Challenges and opportunities for improving eco-efficiency of tropical forage-based systems to mitigate greenhouse gas emissions

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Abstract. Forage-based livestock production plays a key role in national and regional economies, for food security and poverty alleviation. Livestock production is also considered as a major contributor to agricultural GHG emissions, however. While demand for livestock products is predicted to continue to increase, there is political and societal pressure both to reduce environmental impacts and to convert some of the pasture area to alternative uses such as crop production and environmental conservation. Thus it is essential to develop approaches for sustainable intensification of livestock systems to mitigate GHG emissions, addressing biophysical, socioeconomic and policy challenges. This paper highlights the potential of improved tropical forages in crop-livestock systems, and linked with policy incentives, to enhance livestock production while reducing its environmental footprint. We give examples for sustainable intensification to mitigate GHG emissions based on improved forages in Brazil and Colombia and suggest future perspectives.

Keywords: Climate change, environmental services, environmental footprint, crop-livestock, tropical grasslands

Global importance of forage-based crop-livestock systems and the challenge to improve eco-efficiency

Livestock play a central role for global food systems and thus for food security. Livestock account for 40% of global agricultural gross domestic product and at least 600 million of the world's poor depend on income from livestock (Thornton *et al*. 2002). Livestock products supply one-third of humanity's protein intake, causing obesity for some while remedying undernourishment of others (Steinfeld *et al*. 2006). Livestock products are key in the context of global biomass production and consumption systems. Nearly one-third of the global human appropriation of net primary production (HANPP) occurs on grazing lands (Haberl *et al*. 2007). Livestock consumed nearly two-thirds of global biomass harvest from grazing lands and cropland in the year 2000 (Krausmann *et al*. 2008). Forage grass is the most consumed feed in the world (2.3 G t in 2000), representing 48% of all biomass consumed by livestock; of this, 1.1 G t are used in mixed systems and 0.6 G t in grazing-only systems (Herrero *et al*. 2013a). Grazing lands are by far the largest single land-use type, estimated to extend over 34–45 M km² (Lambin and Meyfroidt 2011). A wide range of ecosystems are grazed, from intensively managed pastures to savannas and semi-deserts. Additionally, a substantial share of crop production is fed to livestock. In the year 2000, of the total of 15.2 M km² cropland, approximately 3.5 M km² provided feed for livestock. Thus feed production for livestock uses about 84% of world's agricultural land (Table 1; Foley *et al*. 2011). The share is even higher in developing countries (FAO 2009).

Livestock production is a major contributor to greenhouse gas (GHG) emissions. Figure 1 shows the spatial distribution of GHG emission intensities by livestock (Herrero *et al*. 2013a). Sub-Saharan Africa (SSA) is the global hotspot of high emission intensities due to low

Table 1. Global land use.

Land use class		Land use (ice-free) in 2000 M km²	%	Source and remarks
a	Urban & infrastructure	1.4	1.1	Erb *et al.* 2007
b	Forests under use	35.0	26.8	Erb *et al.* 2007
c	Remote, wilderness (productive)	15.8	12.1	Erb *et al.* 2007
d	Non-productive	16.2	12.4	Erb *et al.* 2007
e	Cropland	15.2	11.6	FAO 2011a; Erb *et al.* 2007
f	- fodder crops	1.4	1.1	Monfreda *et al.* 2008
g	- used as feedstuff	3.9	3.0	Kastner *et al.* 2012
h	Permanent pastures	34.1	26.1	FAO 2011b
i*	Other land, maybe grazed	12.8	9.8	Difference between FAO 2011b and Erb *et al.* 2007
Agricultural land (e+h+i)		62.1	47.6	
Total ice-free (a+b+c+d+e+h+i)		130.5	100.0	
Livestock feeding (f+g+h+i)		52.2	40.0	of ice-free land
			84.1	of land used for agriculture (e+h+i)

* The productive land that is not used for forestry, cropping, urban, but also not remote or wild, minus the land used as permanent pastures (Erb *et al.* 2007).

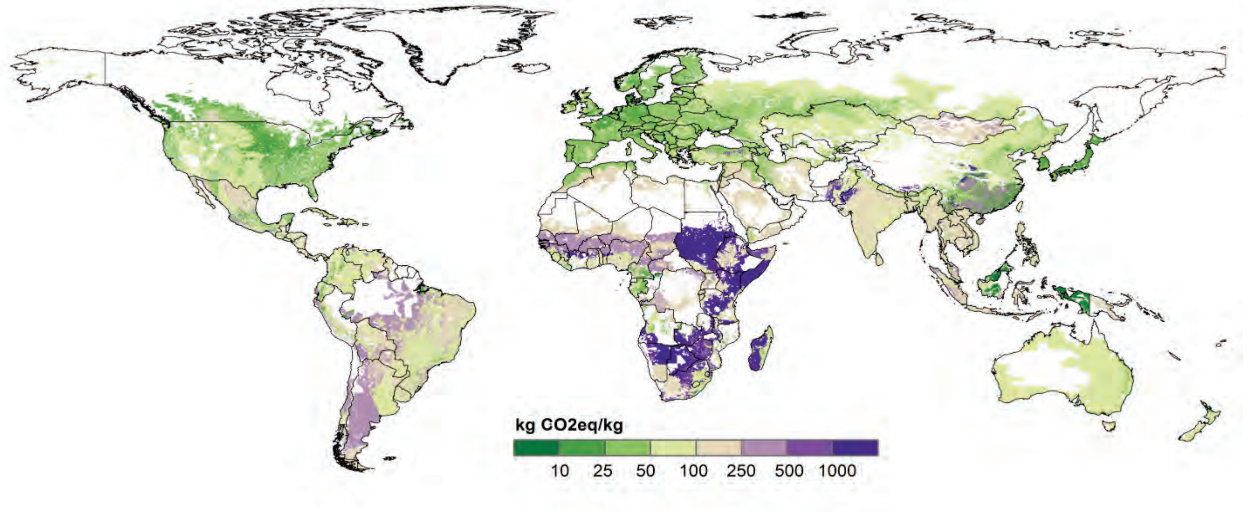

Figure 1. Global greenhouse gas efficiency per kilogram of animal protein produced (Herrero *et al.* 2013a).

animal productivity across large areas of arid lands where feed is scarce and of low quality and animals have low productive potential. Moreover, most ruminants in SSA are raised for meat, and meat production is associated with lower feed efficiency and higher emission intensities compared with milk production, by a factor of 5 or more (Herrero *et al*. 2013a). Moderate emission intensities occur throughout the developing world, in arid regions with large rangeland areas, in places with important beef production (Amazonia), and in places where diet intensification in ruminants is low (large parts of South Asia). In most of the developed world, emission intensities are low, due to more intensive feeding practices, feed conversion-efficient breeds of livestock, and temperate climates where feed quality is inherently higher.

Livestock emit 14-18% of global non-CO_2 GHG emissions (Herrero *et al.* 2011). An additional 17% of emissions are attributed to land-use changes related to agriculture and deforestation for grazing (IPCC 2007). Expansion of livestock production is often considered a major driver of deforestation, especially in Latin America, with impacts on biodiversity and the global climate system (Szott *et al.* 2000), although the causal relationships are debated (Kaimowitz and Angelsen 2008). Moreover, overgrazing is claimed a central force of land degradation, in particular with respect to erosion and soil organic carbon (C) stocks (Vågen and Winowiecki 2013). In low-income countries, the contribution of agriculture to overall country GHG emissions (as a % of total emissions) is considered to be even greater, with 20% and 50% attributed to agriculture and land-use changes, respectively (The World Bank 2010).

We can expect much more intensification and industrialisation in animal production systems in the near to midterm future (Delgado *et al.* 1999; Haan *et al.* 2010) as extensive and pasture-based systems move towards mixed crop-livestock systems (Herrero *et al*. 2012). Havlik *et al.* (2013) found that this transition could allow for mitigating GHG emissions without compromising food security. Reduced methane (CH_4) production can result from land sparing effects (less area needed to produce feed) and input-output efficiency gains allow reducing the number of animals required for the same production. Almost landless, grain-fed livestock systems have economic advantages in terms of production rates and scale effects, but can potentially lead to competition of land use for direct food production (Smith *et al.* 2010, Erb *et al.* 2012). Extensive grazing systems that collectively occupy large areas of land, much of it degraded due to mismanagement and soil mining, may gradually transform giving enhanced efficiency in the use of resources and land. Possible transformations include switching to monogastric species, improved breeds, and changing from roughage-based diets to high-concentrate feedstuffs from cropland.

The global concentrate-feed market is 1 Gt DM/yr, compared with 5.4 Gt DM/yr of roughage. Market feed, such as oil cakes and cereals, is essential for monogastrics and is also important in ruminant livestock systems, particularly when they are industrialised. However, ruminants can digest biomass unsuitable for human food (Erb *et al.* 2012). Comparing the environmental footprint of systems requires not only analysis of their direct GHG emissions but the environmental costs of feed production. For example, transport accounts for 11–12% of GHG emissions from feedlots in Europe feeding soybean produced in Brazil (Garnett 2011), compared with feed produced near feedlots in midwestern USA (Pelletier *et al*. 2010). Furthermore, the potential to mitigate climate change and other environmental benefits of forage-based systems (see following sections) are often not considered.

Opportunities through forage-based systems to reduce GHG emissions

Reducing agriculture's GHG emissions and increasing C stocks in the soil and biomass could reduce global GHG emissions by 5.5-5.9 giga tons of CO_2 equivalent (Gt CO_2eq)/yr (Olander *et al.* 2013). In 2000, non-CO_2 emissions from livestock systems ranged between 2.0 and 3.6 Gt CO_2eq (Herrero *et al.* 2013b). These are expected to increase by 70% by 2050. Forage-based systems can mitigate GHG emissions by (1) increasing C stocks; (2) reducing CH_4 emissions per unit of livestock product and net CH_4 emissions by reducing animal numbers; and (3) reducing nitrous oxide (N_2O) emissions (Peters *et al*. 2013).

Improving carbon accumulation.

In a meta-analysis of studies on the effects of grassland management on soil C stocks, three-quarters showed increases (mean 0.54 Mg C/ha/yr, n = 167, Conant *et al.* 2001). Summarising 74 papers on land-use change, Guo and Gifford (2002) showed that, compared with forests, pastures in areas with 2000–3000 mm/yr rainfall have a higher potential to accumulate soil C. Land-use change affected soil C stocks, which declined when pastures were converted to tree plantations and when either forests or pastures were converted to crops. In contrast, soil C stocks increased when annual crop land was converted to tree plantations, pastures, or secondary forest. When either forest or savanna was converted to pasture, soil C stocks increased by 5–12% and 10–22%, respectively (Powers *et al.* 2011).When forests are cleared for pastures, most of the aboveground C is lost, but soil C stocks in the long term either remain the same or increase substantially (Amézquita *et al.* 2010). In the Colombian Amazon, total C stocks were highest in native forests, followed by well-managed sown pastures and silvopastoral systems; degraded pastures and degraded soils were lowest (Amézquita *et al.* 2010). In contrast to annual crops, well-managed pastures maintain soil cover, reduce fluctuations in soil temperature and add organic matter (Guo and Gifford 2002).

The main opportunities to mitigate GHG emissions by increasing soil C stocks are: (1) improved management of crops and grasslands; and (2) restoration of degraded lands (Smith *et al.* 2008). Of the overall C-mitigation potential, 29% were claimed to be from pasture land (Lal 2010). In Latin America and the Caribbean (LAC), sown pastures of *Brachiaria* grasses have a high potential to increase soil C stocks (Thornton and Herrero 2010).

Sown tropical forages can accumulate large amounts of C in soil, particularly in the deeper layers (Fisher *et al.* 2007). The potential of sown forages under adequate pasture and animal management to increase C stocks is second only to forest (Mosier *et al.* 2004; Fisher 2009). Pastures in Bahia, Brazil, accumulated only half as much C as those in the Colombian Llanos, probably because lower temperatures limit net primary productivity (Fisher *et al.* 2007). Pastures generally have the capacity to accumulate C, but magnitudes and rates are likely to be site-specific (*e.g*., Conant *et al*. 2001; da Silva *et al.* 2004). The controlling factors are imperfectly understood.

Reducing methane emissions

CH_4 from enteric fermentation in ruminants accounts for 25% of GHG emissions from livestock, or 65% of non-CO_2 emissions (Thornton and Herrero 2010). In terms of CH_4, monogastrics (largely pigs and poultry) produce protein more efficiently than ruminants. The comparison is simplistic, however, by not accounting for the suitability of land only for pasture or feed production, and the nutritional value of the produce beyond protein or the use of by-products (Garnett 2009). Forage diets with high digestibility and high energy and protein concentrations produce less CH_4 per unit of meat or milk produced (Waghorn and Clark 2004; Peters *et al.* 2013). Forages integrated in tropical agropastoral systems provide enhanced soil fertility and more crop residues of higher quality, giving higher system efficiency (Ayarza *et al.* 2007). Use of forages in mixed crop-livestock systems can not only reduce CH_4 emission per unit livestock product but also contribute to overall GHG balance of the system (Douxchamps *et al*. 2012). Dietary additives such as oils to ruminant feed (Henry and Eckard 2009), and feeding silage instead of hay (Benchaar *et al.* 2001), reduce CH_4 emissions by changing the rumen flora (Henry and Eckard 2009). Condensed tannins from some legumes can reduce CH_4 production in ruminants (Woodward *et al.* 2004), but they often reduce feed digestibility leading to lower animal performance (Tiemann *et al.* 2008).

Reducing nitrous oxide emissions.

The soil microbial processes of nitrification and denitrification drive N_2O emissions in agricultural systems. Nitrification generates nitrate (NO_3^-) and is primarily responsible for the loss of soil nitrogen (N) and fertiliser N by both leaching and denitrification (Subbarao *et al.* 2006). Current emissions of N_2O are about 17 Mt N/yr and by 2100 are projected to increase four-fold, largely due to increased use of N fertiliser. Up to 70% of fertiliser N applied in intensive cereal production systems is lost by nitrification (Subbarao *et al.* 2012). If this could be suppressed, both N_2O emissions and NO_3^- contamination of water bodies could be reduced substantially. Some plants release biological nitrification inhibitors (BNIs) from their roots, which suppress nitrifier activity and reduce soil nitrification and N_2O emission (Subbarao *et al.* 2012). This biological nitrification inhibition (BNI) is triggered by ammonium (NH_4^+) in the rhizosphere. The release of the BNIs is directed at the soil microsites where NH_4^+ is present and the nitrifier population is concentrated. Tropical forage grasses, cereals, and crop legumes show a wide range in BNI ability. The tropical *Brachiaria* spp. have high BNI capacity, particularly *B. humidicola* and *B. decumbens* (Subbarao *et al.* 2007). *Brachiaria* pastures can suppress N_2O emissions and carrying over their BNI activity to a subsequent crop might improve the crop's N economy, especially when substantial amounts of N fertiliser are applied (Subbarao *et al.* 2012). This exciting possibility is currently being researched and could lead to economically profitable and ecologically sustainable cropping systems with low nitrification and low N_2O emissions.

The Intergovernmental Panel on Climate Change (IPCC) (Stehfest and Bouwman 2006) did not consider BNI in estimating N_2O emissions from pastures and crops. For example, 300 Mha in the tropical lowlands of South America are savannas with native or sown grasses such as *Brachiaria* spp. that have moderate to high BNI ability. Substantial areas of these savannas have been converted to soybean and maize, which lack BNI ability. Continuing conversion has important implications for N_2O emissions (Subbarao *et al.* 2009), but the impact might be reduced if the system included agropastoral components with a high-BNI pasture phase (Ayarza *et al.* 2007).

Role of silvopastoral systems

Agroforestry is the practice of growing of trees and crops, often with animals, in various combinations for a variety of benefits and services. It is recognised as an integrated approach to sustainable land use (Nair *et al.* 2009). Agroforestry arrangements combining forage plants with shrubs and trees for animal nutrition and complementary uses, are known as silvopastoral systems (SPS) (Murgueitio *et al.* 2011). The main SPS include scattered trees in pastures, live fences, windbreaks, fodder-tree banks for grazing or cut-and-carry, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (ISPS).

The main benefits of SPS compared to treeless pastures are: (1) increased animal production per ha (up to 4-fold) (Murgueitio *et al.* 2011); (2) improvement of soil properties due to increased N input by N-fixing trees, enhanced availability of nutrients from leaf litter and greater uptake and cycling of nutrients from deeper soil layers (Nair *et al.* 2008); (3) enhanced resilience of the soil to degradation, nutrient loss and climate change (Ibrahim *et al.* 2010); (4) higher C storage in both aboveground and belowground compartments of the system (Nair *et al.* 2010); and (5) improved habitat quality for biodiversity (Saenz *et al.* 2007). ISPS are a form of SPS that combine: (1) the high-density cultivation of fodder shrubs (more than 8000 plants per ha) for grazing with (2) improved tropical grasses, and (3) trees or palms at densities 100–600 per ha (Calle *et al.* 2012). In the 1970s, Australian graziers started sowing *Leucaena leucocephala* at high density integrated with grasses for grazing by cattle. There were about 150,000 ha of this highly productive system in 2006 (Shelton and Dalzell 2007). In Latin America, ISPS are being adopted in Colombia, Mexico, Brazil and Panama (Murgueitio *et al.* 2011).

Due to the positive interactions between grasses and trees (in particular N-fixing trees), SPS produce more DM, digestible energy and crude protein (CP) per ha and increase the production of milk or meat while reducing the need for chemical fertilisers. For SPS, the aboveground C accumulation potential ranges from 1.5 Mg/ha/yr (Ibrahim *et al.* 2010) to 6.55 Mg/ha/yr (Kumar *et al.* 1998), depending on site and soil characteristics, the species involved, stand age, and management practices (Nair *et al.* 2010).

Animals fed with tropical legumes produced 20% less CH_4 than those fed with C4 grasses (Archimède *et al.* 2011). Thornton and Herrero (2010) estimated that by replacing some concentrates and part of the basal diet with leaves of *L. leucocephala*, the GHG emissions per unit of milk and meat produced were 43% and 27% of the emissions without the legume. The mitigation potential was 32.9 Mt CO_2eq over 20 years, 28% coming from the reduction in livestock numbers, and 72% from C accumulation.

Despite their on- and off-farm benefits, SPS are not widely established in the tropics and subtropics. The main barriers to adoption are financial capital barriers as SPS require high initial investment, which defies the prevailing view of tropical cattle ranching as a low-investment activity, and knowledge barriers as the technical complexity of some SPS requires specialised knowledge, which farmers often do not have (Murgueitio *et al.* 2011).

Economic analysis and environmental and policy implications

Adoption of improved forage-based livestock systems

Each of the principal forage-based livestock system alternatives has its environmental costs, benefits and impacts (Table 2). Some of these systems have been shown to reduce GHG emissions while improving productivity (Fearnside 2002). But the question remains why adoption of improved forage-based crop–livestock systems is low. Their adoption is related to the costs and benefits to the farmer and land, capital, labor and technology barriers, and depends also on a delicate balance between short-term benefits as a direct incentive (often market related and *in situ*) and the long-term, usually environmental and often *ex-situ*, benefits. Thus research on mitigation of climate change by forage-based livestock systems must address the tradeoffs between the livelihood concerns of farmers, market- and value-chain-related incentives, societal, and environmental considerations.

Table 2. Principal forage-based livestock system alternatives: Environmental costs, benefits and impacts.

System/ technology option	Costs and benefits to the farmer			Costs and benefits to society		
	Livelihood benefits	Initial investment	Year-after-year investment	Climate change mitigation impacts	Biodiversity impacts	Hydrological impacts
Native savannas	Limited by low productivity	Usually little initial investment	Usually little or none	Emissions or sequestration depends on stocking rate and pasture degradation	Maintained species biodiversity	Increased runoff and soil erosion when overstocked
Business as usual (improved forage species but subsequent pasture degradation)	Decrease as pastures degrade	Seeds, land preparation, planting, fertiliser; overall large initial investment	Usually very low	Initial reduction in carbon stocks with land clearing, higher biomass of improved pastures	Reduction in species diversity due to monoculture planting	Increased runoff with overstocking; soil erosion
Improved and well-managed pastures	Higher stocking rate and higher animal productivity	Seeds, land preparation, planting, fertiliser; overall large initial investment	Fertiliser	Higher biomass in improved pastures; carbon accumulation in the soil	Reduction in species diversity with monocultures, but could have positive effects on soil fauna	Higher water demand; less runoff
(Agro) Silvopastoral systems	Income from livestock; income in long-term from trees; higher productivity benefits from soil maintenance	Forage and tree seeds, nursery, land preparation, planting, fertiliser, fencing; overall large initial investment	Fertiliser (but reduced when N fixing trees are used)	Carbon stock increased from biomass in trees; carbon accumulation in the soil	Biodiversity benefits from trees	Less runoff, higher regulation of discharge, high water demand

Livelihood considerations for farmers

The nature of livelihood benefits of forage-based systems for reducing GHG emissions and improving productivity depends very much on the context of the farm and the farmer (Table 2). For example, native savanna systems have low productivity, but require very little investment by the rancher. If land is abundant, there may be little incentive to improve these systems (White *et al.* 2001). A common alternative scenario is to replace natural vegetation by introduced ("improved") forages, which can be exploited for many years with little or no annual maintenance. After the initial investment at establishment, this system costs little, but without annual investment in fertiliser these pastures will degrade over time, especially if they are overstocked, leading to pasture and soil degradation and loss of productivity. If the sown pasture is managed with applications of modest amounts of maintenance fertiliser, usually N and P, and with stocking rates that match pasture productivity, pasture systems can maintain productivity and reduce GHG emissions for many decades (Peters *et al.* 2013). More recently, SPS combining trees and forages have received increased attention because of their potential to improve productivity and reduce GHG emissions (Ibrahim *et al*. 2007, see previous section). The initial investments in these systems are substantial, however (see previous section).

Ex-situ *environmental considerations*

While improved forage-based livestock systems can improve productivity and mitigate GHG emissions, *ex-situ* environmental costs and benefits vary widely with respect to GHG emissions and impacts on biodiversity and water (Table 2). Unwise fertiliser use could result in downstream contamination of the watershed. Where farmers introduce improved pasture varieties and subsequently allow the pastures to degrade, C stocks are substantially reduced. Compared to degraded pastures, improved and well-managed systems have many positive benefits for the hydrological cycle, as they promote increased water holding capacity and reduce runoff and soil erosion (Peters *et al.* 2013). Silvopastoral systems improve soil quality, particularly when they involve N-fixing trees, provide shade for livestock, accumulate soil organic carbon (SOC), and through the presence of trees in the system enhance biodiversity compared to monospecific pastures, and reduce runoff and soil erosion as they regulate the hydrological system (see above).

Carbon insetting

There are two types of carbon market; the regulatory compliance and the voluntary markets. The compliance market is used by companies and governments that by law have to account for their GHG emissions. It is regulated by mandatory national, regional or international carbon reduction regimes. The voluntary market trades carbon credits on a voluntary basis. The size of the two markets differs considerably. In 2008, the regulated market traded US$119 billion, while trades on the voluntary market were only US$704 million (Hamilton *et al.* 2009). Carbon insetting refers to any GHG emission reduction/carbon accumulation activity that is linked to the supply chain or direct sphere of influence of the company that acquires or supports the insetting activity. Benefits are therefore directly transferred to actors of the chain including smallholder producers. This can take the form of credit trading or other forms of compensation or support for the insetting activity. Carbon-insets are intended to generate

Table 3. The Low Carbon Agriculture Plan (*Plano ABC*) in Brazil (Brasil 2011).

Action	Target area (M ha)	Associated mitigation (M t CO_2eq)
Recuperation of degraded pasturelands	15	83-104
Integration of crop-livestock forest systems	4.0	18-22
Expansion of no-tillage systems	8.0	16-20
Biological nitrogen fixation	5.5	10

mutual benefit between the partners that are additional to the climate change mitigation itself. On the other hand, carbon offsetting refers to compensation of GHG emissions outside the company's supply chain or sphere of influence lacking additional benefits. For most food products, these GHG mitigation potentials are concentrated at the farm level. Integrating carbon credit purchases into a company's own supply chain, or carbon 'insetting' (*vs.* carbon offsetting), has multiple benefits. For farmers, it will improve animal productivity, increase adaptability to climate change and provide supplementary income. For companies, it will reduce the environmental 'hoofprint' of the livestock sector and enable companies to keep carbon mitigation activities within their own supply chain.

Political considerations for use of integrated crop-livestock systems in Brazil and Colombia

In Brazil and Colombia, as part of national policies, sustainable intensification of pasture/forage based livestock production has been recognised as a means to contribute to mitigate GHG emissions. Improved forages and agro-forestry systems are key strategies in these endeavours. Pathways include both increased C accumulation through reversing pasture degradation and maximising accumulation through tree integration as well as freeing land areas for conservation purposes and other agricultural uses.

Brazil

Brazil is the country with the largest forecast increase in agricultural output until 2050 (Alexandratos and Bruinsma 2012), but in addition to this agricultural expansion the country also aims to reduce deforestation in the Amazon by 80% and in the Cerrado by 50% in relation to historic levels by 2020. The latest estimates indicate that Brazil is on course to reach this target, but there are doubts about the long-term sustainability of recent reductions. A major pathway to reach these two ambitious goals simultaneously is through the sustainable intensification of pasture lands (Strassburg *et al.* 2012). Native and sown pasturelands (189 M ha) comprise about 70% of Brazil´s area under agriculture (including forest plantations). These lands support 212 million cattle (IBGE 2011), offering substantial scope for increasing stocking rates. Improvements are also possible in herd management. For example, Brazil´s slaughter rate of 18% is the lowest among the top 20 beef producing countries. The GHG mitigation potential of improving agriculture, in particular cattle ranching, has been recognised by the Brazilian government through its Low Carbon Agriculture Plan (*Plano ABC*, Table 3). The recuperation of 15 Mha of Brazil´s estimated 40 M ha of degraded pastures would supply two-thirds of planned mitigation activities in the agricultural sector. This estimate does not include the associated reduction in deforestation, which is forecasted to mitigate an additional 669 Mt of CO_2eq. The ABC plan also has a target of increasing planted forests from 6 to 9 M ha and treating animal waste, the latter estimated to mitigate 6.9 M t of CO_2eq.

Colombia

In Colombia there are currently 39.6 M ha of land used for livestock production (34.7% of the Colombian territory), with an average of 0.6 animals/ha, while crops occupy 3.3 M ha (2.9%) (MADR 2011). The agricultural sector in Colombia contributes 7% of the national GDP with livestock production contributing 1.6% (FEDEGAN 2012). Agriculture is responsible for 7.8% of national exports, the livestock sector 0.64% (Mincomercio 2012). The livestock sector is responsible for 17.6% of total national GHG emissions while crops account for 18.9% (IDEAM 2010). The goal of the government is to reduce the area under pastures by almost 10 M ha by 2032 while increasing meat and milk production by 95.4% and 72.6%, respectively (FEDEGAN 2011). Major pathways identified for sustainable intensification of livestock production include reversing pasture degradation, enhancing pasture management, and introducing improved pastures and management systems such as silvopastoral systems as key strategies.

Future perspectives and overall synthesis

The livestock sector is important at the global scale accounting for 40% of agricultural GDP, while at least 600 million of the world's poor depend on income from livestock production. But livestock production is also a large source of GHG, with extensive ruminant systems giving more emissions because they are less efficient in feed conversion than intensive feedlot systems and monogastric systems. Thus shifting meat consumption from ruminant to non-ruminant systems could have environmental benefits (Wirsenius *et al.* 2010). A thorough analysis of the effects of livestock production, however, will need to contrast emissions with compensating factors such as C accumulation and reduction of N_2O emissions, especially in pastures. We argue that the environmental cost of feed production from different livestock systems would need to be analysed through inclusive life-cycle analyses (De Vries and De Boer 2010; Pelletier *et al.* 2010; Thoma *et al.* 2013). For example, assessments of grain-based feedlots must account for the whole GHG cost of the feed supplied and the analysis should also take into account that forages are often produced on land less suitable for crop production (Peters *et al.* 2013).

As described in examples from Brazil and Colombia, sustainable intensification of pasture-based livestock production is being implemented as a major strategy to mitigate GHG impacts and reduce GHG emissions per unit livestock product (Bustamante *et al.* 2012). Thus, sustainable intensification of forage-based systems is critical to mitigate GHG emissions from livestock production, while providing a number of co-benefits including increased productivity, reduced erosion, improved soil quality, and nutrient and water use efficiency. Much wider attention of the international community would need to be given to forage-based livestock systems if a reduction of GHG emissions in agriculture is aspired, considering that more than 70% of agricultural land is covered by these systems. Ignoring the importance of forage-based systems in our view may leave 50 to 80% of the mitigation potential of agriculture untapped (Peters *et al*. 2013). This also needs to be seen in the context of human nutrition. Reduced consumption of animal products may be desirable in rich countries, but from a nutritional and sociocultural standpoint it is probably not an option for countries where consumption is currently low (Anderson and Gundel 2011).

Further research is required both in the biophysical as well as socio-economic fields, to

- Assess in detail the carbon accumulation potential of forage-based systems. There is very limited information on the long-term accumulation potential. Few studies such as by INRA–CIRAD in French Guiana (Blanfort *et al.* 2010) and Corpoica-CIAT in Colombia (G Hyman and A Castro, unpublished) suggest that carbon may accumulate over a longer time span and at a greater soil depth than previously expected. Guianese tropical grasslands are capable, under certain conditions, of compensating partly for the loss of soil C caused by deforestation.
- 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.
- Analyse trade-offs between C accumulation in soil and N_2O emission in grass alone, grass-legume, and grass-legume-tree associations, and determine the role of soil fauna (*e.g*. earthworms) and flora in GHG balance and improvement of soil quality. Use Brazil and Colombia as examples to stimulate policy influencing mitigation of GHG emissions in other tropical countries.
- Estimate the impacts of forage-based systems as either trade-offs or win-win options for productivity, food security and environmental benefits at different scales (from plot to farm to landscape to global), and compare them with alternative scenarios.
- In this context, assess direct economic benefits for farmers through product differentiation of environmentally friendly products (*e.g*. consumers paying premium prices for beef produced at low environmental impact).
- Develop payment-for-ecosystem-services (PES) schemes to stimulate optimisation of pasture management.
- Target forage interventions to different farming systems, from extensive to semi-intensive, identifying entry points for each system.

In summary, there is a need for strategies that allow for reducing GHG emissions through sustainable intensification of forage-based systems to enhance productivity without compromising the ability of ecosystems to regenerate and provide many ecosystem services. We suggest that transformation of forage-based systems directed at these goals through enhancing eco-efficiency is essential for balancing livelihood and environmental benefits.

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