CHAPTER
11

Tropical Forage-based Systems to Mitigate Greenhouse Gas Emissions

Michael Peters,[1] Idupulapati Rao,[1] Myles Fisher,[1] Guntur Subbarao,[2] Siriwan Martens,[1] Mario Herrero,[3] Rein van der Hoek,[1] Rainer Schultze-Kraft,[1] John Miles,[1] Aracely Castro,[1] Sophie Graefe,[1] Tassilo Tiemann,[1] Miguel Ayarza,[4] and Glenn Hyman[1]*

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Abstract

Agriculture and livestock production are major contributors to greenhouse gas emissions. Forage-based systems dominate much of agriculture in the tropics, providing livelihoods to farmers but also affecting local and global environments. In this paper, we attempt to answer the question, how can farmers and livestock keepers improve their livelihoods while reducing negative impacts on the environment? We focus on forage-based systems in the tropics, emphasizing smallholders and the role of forages. In particular, we address the potential of tropical forage-based systems not only to contribute to reducing greenhouse gas emissions but also to sequester carbon in soil in substantial amounts to mitigate climate change. We also discuss the associated benefits of forage-based systems to enhancing the eco-efficiency of farming in the tropics and to improving rural livelihoods. We identify opportunities in forage-based systems that are economically sustainable and socially equitable with the lowest possible ecological footprint. With the global community increasingly aware of the environmental implications of agriculture, forage-based systems should figure prominently as "LivestockPlus" (meat, milk, and more) options in future innovative agricultural systems. We hope that this paper will stimulate discussion that leads to further investment from donors in research on improving the eco-efficiency of forage-based systems in the tropics.

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[1] International Center for Tropical Agriculture (CIAT), Cali, Colombia.

[2] Japan International Research Center for Agricultural Sciences (JIRCAS), Ibaraki 305-8686, Japan.

[3] International Livestock Research Institute (ILRI), Nairobi, Kenya.

[4] Colombian Corporation of Agricultural Research (Corpoica), Bogotá, Colombia.

* Corresponding author: m.peters-ciat@cgiar.org

Background

Climate change is one of the greatest challenges to human development in general and food security in particular in recent history. Even if we act decisively now, by 2050 temperatures will be at least 2 °C, and perhaps as much as 5 °C, above those of pre-industrial times (IPCC, 2007; World Bank, 2010), threatening sustainable food production worldwide. Developing countries are more exposed to the hazards of climate change and less resilient to them (Morton, 2007). Moreover, they will have to bear an estimated 75–80% of the costs associated with the impacts of climate change (Hope, 2009; Smith et al., 2009; World Bank, 2010). Undernourished people, estimated at 925 million worldwide in 2010 (FAO 2010a), most of whom live in the tropics, are especially vulnerable.

Contribution of agriculture and livestock to climate change: greenhouse gas emissions

Agriculture, including meat and milk production, produces three main greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In terms of climate forcing, one unit of CH_4 is equivalent to around 21 units of CO_2 and one unit of N_2O is equivalent to 310 units of CO_2 (Forster et al., 2007). Agriculture is a major contributor to climate change, producing 14% of GHG emissions at the global level, with a further 17% attributed to land-use change and deforestation. In low-income countries, the contribution of agriculture to emissions is even higher, with 20% and 50% attributed to agriculture and land-use change, respectively (World Bank, 2010). Although debate continues about the actual numbers, there is little doubt about the relative importance of agriculture, and livestock production in particular, as emitters of GHG (Anderson and Gundel, 2011; Herrero et al., 2011).

Livestock systems are estimated to contribute about 50% of all agricultural sector GHG emissions (Steinfeld et al., 2006; Scherr and Sthapit, 2009), contributing up to 9% of all anthropogenic CO_2 emissions, 37–52% of CH_4, and 65–84% of N_2O (Smith et al., 2008; FAO, 2009). Large ruminants (cattle and buffalo) emit more GHG per kilogram of meat than monogastrics (pigs and poultry).[5] In addition to GHG from enteric fermentation and manure, large ruminants are also associated with land-use changes such as deforestation (Steinfeld et al., 2006; FAO, 2009), particularly in Central and South America (Szott et al., 2000; Wassenaar et al., 2007; Barona et al., 2010; Pacheco et al., 2011). However, the direct and indirect causes of deforestation are complex and can be difficult to attribute (Geist and Lambin, 2002), and the impact of improving livestock technologies is debated (e.g., Angelsen and Kaimowitz, 2004; Kaimowitz and Angelsen 2008). For particular locations, these data require further analysis, since land-use change is strongly influenced by policy interventions and the level of enforcement (Steinfeld and Gerber, 2010).

LivestockPlus

Comparative analysis of GHG emissions between diverse production systems should include the environmental costs of feed production, including its transport. For example, in the case of soybean produced in the Amazon that supplies European feedlots (Herrero et al., 2009; Anderson and Gundel, 2011), transport accounts for 11–12% of GHG emissions (Garnett, 2011) and contributes more to GHGs than feed produced near feedlots in midwestern USA (Pelletier et al., 2010). Feed-lot cattle produce fewer GHG emissions than forage-fed cattle, mainly due to better feed conversion (Casey and Holden, 2006; Gerber et al., 2010; Pelletier et al., 2010). However, the potential to mitigate climate change and other co-benefits of forage-based systems[6] (Figure 1) are often not considered. It is these benefits of forage-based systems in the tropics that need to be recognized

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[5] Because of their relative unimportance as emitters of GHGs, we consider monogastrics further only in passing.

[6] In addition to perennial pastures for grazing, forages include herbaceous and woody plants, and perennial and short-lived forage crops for cut-and-carry. We use the term “forage-based systems” to include all systems that include forage plants as a component, including ley systems that include several years’ cropping before returning to pasture, agropastoral systems, and rangelands (native grasslands and savannas). They all contain a substantial component of animal production.

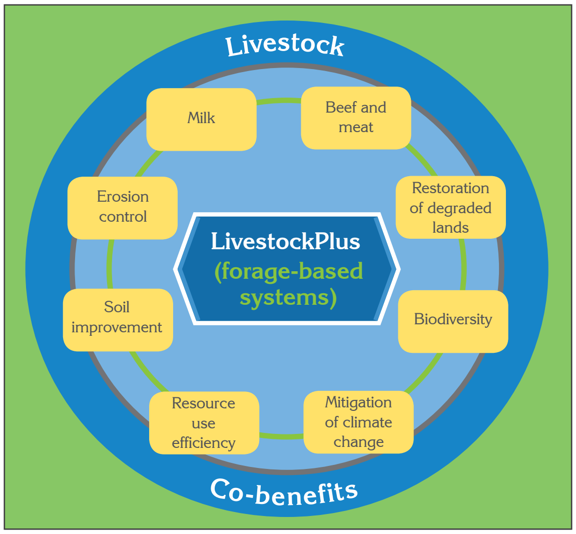

Figure 1. LivestockPlus: forage-based systems for agriculture and the environment.

by the global community. We call this concept "LivestockPlus".

The importance of tropical forage-based systems and the role of sown forages

In this paper, we discuss the role of tropical forages in mitigating climate change. We focus on forage-based production systems in which forages have a multifunctional role, in contrast to feedlot-based systems. Sown tropical forages are mostly selections from undomesticated grass and legume species but can include genetically-improved varieties. In Latin America and the Caribbean (LAC), cattle are raised largely on sown pastures; in West Africa, cattle typically graze native pastures; in tropical Asia cut-and-carry systems are predominant; and in eastern, central, and southern Africa both grazing native pastures and cut-and-carry systems are common. Monogastrics are fed with a diverse range of materials, particularly by smallholders where locally-produced feed is important.

Sown forages also have a role in many systems to enhance production efficiency and contribute to other functions such as erosion control, soil improvement, restoration of degraded lands, and improving biodiversity.

Livestock are a crucial component of livelihoods and food security of nearly 1 billion people in the developing world, contributing 40% of the global value of agricultural output. Livestock contribute 15% of total food energy, 25% of dietary protein, and some micronutrients that are not available from plants. Globally, four of the five agricultural commodities with the highest economic value are livestock-related; in order of value, these are milk, rice, and meat from cattle, pigs, and poultry. East and Southeast Asia and LAC show the largest increases in consumption of livestock products between 1961 and 2005 (FAO, 2009). Consumption is expected to continue to increase (Delgado et al., 1999; Herrero et al., 2009).

The livestock sector is the largest user of land resources, employing 3.4 billion hectares for grazing and 0.5 billion hectares for feed crops (Steinfeld et al., 2006), 30% of the ice-free terrestrial surface, and nearly 80% of all agricultural land. The share of grazing land in the overall land area is higher in developing countries than in developed countries (FAO, 2009).

There are regional differences in the types of mixed crop-livestock systems (FAO, 2009). The temperate regions of Europe, Central Asia and the Americas, and the subhumid regions of tropical Africa, LAC, the Middle East, and parts of Southeast Asia have rainfed mixed-farming systems. Globally, they produce 48% of beef, 53% of milk, and 33% of mutton. Livestock are mostly fed grass, crop residues, and crop by-products (Herrero et al., 2010). Irrigated mixed systems in areas of high population density in East and South Asia provide about one third of the world's pork, mutton, and milk, and one fifth of its beef.

Of the world's total, developing countries produce about 50% of beef, 41% of milk, 72% of mutton, 59% of pork and 53% of poultry. Crop-livestock systems produce 50% of global cereals; on current trends, feed grain may amount to more than 40% of global cereal use by 2050, mainly utilized in industrial pig and poultry production (Herrero et al., 2009, 2010).

The demand for livestock products must be reconciled with the environmental impacts of livestock. The aim should be greater eco-efficiency, i.e., highly productive forage-based systems with a small ecological footprint that are economically sustainable and socially equitable (CIAT, 2009; Keating, 2010). Although tropical agriculture contributes to GHG emissions, it can also mitigate climate change by reducing emissions (abatements) and absorbing GHGs (Rosegrant et al., 2008). In the remainder of this paper, we focus on the role of sown forages in mitigating the contribution of tropical agriculture to climate change.

Productivity, profitability, and environmental impacts of land used for forages are interrelated. The extent of land degradation influences the potential of forages to mitigate climate change, because degradation reduces the potential to sequester carbon and is difficult to reverse (Lal, 2010). Heerink et al. (2001) estimate that 35% of all land in Asia, 45% in South America, 75% in Central America, and 65% in sub-Saharan Africa is in various stages of degradation,[7] largely due to overuse and overgrazing. Globally, 20% of the world's pasture and grasslands are degraded (FAO, 2009), reaching 50% in tropical Brazil (Boddey et al., 2004; Cederberg et al., 2009), up to 60% in Central America (Szott et al., 2000), and as high as 73% in dry areas (UNEP, 2004). Many tropical forages are well adapted to marginal environments (Peters et al., 2001) and have the capacity to reverse degradation and enhance soil fertility (Fisher et al., 1997; Guimarães et al., 2004; Rao et al,. 2004; Amézquita et al., 2007; Ayarza et al., 2007).

Opportunities to Utilize Improved Tropical Forage Options to Reduce Greenhouse Gas Emissions and Mitigate Climate Change

There are five strategies to reduce terrestrial GHG emissions (Scherr and Sthapit, 2009): (1) carbon-rich farming; (2) farming with perennials; (3) climate-friendly livestock systems; (4) conserving and restoring habitats; and (5) restoring watersheds and degraded pastures. Sown tropical forages can contribute directly to all five strategies. In particular, forages mitigate GHG emissions in three ways: (1) by sequestering atmospheric CO_2;[8] (2) by reducing ruminant CH_4 emissions per unit livestock product as compared to a lower quality rangeland/degraded pasture and/or offsetting emissions via carbon sequestration; and (3) by reducing N_2O emissions. We discuss the role of sown forages in influencing the atmospheric concentrations of each of these three important GHGs. Additionally, through their role in intensification of production systems, improved tropical forages can reduce pressure on forests by producing more output from the same unit of land and thus contribute to abating emissions. This, however, requires policies to prevent expansion beyond existing agricultural land and thus protect forests and other natural reserves.

Improving carbon sequestration

Agriculture could offset up to 20% of total global CO_2 emissions (Smith et al., 2008). Eighty-nine percent of the potential climate-change mitigation of agriculture comes from terrestrial carbon sequestration, 9% from CH_4 reduction, and 2% from reduction of N_2O emissions, although this potential has largely been ignored in climate change discussions (Smith et al., 2007a, 2008; Scherr and Sthapit, 2009). Guo and Gifford (2002) analyzed the results from 74 papers on the effects of land-use changes on soil carbon stocks. While soil carbon stocks declined in conversion from pastures to plantations and from forests or pastures to crops, they increased when converting annual crops to plantations, crops to pastures, crops to secondary forest, and, interestingly, forest to pastures (Table 1). Powers et al. (2011) reported increases in soil carbon stock when forest or savanna was converted to pastures (5–12% and 10–22%, respectively).

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[7] We define land degradation as a temporary or permanent lowering of the land's productive capacity.

[8] The term "sequestered" is widely used in the literature. Strictly, unless it is known that the accumulated carbon is held in some recalcitrant form (and usually it is not known) it should not be termed "sequestered". We forego this distinction in this paper and use "sequestered".

Table 1. Effects of land-use change on soil carbon stocks (%), from 74 papers analyzed by Guo and Gifford (2002).

From\To	Pasture	Forest	Plantation	Crops
Pasture		no data	-10	-59
Forest	8		no data	-42
Crop	19	53	18	

Most of the above-ground carbon in vegetation is lost when forests are cleared for pastures but soil carbon stocks are often the same over the long term or can increase substantially (Amézquita et al., 2010). Studies from the tropical rainforest of the Colombian Amazon region indicate that total carbon stocks are highest in native forests, followed by well-managed sown pastures and silvopastoral systems, with degraded pastures and degraded soils lowest (Gobbi et al., 2008; Amézquita et al., 2010). In contrast to annual crops, well-managed pastures maintain a cover of vegetation on the soil, which reduces fluctuations in soil temperature and adds organic matter (Brown and Lugo, 1990). Pastures in areas receiving 2000–3000 mm annual rainfall have a higher potential to sequester carbon than forests under similar climatic conditions (Guo and Gifford, 2002).

Improved management of crops and grassland and restoration of degraded land and organic soils offer the greatest opportunities for mitigation of GHG emissions (Smith et al., 2008). Agriculture in 2030 could potentially offset 5,500–6,000 million metric tons (t) of CO_2 equivalent[9] per year, although lower levels could be economically viable depending on the market prices for carbon. The mitigation potential of improved grassland and cropland management is about 1,350–1,450 million t CO_2 equivalent/year each, which, together with 1,350 million t CO_2 equivalent/year for restoring cultivated organic soils, and 650 million t CO_2 equivalent/year for restoring degraded land, is about 75% of the global biophysical mitigation potential (Smith et al., 2008). Sown forages, through their effects on livestock systems and cropping systems, can contribute to this potential in all of them.

Regionally, Southeast Asia, South America, and East Asia have the highest total mitigation potentials, while South America and Africa have the potential for carbon sequestration from recuperating degraded grasslands (Conant et al., 2001; Conant and Paustian, 2002). Sown pastures of *Brachiaria* grasses have large potential for carbon sequestration in LAC (Thornton and Herrero, 2010), with Central America having particular potential for carbon sequestration because of higher levels of land degradation (Heerinck et al., 2001). Of the overall carbon mitigation potential, 29% will be from pasture land (Lal, 2010).

Forages are also key components of minimum- and no-till cropping systems in Brazil (Landers, 2007) and Colombia (Sanz et al., 2004). Conversion of native grassland to agropastoral systems in the cerrado of Brazil and the llanos of Colombia, with adequate soil and crop management, generates benefits to both agriculture and the environment (Guimarães et al., 2004; Rondón et al., 2006; Fisher, 2009; Subbarao et al., 2009). For example, in contrast to annual crop species, most tropical forages are perennials and provide a permanent soil cover and thus prevent soil surface erosion. The latter is of particular importance as erosion also results in loss of soil organic matter, which is largely oxidized, releasing CO_2 to the atmosphere (Lal, 2010).

Within a given grassland ecosystem, climatic and management-related factors interact to

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[9] Invariably practitioners measure the carbon in soil and vegetation. It is converted to CO_2 equivalent, which is relevant to the atmospheric concentration, by multiplying by 3.67.

influence GHG balance over a specified period of time (Liebig et al., 2010). Management practices that reduce carbon loss and increase carbon sequestration in European grasslands include: (1) avoiding soil tillage and the conversion of grasslands to arable use; (2) moderately intensifying nutrient-poor permanent grasslands; (3) using light grazing instead of heavy grazing; (4) increasing the duration of grass leys; and (5) converting grass leys to grass–legume mixtures or to permanent grasslands (Soussana et al., 2010). The mitigation potential of tropical forage plants is favored by prostrate growth habits (e.g., *Brachiaria humidicola, Arachis pintoi*) but a precondition is proper pasture management. Optimal grazing management can enhance accrual of soil carbon (Guo and Gifford, 2002), highlighting the importance of grassland productivity in carbon sequestration. Sown tropical forages can sequester large amounts of carbon in soil, particularly in the deeper layers (Fisher et al., 1994, 1997, 2007; Rao, 1998). The potential of sown forages under adequate pasture and animal management to sequester carbon is second only to forest (Fisher et al., 2007; Fisher, 2009). Soil organic carbon (SOC) levels under the Colombian Llanos are as high as 268 t carbon/ha in the top 80 cm of soil under a *B. humidicola–Arachis pintoi* pasture, with 75% of the carbon found below 20 cm (Fisher et al., 1994).

Compared with the native savanna, a sown grass pasture sequestered an additional 26 t carbon/ha in 5 years, increasing 2.7-fold with an associated legume (Fisher et al., 1994). Unlike the carbon accumulated in most other systems, which is rarely deeper than 20 cm, carbon accumulated in the deeper soil layers is likely to have long residence times, even if it is not truly sequestered (i.e., it is not physically protected or chemically inert). It is also likely to be unaffected in any cropping phase that there might be in mixed crop–pasture systems (Fisher et al., 1994). Pasture in Bahia, Brazil, sequestered half as much carbon as the Colombian Llanos, probably due to seasonally lower temperatures that limit net primary productivity (Fisher et al., 2007). It should be noted, however, that there is discussion in the literature on the potential of carbon sequestration of pastures and the interactions with a particular environment and intensity of degradation (e.g., Conant et al., 2001; da Silva et al., 2004).

Globally, agroforestry systems show lower potential for carbon sequestration than do croplands under improved management, grazing land and livestock, and restoration of degraded lands (Smith et al., 2008). Above-ground carbon stock is usually higher in land-use systems that include trees, however, and planting trees may also increase soil carbon sequestration (Smith et al., 2007b). We suggest that the inclusion of trees in agroforestry and agrosilvopastoral systems could further enhance the overall efficiency of crop–livestock systems (Fujisaka et al., 1998; see also Chapter 4 of this volume).

It is expensive to measure carbon sequestration in soil with the current methods of soil sampling, hence simple indicators (proxies) are needed to allow for transparent consolidation over larger areas (Fisher, 2009). FAO has developed an ex-ante carbon calculator (Bernoux et al., 2010; FAO, 2010b), which shows promise. The carbon calculator assumes that renovated pastures would increase soil carbon stock by 17% in natural pastures, 21% in moderately degraded pastures, and 67% in severely degraded pastures. Based on this, and assuming that there are 78 million hectares of moderately degraded sown pastures in Brazil, renovating them with improved and highly productive sown forages would sequester on average 146 million t CO_2 equivalent/year over a period of 14 years (S. Graefe and G. Hyman, unpublished data). This is equivalent to 18.6 years of current emissions of diesel vehicles in Brazil.

Reducing methane emissions

Emissions of CH_4 from enteric fermentation in ruminants account for 25% of GHG emissions from livestock (Thornton and Herrero, 2010) (Table 2), and is the largest single-source agricultural emission. Although there are differences among regions and production systems (Herrero et al., 2008), increasing animal productivity per unit of CH_4 emitted can be a viable strategy for reducing GHG emissions from livestock production. Diets with high digestibility and high energy and high protein concentrations

Table 2. Methane production according to pasture type and product in grassland-based humid–subhumid systems in tropical Central and South America.

Option	kg CH_4/t milk	kg CH_4/t meat
Native grassland (cerrado)	78	1,552
100% adoption† of *Brachiaria* pasture	31	713
30% adoption† of *Brachiaria* pasture	64	1,300

† "Adoption" refers to the proportion of total milk and meat production in 2030 from implementing the option analyzed.

SOURCE: Adapted from Thornton and Herrero (2010).

produce less CH_4 per unit of livestock product. Improving these characteristics in forages could reduce CH_4 emissions from beef production by 15–30% (Gurian-Sherman, 2011). Legumes contain less structural carbohydrates and more condensed tannins than does grass, and adding legumes to the diet can further reduce CH_4 emissions per unit of meat or milk produced (Woodward et al., 2004; Waghorn and Clark 2004). In addition to reducing GHG emissions, intensification of animal production using high-yielding sown forages requires fewer animals for the same output, and reduces pressure on land and water resources if managed appropriately (LivestockPlus). Feeding crop residues and by-products is also an option to reduce GHG. The use of this highly digestible crop "waste" has a greater impact on both CH_4 and CO_2 emissions than grain supplements (Thornton and Herrero, 2010). Integrating tropical forages with crops can enhance soil fertility as well as the quality and quantity of crop residues, giving higher system efficiency (Ayarza et al., 2007). There are trade-offs between crop and livestock production, however, such as using forages either as animal feed or as green manure (Douxchamps et al., 2012).

Emissions of CH_4 can be reduced by dietary additives (Smith et al., 2008), including oils (Henry and Eckard, 2009), feeding silage instead of hay (Benchaar et al., 2001), and by manipulating the rumen flora (Henry and Eckard, 2009). While legumes can help to reduce GHG production, there are trade-offs. Condensed tannins from legumes can reduce CH_4 production in ruminants (Woodward et al., 2001), but they often also reduce animal performance mostly by reducing feed digestibility (Woodward et al., 2001; Waghorn et al., 2002; Tavendale et al., 2005; Tiemann et al., 2008). Condensed tannins in tropical legumes are highly reactive and are variable in quantity and quality, which remains a challenge to their use to reduce CH_4 production by ruminants. If a tropical species with the typically good agronomic performance on poor soils of tanniniferous shrub legumes, combined with a reduction of ruminal CH_4 production without inhibiting forage digestibility and protein availability (as found for some temperate Lotus species), were to be identified, it could have large beneficial impact on climate-friendly livestock production.

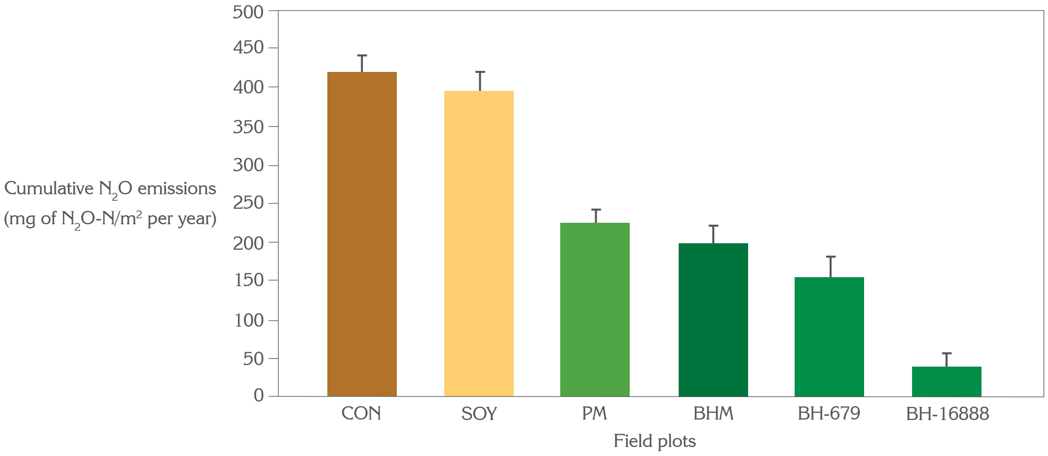
While tropospheric OH (hydroxyl radical) is the largest sink, aerobic soils are the second largest global sink for tropospheric CH_4, removing methane equal to 10–15% of global emissions (Reeburgh et al., 1993; IPCC, 1995). In a comparison of arable land with woodland and grassland, the methane oxidation rate of grassland was about 10 times that of arable land and equal to that of woodland in temperate conditions (Willison et al., 1997). Especially during the dry season, abandoned tropical pastures are strong sinks of CH_4, consuming even more than secondary and some primary forests. This general ability depends largely on grazing management and is inhibited, for example, if gas diffusion is restricted by soil compaction through trampling (Mosier et al., 2004), so that the potential of pastures as CH_4 sinks must take account of the livestock production system under consideration.

Reducing nitrous oxide emissions

Nitrification is a key process in the global nitrogen cycle. It generates nitrate through microbial activity and is primarily responsible for the loss of soil and applied nitrogen via leaching and denitrification (Subbarao et al., 2006). In agricultural systems, N_2O is generated largely from nitrification and denitrification processes (Bremner and Blackmer, 1978). Nearly 17 million t of nitrogen is currently emitted to the atmosphere as N_2O each year (Galloway et al., 2008; Schlesinger, 2009). By 2100, global N_2O emissions are projected to be four times the current level, due largely to increasing use of nitrogen fertilizers (Galloway et al., 2008; Burney et al., 2010; Kahrl et al., 2010). Up to 70% of the nitrogen applied as fertilizer in intensive cereal-production systems is lost following rapid nitrification (Raun and Johnson, 1999). Controlling nitrification in agricultural systems is thus critical to reduce both N_2O emissions and nitrate contamination of water bodies (Subbarao et al., 2012).

Tropical forages, in particular *Brachiaria* spp., suppress activity of nitrifying bacteria by releasing inhibitors from roots and therefore reduce soil nitrification (Sylvester-Bradley et al., 1988; Subbarao et al., 2009) in a process called biological nitrification inhibition (BNI) (Subbarao et al., 2007, 2009). There is a wide range in the BNI ability of the root systems of tropical forage grasses and cereal and legume crops (Subbarao et al., 2007). *Brachiaria humidicola* and *B. decumbens*, both of which are well adapted to the low-nitrogen soils of South American savannas (Miles et al., 2004), showed the greatest BNI-capacity among the tropical grasses tested (Subbarao et al., 2007). In contrast, the major cereals (rice, wheat, and maize) have little BNI capacity (Subbarao et al., 2007). The major nitrification inhibitor in *Brachiaria* forage grasses is brachialactone, a cyclic diterpene (Subbarao et al., 2009).

Brachiaria humidicola also has substantial genotypic variation for BNI. The ongoing *Brachiaria* breeding program at the International Center for Tropical Agriculture (CIAT, its Spanish acronym), conducted in collaboration with the Japan International Research Center for Agricultural Sciences, plans to identify genetic markers associated with BNI ability in crosses between apomictic and sexual accessions of *B. humidicola*. Field studies at CIAT (Palmira, Colombia), on a Mollisol, indicated a 90% decrease in the oxidation rates of soil NH_4^+ in *B. humidicola* plots, largely due to low nitrifier populations. N_2O emissions were also suppressed by more than 90% in field plots with *B. humidicola* compared with the emissions from plots planted to soybean, which lacks BNI ability (Figure 2). Grasses with greater BNI ability in their roots emitted proportionally less N_2O in a field experiment over 3 years (Subbarao et al., 2009).



CON: control (plant-free) plots; SOY: soybean; PM: *Panicum maximum;* BHM: *Brachiaria* hybrid cv. Mulato; BH-679: *B. humidicola* CIAT 679 (standard cultivar); BH-16888: *B. humidicola* CIAT 16888 (a germplasm accession). Values are means ± SE from three replications.

Figure 2. Cumulative N_2O emissions (mg of N_2O-nitrogen/m^2 per year) from field plots of tropical pasture grasses monitored monthly over a 3-year period, from September 2004 to November 2007.

SOURCE: Adapted from Subbarao et al. (2009).

Tropical forage grasses with high BNI ability and perennial growth habit favor the accumulation of sufficient inhibitors to suppress soil bacterial nitrifier activity. The pasture component in an agropastoral rotational system could provide the required BNI-activity to improve the nitrogen-economy of annual crops that follow the pasture phase. For example, *Brachiaria* pastures that have high BNI ability could be rotated with annual crops such as maize or upland rice, which have low or very low BNI ability but receive substantial nitrogen fertilizer. The inhibitors accumulated in the soil in the pasture phase would increase the recovery of applied fertilizer nitrogen, which could lead to improvement in the overall nitrogen economy of the system (Subbarao et al., 2012).

Potential differences in N_2O emissions exist among plant species in general and among pasture plants in particular (Subbarao et al., 2009). These differences are not considered by the Intergovernmental Panel on Climate Change (IPCC) in their estimates of projected N_2O emissions from agricultural systems (Stehfest and Bouwman, 2006). For example, there are more than 250 million hectares of South American savannas occupied by native grasses or by sown grasses such as *Brachiaria* spp. (Fisher et al., 1994) that have moderate to high BNI ability; these areas emit markedly lower amounts of N_2O than if they were planted to field crops. If a substantial area of these savannas were to be converted to soybean and maize, which lack BNI ability, there would be profound implications for N_2O emissions (Subbarao et al., 2009). The impact of such a conversion could be reduced if an adequate BNI ability were to be incorporated into the system, such as by integrating a high-BNI pasture phase into the system (Ayarza et al., 2007). These systems, however, must remain highly productive to meet the ever increasing demands for food from a growing world population, a challenging task for researchers, policy makers, and farmers alike.

Animal urine and manure are also major sources of N_2O. One way in which N_2O emissions from urine may be reduced is by increasing the content of hippuric acid in the urine, as demonstrated in laboratory trials (Bertram et al., 2009). The effect could not, however, be replicated in the field (Clough et al., 2009). Phenolic compounds of tropical forages can cause a shift in the nitrogen excretion in urine towards hippuric acid (Lowry et al., 1993). Grazing management may also affect N_2O emissions from pasture; for example, in Inner-Mongolia, increasing stocking rates of sheep reduced N_2O emissions compared with those from ungrazed pasture (Wolf et al., 2010). However, there are no comparable data from the tropics, an obvious research gap.

Reciprocity of CH_4 and NO, N_2O, and NO_x release and decomposition

Microbes such as methanogenic archeae, methanotrophs, nitrifiers, and denitrifiers are important in both the formation and the oxidation of GHGs in natural and agricultural systems. These microbes interact closely, especially in the soil, and possibly also in the rumen (Mitsumori et al., 2002; Kajikawa et al., 2003). It is therefore possible that nitrification inhibition might also inhibit the desirable oxidation of methane in soils (Bronson and Mosier, 1994); as demonstrated by Yue et al. (2005). A possible explanation is that some methanotrophs produce nitrous oxide (Lee et al., 2009) through various biochemical pathways (Powlson et al., 1997). Because of the radiative forcing difference between CH_4 and N_2O (Forster et al., 2007), reciprocal effects should always be considered and studied in a holistic mitigation concept.

Land-use Change and Leakage

Land-use change and leakage (i.e., the effects of reducing an activity in one location but increasing it in another) affect the contribution of agriculture to GHG emissions and strategies are needed to mitigate these. Wassenaar et al. (2007), using a novel approach to project the spatial trends of deforestation for the neotropics from 2000 to 2010, concluded that livestock production causes deforestation, since it is the main land use after clearing the forest. They also concluded that livestock production is to some extent responsible for the expansion of cropland into forest. Using the Amazon region as an example, however, the intensification of pastures using sown forages could just as well reduce deforestation by reducing pressure on land through increased efficiency of livestock production (higher livestock output per unit of land). But higher efficiency also increases the productivity of livestock operations, which could prompt further deforestation (White et al., 1999; Kaimowitz and Angelsen, 2008). Pasture establishment is also often used in conjunction with expansion of soybean production (i.e., a pasture phase employed after deforestation, which then is succeeded by soybean cultivation) further increasing pressure on forests (Hecht, 2005). In summary, it is not clear what effect the intensification of livestock production based on improved forages would have on deforestation, and any effects would also depend on policy interventions (e.g., White et al., 1999; Steinfeld and Gerber, 2010).

Life-cycle analysis

Life-cycle analysis (LCA) has been used recently to analyze the implications of system intensification for GHG emissions. To assess the net abatement potential of each strategy, it must be subjected to whole-farm systems modeling and a full LCA, to ensure that a reduction in emissions at one point does not stimulate higher emissions elsewhere in the production system (Eckard et al., 2010). Peters et al. (2010) and Pelletier et al. (2010) have discussed the case for reducing emissions through systems with higher feed-conversion efficiency such as feedlots. Most studies assess emissions only (Cederberg et al., 2009; Gerber et al., 2010; Peters et al., 2010), however, and do not consider the positive effects of mechanisms such as carbon sequestration and BNI from pastures. Similarly, the majority of GHG balances assume equilibrium conditions in SOC in established systems (Pelletier et al., 2010).

Increasing the digestibility of cattle rations by feeding grains and whole-plant silage from maize does mitigate CH_4 emissions, but the loss of SOC and the loss of carbon sequestration potential caused by plowing grassland to grow maize are much larger than the mitigation obtained by feeding more maize (Vellinga and Hoving, 2011). A sensitivity analysis in the USA that compared the total GHG balance in intensified grazing systems, including SOC sequestration, with that of feedlot-finished beef found that pasture-fed beef produced 15% less net GHG (Pelletier et al., 2010). This supports our analysis of the mitigation potential of forages through carbon sequestration outlined above.

Technology options and decision-support tools

Where the positive and negative impacts of technology on land use are closely related, and in view of the global implications (Foley et al., 2005), it is useful that technology options be combined with decision-support tools. The aim is to foster policies with a minimum ecological footprint, such as the conservation of forests (Szott et al., 2000; Neidhardt and Campos Monteros, 2009), to reduce land degradation and to maintain vital ecosystem services. Avoiding land clearance in the Amazon, Central America, and the Caribbean regions could save GHG emissions of 1.8 billion t CO_2 equivalent/year (Vosti et al., 2011). Increasing the eco-efficiency[10] of agriculture in these regions, in which land is often degraded, may have the largest effect on mitigation of GHGs, through the combined effects of avoiding deforestation and realizing the land's mitigation potential.

Financing Schemes Involving Integration of Improved Tropical Forage Options

Options to mitigate agricultural GHGs are cost-competitive with options to mitigate GHGs from other sources such as energy, transportation, and forestry (Smith et al., 2007a). However, these options have not received adequate attention in the climate-change negotiations. Benefit schemes are difficult to implement in terms of accurate

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[10] Eco-efficiency, as explained elsewhere in this volume, includes the economic, social, and environmental components of a particular technology that is within the reach of the less-wealthy, together with policies that enable its users to generate both cash profits and environmental benefits.

measurements of emissions and uptakes, and the definition of appropriate and equitable funding schemes. Curbing deforestation, reforestation, and payments for improved carbon management are among the most promising strategies (Stern, 2006). Important elements in agriculture include management of rice paddy, reduced tillage, perennial land covers, restoration of degraded lands, and improved livestock and manure management (Scherr and Sthapit, 2009; World Bank, 2010). Selecting or breeding a new generation of crops and forages that will reduce GHG emissions is a paradigm shift in agriculture that offers the possibility of securing crop and livestock productivity while at the same time moderating the effect of agriculture on climate change (Kell, 2011; Philippot and Hallin, 2011). The barriers to realizing the mitigation potential of agriculture include: (1) lack of permanence of sequestered carbon; (2) the requirement for additionality, i.e., the net reduction of GHG emissions should be supplemental to ongoing activities; (3) uncertainty, in terms of the complex biological and ecological processes and seasonal/annual variability; and (4) leakage, discussed above (Smith et al., 2007b).

Further biophysical research is needed to assess the mitigation potential of tropical forages in crop–livestock systems (including other interventions such as including trees in the production system, and crop management). This needs to be combined with assessment of economic feasibility of mitigation options and socio-economic modeling to target policy support. Another level of complexity is the assessment of co-benefits, especially win–win situations. For example: (1) Increased SOC enhances soil quality and pasture productivity, which frees other areas for alternative production and conservation, although explicit policy regulation may be needed to avoid negative outcomes such as deforestation; (2) Reduced soil nitrification of sown pastures with high BNI capacity can improve the recovery of applied nitrogen by subsequent cereal crops in agropastoral systems; and (3) Increased below- and above-ground biodiversity has both landscape and sociocultural implications (Smith et al., 2007b; Herrero et al., 2009; Anderson and Gundel, 2011). Linking complementary farming systems in space and time, particularly specialist crop and livestock farms, for nutrient and, to a lesser extent, feed exchanges, also increases eco-efficiency in land management (Wilkins, 2008).

It is expensive to measure soil carbon sequestration and CH_4 and N_2O balances over broad areas. We need tools that allow us to estimate GHG fluxes accurately, supported by cost-effective measurements and modeling techniques (World Bank, 2010). Promising approaches include satellite imaging, combined with airborne light detection and ranging and field plots for carbon assessment (Asner et al., 2010), together with methods such as the FAO *Ex Ante* Appraisal Carbon-balance Tool (EX-ACT) (Bernoux et al., 2010; Branca and Medeiros, 2010), but they need further development before they can be applied widely. We also need methodologies to assess the opportunity costs of land-use change for smallholders to evaluate the impacts of management options on both livelihoods and the environment (White and Minang, 2010). The global climate change community has not yet broadly addressed N_2O emissions, but they need to be included in the future in schemes to mitigate GHG emissions (Smith et al., 2007b).

Because of their national, regional, and global mitigation potential, all forage-based systems (grasslands and pastures as well as forage production on croplands) should be included as potential components in negotiations of GHG emissions. If the mitigation potential of agriculture is to be realized, it should be included in schemes such as reducing emissions from deforestation and degradation (REDD), the clean development mechanism (CDM), and expanded REDD schemes such as carbon in agriculture, forestry, and other land uses. If the cost of establishing forage-based systems and agroforestry systems, for instance, could be met through payment for environmental services (PES) via REDD program financing, we could anticipate a triple-win situation combining social, economic, and environmental benefits. Direct-cost recovery with minimum time lags in the payment scheme is a critical requirement for smallholders with limited resources and in risky production environments (World Bank, 2010).

Market differentiation and price premiums would be feasible by combining direct payment with certification for climate-smart forage-based systems such as livestock and crop production based on improved forages and better utilization of crop residues. If so, higher returns to smallholder farmers would be possible, providing both improved equity and mitigation of GHG emissions. It is essential, however, that national agricultural policies are aligned with global environmental objectives (Steinfeld and Gerber, 2010).

Conclusions and the Way Forward

Livestock production is a large source of GHG emissions, and reducing meat consumption or changing from ruminant to non-ruminant meat could have a number of environmental benefits (Stehfest et al., 2009; Wirsenius et al., 2010). However, in many publications analysis is restricted to the emissions from livestock production without mentioning compensating factors such as potential for carbon sequestration and reducing N_2O emissions. For example, Wirsenius et al. (2010) suggest substituting beef with pork and poultry, due to their higher feed conversion efficiency. We argue, however, that comparing GHG emissions from livestock production in the tropics with other systems must be based on LCA analysis and that the potential contribution of forages to mitigation must be taken into account. Assessments of grain-based feedlots must account for the whole GHG cost of the feed supplied and take into account that forages are often produced on land less suitable for crop production (Schultze-Kraft and Peters, 1997; Peters et al., 2001). As we describe here, improved grassland management and intensification of forage-based systems (through improved resource-use efficiency, improved carbon sequestration, and reduced emissions due to BNI) are key to mitigating GHG emissions from livestock production, and will deliver other co-benefits such as resource conservation, reduced costs, and social and cultural benefits.

Due to the importance of forage-based systems, including feed production on cropland, we argue that the international community should give much greater attention to systems based on sown forages. At least 70% of agricultural land is covered by these systems and they impact GHG emissions, resource-use efficiency, and resource degradation. Sown forages have substantial potential for carbon sequestration and for reducing CH_4 and N_2O emissions per unit livestock produced. Because of their multipurpose role (feed, green manure, soil improvement, erosion control, and biodiversity), sown-forage-based systems may be among the most promising means of mitigating the impacts of agriculture on GHG emissions (Smith et al., 2008). We estimate that sown forages alone could contribute 60–80% of the total potential carbon sequestration on agricultural lands through their contribution to the management of crop and grazing land and to the restoration of degraded lands and cultivated organic soils. IPCC (2007) reports that improving management of grazing land has the greatest mitigation potential of all agricultural interventions, over 1.5 billion t CO_2 equivalent/year, sufficient to offset all the emissions from livestock production. In view of the extent of pasture areas and the dominance of crop–livestock systems in land use, we suggest that no strategy for mitigating global climate change can be comprehensive or successful if it fails to recognize the importance of forage-based systems. Sown forages can also be integrated into agroforestry systems to enhance their eco-efficiency, not only to mitigate GHG emissions but to optimize resource use equitably and profitably.

Reduced consumption of animal products may be desirable in rich countries, but from a nutritional and sociocultural standpoint is probably not an option for countries where consumption is currently low (Herrero et al., 2009; Steinfeld and Gerber, 2010; Anderson and Gundel, 2011). Failing to take advantage of the mitigation potential of sown forages may leave 50–80% of the mitigation potential of agriculture untapped. It is therefore essential to: (1) further increase knowledge about the quantitative contribution of different processes such as carbon sequestration, BNI, reduced GHG emissions per unit of livestock produced, and co-benefits in terms resource use efficiency (e.g., land, water, and nutrients);
(2) refine comprehensive assessment of complex systems by using approaches such as LCA;
(3) integrate these results into more manageable

monitoring systems using proxies (parameters representative of the actual situation that can be collected at relatively low financial and time cost to allow for regular revisions); (4) develop policy and financial incentives for livestock and crop producers via direct PES, e.g., to enhance efficiency of crop–livestock systems through prefinancing planting of improved forages and establishing agroforestry systems; and (5) provide additional market incentives for producers/farming communities through certification of climate- and resource-friendly livestock production.

The majority of GHG emissions originate in the 151 non-Annex 1 countries (less industrialized countries without binding Kyoto Protocol obligations to reduce emissions) where growth of livestock production is expected to be particularly high (Gerber et al., 2010). It is essential to develop a climate-policy framework that provides incentives for these countries to participate (Gerber et al., 2010; Anderson and Gundel, 2011). To address issues of leakage, incentives need to be accompanied by policy regulations to avoid deforestation and conversion of fragile lands into croplands.

Further research to enhance eco-efficiency of agricultural systems should focus on the following actions to realize the potential of sown tropical forages to mitigate GHG emissions:

- Conduct long-term field experiments and rigorous data collection combined with simulation modeling for rainfed smallholder agricultural systems with a particular emphasis on crop–livestock systems to assess the potential of tropical forage options for reducing GHG emissions.
- Continue research to quantify further the carbon sequestration effects of agropastoral systems such as crop–pasture rotations, as there is very limited information on synergies between the crop and livestock components.
- Conduct full LCAs that include CO_2, CH_4, and N_2O emissions in various target regions to define better the role of sown tropical forage plants (grasses and legumes) in improving eco-efficiency of crop–livestock systems and mitigation of GHG emissions.
- Develop new approaches to integrating sown forages to achieve eco-efficiency in smallholder agriculture in the tropics, e.g., through enhancing capacity building and their inclusion in schemes for payment for environmental services, possibly linked to access to credit and certification of climate-friendly livestock production.
- Breed tropical grasses for increased BNI to reduce N_2O emissions, while at the same time exploring the best ways to exploit BNI.
- Assess the importance of microbial interactions on reciprocity of GHG emissions.
- Assess the impacts on GHG emissions of pasture management and changes in ruminant nitrogen excretions resulting from changes in forage sources.
- Investigate the potential of tropical forage legumes to (1) supply nitrogen to grass and to improve carbon accumulation in deep soil layers, and (2) contribute, via legume-specific chemical compounds such as tannins, to reduced CH_4 production by ruminants.

In summary, we consider that well-managed tropical forage-based systems can contribute not only to improved livelihoods of the rural poor in the tropics, but also to the overall quality of the environment. With a global community increasingly cognizant of the environmental implications of agriculture, forage-based systems should figure prominently in future innovative agricultural systems. We hope that this paper stimulates intensive discussion that leads to further investment from donors for research on improving eco-efficiency of forage-based livestock production in the tropics.

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