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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, but is considered a major contributor to agricultural GHG emissions. While demand for livestock products is predicted 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, socio-economic and policy challenges.

This paper highlights the potential of improved tropical forages, linked with policy incentives, to enhance livestock production, while reducing its environmental footprint. Emphasis is on crop-livestock systems. We give examples for sustainable intensification to mitigate GHG emissions, based on improved forages in Brazil and Colombia, and suggest future perspectives.

Resumen

La producción ganadera a base de forrajes desempeña un papel clave en las economías nacional y regional en cuanto a seguridad alimentaria y mitigación de la pobreza. No obstante, se considera como un factor importante que contribuye a las emisiones de gases de efecto invernadero (GEI) producidos por la agricultura. Mientras que se prevé que la demanda de productos pecuarios seguirá en aumento, existe presión política y social para no solo reducir los impactos ambientales sino también para convertir parte del área en pasturas a usos alternativos como la producción agrícola y la conservación del medio ambiente. Por tanto, es esencial desarrollar enfoques para la intensificación sostenible de sistemas pecuarios para mitigar las emisiones de GEI, abordando desafíos biofísicos, socioeconómicos y políticos.

En este documento se destaca el potencial de los forrajes tropicales mejorados, junto con incentivos a nivel de políticas, para mejorar la producción pecuaria mientras se reduce su huella ambiental. Se hace énfasis en sistemas mixtos (cultivos-ganadería) y se dan ejemplos de intensificación sostenible para mitigar las emisiones de GEI con base en forrajes mejorados en Brasil y Colombia, y se señalan algunas perspectivas para el futuro.

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

Livestock play a central role in global food systems and thus in food security, accounting for 40% of global agricultural gross domestic product; 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 crucial 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). In the year 2000, livestock consumed nearly two-thirds of global biomass harvest from grazing lands and cropland (Krausmann et al. 2008). Forage grass is the most consumed feed in the world (2.3 Gt in 2000), representing 48% of all biomass consumed by livestock; of this, 1.1 Gt are used in mixed systems and 0.6 Gt 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 Mkm² (Lambin and Meyfroidt 2011). Grazed ecosystems range 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 Mkm² cropland, approximately 3.5 Mkm² provided feed for livestock. Thus, producing feed for livestock uses about 84% of the 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 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.

Herrero et al. (2011) estimate livestock emit 14−18% of global non-CO_2 GHG emissions. An additional 17% of emissions is 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

Table 1. Global land use.

	Land use class	Land use (ice-free) in 2000 (Mkm²)	(%)	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 land	16.2	12.4	Erb et al. 2007
e	Cropland	15.2	11.6	Erb et al. 2007; FAO 2011a
f	- of which fodder crops	1.4	1.1	Monfreda et al. 2008
g	- of which area used for feedstuff production	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)

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

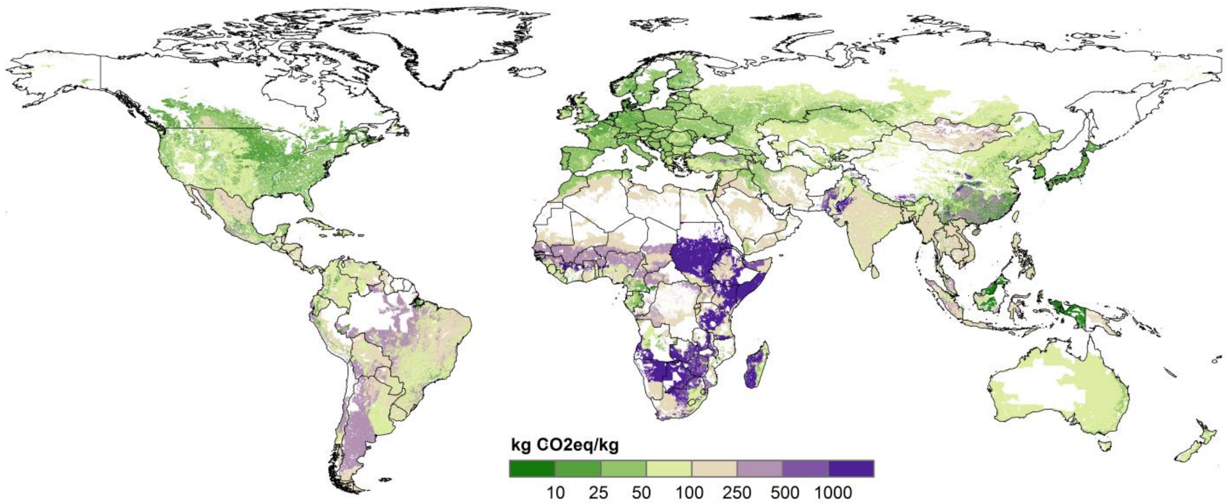

Figure 1. Global greenhouse gas efficiency per kilogram of animal protein produced (Herrero et al. 2013a).

organic carbon (C) stocks (Vågen and Winowiecki 2013). In low-income countries, the contribution of agriculture to overall 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 industrialization in animal production systems in the near to mid-term 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 reduce 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 that reduce 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 in 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 be transformed, giving enhanced efficiency in the use of resources and land. Possible transformations include switching to monogastric species, using improved breeds and changing from roughage-based diets to high-concentrate feedstuffs from cropland.

The global feed market is 1 Gt concentrate DM/yr, and 5.4 Gt roughage DM/yr. Market feed, such as oil cakes and cereals, is essential for monogastrics and is also important in ruminant livestock systems, particularly when they are industrialized. 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 also 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 mid-western 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 Gt CO_2-equivalent/yr (Olander et al. 2013). In 2000, non-CO_2 emissions from livestock systems ranged between 2.0 and 3.6 Gt CO_2-eq (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 t C/ha/yr, n = 167, Conant et al. 2001). Summarizing 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 above-ground 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 with 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: (i) improved management of crops and grasslands; and (ii) restoration of degraded lands (Smith et al. 2008). Of the overall C-mitigation potential, 29% was claimed to be from pasture land (Lal 2010). In Latin America and the Caribbean, 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 limited 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 emissions, 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 plus 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 emissions per unit livestock product but also contribute to the 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 fertilizer 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 fertilizer. Up to 70% of fertilizer 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 fertilizer 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 production of 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 recognized 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 (SPSs) (Murgueitio et al. 2011). The main SPSs 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 (ISPSs).

The main benefits of SPSs compared with treeless pastures are: (i) increased animal production per ha (up to 4-fold) (Murgueitio et al. 2011); (ii) 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); (iii) enhanced resilience of the soil to degradation, nutrient loss and climate change (Ibrahim et al. 2010); (iv) higher C storage in both above-ground and below-ground compartments of the system (Nair et al. 2010); and (v) improved habitat quality for biodiversity (Sáenz et al. 2007). ISPSs are a form of SPSs that combine the high-density cultivation of fodder shrubs (more than 8000 plants per ha) for grazing with: (i) improved tropical grasses; and (ii) trees or palms at densities of 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, ISPSs are being adopted in Colombia, Mexico, Brazil and Panama (Murgueitio et al. 2011).

Owing to the positive interactions between grasses and trees (in particular N-fixing trees), SPSs produce more DM, digestible energy and crude protein (CP) per ha than grass-alone pastures and increase the production of milk or meat, while reducing the need for chemical fertilizers. Tree incorporation in croplands and pastures results in greater net C storage above- and below-ground (Nair et al. 2010). For SPSs, the above-ground C accumulation potential ranges from 1.5 t/ha/yr (Ibrahim et al. 2010) to 6.55 t/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, respectively. The mitigation potential was 32.9 Mt CO_2-eq over 20 years, 28% coming from the reduction in livestock numbers, and 72% from C accumulation.

Despite their on- and off-farm benefits, SPSs are not widely established in the tropics and subtropics. The main barriers to adoption are financial capital barriers as SPSs require high initial investment, which is contrary to the prevailing view of tropical cattle ranching as a low-investment activity, and knowledge barriers, as the technical complexity of some SPSs requires specialized 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). However, 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 trade-offs between the livelihood concerns of farmers, market- and value-chain-

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	On-going 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 sequestrations depend 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)	Higher animal production initially with decrease as pastures degrade	Seeds, land preparation, planting, fertilizer; overall large initial investment	Usually very low	Initial reduction in carbon stocks with land clearing, higher biomass in 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, fertilizer; overall large initial investment	Fertilizer	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, fertilizer, fencing; overall large initial investment	Fertilizer (but reduced when N-fixing trees are used)	Carbon stocks increased from biomass in trees; carbon accumulation in the soil	Biodiversity benefits from trees (not great)	Less runoff, higher regulation of discharge, high water demand

related incentives, and societal and environmental considerations.

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 native vegetation by introduced ("improved") forages, which are utilized for many years with little or no annual maintenance. After the initial investment at establishment, this system costs little, but pastures will degrade over time without annual investment in fertilizer, especially if they are overstocked, leading to soil degradation and loss of productivity. If the sown pasture is managed with applications of modest amounts of maintenance fertilizer, 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, SPSs combining trees and forages have received increased attention, because of their potential to improve productivity and reduce GHG emissions (Ibrahim et al. 2007), but the initial investments in these systems are substantial (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 fertilizer 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 with 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, enhance biodiversity compared with monospecific pastures, and reduce runoff and soil erosion as they regulate the hydrological system (see above).

Carbon insetting

There are 2 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 these 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, which 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 mutual benefits 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 recognized as a means to contribute to mitigating GHG emissions. Improved forages and agroforestry systems are key strategies in these endeavors. Pathways include both increased C accumulation through reversing pasture degradation and maximizing 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 Cerrados by 50% of 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 for reaching these ambitious goals simultaneously is through the sustainable intensification of pasture lands (Strassburg et al. 2012). Native and sown pasturelands (189 Mha) 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 recognized by the Brazilian government through its Low Carbon Agriculture Plan (*Plano ABC*, Table 3). The recuperation of 15 Mha of Brazil´s estimated 40 Mha 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 forecast to mitigate an additional 669 Mt CO_2-eq. The ABC plan also has a target of increasing planted forests from 6 to 9 Mha and treating animal waste, the latter estimated to mitigate 6.9 Mt CO_2-eq.

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

Action	Target area (Mha)	Associated mitigation (Mt CO_2-eq)
Recuperation of degraded pasturelands	15.0	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

Colombia

In Colombia, currently 39.6 Mha of land are used for livestock production (34.7% of the Colombian territory), with an average of 0.6 animals/ha, while crops occupy 3.3 Mha (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 for 0.64% (MinCIT 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 Mha 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 pasture 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. However, livestock production is also a large source of GHG, with extensive ruminant systems producing 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 analyzed 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. The international community would need to pay much greater attention to forage-based livestock systems, if a reduction of GHG emissions in agriculture is the goal, considering that more than 70% of agricultural land is covered by these systems. In our view, ignoring the importance of forage-based systems may leave 50−80% 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 socio-cultural standpoint, it is probably not an option for countries where consumption is currently low (Anderson and Gundel 2011).

Further research is required in both the biophysical and 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 results) suggest that C 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 carbon 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.
- Analyze 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-win options for productivity, food security and environmental benefits at different scales (from plot to farm to landscape to globe), 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 with low environmental impact).
- Develop payment-for-ecosystem-services (PES) schemes to stimulate optimization 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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References

Alexandratos N; Bruinsma J. 2012. World agriculture towards 2030/2050: The 2012 revision. ESA working paper No. 12-03. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy.
(Retrieved 19 June 2013 from http://goo.gl/xn9ijA).

Amézquita MC; Murgueitio E; Ibrahim M; Ramírez B. 2010. Carbon sequestration in pasture and silvopastoral systems compared with native forests in ecosystems of tropical America. In: Abberton M; Conant R; Batello C, eds. Grassland carbon sequestration: Management, policy and economics. Proceedings of the Workshop on the role of grassland carbon sequestration in the mitigation of climate change, Rome, April 2009. Integrated Crop Management No. 11. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. p. 153–161.

Anderson S; Gundel S. 2011. Foresight project on Global Food and Farming Futures. Workshop report W5. Evidence of livestock sector impacts on the climate and the wider environment: A brief science review. The Government Office for Science, London, UK.

Archimède H; Eugène M; Magdeleine CM; Boval M; Martin C; Morgavi DP; Lecomte P; Doreau M. 2011. Comparison of methane production between C3 and C4 grasses and legumes. Animal Feed Science and Technology 166-167:59–64.

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

Benchaar C; Pomar C; Chiquette J. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. Canadian Journal of Animal Science 81:563–574.

Blanfort V; Fontaine S; Picon Cochard C; Klumpp K; Huguenin J; Soussana JF. 2010. Evaluation of carbon sequestration in tropical grassland, ecological processes and farm practices in Amazonian cattle systems. Advances in Animal Biosciences 1:493–494.

Brasil. 2011. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura – Plano de Agricultura de Baixa Emissão de Carbono (Plano ABC), Brasília, DF, Brazil.
(Retrieved 19 June 2013 from http://goo.gl/MgoMsZ).

Bustamante MMC; Nobre CA; Smeraldi R; Aguiar APD; Barioni LG; Ferreira LG; Longo K; May P; Pinto AS; Ometto JPHB. 2012. Estimating greenhouse gas emissions from cattle-raising in Brazil. Climatic Change 115: 559–577.

Calle Z; Murgueitio E; Chará J. 2012. Integrating forestry, sustainable cattle-ranching and landscape restoration. Unasylva 63:31–40.

Conant RT; Paustian K; Eliott ET. 2001. Grassland management and conversion into grassland: Effects on soil carbon. Ecological Applications 11**:**343–355.

da Silva JE; Resck DVS; Corazza EJ; Vivaldi L. 2004. Carbon storage in clayey Oxisol cultivated pastures in the “Cerrado” region, Brazil. Agriculture, Ecosystems and Environment 103:357–363.

Delgado C; Rosegrant M; Steinfeld H; Ehui S; Courbois C. 1999. Livestock to 2020 – the next food revolution. Food, Agriculture and the Environment Discussion Paper 28. IFPRI (International Food Policy Research Institute), Washington, DC, USA; FAO (Food and Agriculture Organization of the United Nations), Rome, Italy; ILRI (International Livestock Research Institute), Nairobi, Kenya.

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

Douxchamps S; Rao IM; Peters M; van der Hoek R; Schmidt A; Martens S; Polania J; Mena M; Binder C; Schöll R; Mosimann A; Holmann F; Quintero M; Kreuzer M; Frossard E; Oberson A. 2013. Farm-scale tradeoffs between legume use as forage versus green manure: The case of *Canavalia brasiliensis*. Agroecology and Sustainable Food Systems 38:25–45.
DOI:10.1080/21683565.2013.828667.

Erb KH; Gaube V; Krausmann F; Plutzar C; Bondeau A; Haberl H. 2007. A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. Journal of Land Use Science 2:191–224.

Erb KH; Mayer A; Kastner T; Sallet K-E; Haberl H. 2012. The impact of industrial grain fed livestock production on

food security: An extended literature review. Alpen Adria University Klagenfurt - Vienna - Graz, Austria.
(Retrieved 19 June 2013 from http://goo.gl/6smPcP).

FAO. 2009. The state of food and agriculture: Livestock in the balance. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy.
(Retrieved 19 June 2013 from http://goo.gl/RRpE5).

FAO. 2011a. World Livestock 2011. Livestock in food security. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy.

FAO. 2011b. FAOSTAT statistical database.
http://faostat.fao.org

Fearnside, P. 2002. Can pasture intensification discourage deforestation in the Amazon and Pantanal regions of Brazil? In: Wood CH; Porro R, eds. Deforestation and land use in the Amazon. University Press of Florida, Gainesville, FL, USA. p. 283–364.

FEDEGAN (Federación Colombiana de Ganaderos). 2011. Carta FEDEGAN No. 125.
(Retrieved 19 June 2013 from http://goo.gl/zZu25F).

FEDEGAN (Federación Colombiana de Ganaderos). 2012. Plan Estratégico de la Ganadería Colombiana (PEGA) 2019: Cifras de referencia.
(Retrieved 19 June 2013 from http://goo.gl/vHx1wq).

Fisher MJ. 2009. Harry Stobbs Memorial Lecture – Carbon sequestration: Science and practicality. Tropical Grasslands 43:239–248.

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

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

Garnett T. 2009. Livestock-related greenhouse gas emissions: Impacts and options for policy makers. Environmental Science and Policy 12:491–503.

Garnett T. 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36:S23–S32.

Guo LB; Gifford RM. 2002. Soil carbon stocks and land use change: A meta analysis. Global Change Biology 8: 345–360.

Haan C de; Gerber P; Opio C. 2010. Structural change in the livestock sector. In: Steinfeld H; Mooney HA; Schneider F; Neville L, eds. Livestock in a changing landscape: Drivers, consequences and responses. Vol 1. Island Press, Washington, DC, USA. p. 35–50.

Haberl H; Erb KH; Krausmann F; Gaube V; Bondeau A; Plutzar C; Gingrich S; Lucht W; Fischer-Kowalski M. 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences of the United States of America 104:12942–12947.

Hamilton K; Sjardin M; Shapiro A; Marcello T. 2009. Fortifying the foundation: State of the voluntary carbon markets 2009. New Carbon Finance, New York, USA; Ecosystem Marketplace, Washington DC, USA.

Havlik P; Valin H; Mosnier A; Obersteiner M; Baker JS; Herrero M; Rufino MC; Schmid E. 2013. Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. American Journal of Agricultural Economics 95:442–448.

Henry B; Eckard R. 2009. Greenhouse gas emissions in livestock production systems. Tropical Grasslands 43: 232–238.

Herrero M; Gerber P; Vellinga T; Garnett T; Leip A; Opio C; Westhoek HJ; Thornton PK; Olesen J; Hutchings N; Montgomery H; Soussana J-F; Steinfeld H; McAllister TA. 2011. Livestock and greenhouse gas emissions: The importance of getting the numbers right. Animal Feed Science and Technology 166-167:779–782.

Herrero M; Thornton PK; Notenbaert A; Msangi S; Wood S; Kruska R; Dixon J; Bossio D; van de Steeg J; Freeman HA; Li X; Parthasarathy Rao P. 2012. Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human wellbeing to 2030: A study commissioned by the CGIAR Systemwide Livestock Programme. ILRI Project Report. ILRI (International Livestock Research Institute), Nairobi, Kenya.
(Retrieved 19 June 2013 from http://goo.gl/KbZxDa).

Herrero M; Havlik P; Valin H; Notenbaert A; Rufino M; Thornton PK; Blummel M; Weiss F; Obersteiner M. 2013a. Global livestock systems: Biomass use, production, feed efficiencies and greenhouse gas emissions. Proceedings of the National Academy of Sciences of the United States of America. (In review).

Herrero M; Conant R; Havlik P; Hristov A; Smith P; Gerber P; Gill M; Butterbach-Bahl K; Henderson B; Thornton PK. 2013b. Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change. (Submitted).

IBGE (Instituto Brasileiro de Geografia e Estatística). 2011. Pesquisa Pecuária Municipal 2010.
(Retrieved 19 June 2013 from http://goo.gl/YTKL95).

Ibrahim M; Chacón M; Cuartas C; Naranjo J; Ponce G; Vega P; Casasola F; Rojas J. 2007. Almacenamiento de carbono en el suelo y la biomasa arbórea en sistemas de usos de la tierra en paisajes ganaderos de Colombia, Costa Rica y Nicaragua. Agroforestería en las Américas 45: 27–36.

Ibrahim M; Guerra L; Casasola F; Neely C. 2010. Importance of silvopastoral systems for mitigation of climate change and harnessing of environmental benefits. In: Abberton M; Conant R; Batello C, eds. Grassland carbon sequestration: Management, policy and economics. Proceedings of the Workshop on the role of grassland carbon sequestration in the mitigation of climate change, Rome, April 2009. Integrated Crop Management No. 11. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. p. 189–196.

IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia). 2010. Segunda Comunicación Nacional ante la Convención Marco de las Naciones Unidas sobre Cambio Climático.
(Retrieved 19 June2013 from http://goo.gl/2da86t).

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: IPCC fourth assessment report. Cambridge University Press, Cambridge, UK.

Kaimowitz D; Angelsen A. 2008. Will livestock intensification help save Latin America's forests? Journal of Sustainable Forestry 27:6–24.

Kastner T; Rivas MJI; Koch W; Nonhebel S. 2012. Global changes in diets and the consequences for land requirements for food. Proceedings of the National Academy of Sciences of the United States of America 109:6868–6872.

Krausmann F; Erb KH; Gingrich S; Lauk C; Haberl H. 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecological Economics 65: 471–487.

Kumar BM; George SJ; Jamaludheen V; Suresh TK. 1998. Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. Forest Ecology and Management 112:145–163.

Lal R. 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. BioScience 60:708–721.

Lambin EF; Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences of the United States of America 108:3465-3472.

MADR (Ministerio de Agricultura y Desarrollo Rural). 2011. Anuario estadístico del sector agropecuario y pesquero 2010. MADR, Bogotá, Colombia.

MinCIT (Ministerio de Comercio, Industria y Turismo). 2012. Informe de Exportaciones: Exportaciones colombianas enero-diciembre 2012. Oficina de Estudios Económicos, MinCIT, Bogotá, Colombia.
(Retrieved 19 June 2013 from http://goo.gl/tPF017).

Monfreda C; Ramankutty N; Foley JA. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical Cycles 22:1–19.

Mosier A; Wassmann R; Verchot L; King J; Palm C. 2004. Methane and nitrogen oxide fluxes in tropical agricultural soils: Sources, sinks and mechanisms. Environment, Development and Sustainability 6:11–49.

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

Nair PKR; Gordon AM; Mosquera-Losada MR. 2008. Agroforestry. In: Jorgensen SE; Fath BD, eds. Ecological engineering. Encyclopedia of Ecology, Vol. 1. Elsevier, Oxford, UK. p. 101–110.

Nair PKR; Kumar BM; Nair VD. 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172:10–23.

Nair PKR; Nair VD; Kumar BM; Showalter J. 2010. Carbon sequestration in agroforestry systems. Advances in Agronomy 108:237–307.

Olander L; Wollenberg E; Tubiello F; Herold M. 2013. Advancing agricultural greenhouse gas quantification. Environmental Research Letters 8:011002.
DOI:10.1088/1748-9326/8/1/011002.

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

Peters M; Rao I; Fisher M; Subbarao G; Martens S; Herrero M; van der Hoek R; Schultze-Kraft R; Miles J; Castro A; Graefe S; Tiemann T; Ayarza M; Hyman G. 2013. Tropical forage-based systems to mitigate greenhouse gas emissions. In: Hershey CH; Neate P, eds. Eco-Efficiency: From vision to reality. CIAT (Centro Internacional de Agricultura Tropical), Cali, Colombia. p. 171–190.

Powers JS; Corre MD; Twine TE; Veldkamp E. 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proceedings of the National Academy of Sciences of the United States of America 108:6318–6322.

Sáenz JC; Villatoro F; Ibrahim M; Fajardo D; Pérez M. 2007. Relación entre las comunidades de aves y la vegetación en agropaisajes dominados por la ganadería en Costa Rica, Nicaragua y Colombia. Agroforestería en las Américas 45:37–48.

Shelton M; Dalzell S. 2007. Production, economic and environmental benefits of leucaena pastures. Tropical Grasslands 41:174–190.

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

Smith P; Gregory PJ; van Vuuren D; Obersteiner M; Havlík P; Rounsevell M; Woods J; Stehfest E; Bellarby J. 2010. Competition for land. Philosophical Transactions of the Royal Society B 365:2941–2957.

Stehfest E; Bouwman L. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems 74:207–228.

Steinfeld H; Gerber P; Wassenaar T; Castel V; Rosales M; de Haan C. 2006. Livestock's long shadow: Environmental issues and options. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy.
(Retrieved 19 June 2013 from http://goo.gl/MQIXE).

Strassburg B; Micol L; Ramos F; da Motta RS; Latawiec A; Lisauskas F. 2012. Increasing agricultural outputs while

avoiding deforestation – a case study for Mato Grosso, Brazil. IIS (International Institute for Sustainability), Rio de Janeiro, RJ, Brazil.
(Retrieved 19 June 2013 from http://goo.gl/CMLt24).

Subbarao GV; Ito O; Sahrawat KL; Berry WL; Nakahara K; Ishikawa T; Watanabe T; Suenaga K; Rondón M; Rao IM. 2006. Scope and strategies for regulation of nitrification in agricultural systems – challenges and opportunities. Critical Reviews in Plant Sciences 25:303–335.

Subbarao GV; Rondón M; Ito O; Ishikawa T; Rao IM; Nakahara K; Lascano C; Berry WL. 2007. Biological nitrification inhibition (BNI) – is it a widespread phenomenon? Plant and Soil 294:5–18.

Subbarao GV; Nakahara K; Hurtado MP; Ono H; Moreta DE; Salcedo AF; Yoshihashi AT; Ishikawa T; Ishitani M; Ohnishi-Kameyama M; Yoshida M; Rondón M; Rao IM; Lascano CE; Berry WL; Ito O. 2009. Evidence for biological nitrification inhibition in *Brachiaria* pastures. Proceedings of the National Academy of Sciences of the United States of America 106:17302–17307.

Subbarao GV; Sahrawat KL; Nakahara K; Ishikawa T; Kudo N; Kishii M; Rao IM; Hash CT; George TS; Srinivasa Rao P; Nardi P; Bonnett D; Berry W; Suenaga K; Lata JC. 2012. Biological nitrification inhibition (BNI) – A novel strategy to regulate nitrification in agricultural systems. Advances in Agronomy 114:249–302.

Szott L; Ibrahim M; Beer J. 2000. The hamburger connection hangover: Cattle, pasture land degradation and alternative land use in Central America. CATIE (Tropical Agricultural Research and Higher Education Center), Turrialba, Costa Rica.

The World Bank. 2010. World Development Report 2010: Development and climate change. The World Bank, Washington, DC, USA.

Thoma G; Popp J; Nutter D; Shonnard D; Ulrich R; Matlock M; Kim DS; Neiderman Z; Kemper N; East C; Adom F. 2013. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. International Dairy Journal 31(Supplement 1):S3–S14.

Thornton PK; Kruska RL; Henninger N; Kristjanson PM; Reid RS; Atieno F; Odero AN; Ndegwa T. 2002. Mapping poverty and livestock in the developing world. ILRI (International Livestock Research Institute), Nairobi, Kenya.

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

Tiemann TT; Lascano CE; Wettstein H-R; Mayer AC; Kreuzer M; Hess HD. 2008. Effect of the tropical tannin-rich shrub legumes *Calliandra calothyrsus* and *Flemingia macrophylla* on methane emission and nitrogen and energy balance in growing lambs. Animal 2:790–799.

Vågen T-G; Winowiecki LA. 2013. Mapping of soil organic carbon stocks for spatially explicit assessments of climate change mitigation potential. Environmental Research Letters 8:015011. DOI:10.1088/1748-9326/8/1/015011.

Waghorn GC; Clark DA. 2004. Feeding value of pastures for ruminants. New Zealand Veterinary Journal 52:320–331.

White D; Holmann F; Fujisaka S; Reategui K; Lascano C. 2001. Will intensifying pasture management in Latin America protect forests – or is it the other way round? In: Angelsen A; Kaimowitz D, eds. Agricultural technologies and tropical deforestation. CABI Publishing, Wallingford, UK and New York, USA, in association with CIFOR (Center for International Forestry Research), Bogor, Indonesia. p. 91–11.

Wirsenius S; Azar C; Berndes G. 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems 103:621–638.

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

Peters M; Herrero M; Fisher M; Erb KH; Rao I; Subbarao GV; Castro A; Arango J; Chará J; Murgueitio E; van der Hoek R; Läderach P; Hyman G; Tapasco J; Strassburg B; Paul B; Rincón A; Schultze-Kraft R; Fonte S; Searchinger T. 2013. Challenges and opportunities for improving eco-efficiency of tropical forage-based systems to mitigate greenhouse gas emissions. Tropical Grasslands – Forrajes Tropicales 1:156–167.
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