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

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Abstract

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

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

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

Resumen

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

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

Introduction

The need to increase livestock production

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

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

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

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

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

Diverse crop-forage-livestock systems

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

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

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

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

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

Livestock production and the environment

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

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

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

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

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

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

Eco-efficiency and sustainable intensification

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

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

LivestockPlus: Concept and principles

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

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

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

LivestockPlus: Sustainable intensification of forage-based systems

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

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

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

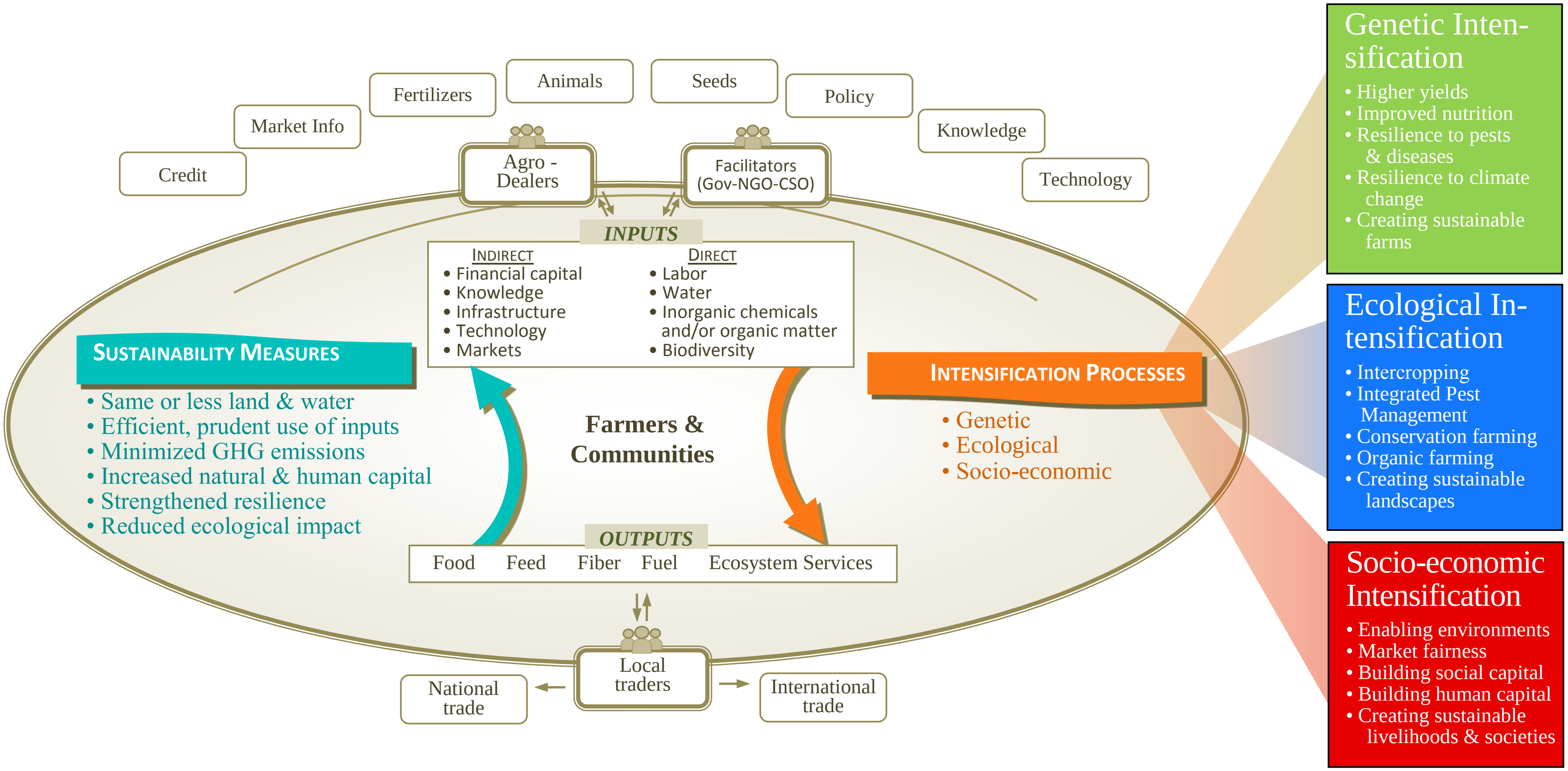

Figure 1. A sustainable intensification approach for improved forages to realize widespread social, economic and environmental benefits (modified from The Montpellier Panel 2013).

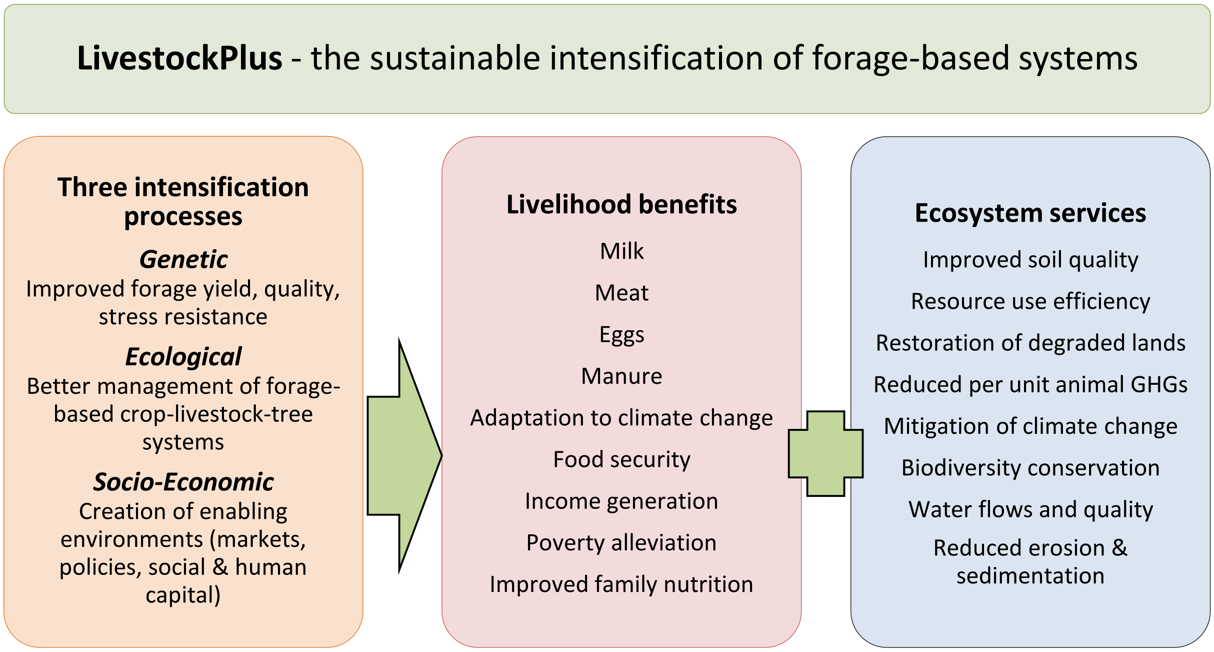

Figure 2. LivestockPlus: A concept to improve livelihoods and ecosystem services via the sustainable intensification of forage-based crop-livestock-tree systems.

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

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

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

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

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

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

In the 1930s in North Queensland, Australia, the presence of naturalized *Stylosanthes humilis* (then *S. sundaica*, "Townsville lucerne") in natural pastures was observed to boost animal growth rates (McTaggart 1937), resulting in extensive research on the benefits of including adapted legumes in tropical grass pastures. The technology was subsequently taken up elsewhere in the tropics (Table 3). Selection from within large collections of germplasm identified cultivars of species in the genera *Centrosema*, *Desmodium*, *Leucaena* and *Stylosanthes* for use in tropical and subtropical Australia (Table 2). Only few cultivars were bred, e.g. *Macroptilium* *atropurpureum* cv. Siratro (Hutton 1962) and *Centrosema pascuorum* cv. Cavalcade (Clements et al. 1986) in Australia and psyllid-tolerant *Leucaena* hybrids in Hawaii (Austin et al. 1998).

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

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

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

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

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

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

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

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

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

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

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

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

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

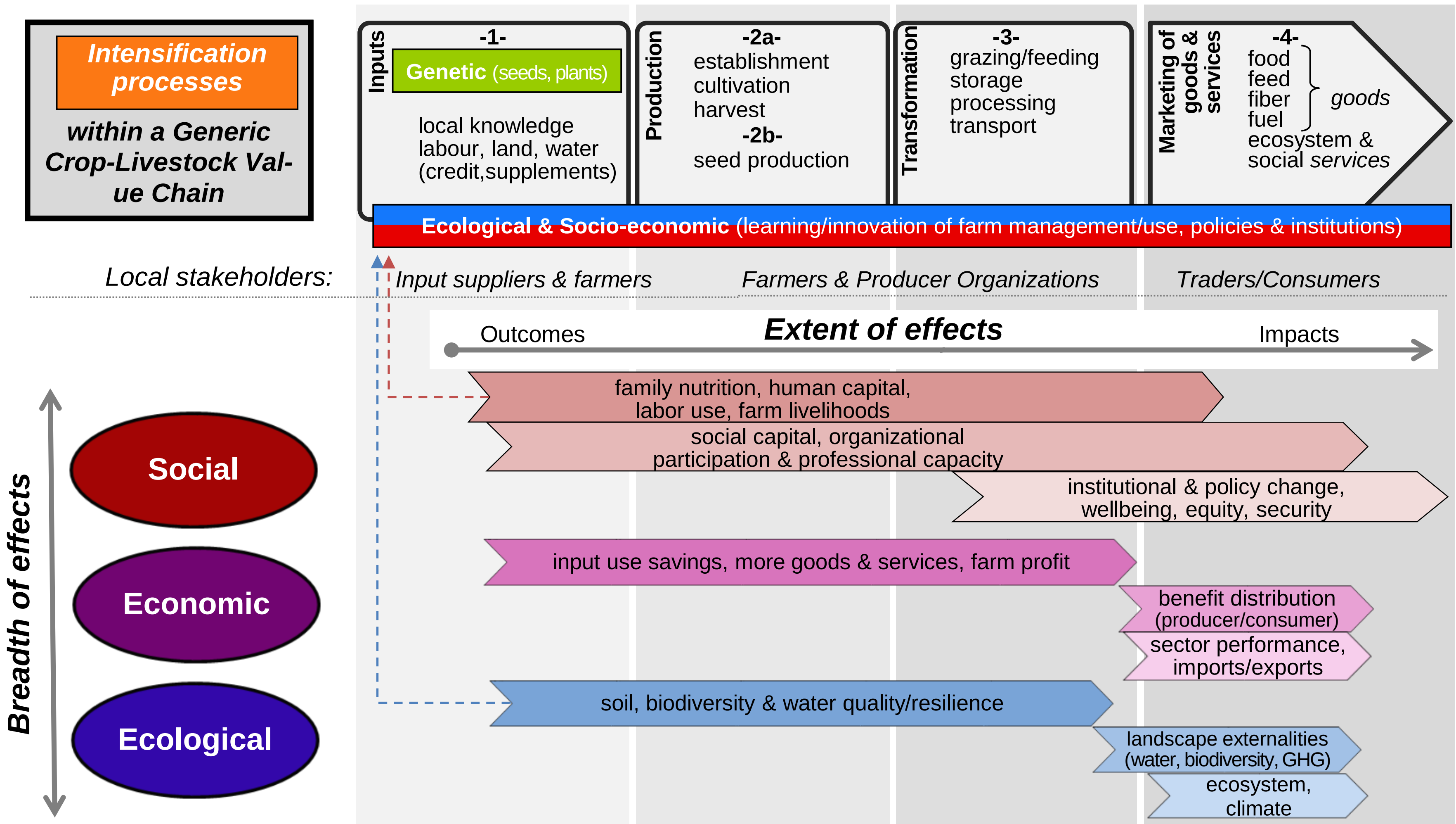

Figure 3. An array of effects generated by sustainable intensification processes of forages within a generic crop-livestock value chain (adapted from White et al. 2013).

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

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

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

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

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

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

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

Limitations. Negative impacts of improved forages include soil acidification by legume-only swards (Haynes 1983) and the potential invasiveness of exotic species (Richardson and Pysek 2012). At larger scales, the cumulative effects of increased farm productivity can reduce water flows and quality downstream. Whether off-farm environmental effects are beneficial or detrimental depends on the site-specific context and management practices (Quintero et al. 2009). A serious environmental concern is the potential destruction of natural ecosystems, such as rainforests, by replacing them with improved pastures, with the concurrent loss of biodiversity at all levels (mainly when monospecific grass pastures replace native multi-species vegetation).

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

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

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

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

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

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

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

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

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

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

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

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

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

Dialogue between farmers, extensionists, researchers and policymakers is needed to integrate forages into crop-livestock-tree systems. Processes of co-discovering and co-developing multiple benefits of forages reduce the gaps between research, development and implementation. For example, the Feed Assessment Tool (FEAST) assists in formulating site-specific strategies and interventions for improved livestock feeding and production. It offers a systematic and rapid methodology to assess existing feed resources, constraints and opportunities (Duncan et al. 2012; Wassena et al. 2013).

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

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

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

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

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

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

Conclusions and future perspectives

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

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

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

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

Genetic intensification

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

Ecological intensification

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

Socio-economic intensification

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

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

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

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