

The experience in tropical South America has shown acceptance of grasses by farmers; however, lack

of acceptance of legumes has been a major bottleneck when developing improved pasture technologies. The challenge is to find means of: (1) better interaction with the farmers not only during the development process of legume-based technologies but also thereafter; and (2) appropriate incentives to encourage farmers' adoption of legumes in more intensive systems. Furthermore, well-defined grazing/fertilizer management practices and improved genetic potential of livestock are required.

Central America



A child herds goats during Nicaragua's intense dry season

Pressure on arable land resources in Central America has become more acute as the population has increased. Maize and beans, smallholder staples, are often grown on sloping lands that are prone to erosion. Soil organic matter and nutrients are being depleted due to inadequate nutrient management so that crop and pasture productivity is decreasing, reducing income and food security (Johnson and Baltodano 2004; Pfister and Baccini 2005).

Grasses like *Hyparrhenia rufa* and *Panicum maximum* were introduced with the slave trade centuries ago, became naturalized, and almost completely replaced native species. More recently *Cynodon nlemfuensis* (African stargrass) and drought-adapted *Brachiaria brizantha*, *B. humidicola*, and the *Brachiaria* hybrids Mulato, Mulato II, and Cayman have been adopted by medium- and large-scale farmers. They occupy 10–20% of total grazing areas. There has been

little adoption of improved grasses by smallholders, however, whose animal productivity remains low. A lack of resources to manage pastures properly, coupled with the poor genetic potential of dual-purpose cattle breeds, prevents smallholders from realizing economic benefits associated with improved forages (Holmann et al. 2004).

Forage legume research in Central America has focused on overcoming feed shortages in the dry season and declining soil fertility by integrating multipurpose forage legumes (both herbs and shrubs) in smallholder mixed crop–livestock systems. Due to their drought tolerance, some forage legumes allow farmers to improve animal feeding with crop residues and enhance soil fertility when used as green manure. For example, supplementing maize residues grazed by cows with *Canavalia brasiliensis* increased milk yield by 20–30% (Douxchamps et al. 2014).



Canavalia brasiliensis

Sub-Saharan Africa



Children enjoy fresh milk from the cow in Rwanda

Lack of sufficient quantity and quality of livestock feed is the major constraint faced by farmers in smallholder mixed farming and pastoral production systems (Hall et al. 2008). The problem is especially acute during the dry season. In the East African highlands, Napier grass and natural pastures form the bulk of feed resources during both rainy and dry seasons. Cattle are usually kept in zero-grazing systems or on unimproved pastures year-round, many of which are overgrazed. During the dry season, a wider range of resources is used to supplement livestock feed, including crop residues, purchased off-farm feeds, and public land for grazing (Lukuyu et al. 2009). In the eastern Democratic Republic of the Congo, feed shortages are common during the dry season, but planted forages only contribute 6% of the livestock diet (Bacigale et al. 2014). Increasing population pressure and continuous subdivision of land has led to diminished farm sizes and increased food-feed competition. Concurrently the use of fallows, the traditional method of managing soil fertility, has decreased, leading to soil degradation. This natural resource degradation is often linked to impoverishment of smallholder farmers (Shepherd and Soule 1998).

Planted forage legumes were introduced in West Africa as early as in the 1940s (Boonman 1993) but major research started in the 1970s, with main focus on *Stylosanthes* species as fodder banks (Elbasha et al. 1999; Tarawali et al. 2005). Subsequently, the West and Central African Feed Research Network (RABAOC, its French acronym) conducted multilocational testing of standard sets of 32 grass and legume accessions in West and Central Africa in the 1990s. *Aeschynomene histrix*, *Centrosema molle* (formerly *C. pubescens*), and *Mucuna pruriens* var. *utilis* were selected and strategies for their introduction into farming systems were evaluated (Adjolohoun et al. 2008). With increasing

population, fallow periods were shortened, and the traditional millet-based crop–livestock systems were intensified with food-feed legumes, cowpea being one of most promoted species (Shetty et al. 1995; Singh and Tarawali 1997; Kristjanson et al. 2005). These food-feed crops are becoming more popular, especially in areas where farmers have good market access and there is high pressure on land (Tarawali et al. 2005).

Extensive research conducted, mainly in West Africa, with the multipurpose legumes mucuna (or velvet bean), *Mucuna pruriens* var. *utilis* (Vissoh et al. 1998) and leucaena (*Leucaena leucocephala*), the latter used in the so-called alley-farming system (Kang et al. 1990), have shown the soil improvement potential of both species. Both technologies have been adopted by farmers, alley-farming less than mucuna due to competition for water (Douthwaite et al. 2002). The contribution of woody legumes, such as *Cajanus cajan*, *Pterocarpus* sp., *Acacia* sp., and *Leucaena leucocephala*, to livestock nutrition is being evaluated in drier zones. They are seen as highly promising in the context of climate change (Olafadehan 2013; Zampaligré et al. 2013). In East African highlands, a fodder shrub planted by smallholder dairy farmers is *Calliandra calothyrsus* to replace supplements fed to dairy cows (Franzel et al. 2005).



Mucuna for control of the weed *Imperata cylindrica*, Benin

Another successful technology involving forage legumes is the push-pull system, which integrates pest, weed, and soil management in cereal–livestock farming systems (Khan et al. 2014). Maize, sorghum, or millet is planted together with Napier grass and the legume *Desmodium uncinatum*. Root exudates from the desmodium cause abortive germination of the parasitic weed *Striga*, while improving soil fertility through symbiotic nitrogen fixation and soil cover. Desmodium further repels stem borer moths and attracts their natural enemies. Napier grass attracts

and traps stem borers. Maize and sorghum yields have been improved from below 1 t/ha to 3.5 and 2 t/ha, respectively. In addition, farmers have benefited from increased milk production through high-quality fodder from the desmodium and Napier grass. This push-pull system results in significantly higher returns to land and to labor compared to conventional practices. The technology has been adopted by more than 28,000 farmers in Kenya and 4,000 in Uganda and Tanzania (Khan et al. 2011). More recently, the push-pull system has been amended by using *Brachiaria* hybrid cv. Mulato instead of Napier as a trap crop. Mulato proved to be more drought tolerant, while still providing effective control of stem borers and *Striga*, resulting in significant grain yield increases (Khan et al. 2014).

Improved *Brachiaria* spp. were introduced by CIAT and partners in East Africa in 2006. In acidic soils in Rwanda, dry matter (DM) yields of *Brachiaria decumbens* cv. Basilisk, *B. brizantha* cv. Marandu and Toledo, and *Brachiaria* hybrid cv. Mulato II ranged from 4.2 to 4.6 t/ha, while the biomass of the local controls (*B. decumbens* and *Cenchrus ciliaris*) were 3.7 and 1.0 t/ha, respectively. The crude protein (CP)



content of Mulato II was consistently higher than that of all other grasses during both the dry and wet seasons. In on-farm trials, *Brachiaria* cv. Mulato II was preferred by farmers because of its adaptation to low rainfall and low soil pH, high nutritional quality, palatability, and its ability to reduce erosion (Mutimura and Everson 2011; 2012). Intercropping trials in Uganda showed that 0.5 ha Napier grass with *Centrosema molle* and 0.5 ha Mulato with *Clitoria ternatea* increased milk yield by 80% and household income by 52% when compared with Napier monoculture. The Mulato intercrop had a lower DM yield than the Napier intercrop, but had 12.1% CP compared with 8.4% (Kabirizi et al. 2013).

Southeast Asia



Grass-cropping for sale as fresh forage, Thailand

Productivity of livestock in Southeast Asia is generally low, and feeding animals appropriately is often a major challenge. Smallholders often find themselves caught in what Connell et al. (2010) term the 'labor-productivity trap:' more labor is needed to improve the feeding of animals, but the low productivity of the animals does not justify the extra investment in time. Meanwhile, a strong increase in per-capita meat consumption is driving demand for regional livestock production, while improving infrastructure is opening access to markets for previously remote uplands.

Although forage research has been conducted in Southeast Asia for at least 50 years (Peters et al. 2001), it is only in the past 2–3 decades that this research has focused on smallholders (Roothaert et al. 2005). In the mid-1980s, research institutions in China (Hainan), Indonesia, Malaysia, the Philippines, and Thailand introduced a large range of forage accessions from Australia and CIAT for on-station evaluation and cultivar development. In 1992, CIAT, together with local and international partners, initiated participatory forage research with smallholders in these countries and later in Lao PDR, Vietnam, and Cambodia (Stür et al. 2006). Subsequently, a series of smallholder-focused projects introduced forage species that were released as commercial cultivars, such as *Panicum maximum* cv. Simuang, *Brachiaria ruziziensis*, *B. humidicola* cv. Tully and Yanero, *B. brizantha* cv. Marandu, *Brachiaria* hybrid cv. Mulato, *Paspalum atratum* cv. Terenos, *Setaria sphacelata* cv. Lampung, *Pennisetum* hybrid cv. King grass, and *Stylosanthes guianensis* CIAT 184 into target areas. By mid-2005, almost 10,000 households had adopted planted forages at pilot sites throughout Southeast Asia. The success of improved forage technologies has since led to their incorporation into development plans by local governments and NGOs. This has facilitated their spread to at least another 10,000 households beyond the initial project sites (Stür et al. 2006).

In tropical Asia, the most important forage legume is *Stylosanthes guianensis* (cultivars developed from accession CIAT 184), particularly in tropical and subtropical China. In China, *S. guianensis* is mainly used as cover crop to improve the soil in fruit orchards, as fresh forage and to produce leaf meal for monogastrics (Liu and Chakraborty 2005). The adoption of other forage legumes is often constrained by lack of seed, however, and more generally to less developed systems of animal production.

Forages have enabled smallholders to transform livestock from a marginal farm activity to a productive, profitable, market-oriented enterprise (Table A-1). The major impact of sown forages on livelihoods has been on labor savings and higher income from increased animal



Improved CIAT forages in Vietnam

sales. In turn, this led to both enhanced productivity of the animals and the ability of the household to raise more animals (Stür et al. 2006; Connell et al. 2010).

Table A-1. Examples of quantified livelihood benefits of three forage-based livestock production systems practiced by smallholder farmers in Southeast Asia.

System/site	Measured variables	Traditional system	Planted forage system
Cattle or buffalo fattening	Minimal area of planted forage required:		800–1,000 m ² /an
Dak Lak Province, Vietnam ^a	Net profit Liveweight gain	USD 75/0.1 ha/yr	USD 425/0.1 ha/yr 670 g/cow/d
Xieng Khouang Province, Lao PDR ^b	Dependence on shifting cultivation (SC) Net profit from individual cases	40 ha under SC USD 0–16/an/mo	11 ha under SC area after 5 years USD 23–38/an/mo
Cow-calf system	Minimal area of planted forage required:		500–1,000 m ² /cow
Dak Lak Province, Vietnam ^c	Herd size per household Income from cattle sale in preceding year Time spent looking after cattle Return to labor	4 an USD 441 6.8 h/d USD 0.18/h	7 an USD 756 3 h/d USD 0.69/h
East Kalimantan, Indonesia ^d	Head of cattle sold over a 3-year period Time spent collecting feed for cattle Sale value of calf	< 1 an 120 h/head/mo USD 200/calf	3 an 6 h/an/mo USD 250/calf
Grass carp production	Minimal area of planted forage required:		500–700 m ² /pond
Tuyen Quang Province, Vietnam ^e	Labor requirement Pond productivity Net income per pond Return to labor Minimal area of planted forage required	648 h 75 kg/100 m ² of pond USD 84 USD 0.2/h	308 h 122 kg/100 m ² of pond USD 283 USD 1.28/h 500–700 m ² /pond

^a Average based on a 2005 survey of 30 households in Ea Kar District for either coffee (= Traditional system) or cattle fattening using planted forages (mainly *Panicum maximum* cv. Simuang) supplemented with approx. 2 kg of commercial feed concentrate per day (Stür et al. 2006). In 2010, after 10 years of forage projects in the district, forage adoption had stabilized at around 3,100 smallholder households (~30% of all cattle producers in the district). Of these, 532 households fattened cattle for urban markets and 800 produced cross-bred and Laisind calves in cow-calf systems (Stür and Khanh 2010).

^b Based on a survey of all 21 households of Xang Village, Xieng Khouang Province, Lao PDR (Connell et al. 2010).

^c Mean values of a 2005 survey of 27 households growing forages and 20 households practicing traditional cow-calf production with native feeds and extensive grazing in Ea Kar District (Stür et al. 2006).

^d Mean values of a survey of 22 farmers of Samboja Village, East Kalimantan, Indonesia, that integrated forages into their coconut plantations (Connell et al. 2010). The number of non-forage farmers is not specified.

^e Mean values of one production cycle based on a survey of 30 households in Yon Sen District, Tuyen Quang Province, northern Vietnam (Stür et al. 2006).

South Asia



Himachal Pradesh, India

In India, crop residues (CR) are the most important single fodder resource (NIANP 2003). Fodder from other sources includes common property resources, forests, pastures, and fallow lands, which constitute less than 18% of the available fodder and is declining. Concentrates represent less than 4% of the available feed resources. Among planted legumes, *Stylosanthes*, mainly *S. hamata*, is an important legume for restoration of wastelands and as forage crop (Ramesh et al. 2005).

The improvement of CR by processing roughages has been extensively researched, but processing technologies have not been widely adopted (Singh and Schiere 1993). Thus, research has targeted improving the fodder value of CR by plant breeding and selection

(Reed et al. 1988; Kristjanson and Zerbini 1999). Until recently, the feed quality of CR was largely ignored in crop improvement programs. This neglect often resulted in new cultivars with improved grain yields that, however, were rejected by farmers because of low CR quantity and quality (Kelley et al. 1996).

Increasing the feeding value of CR by multidimensional crop improvement depends upon: (1) close collaboration between crop and livestock scientists; (2) nutritionally significant genetic variation in CR fodder quality; (3) sufficient independence between CR fodder traits and primary traits such as grain yield; and (4) technologies for quick and inexpensive phenotyping of large sets of samples for fodder quality traits. These conditions were met in several key crops, such as sorghum, pearl millet, rice, cowpea, and maize (Grings et al. 2010; Sharma et al. 2010; Blümmel et al. 2012; Ertiro et al. 2012), that were studied in collaborative work between the International Livestock Research Institute (ILRI), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), National Research Center for Sorghum (NRCS) in India, International Rice Research Institute (IRRI), International Institute of Tropical Agriculture (IITA), and International Maize and Wheat Improvement Center (CIMMYT). This work showed that about 3 to 5 units of difference in CR digestibility can be exploited in these key crops by phenotyping for CR fodder quality. Genetic improvement using conventional or molecular breeding techniques resulted in 10 to 30% higher income from CR feeding or fodder trading. This was achieved with no decrease in grain yields (Blümmel et al. 2013).

National examples

Colombia



Livestock in Colombia's Eastern Plains

The tropical savannas of South America represent one of the last frontiers in the world for agricultural expansion of integrated crop–livestock systems (Borlaug and Dowsell 1994). Starting in the 1970s, Colombian ranchers in the Llanos replaced native grasses by selected *Brachiaria* grasses. The result was a twofold increase in liveweight gain (LWG) per animal and up to 10- to 15-fold increase in LWG per ha (Lascano 1991). These grass-alone pastures often degraded after several years because of overgrazing, no maintenance fertilizer, and attack by spittlebug (Homoptera: Cercopidae) (Miles et al. 2004). Researchers made a major effort to introduce forage legumes to supply N to the system and increase livestock production (Thomas et al. 1995). However, the legume-based technology was not widely adopted

by farmers because the legume component often failed to persist, seed was scarce and expensive, and there was little economic incentive to provide maintenance fertilizer and adequate grazing management practices (Guimarães et al. 2004).

Research in the last two decades focused on developing improved *Brachiaria* hybrids and crops adapted to acid soils. The *Brachiaria* hybrids developed are adapted to acid, infertile soils, and resistant to spittlebug (Miles et al. 2004; Rao et al. 2011; Rao 2014). The crops are upland rice, maize, cassava, sorghum, and soybean that have moderate resistance to high levels of Al and tolerance of low levels of P (Rao et al. 1993; Guimarães et al. 2004). This was a long-term inter-institutional collaborative research effort between the Colombian Corporation of Agricultural Research (Corpoica), CIAT, and CIMMYT. Replacing native savanna with adapted rice and maize undersown with *Brachiaria* gave 2.5 to 3.5 t/ha grain and excellent pasture establishment (Guimarães et al. 2004). The income from the crop paid the cost to establish the pasture. The carrying capacity and LWG per head in the crop–pasture systems was twice that of degraded pasture and 10 times that of the native savanna (Rincón and Ligarreto 2008; Rincón et al. 2010). Recent data show LWG of 1,000 kg/ha/yr on pastures sown after 3 years of a maize–soybean rotation (Rincón and Flórez 2013; Figure A-1).

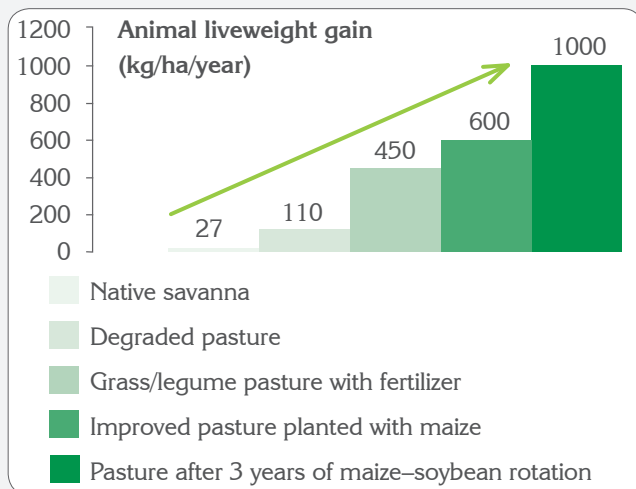
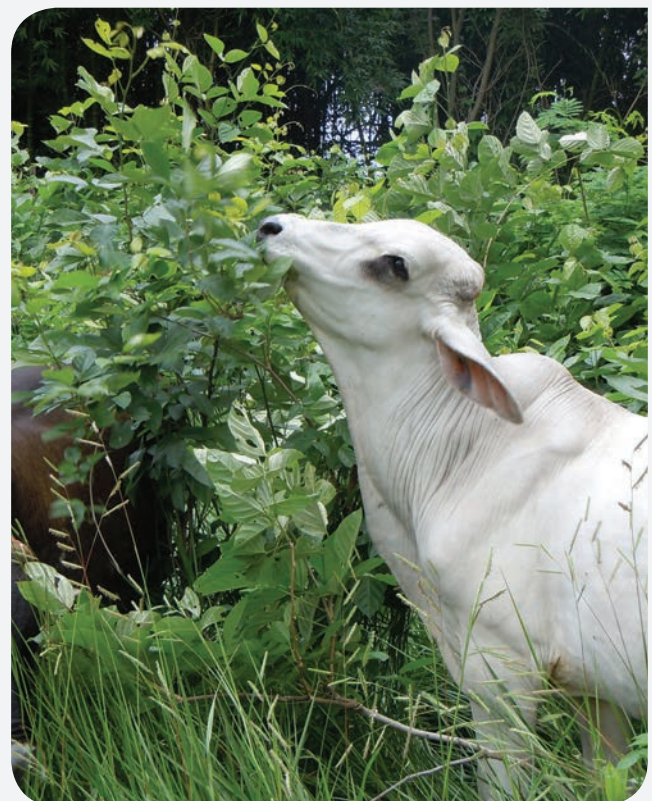


Figure A.1. Role of improved tropical pastures in increasing livestock production in terms of animal liveweight gain (kg/ha/yr) in the tropical savannas of Colombia
Source: Adapted from Rincón and Flórez (2013).

Researchers tested grain legumes, green manures, intercrops, and leys as components that could increase the stability of systems involving annual crops (Friesen et al. 1997; Ayarza et al. 2007). A problem, however,

is that the soils of the Llanos have fragile structure, which required innovative strategies to manage them in intensive systems. The solution was to develop an ‘arable layer,’ which consists of using vertical tillage with a chisel plough, adding lime and fertilizers to correct the soil chemistry, and growing productive and deep-rooted grasses and adapted crops (Amézquita et al. 2007). An arable layer promotes vigorous root growth of pasture grasses that accumulate C in the soil (Fisher et al. 1997; Rao 1998; Rondón et al. 2006), reduces nitrification and N₂O emission from soil (Subbarao et al. 2015), and enhances recycling of P (Rao et al. 2004). It also enhances soil biodiversity and biological activity, and stabilizes soil physical structure (Amézquita et al. 2007; Ayarza et al. 2007).

Using the arable layer technology, hybrid maize yields 3.7 t/ha in the first year after conversion from native savanna and 5.4 t/ha in the third year (Amézquita et al. 2007). Carrying capacity of improved *Brachiaria* pastures in the short term is 3–4 head/ha with LWG of 0.6–0.8 kg/head/d (Rincón and Flórez 2013). Water infiltration rates increased two- to five-fold, soil porosity increased 13–21%, and soil compaction decreased 10–15%. Amézquita et al. (2007) estimated the potential economic impact of improved systems using arable-layer technology for the Llanos at USD 239 million/yr.



Grazing *Cratylia argentea-Brachiaria humidicola*

Brazil

Brazil is the second largest producer of beef globally, with a national cattle herd of 209.5 million head in 2010, an increase of 42.4% compared with 1990 (Newton et al. 2013). Beef production is the primary driver of deforestation in the Amazon (Bustamante et al. 2012). Livestock production in Brazil is based on pastures, which cover about 190 Mha with 74 Mha native pastures and 116 Mha sown pastures (ANUALPEC 2008). Most of the sown pastures are *Brachiaria* species (99 Mha), which were first introduced more than 50 years ago. The widely planted spittlebug-resistant *B. brizantha* cv. Marandu occupies about 50 Mha and is the world's largest monoculture (Jank et al. 2014). Improved pastures are a major asset in Brazil for both beef and milk production.

Most pastures are not well managed and both overgrazing and lack of maintenance fertilization are common. About 47% of sown pastures in Brazil show some level of degradation and need restoration (Nogueira and Aguiar 2013). Pasture restoration, which is estimated about 8 Mha/yr (Jank et al. 2014), is often more expensive than clearing land because of severe decline in soil quality. Late in the 1980s, the Brazilian Agricultural Research Corporation (Embrapa) developed an economically viable system, called “Barreirão,” to restore pastures using annual crops (Oliveira et al. 1994). Latawiec et al. (2014) argued that sustainable intensification of pasture lands in Brazil is a viable way to increase agricultural output while simultaneously sparing land for nature. Since, in Brazil, environmental

degradation is often associated with low-yielding extensive systems, it is possible to obtain higher yields, while reversing degradation by adopting practices such as rotational grazing, incorporation of legumes and integrated crop–livestock–forestry systems.

Integrated crop–pasture systems (about 4 Mha) (José 2012) are important in areas where cash crops are traditional, but are not suited to regions with poorer soils and little infrastructure. In such areas, an alternative has been introduced integrating trees with livestock and crops. Agrosilvopastoral systems (ASPS) have shown promising results, but their adoption by farmers is slow because they are costly to establish and more complex to manage than *Brachiaria* monocultures (Almeida et al. 2013). In addition, choosing the right combination of tree species, forage and crop cultivars, together with appropriate inputs and machinery, requires experience that few have (WWF-Brazil and Embrapa Beef Cattle 2011). Tax incentives have shown to play an important role in rapid uptake of new technologies (Bungenstab 2012). Nevertheless, high global demand for beef and grains along with logging restrictions on native forests create favorable market conditions and prices of all three products (beef, grains, wood), thereby encouraging farmers to adopt ASPS technologies. The sustainable intensification of ASPS not only helps reduce the negative environmental footprint of cattle in greenhouse gas emissions, to which the Brazilian Government is formally committed, but also diversifies the production system leading to greater ecological and economic resilience (Bungenstab 2012).



Silvopastoral system in Brazil

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