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Silvopastoral Systems Ecological Strategy for Decreases C Footprint in Livestock Systems of Piedmont (Meta), Colombia

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HIGHLIGHTS

- Soil and Biomass C sequestration are agricultural practices to mitigate GHG emissions
- Carbon footprint is use as indicator for livestock systems efficiency.
- Silvopastoral systems cause lower CF per LW.
- Degraded pasture cause higher CF per LW.

Abstract: The objective of this work was to evaluate different pastures types on carbon footprint (CF). The cattle in the Piedmont zone, Cumaral, Meta, Colombia are principally Brahman, the pastures are formed with the tropical forage grasses *Brachiaria decumbens* for improved pastures (IP) and degraded pastures of *B. brizantha* (DP), also, various silvopastoral systems (SPSs) depending of planting trees on pasture at the same time and in the same space were evaluated. GHG emissions per kg of live weight (LW) were estimated to be reduced from 9.14, and 7.17 to 4.4 $kgCO_2eq.kgLW^{-1}$ in SPSs, and IP to DP, respectively. In all systems the largest GHG emission were enteric fermentation CH_4, manure management N_2O, feed animal management CO_2. Soil C sequestration rates ranged from 2.46 to -1.72 $tCO_2.ha^{-1}.yr^{-1}$ in DP to SPSs, respectively, IP account for -1.35$tCO_2eq.ha^{-1}yr^{-1}$. CF were neutralized from 8.12 to -11.6 kg $CO_2eq.kg\ LW^{-1}$ in DP to IP. The beef production system with the lowest CF studied were that based on SPSs, mainly *B. decumbens* associated with *Acacia mangium*, accounting -60 kg $CO_2eq.kgLW^{-1}$. In our study, all other SPSs had a very large impact on negative CF, due to differences in C stored in biomass that would account for GHG neutralization of -15.3, -21.8, -24.31, -20.42 kg $CO_2eq.kgLW^{-1}$ in SPSs of *B. decumbens* + *Gliricidia sepium, B. decumbens* + *Mangifera indica, B. decumbens* + *G. angustifolia* and *B. decumbens* + *citrus*

cinensis, respectively. It is possible to neutralize CF in beef cattle production through several SPSs in Piedmont's case study.

Keywords: Climatic change; Environmental technology; Pasture; Soil and biomass C sequestration.

INTRODUCTION

Colombia has an inventory of 22.6 million of bovine and annually produces 933 million per kg of the 39 beef, located in 39.2 million per hectares, from which, Meta department of Colombia in Piedmont zone, contributes with 7.7%. On those areas, livestock production is closely linked to the extensive systems, characterized by degraded pastures as also improved pastures. Extensive cattle ranching accounts for almost 60% of deforestation in Colombia [1].

Estimated the emissions, it is possible to generate the amount of greenhouse gases (GHG) emitted per quantity of product or generated services for activity, this environmental indicator known as carbon footprint (CF), is measured in terms of kilograms of equivalent CO_2 per unit of product [2].

Carbon dioxide-equivalents (CO_2eq) aggregate the impacts of all greenhouse gases into a single metric using 'global warming potential' [3]. Livestock production systems are associated with a number of GHG emissions, and have made a significant contribution to anthropogenic climate change [4]. Improved pastures have been adopted intensively with high utilization of agricultural inputs such as soluble fertilizers, mainly nitrogen and pesticides [1], which also results in direct and indirect GHG emissions.

Silvopastoral systems represent an important ecological strategies that are usually defined as strategies that use knowledge of the ecology and behavior of organisms to meet more efficiently and effectively goals that would have been more difficult with traditional methods for the recovery of degraded areas of pastures in Piedmont zone [1].

Silvopastoral systems (SSPs), included in different Agroforestry Systems (SAFs) modalities, use trees, animals and pasture and working like potential carbon sinks [5]. Soil organic carbon (SOC) is mainly derived from animal and plant residues, soil microorganisms and their secretions, which are active into soil providing increased nutrient recycling. A reduction of SOC content in livestock systems is correlated with a degree of soil degradation. Restoring degraded grassland by silvopastoral systems can increase grassland ecosystem carbon stocks, particularly soil and biomass C stocks [3]. Silvopastoral systems can also have a major effect on the productivity of livestock systems, especially in the extensive systems, where there is rarely addition of fertilizers and nitrogen is often a limiting factor in production. The ability of silvopastoral systems for carbon capture, if focuses on biomass, both aerial and root of pastures and trees is performed by means of the total biomass in inventory systems [3]. Despite all the efforts, there is still some resistance to adopt silvopastoral systems in the Piedmont region, mainly due to socioeconomic aspects.

There are no GHG balance studies that have evaluated the environmental performance of Piedmont, Meta´Colombia bovine cattle systems accounting carbon footprint.

This carbon footprint can also be used as an indicator of the efficient use of natural resources [6] at the farms. In the case of the carbon footprint of beef cattle, a common functional unit is a kg of live weight (LW), which is the weight of the animal at the farm gate. Meat has become an important source of protein in the diet of human beings, especially in industrialized countries. About 58% of the protein included in the diet of the countries comes from livestock products, of which about 12% is meat.

In terms of greenhouse gas (GHG) emissions, livestock is an important source in the world, generating carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) throughout the production process. Grazing ruminants utilize relatively little of the N in feed and 75–90% of their dietary N (which originates from inputs of N fertilizer and biological N fixation) is recycled back into the system via urine and dung [3]. Several transformations from manure management occur via combined nitrification and denitrification of N contained in the manure (N_2O direct emissions) by microbial action.

Silvopastoral systems can substantially reduce the use of synthetic fertilizers through biological nitrogen fixation (BNF) of leguminous tress [5], which in turn, reduces the consumption of fossil fuels in the production of fertilizers [3]. Biological nitrogen fixations (BNF) in silvopastoral systems contribute significantly to the nitrogen nutrition and pasture productivity.

Methane is produced in the rumen by Archeas methanogenic as a by-product of the fermentation process. There are a variety of factors that affect CH_4 production in ruminant animals, such as: the physical and chemical characteristics of the feed, the feeding level and schedule, the use of feed additives to promote production efficiency, and the activity and health of the animal. It has also been suggested that there may be genetic factors that affect CH_4 production [3]. The IPCC [3] consider CO_2 emissions from all lime added in the year of application, although the effect of liming usually lasts for a few years (after the new addition of lime), depending on climate, soil and cultivation practices.

Agricultural phosphates and potassic fertilizers are commonly used in the management of grasslands to increased productivity. According to Intergovernmental Panel on Climate Change [3], emission factors of phosphates and potassic fertilizers are associated with manufacturing, transportation, storage and application. On silvopastoral systems, nutrient recycling is higher, reducing dependence on phosphatic and potassic fertilizers.

In this sense, it is estimated that the livestock sector contributes with 14.5% of global anthropogenic emissions, where meat represent 41%, 50% more that milk with 21% [7]. Cattle dedicated to meat production contribute 2.5 Gt of CO_2eq per year, equivalent to 41% of total emissions from the livestock sector. The largest GHG emissions are produced in Latin America and the Caribbean with more than 800 million tons per year, followed by North America, East and Southeast Asia and South Asia with 400, 380 and 280 million tons per year, respectively [7]. Carbon footprint of beef cattle can to decreases mainly due to improved genetics, better diets, and more sustainable land management practices.

The present study aimed to quantify the carbon footprint (CF) of beef production of three production livestock systems of Piedmont Llanero, Meta, Colombia, in order to identify the ecological strategies that reduce the GHG emissions per kg LW. The proposed hypothesis is that differences in C footprint of beef produced in different livestock systems of Piedmont, may be due to the different level of intensification systems, that affects GHG emissions, beef production, and ecological strategies of silvopastoral systems for soil and biomass C sequestration that can to reduce GHG emissions.

MATERIAL AND METHODS

The project was developed in a Piedmont landscape in the municipality of Cumaral, department of Meta, which it is located in a depositional zone, corresponding to a slightly inclined plain to the East and Northeast, and a mountainous region to the West and Northwest. Geographically, this subregion is between 700 and 300 meters above sea level, with average temperatures of 23 to 30 ºC and a bimodal rainfall regime with 3,000 to 4,000 mm of annual precipitation where there are rainy seasons from April to June and from August to November. The sub-recent alluvial fans of the Piedmonts were possibly formed during the Holocene and its remains are found in an elevated position, on undulating surfaces called "tables". Locally they present slopes of the order of 5%, in the direction Oriental. The materials from which they are formed are sandy with boulders, which It produces a high drainage and therefore a great dryness during the summer periods. The plant cover in the Piedmonts currently has few areas of forest and grass native, on the other hand there is a predominance of introduced grasses of Brachiaria, managed in extensive production systems. They are soils of low fertility, acidic, mainly oxisols [8].

For the estimation of the GHG mitigation potential of livestock systems in Piedmont zone of Cumaral were consider three different pastures production agricultural systems:

Improved pasture (IP) scenario

In Piedmont, Cumaral (Meta), improved pastures (IP) occupy 70% of the area of the evaluated livestock farms. In the IP scenario new grass species with increased quality and productivity are introduced to the pasture, which includes the introduction of lime as a soil amendment during soil preparation, pastures fertilization mainly with N, adequate rotation, which means it may support higher stocking rates of 1.5 animal units (AU) per ha, one AU corresponds to 450 kg of live weight. Although a wide range of species are considered mainly *Brachiaria humidicola* and *Brachiaria decumbens*. The use of these species in the context lead to a higher meat production, 500 kg $ha^{-1}yr^{-1}$.

Degraded pasture

The DP scenario represents the baseline scenario in the case-study region of 30% of the area, with cattle grazing on very unproductive pastures dominated by grass *Brachiaria brizantha*, low stocking rates, 0.8 animal units (AU) per ha (one AU corresponds to 450 kg of live weight), with a meat production mean of 250 kg $ha^{-1}yr^{-1}$. Degraded pasture (DP) are native or planted pastures which have experienced a sharp decrease in carrying capacity, productivity and biomass production. Degradation may result from inadequate soil, plant or herd management. Degradation is normally related to overgrazing, insufficient weed and pest controls, and low or no fertilization.

Silvopastoral systems

In Piedmont, Cumaral (Meta), Silvopastoral systems (SPSs) occupy only 5% of the area of the evaluated livestock farms, which emphasizes the importance of the tree component in C stocks on the pastures. Different tree species are planted in rows directly on the IP, mainly *Gliricidia sepium*, *Mangifera indica*, *G. angustifolia*, *Acacia mangium*, and *Citrus cinensis*, including *Brachiaria decumbens* in an extensive production system as forage grass for beef cattle. All farmers have some trees in their pastures and also as living fences (SPSs), trees provide shade for livestock and contribute to mitigate heat stress, which in turn offers a further increase in meat productivity, 350 kg $ha^{-1}yr^{-1}$, with a stocking rate of 1.0 animal units (AU) per ha (one AU corresponds to 450 kg of live weight). Most common species are *Acacia mangium* and *Gliricidia sepium*, which are used for firewood, forage, as shade and construction timber.

Estimation of GHG emissions

All emissions were calculated using standard IPCC GHG inventory methodologies [3], for to estimate system GHG fluxes for processes such as enteric fermentation (enteric CH_4), manure management, and feed production. All major GHGs methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) from direct and indirect sources were calculated using emission factors (EF) either tier 1. Tier 1 refers to emissions based on default factors of different sources (Table 1). The CH_4 EF in tier 1 come from enteric fermentation and manure, N_2O EF from manure management and N fertilizers. The CO_2 EF in tier 1 come from fossil fuels used in machinery, and the production of herbicides, lime, P and K fertilizers and concentrates (Table 1). All gasses were converted to CO_2 equivalents (CO_2eq) using current 100-year global warming potentials (CO_2 = 1, CH_4 = 25, N_2O = 298) as showed expressed by the following equation: GHG kg COeq $=$ kg $CH_4 \times 25 +$ kg $N_2O \times 298 +$ kgCO_2.

Table 1. Emissions Factors used and GHG emissions generated

GHG sources	Authors, emission factors (EF) used	GHG emissions kg CO_2eq $ha^{-1}yr^{-1}$		
		IP	SPS	DP
N_2O Nsintetic fertilizer	IPCC [3], 0.01 kgN/Kg N applied	394.85	150.78	68.54
N_2O Ncomplet fertilizer	IPCC [3], 0.01 kgN/Kg N applied	107.28	16.09	0
N_2O Norganic fertilizer	IPCC [3], 0.01 kgN/Kg N applied	71.52	61.09	0.923
CO_2_lime	IPCC [3], 0.4777 $kgCO_2$/K applied	164.8	36.59	0
CO_2_concentrate	IPCC [3], 0.59 $KgCO_2$eq/kg applied	306.8	189.98	71.09
CO_2_mancozeb	Lal [9], 2 $kgCO_2$/kg	4	2.4	2
CO_2_cypermetrina	Lal [9], 4.6 $kgCO_2$/kg	16.1	14.72	2.3
CO_2_gramoxone	Lal [9], 9.2 $kgCO_2$/kg	41.4	29.44	4.6
CH_4_enteric fermentation cows	IPCC [3], 63$kgCH_4$/head/year	241.92	207.27	102.06
CH_4_enteric fermentation_heifers	IPCC [3], 56$kgCH_4$/head/year	34.16	32.48	38.08
CH_4_enteric fermentation weaned	IPCC [3], 56$kgCH_4$/head/year	10.08	10.08	10.08
CH_4_enteric fermentation adult goats	IPCC [3], 5$KgCH_4$/head/year	50	75	0
CH_4_enteric fermentation_heifers	IPCC [3], 18$KgCH_4$/head/year	8.64	16.2	10.8
CH_4_manure management cows	IPCC [3], 2$KgCH_4$/head/year in hot weather	7.68	6.58	3.24
CH_4_manure managements heifers	IPCC [3], 1$KgCH_4$/head/year in hot weather	0.61	0.58	0.68
CH_4_manure managements weaned	IPCC [3], 1$KgCH_4$/head/year in hot weather	0.18	0.18	0.18
CH_4_manure managements adult goats	IPCC [3], 0.22$KgCH_4$/head/year in hot weather	2.2	3.3	0
CH_4_manure managements heifers	IPCC [3], 2.19$KgCH_4$/head/year in hot weather	1.05	1.97	1.31
N_2O_Nmanure managements cows	Calculated of IPCC [3], 0.48KgNexcreted for each 1,000 kg animal mass/year.	274.63	235.3	115.86
N_2O_Nmanure managements heifers	Calculated of IPCC [3], 0,36KgNexcreted for each 1,000kg de animal mass/year (weight = 350 kg)	22.9	21.77	25.53
N_2O_Nmanuremanagement_ weaning	Calculated of IPCC [3], 0,36KgNexcreted for each1,000kg animal mass/year (weight = 150 kg)	2.89	2.89	2.89
N_2O_Nmanure management goats	Calculated of IPCC [3], 1,37KgNexcreted for each1000kg animal mass/year (weight = 140 kg)	571.5	857.3	0
N_2O_Nmanure management horses	Calculated of IPCC [3], 0,46KgNexcreted for each1000kg animal mass/year (weight = 350 kg)	30.62	57.42	38.28
CO_2_Gasoline	Hassan [8], 2.2 $kgCO_2$/L	15.95	17.6	13.2
CO_2_mineralized salt	32.8$kgCO_2$/kgapplied	820	656	615
CO_2_molasses	0.0317$kgCO_2$/kg applied	0	0	0,19
CO_2_Pcomplet fertilizer	Lal [9], 0.2 $kgCO_2$/kg applied	5.62	3.54	0.36
CO_2_Kcomplet fertilizer	Lal [9], 0.15$kgCO_2$/kg applied	4.21	2.65	0.27
Total GHG emissions $kgCO_2eq$ $ha^{-1}yr^{-1}$		**3,227**	**2,709**	**1,127**
Total GHG emissions tCO_2eq ha^{-1} yr^{-1}		**3.2**	**2.7**	**1.1**

GHG mitigation practices (Soil and Biomass C sequestration)

Soil C sequestration

We also measured soil organic carbon (SOC) stock at 0.30m from year 0, and projected losses and gains of SOC to year 20 with IPCC methodology, considering changes in soil management factors. IPCC recommendation, a large proportion of SOC stocks is found below 30 cm, as just about 40% of SOC is in the topsoil [10]. According to Conant and coauthors [11], while shorter-term changes in SOC mostly appear in the top of the prole, longer-term stabilization of SOC can occur in the deeper soil layers. While IPCC [3], tier 1 methodology proposes a time period of 20 years, as used in many IPCC's modellings land use, pasture type and input changes, many have argued and shown that carbon stocks may not reach an equilibrium after 20 years [12]. SOC gain rate in SSPs is reported as an average of all the values obtained in these systems, regardless of the type of tree in the pasture, since the arrangement in all cases was of scattered trees in pastures and/or barrier live. SOC losses and gains rates were expressed in $tCO2eqha^{-1}yr^{-1}$ and considering meat production in kg CO_2eq per kg LW.

Biomass C sequestration

The major part of plant-derived carbon inputs in grassland systems is derived from roots, due to difficulties in determining this parameter directly, it has to be estimated, which is usually done by literature-derived o default values [3]. Through the examination of two different livestock systems IP and DP compared with progressively-increased SPSs complexity, we find that IP of *Brachiaria decumbens* can fix 1.85 t C $ha^{-1}yr^{-1}$, calculated of Reyes-Pérez and coauthors [13]; DP of *B. brizantha* can fix 1.38 t C $ha^{-1}yr^{-1}$, calculated of Gasca-Silva and coauthors [14], and each SPSs evaluated that result of association with IP of *B. decumbens* can fix large amount of C in the biomass depending on the type of tree and grass involved, table 2 showed C fixation in trees biomass.

Table 2. Biomass C sequestrations in trees

Biomass C	t C $ha^{-1}yr^{-1}$	Author
***Gliricidia sepium* (Mataratón)**	0.12	Arias et al. [15],
***Mangifera indica* (Mango)**	0.73	Patiño et al. [16],
Acacia mangium	2.2	Ávila et al. [17],
***Acacia* sp.**	4.5	IPCC [3],
***G. angustifolia* (Guadua)**	0.98	Patiño et al. [16],
***Anadenanthera peregrina* (Yopo)**	NR[1]	NR[1]
***Cítrus cinensis* (Naranja)**	0.63	Calculated of Marín et al. [18],

[1] NR: not registered

Carbon balance

According to Parra and coauthors [19], the carbon balance was carried out comparing annually the greenhouse gas emissions with the carbon sequestered in soil and biomass in a single unit t CO_2eq $ha^{-1}yr^{-1}$ and/or kg CO_2eq per kg LW.

GHG balance ($tCO_2eq.ha^{-1}.yr^{-1}$) = Emissions – Soil and biomass C sequestration ($tCO_2eq.ha^{-1}.yr^{-1}$)

Carbon footprint

Livestock GHG footprints were calculated using accepted Intergovernmental Panel on Climate Change IPCC [3], methodologies, which is an accounting approach that reports emissions resulting from all inputs (GHG) and outputs (mitigation GHG practices). We defined the functional unit for this C footprint as kg of CO_2eq per kg of live weight (LW). Total of meat production reported as live weight (LW) is 500, 350, and 250 kg in IP, SPS and DP, respectively, data obtained in situ in the farms, respectively.

RESULTS

GHG emissions

The total GHG emission were 3,227 kg CO_2eq $ha^{-1}yr^{-1}$ and 2,709 kg CO_2eq $ha^{-1}yr^{-1}$ for IP and SPS, respectively. This result was already expected for both systems were managed almost similarly, differing basically of DP (Table 3).

Table 3. Sources of GHG emissions in livestock systems of Cumaral

Item	IP			SPS			DP		
	GHG kg CO_2eq per hectare	Contribution %	CF kg CO_2eq per kg LW	GHG kg CO_2eq per hectare	Contribution %	CF kg CO_2eq per kg LW	GHG kg CO_2eq per hectare	Contribution %	CF kg CO_2eq per kg LW
N_2O_ Nsintetic fertilizers	394.85	12.23	0.78	150.78	5.56	0.43	68.54	6.08	0.27
N_2O_ Ncompleted fertilizers	107.28	3.32	0.21	16.09	0.59	0.04	0	0	0
N_2O_Norganic fertilizer	71.52	2.21	0.14	61.09	2.25	0.17	0.923	0.08	0.003
CH_4_enteric fermentation	344	10.6	0.68	341	12.5	0.97	161	14.2	0.644
CH_4_manure management	11.72	0.36	0.023	12.61	0.46	0.03	5.41	0.48	0.021
N_2O_manure management	902	27.95	1.80	1,174	43.3	3.35	182	16.1	0.728
CO_2_gasoline	15.95	0.49	0.031	17.6	0.66	0.05	13.2	1.19	0.05
CO_2_mineralized salt	820	25.41	1.64	656	24.2	1.87	615	54.5	2.46
CO_2_molasse CO_2_mineralizated salt	0	0	0	0	0	0	0.19	0.01	0.0007
CO_2_phosphoro fertilizers	5.62	0.17	0.011	3.54	0.13	0.010	0.36	0.03	0.0014
CO_2_potasium fertilizers	4.21	0.13	0.008	2.65	0.09	0.0075	0.27	0.02	0.0010
CO_2_lime	164.8	5.10	0.32	36.59	1.35	0.1045	0	0	0
CO_2_concentrated	306.8	9.50	0.613	189.98	7.01	0.542	71.09	6.30	0.284
CO_2_mancozeb	4	0.12	0.008	2.4	0.09	0.0068	2	0.17	0.008
CO_2_cypermetrina	16.1	0.49	0.032	14.72	0.54	0.042	2.3	0.20	0.0092
CO_2_gramoxone	41.4	1.28	0.082	29.44	1.10	0.084	4.6	0.40	0.018
$KgCO_2eqha^{-1}yr^{-1}$	**3,227**	**100**		**2,709**	**100**		**1,127**	**100**	
kg CO_2-eq per kg LW	**6.45**			**7.74**			**4.5**		

Considering CF, on average, GHG emissions per kg LW, beef production were lower on DP at 4.5 kg of CO_2eq per kg LW than on IP and SPS at 6.45 and 7.74 kg of CO_2eq per kg LW (Table 3). This represents a reduction of 1.95, and 3.24 kg CO_2eq per kg LW produced compared with IP and SPS, respectively. Contrary, GHG emissions per hectare on both systems were higher (Table 3), yielding a difference of 2,100 and 1,582 kg of CO_2eq $ha^{-1}yr^{-1}$, respectively. Across all systems in the sample, 12.43% of total GHG emissions were CH_4 from enteric fermentation, 29.12% N_2O from manure management, 7.60% CO_2 from feed (production and transportation emissions by concentrates), 1.90% N_2O from N fertilizers, and less than 1% CO_2 from pesticides (Table 3)

Potential mitigation GHG emissions

Potential of SOC sequestration

Initially, SOC stocks were 44 t C ha^{-1} and increased to 47 t C ha^{-1} in IP, 30 t C ha^{-1} and increased to 39 t C ha^{-1} in SSP, 31.7 t C ha^{-1} and decreased to 23 t C ha^{-1} in 20 years old. Soil carbon stocks increased linearly at a rate of +0.36 and + 0.47 t C $ha^{-1}yr^{-1}$ in IP and SPS, respectively, which represents -1.35, and -1.72 tCO_2 $ha^{-1}yr^{-1}$ of soil CO_2 sequestration, and decreased at a rate of -0.67 t C $ha^{-1}yr^{-1}$ in DP, accounting emissions of 2.46 t CO_2 $ha^{-1}yr^{-1}$ (Table 4).

Table 4. Soil C stocks

Systems	SOC Stock C_0 t C ha^{-1}	SOC Stock C_{0-1} t C ha^{-1}	ΔSOC due to SMF[1] t C $ha^{-1}yr^{-1}$	Potential SOC mitigation t CO_2eq $ha^{-1}yr^{-1}$	Potential SOC mitigation kg CO_2eq per kg LW
IP[2]	44.02	46.59	+0.36	-1.35	-2.7
SPS[3]	30.63	39.17	+0.47	-1.72	-4.9
DP[4]	31.73	23.09	-0.67	+2.46	+9.84

[1]SMF: Soil management factors FLU factor land use, FMG pasture management, FI factor input (IPCC, 2006). [2]IP = Improved pastures of *B. decumbens*. [3]SPS = Silvopastoral systems. [4]DP = Degraded pastures of *B. brizantha*

GHG balance and Carbon footprint due to potential de soil and biomass C sequestration

Table 5 clearly illustrates GHG emissions, the potential of soil and biomass C sequestration, and C footprint in livestock systems of Piedmont, Cumaral (Colombia). As shown in table 5, different types of SPS have different capacity for GHG mitigation depending on their capacity to both decrease GHG and/or to sequester soil and biomass C. IP (*B. decumbens*) resulted in a rapid increase in SOC, neutralizing GHG emissions of 2.7 t CO_2eq $ha^{-1}yr^{-1}$, accounting a CF of -11.6 kg CO_2eq per kg of LW, compared with DP that produces less GHG but does not absorb GHG, accounting for CF of 8.12 kg CO_2eq per kg of LW, behaving as emissary (Table 5). The carbon footprint resulting from each system ranged from 8.12 kg CO_2eq per kg LW in the degraded pasture DP to -23.21 kg CO_2eq per kg LW in the SPS of *B. decumbens* + *Acacia mangium* (Table 5). The carbon footprint resulting from each system ranged from 8.2 kg CO_2eq per kg live weight (LW) in the DP to -60 kg CO_2eq per kg LW in SPS of *B. decumbens* + *Acacia mangium* (Table 5). IP account GHG neutralization from -11.6 kg CO_2eq per kg LW. This value is lower than the most current CF in SPSs evaluated.

Table 5. Total GHG balance and C footprint

Systems	Silvopastoral systems (SPS)	Improved pasture (IP)	Degraded pasture (DP)
GHG emissions t CO_2eq $ha^{-1}yr^{-1}$	+3.2	+2.7	+1.1
GHG emission kg CO_2eq LW $ha^{-1}yr^{-1}$	9.14	7.71	4.4
Soil C t CO_2eq $ha^{-1}yr^{-1}$	-1.35	-1.72	+2.46
C biomass t CO_2eq $ha^{-1}yr^{-1}$	-7.22 *B. decumbens + Gliricidia sepium*	-6.78 *Brachiaria decumbens*	-1.38 *Brachiaria brizantha*
GHG Balance t CO_2eq $ha^{-1}yr^{-1}$	-5.37	-5.8	+2.03
C footprint kg CO_2eq kg LW^{-1}	-15.3	-11.6	+8.12
C biomass tCO_2eq $ha^{-1}yr^{-1}$	*B. decumbens+Mangifera indica* -9.48		
GHG Balance t CO_2eq $ha^{-1}yr^{-1}$	-7.63		
C footprint kg CO_2eq kg LW^{-1}	-21.8		
C biomass t CO_2eq $ha^{-1}yr^{-1}$	*B. decumbens + G. angustifolia* -10.36		
GHG Balance t CO_2eq $ha^{-1}yr^{-1}$	<<-8.51		
C footprint kg CO_2eq kg LW^{-1}	-24.31		
C biomass t CO_2eq $ha^{-1}yr^{-1}$	*B. decumbens +Acacia mangium* -23.25		
GHG Balance t CO_2eq $ha^{-1}yr^{-1}$	-21		
C footprint kg CO_2eq per kg LW	-60		
C biomass t CO_2eq $ha^{-1}yr^{-1}$	*B. decumbens + Citrus cinensis* -9		
GHG Balance t CO_2eq $ha^{-1}yr^{-1}$	-7.15		
C footprint kg CO_2eq kg LW^{-1}	-20.42		

DISCUSSION

GHG emissions per hectare and per kg LW

We hypothesize that the difference of GHG emissions per hectare between IP and SPSs compared to DP, is due to the high intensification of livestock production, they make up the largest group of animals (stocking rate) in both systems, increasing emissions due to higher consumption of inputs, energy and fuels. Enteric fermentation is a natural part of the digestive process in ruminant animals such as cattle. Archeas methanogenic in the digestive tract, or rumen, decompose and ferment feeds, producing methane as a by-product. GHG emission depend of sources of animal and pasture management used in each livestock system [3]. Agricultural practices in pastures included soil correction, chemical or organic fertilization, gasoline, concentrates, mineralized salt, while innovative management extends to improved pastures (IP) and silvopastoral systems (SPSs). On the other hand, carbon footprint (CF) is a function of GHG emissions and meat production. Meat production plays an important role in kg CO2eq per kg LW obtained. The amount of meat produced per ha increased from 74 to 1,060 kg yr^{-1} in degraded pastures of Colombia [20], and from 456 to 1,971 kg yr^{-1} in an improved pasture and an iSPS in Mexico, respectively [21]. In terms of climate change mitigation, emissions should be differentiated between those that are avoidable, reducible, and compensable. Methane emissions (product of animal physiological processes) are considered reducible emissions as they are directly affected by diet quality [22]. On the other hand, N fertilizers rates were significantly higher in IP and SPSs production systems compared to DP. These values are comparable to the results of Naranjo and coauthors [23]. In IP, N fertilization is essential for enhancing the SOC accumulation [24]. Nitrous oxide is produced from denitrification and nitrification processes in soils, and contributes to global warming and stratospheric ozone depletion.

Soil C sequestration

In this sense, grazing lands are one of the most significant reservoirs of soil organic carbon (SOC) containing more than 30% of total global SOC [25]. Recent studies showed that livestock-induced soil C changes can have large impacts on the GHG balance of these production systems as supported by Conant and coauthors [26], Stanley and coauthors [27]. These values are similar than the ones found in this study for IP and SPSs, however, DP showed soil C losses. In this sense, this difference between the systems is due to different rates of gains and/or losses of soil C due to soil management factors impacted. For example, grazing is an important form of ecological disturbance and control factor in preserving equilibrium in natural grassland ecosystems. The inclusion of forage through cattle and deposition of feces onto the improved pasture leads to long-term storage of SOC. In the Colombian Llanos, SOC (to a depth of 80 cm) with *B. humidicola* was 223 t ha^{-1}, and 268 t ha^{-1} when associated with the legume *Arachis pintoi*. Native savanna in contrast contained SOC of only 197 t ha^{-1} [28]. On rangeland, rates of SOC sequestration range from 0.02 to 1.3 t C $ha^{-1}yr^{-1}$ on restoring degraded grasslands, 0.16 to 0.50 t C $ha^{-1}yr^{-1}$ by systems that may improve grassland productivity, and 0.5 to 1.4 t C $ha^{-1}.yr^{-1}$ by systems involving fire management [29, 30]. Conant and coauthors [31], estimated average positive stock changes for improved grazing (0.28 t C $ha^{-1}yr^{-1}$), sowing legumes (0.66 $tCha^{-1}yr^{-1}$) and fertilization (0.57 t C $ha^{-1}yr^{-1}$). Overgrazing can cause severe degradation of different grassland types, and can further reduce SOC below its already naturally-reduced levels caused by low precipitation and other environmental factors [26]. In this sense, the factors that most influence soil C stocks are land use, pasture management, and the input of aboveground residues.

C footprint considering soil and biomass C

The difference in GHG potential mitigation in SPSs can be explained by different rates of biomass and soil C accumulation per year, as supported also by Landholm and coauthors [32]. In this sense, Resende and coauthors [33] in Coronel Pacheco, MG, showed that in 8 years old silvopastoral systems with eucalypt trees and U. decumbens for beef cattle reached 26.27 tCO_2eq $ha^{-1}yr^{-1}$ stored on tree biomass (crown roots, after tree harvest), while GHG emissions were 23.54 tCO_2eq $ha^{-1}yr^{-1}$ on average, with a net balance of -2.73 tCO_2eq $ha^{-1}yr^{-1}$. For example, without considering land use change, which is a big issue for about 6% of beef production in Brazil, a value of 22 kg CO_2eq per kg of LW has been reported [34], 13.8 kg CO_2eq per kg of LW higher than in DP of this study. According to this author this relatively high value is mainly because of their lower rate of weight gain, requiring a longer time (3 to 4 years) until slaughter. This uptake is able to balance most of the GHG emissions generated from the beef cattle production system, especially in the silvopastoral systems where trees are associated with pastures. According to Murgueitio and coauthors [35], in Colombia, a viability analysis was carried out to replace grasslands degraded by silvopastoral systems, if productivity gains were used for avoiding deforestation of more land, and if farmers planted forests on two of the six million hectares of reduced grazing lands, mitigation of land use could prevent or compensate 1.4 billion tons of carbon dioxide in 15 years. Climatic variation and extreme events can affect livestock production through different mechanisms that operate directly on the animal or indirectly by reductions in forage availability and/or quality [22]. In this sense, according to Nardone and coauthors [36], global scale modelling indicates that the farming systems that depend on grazing will be more drastically affected, particularly those in Africa, Australia, Central America and South Asia. In these regions, studies predict a loss of up to 50% in the edible biomass that is available to livestock. The climate-change adaptation and mitigation mechanisms favored by SPSs are sustainable biomass production, intensification potential, improved resilience to climate change (improved soil nutrient content, reduced risk of soil erosion), reduces pressure on natural forests, product diversification and carbon markets. Available information of C input from the vegetation is useful to help set the limits of possible C inputs. Most N fixed by legume trees returns to the soil and is used by the grass (as opposed to monoculture pastures where N availability is very limited), increasing the quantity and quality of forage. Biological nitrogen fixation (BNF) in SPSs ranges between 200 and 500 $kgN.yr^{-1}$ [21]. For GHG neutralization, finding a net balance of Eucalyptus + Brachiaria which ranged from - 10.92 to - 19.32 tCO_2eq $ha^{-1}yr^{-1}$ and - 2.81 to - 7.98 tCO_2eq $ha^{-1}yr^{-1}$ for Rocha [37], and Torres [38], respectively. Livestock farms can mitigate between 2.2 to 10.6 t CO_2eq $ha^{-1}yr^{-1}$ by the incorporation of SPS that have potential for soil and biomass carbon sequestration according to Ibrahim and coauthors [39] in

Colombia, on the other hand, Naranjo and coauthors [23], iSPS included timber trees as part of their design their GHG mitigation capacity reached up to -26.6 ton CO_2eq $ha^{-1}yr^{-1}$, comparable to SPS of *B. decumbens* + *Acacia mangium* of this study account -21 ton CO_2eq $ha^{-1}yr^{-1}$. In this sense, improved pasture practices usually lead to an increase in production efficiency, resulting in less GHG emissions per unit product. These results in DP are generally consistent across the literature [19, 40], although degraded pasture production systems often have larger GHG footprints associated with facilities. Most of the carbon footprint estimates in the literature are dominated by European, North American, South American and Australian estimates. No estimates are available for countries such as India, China and Africa that have large stocks of cattle. The cattle from these countries are likely to have larger carbon footprints because of their relatively low productivity. Alternatively, some studies report the GHG emissions per kg of carcass weight (CW), which does not include the hide, head, feet and guts. The CW:LW ratio varies substantially (0.68–0.45) depending on a range of factors including breed, sex, time of last feeding, and cold versus warm carcass weight [41]. For example, Rivera and coauthors [42], Dick and coauthors [43], Mazzetto and coauthors [44], found 21 kg CO_2eq per kg CW in Mexico, 22.52 kg CO_2eq per kg CW in systems based on natural pastures in Brazil; 49 and 48 kg CO_2eq per kg CW obtained for the north of Brazil, in extensive and semi-extensive systems, respectively, values higher that reported in DP of this study as kg CO_2eq per kg LW. For example, the mean value for the emission intensity of beef produced in grazing systems in Paraguay (including carbon losses from deforestation for pasture) ranged from 157.8-430.6 kg CO_2eq per kg CW [45]. González-Quintero and coauthors [46], suggest that GHG emissions can be reduced by adopting improved pastures, better agricultural management practices, efficient fertilizer usage, using the optimal stocking rate, and increasing productivity. In an analysis of the EU-27countries, beef had by far the highest GHG emissions with 22.6kg CO_2eq per kg of meat produced [47]. In this sense, we have observed a wide range of carbon footprint values from +8.2 to -60 kg CO_2eq per kg of LW at the DP and SPS of *B. decumbens* + *Acacia mangium*, depending mainly on the type of mitigation practice (soil and biomass C sequestration), however, there are other species of trees in the area that should also be further investigated as agroforestry possibilities *B. decumbens* + *Mangifera indica*; *B. Decumbens* + *Gliricidia sepium*, that allow mitigating CF. Torres and coauthors [38], observed GHG emissions ranging from 2.81 to 7.98 t CO_2eq $ha^{-1}yr^{-1}$, and a net carbon balance ranging from -18.97 to - 192.16 t CO_2eq $ha^{-1}yr^{-1}$ on four agrosilvopastoral systems composed by eucalypt trees associated with *U. decumbens* cv. Basilisk, ageing 3 to 5 years and established in Viçosa, MG. Inclusion of field-measured soil and biomass C sequestration (as a CO_2-e sink) has been shown to completely mitigate the C footprint of intensively managed grass-finished cattle in some specific cases [27], and drastically lower (but not neutralize it) in others [48, 49]. The differences found between the CF for livestock systems of an area of a country can be mainly due to the quality, quantity and level of detail of the information used for the CF estimated [50].

CONCLUSION

In our study we show that SPSs are able to neutralize greenhouse gas emissions for negatives CF values, through soil and biomass carbon sequestration related to pastures and trees in Piedmont zone.

SOC sequestration was very relevant in IP, to the point that they offset the livestock GHG emissions increase that occurs as a result of the system's intensification, sequestering also C in biomass pasture.

In order to optimize its GHG mitigation potential it is important to avoid overgrazing by using adequate stocking rates, to select improved pasture and fodder species and to implement trees-planting associated to improved pastures (SPSs).

GHG neutralization capacity in SPSs are important in meeting the Colombia government's emission reduction targets and in reconciling the increase in livestock production with the reduction of GHG emissions to the atmosphere.

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