

Greenhouse gas emissions in conversion from extensive pasture to other agricultural systems in the Andean region of Colombia

Amanda Silva Parra¹ · Eduardo Barretto de Figueiredo² ·
Ricardo Oliveira de Bordonal³ · Mara Regina Moitinho¹ ·
Daniel De Bortoli Teixeira¹ · Newton La Scala Jr.¹

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Abstract The challenge of agricultural sector is to reduce greenhouse gas (GHG) emissions while increasing food, fiber and energy production without jeopardizing environmental integrity. In the Andean zone of Colombia, there is a growing need to develop GHG mitigation techniques associated with milk production. The present study focuses on GHG emissions and potential sinks associated with milk production scenarios in the Andean zone of Colombia. The scenarios considered were as follows: conventional agriculture of *Pennisetum clandestinum* in rotation with potatoes (PRP), improved pastures of *Lolium multiflorum* (IP) and silvopastoral system of *P. clandestinum* in association with *Acacia decurrens* and *Trifolium repens* (SPS). Based on the IPCC (Guidelines for national greenhouse gas inventories. The intergovernmental panel on climate change, Institute for Global Environmental Strategies, Kanagawa, 2006. http://www.ipcc-nggip.iges.or.jp/support/Primer_2006GLs.pdf) methodologies, the annual GHG emissions considering a 6-year production cycle included agricultural sources and gasoline consumption related to the most important agricultural phases in the field, and a potential for soil carbon accumulation and biomass carbon fixation in all the studied scenarios. The lowest GHG emissions were estimated in PRP scenario (3684 kg CO₂-eq ha⁻¹ year⁻¹), which also presented additional emissions because of soil carbon losses beyond the lower milk productivity. Highest GHG emissions were observed in IP scenario (7711 kg CO₂-eq ha⁻¹ year⁻¹), which exhibited the highest milk productivity and a considerable potential for soil carbon accumulation that could help to offset its emissions. Nevertheless, SPS scenario,

✉ Mara Regina Moitinho
maramoitinho@gmail.com

¹ Department of Exact Sciences, College of Agricultural and Veterinarian Sciences, São Paulo State University, FCAV/UNESP), Via de Acesso Prof. Paulo Donato Castellane s/n, Jaboticabal, SP 14883-292, Brazil

² Department of Rural Development, Centro do Ciências Agrárias, Federal University of São Carlos (UFSCar), Rodovia Anhanguera, km 174, Araras, SP, Brazil

³ Brazilian Bioethanol Science and Technology Laboratory/Brazilian Center for Research in Energy and Materials (CTBE/CNPEM), Rua Giuseppe Máximo Scolfaro 10000, Polo II de Alta Tecnologia, Campinas, SP 13083-970, Brazil

which had milk productivity close to that of IP, presented the highest potential to offset the total GHG emission ($4878 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$) because of soil carbon accumulation and biomass carbon fixation in trees. This study contributed to indicate management strategies that should be prioritized to mitigate the main sources of GHG emission in the extensive and intensive dairy cattle production in the Andean region of Colombia.

Keywords Biomass and soil carbon sequestration · Milk production · Agricultural intensification · Climate change · GHG mitigation · Global warming · Grassland · Trees

1 Introduction

According to Smith et al. (2014), the Agriculture, Forestry and Other Land Use (AFOLU) sector was responsible for approximately a quarter ($\sim 10\text{--}12 \text{ GtCO}_2\text{eq yr}^{-1}$) of anthropogenic greenhouse gas (GHG) emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management, of which annual GHG emissions from agricultural production in 2000–2010 were estimated at $5.0\text{--}5.8 \text{ GtCO}_2\text{eq yr}^{-1}$. These authors identified that opportunities for mitigation in this sector include supply-side and demand-side options, in which emissions from land-use change (LUC), land management and livestock management can be reduced, terrestrial carbon stocks can be increased by sequestration in soils and biomass, and emissions from energy production can be saved through the substitution of fossil fuels by biomass.

Previous studies have indicated that no-tillage cropping practices and the recuperation of degraded pasture have both led to increased soil organic carbon (SOC) stock in different tropical regions (Corazza et al. 1999; Silva et al. 2004; La Scala et al. 2012; De Figueiredo et al. 2017). Accordingly, changes in land use and different crop and soil management in the Colombia Andean Zone can effectively contribute for the reduction of GHG through the introduction of more sustainable agroforestry systems, presenting their respective GHG balance and identifying better management systems with lower emissions and higher yields.

It is worth mentioning that approximately 14,000 ha in the Savannah of the city of Túquerres in southern Colombia are intended for grazing dairy cattle that consists of extensive systems of *Pennisetum clandestinum* (Solarte et al. 2006), which are currently in the process of degradation (Silva et al. 2010), with low forage diversity and low productivity (Silva et al. 2010). On these areas, crop and livestock productions are closely linked to the traditional mixed conventional agricultural system, characterized by the degraded pastures of *P. clandestinum* in rotation with potatoes (Guerrero 1998), or are completely changed each year to plant improved pastures of *Lolium multiflorum* (Bernal 1994).

Several studies have shown that, to support global demand for food, fiber and bioenergy, it is critical to improve the quality of pasturelands and adopt best management practices as a key strategy to avoid additional land degradation (Costa et al. 2015; Papanastasis et al. 2015; Smith et al. 2015). In contrast, conventional agricultural systems have been intensively adopted with high utilization of agricultural inputs such as soluble fertilizers, primarily nitrogen (Smith et al. 1997; Oenema et al. 1997; McGrath et al. 1998) and pesticides (Boul et al. 1994), which also results in higher direct and indirect GHG emissions (Robertson et al. 2000; Saggar et al. 2007).

However, the recent adoption of silvopastoral systems has been reported as resulting in positive aspects when compared with conventional systems in the Andean zone, with

increases in milk productivity (Correa et al. 2008; Aguilar et al. 2009), efficient use of nitrogen through biological fixation (Medina et al. 2008), and restoring the potential for soil carbon sequestration and biomass carbon fixation (Giraldo et al. 2008), including GHG mitigation (Grainger et al. 2009). Evaluating and characterizing FCO₂ (soil CO₂ flux) in degraded and managed pasture areas and describing their spatial–temporal variability and any correlation with possible controlling factors, Figueiredo et al. (2017a) concluded that degraded pasture area released significantly more CO₂–C comparing with the well-managed pasture. This indicates that the introduction of best management practices in pasture areas is an important strategy to reduce additional soil CO₂–C losses and thereby contributes to soil C accumulation in those areas.

Despite several efforts for the introduction of more sustainable agricultural systems in Colombia, there is still some resistance in adopting silvopastoral systems in the tropics (Fedegan-Cipav 2010; FAO 2010), which could be supported by studies that present positive outcomes not only from the GHG balance but also from a more suitable introduction of these agricultural systems. Therefore, the objective of this study was to estimate the GHG emissions and potential C sinks, considering the emission sources and sinks related to conventional agriculture, improved pasture and silvopastoral production systems in the Nariño region, Colombia, in order to identify a promising silvopastoral system toward greater sustainability for tropical conditions.

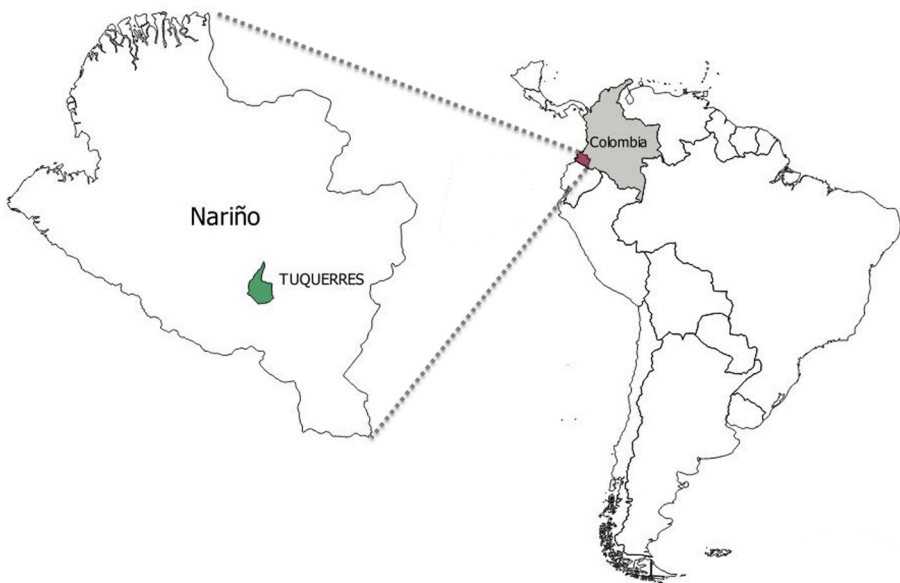


Fig. 1 Schematic picture of the evaluated scenarios located in Túquerres city, Nariño state, Colombia

2 Materials and methods

2.1 Location and production scenarios

The systems considered in this study refer to the milk production areas located in the Andean region, city of Túquerres, state of Nariño, southwest Colombia (Fig. 1). The pasture areas in this region are located at around 3070 m above sea level with geographical coordinates 1°05'14"N and 77°37'08"W. It is one of the highest plateaus of the country exceeding 2900 m above sea level, with an average temperature of 8–12 °C, average annual rainfall around 900 mm, and weather classification of Dfb, according to the Köppen climate classification, cold temperate climate with no dry season and with tempered summer (Köppen 1948).

Our database is related to the real production scenarios applied in the Andean zone of Colombia, considering the practices conducted with animals, soil management and agricultural activities related to agricultural systems described in the following sections. The production scenarios considered are: (1) conventional agriculture under pastures of *P. clandestinum* in rotation with potatoes (PRP); (2) improved pastures of *L. multiflorum* (IP); and (3) silvopastoral system represented by pastures of *P. clandestinum* in combination with *Acacia decurrens* and *Trifolium repens* (SPS). All scenarios investigated run in a 6-year cycle, with PRP having a crop sequence of potatoes, pasture, and animal grazing in the first and fourth year and pasture and animal grazing during the other years. In the case of IP scenario, animal grazing and pasture are considered during all cycles. But in the case of SPS scenario, animal grazing with pasture associated with Acacias trees run in all years during the 6-year cycle.

Table 1 presents the details associated with the zootechnical and agronomic parameters of the production scenarios of Andean region considered in this study. The crop sequence considered in the PRP scenario is potatoes in monoculture with two cycles per year, conventional soil tillage, high input of fertilizers and pesticides, high residue production (Guerrero 1998), followed by pasture of *P. clandestinum*, extensive systems with degraded pastures using 2 years for grazing production (Guerrero 1998), and low inputs of fertilizers and having low milk productivity, with rotational grazing of animals every 90 days (Bernal 1994). Around 10% of pastures with *P. clandestinum* (1400 ha) are used in the Andean zone for dairy cattle (Solarte et al. 2006). The intensification applied in the unfertilized rotations of pastures in PRP had to be sustained through the extraction of soil reserves.

In the IP scenario, the agronomic characteristics are intensive system with high grass production, high residue production from pasture that is replanted every year (Bernal 1994) by using conventional tillage, with high demand for nitrogen fertilizers and concentrates as animal supplementation, and high productivity of milk, with rotational grazing of animals every 45 days (Bernal 1994). Around 1500 ha has been converted to this production system in the Andean region in the last years (Solarte et al. 2006).

The silvopastoral system, i.e., the SPS scenario, is characterized by the introduction of grass species with higher productivity in 6 years consecutively with *A. decurrens* trees, whose fodder comprising leaves and stems is used for grazing and animal feeding (Giraldo et al. 2008; Giraldo and Bolivar 2004). The trees are used as fence for surrounding the pasture area, which are spaced 1 m apart, resulting in a total of 400 trees ha⁻¹ (Giraldo and Bolivar 2004). This system also includes soil management by subsoiling (Noreña 2011) and planting of clover forage legume (Sanchez and Villaneda 2009). Biological nitrogen fixation in SPS displaces the use of synthetic nitrogen fertilizers (Naranjo et al. 2012) with

Table 1 Characterization of the production systems considered: PRP—conventional agriculture with pastures of *Pennisetum clandestinum* in rotation with potatoes; IP—improved pasture of *Lolium multiflorum*; SPS—silvopastoral systems represented by pastures of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens* presented in the Andean region of Colombia with zootechnical and agronomic parameters

Agricultural characterization of the systems ^a	Chronosequence of management in each year					
	1	2	3	4	5	6
PRP	Potato	Pasture	Pasture	Potato	Pasture	Pasture
IP	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
SPS	Permanent pasture of <i>Pennisetum clandestinum</i> with <i>Acacia decurrens</i> and clover					
Zootechnical characterization ^a	PRP		IP		SPS ^b	
Type of pasture	Degraded		Improved		Productive	
Type of management system	Extensive		Intensive		Semi-extensive	
Animal genetics	Holstein		Holstein		Holstein	
Stocking rate (AU ha ⁻¹ yr ⁻¹) ^c	0.5		1.5		1.5	
Production (liter of milk animal ⁻¹ day ⁻¹)	10		18		17	
L of milk ha ⁻¹ yr ⁻¹	1825		9855		9308	

^a Extracted from Guerrero (1998), Bernal (1994), Solarte et al. (2006), Fedegan-Cipav (2010)

^b Silvopastoral system combination of improved pasture of *Pennisetum clandestinum* and legumes with shrubs of *Acacia decurrens* at a density of 400 trees per hectare as living fence

^c AU for 650 mature weights lactating cow (kg)

a stocking rate lower than that of intensive silvopastoral systems (Fedegan-Cipav 2010; Naranjo et al. 2012) and rotational grazing of animals every 60 days (Table 1).

2.2 Emission sources and sinks and amounts of agricultural supplies

Table 2 summarizes the sources and potential sinks of the most important GHG emissions (CO₂, CH₄ and N₂O) associated with each of the production systems considered in the methodological approach of this study. Additionally, the data on the agricultural supplies and fuel consumption due to agricultural activities conducted in each assessed scenario are listed in Table 3.

2.3 The emission factors

2.3.1 CH₄ and N₂O from enteric fermentation and manure management

To estimate the emission associated with CH₄ by enteric fermentation, the equations proposed by the IPCC Tier 2 methodology [IPCC (2006); Chapter 10, Table 10.3] were applied to estimate daily gross energy intake for dairy cattle with 412, 302 and 298 MJ head⁻¹ day⁻¹ for milk production in PRP, IP and SPS scenarios, respectively. Gross energy depends on the digestible energy (DE%) of the food considered in our study as 65, 70 and 72% for PRP, IP and SPS, respectively, and that produced in a CH₄ enteric emission factor of 90, 79 and 59 kg CH₄ head⁻¹ year⁻¹ for PRP, IP and SPS, respectively.

Table 2 Emission sources and respective greenhouse gas considered for each evaluated agricultural system: conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS) in the Andean region of Colombia

	PRP	IP	SPS
Emissions from animal and pasture management	CH ₄ from enteric fermentation	CH ₄ from enteric fermentation	CH ₄ from enteric fermentation
	CH ₄ from manure	CH ₄ from manure	CH ₄ from manure
	N ₂ O from urine and dung on pasture	N ₂ O from urine and dung on pasture	N ₂ O from urine and dung on pasture
Emissions from soil management	N ₂ O from N fertilizer	N ₂ O from N fertilizer	N ₂ O from N fertilizer
	N ₂ O from crop residues and pasture renewal	N ₂ O from residues of pasture renewal	N ₂ O emissions from residues of Acacia leaves
Emissions from agricultural sources	CO ₂ from lime use	CO ₂ from lime use	CO ₂ from lime use
	CO ₂ from potassium and phosphorus use	CO ₂ from potassium and phosphorus use	CO ₂ from potassium and phosphorus use
	CO ₂ from pesticides use	CO ₂ from pesticides use	CO ₂ from pesticides use
	CO ₂ from concentrates	CO ₂ from concentrates	CO ₂ from concentrates
	CO ₂ from fossil fuel (Gasoline)	CO ₂ from fossil fuel (gasoline)	CO ₂ from fossil fuel (gasoline)
Potential for soil C sequestration	Soil C sequestration	Soil C sequestration	Soil C sequestration
Biomass C			<i>Acacia decurrens</i> and <i>Pennisetum clandestinum</i>

CH₄ emission derived from manure management was based on the estimation of the amounts of volatile solid (VS) excretion in manure, which were considered in the present study as 5.3, 5.1 and 4.7 kg DM head⁻¹ day⁻¹ for PRP, IP and SPS, respectively. These also resulted in distinguished methane emission factor associated with manure for each of the studied scenarios as 1.5, 1.4 and 1.3 kg CH₄ head⁻¹ year⁻¹ for PRP, IP and SPS, respectively. Values of VS were estimated based on feed intake and digestibility of food.

N₂O emission associated with manure management was estimated by also taking into account the annual average nitrogen excretions as 18.4, 75.1 and 40 kg head⁻¹ year⁻¹ for PRP, IP and SPS, respectively, resulting in emission factors of 0.4, 4.3 and 2.3 kg N₂O head⁻¹ year⁻¹ for the respective scenarios.

2.4 N₂O from soil management and CO₂ from agricultural activities

The direct and indirect emissions from nitrogen fertilizer application and above-ground residues were estimated by using IPCC (2006) methodology. The emission factor regarding lime was assumed as 0.477 kg CO₂-eq kg⁻¹ (dolomite) in PRP, IP and SPS scenarios (IPCC 2006). The emission factors associated with the manufacturing, transport, and storage of potassium and phosphate fertilizers were 0.2 kg CO₂-eq kg⁻¹ for phosphorus and 0.15 kg CO₂-eq kg⁻¹ for potassium, as proposed by Lal (2004). For pesticides, the

Table 3 Annual amounts of agricultural supplies and fossil fuel use (medium values for a 6-year production cycle), considered for each agricultural system

Supplies ^a	Amounts		
	PRP	IP	SPS
N synthetic fertilizer (kg N ha ⁻¹ yr ⁻¹)	65 ^b	120 ^c	50 ^d
N organic fertilizer (kg N ha ⁻¹ yr ⁻¹)	30	–	–
N from crop residues (kg N ha ⁻¹ yr ⁻¹)	67	102	22
Lime (kg ha ⁻¹ yr ⁻¹)	666 ^e	1000 ^f	166 ^g
P fertilizers (kg ha ⁻¹ yr ⁻¹)	40 ^b	24 ^c	60 ^h
K fertilizers (kg ha ⁻¹ yr ⁻¹)	30 ^b	50 ^d	50 ^h
Concentrated (kg ha ⁻¹ yr ⁻¹)	406	2190	2068
Pesticides (kg ha ⁻¹ yr ⁻¹)	24	10	–
Gasoline (L ha ⁻¹ yr ⁻¹)	282	93	53

PRP conventional agriculture, IP improved pasture, SPS silvopastoral system)

^a Data from Guerrero (1998) and Bernal (1994)

^b 1500 kg 13-26-6 PRP (Guerrero 1998), during 2 years (potato seeding) in cycle of 6 years

^c 400 kg ha⁻¹yr⁻¹ of 30-6-0 (Guerrero 1998) each year in IP

^d 50 kg ha⁻¹yr⁻¹ (Guerrero 1998), 50 kg ha⁻¹yr⁻¹(Guerrero 1998)

^e 2 t ha⁻¹ before of potatoes seeding

^f 1 t ha⁻¹ yr⁻¹ (Guerrero 1998)

^g 1 t ha⁻¹ in all cycle

^h For native pastures in consortium with clover. Some of the amounts presented were obtained directly in the production locations

emission factor depends on the type of pesticide applied (Helsel 1992) to control pests and diseases in PRP and IP scenarios (Lal 2004). The amount of commercial feed concentrate used in each of the systems corresponds to 1 kg per 4.5 L of milk produced (Bernal 1994). The emission factor used was 0.59 kg CO₂-eq kg⁻¹ of concentrate (Hassan 2011).

The fossil fuel used in the agricultural operations (e.g., machinery) in the Andean region of Colombia is usually gasoline, with an emission factor under tropical conditions estimated to be 2.33 kg CO₂-eq L⁻¹ of gasoline (Hassan 2011). All emissions values were converted into CO₂ equivalent following the individual global warming potentials for a period of 100 years, using 1 for CO₂, 25 for CH₄ and 298 for N₂O (IPCC 2007).

2.4.1 Soil and biomass carbon pools

Reference value for the soil carbon stock in extensive pastures of the Andes, Colombia, was based on the data from Silva et al. (2010), which is 147.9 Mg ha⁻¹ in the top 30-cm layer. This value is considered as our baseline for soil carbon stock in extensive pasture, and it is used for estimating changes in soil carbon stocks by converting from extensive pasture to PRP, IP and SPS scenarios (Fig. 2). The ratio of gains/losses of soil carbon in the evaluated scenarios was estimated by using a specific methodology proposed by IPCC (2006), which takes into account the factors related to soil management practices: land use (FLU), tillage practices (FMG) and residue inputs (FI) for a time period of 20 years (IPCC 2006). In addition to the intensity of management adopted (for instance, high, medium and

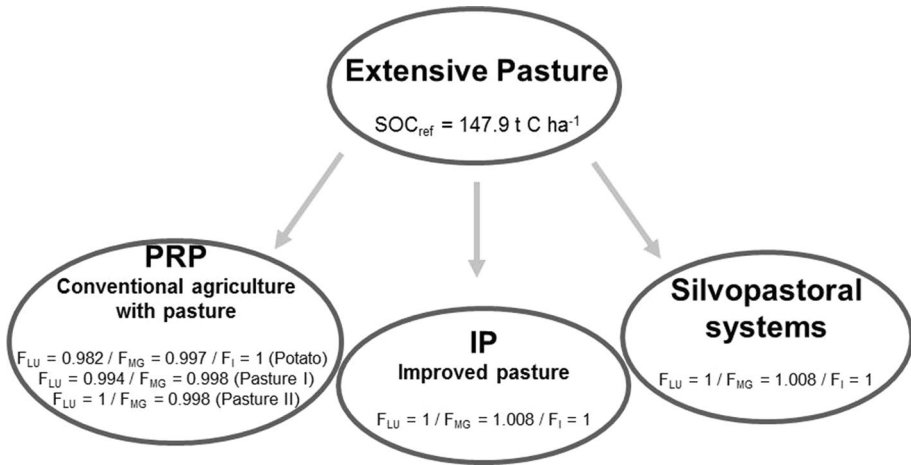


Fig. 2 Representation of the main aspects (SOC reference and stock change factors) considered for estimations of soil C gain/losses (changes) in the conversion from extensive pasture to other studied scenarios: conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS)

low inputs), these factors also take into account climate and soil type in the specific region. The accumulation rate of carbon in biomass was estimated in SPS only. Based on IPCC (2006) methodology, the increase in biomass carbon stock was assumed to be 4.5 Mg C ha⁻¹ year⁻¹, considering the wood component for *Acacia* spp. in South America.

3 Results and discussion

3.1 Greenhouse gas emissions

The highest emissions for all production systems were estimated to be produced from CH₄ due to enteric fermentation, with 1125, 2963 and 2213 kg CO₂-eq ha⁻¹ year⁻¹, corresponding to 31, 38 and 45% of the total GHG emission in PRP, IP and SPS scenarios, respectively (Table 4 and Fig. 3). The second highest emission source varied among the assessed scenarios. In PRP, CO₂ related to fossil fuel use was the second highest emission source, followed by N₂O from cattle dung and urine in IP, and CO₂ from concentrates used to feed cattle in SPS. These emissions correspond to 18, 17 and 25% of the total GHG emission in PRP, IP and SPS scenarios, respectively (Fig. 3). The third higher emission sources were also dissimilar among the scenarios studied. The sources were associated with N₂O emissions from synthetic fertilizer in PRP and N₂O emission from dung and urine in IP and SPS scenarios, corresponding to 11, 16.9 and 14% of the total emissions in PRP, IP and SPS scenarios, respectively.

The total GHG emission differed mostly between IP and PRP scenarios, with the highest and lowest emissions being 7711 and 3684 kg CO₂-eq ha⁻¹ year⁻¹, respectively. This difference of 4027 kg CO₂-eq ha⁻¹ year⁻¹ is primarily due to the varying cattle intensity in the production systems (0.5 × 1.5 stocking rate; Table 1), as this comes mostly from CH₄ emission by enteric fermentation and CO₂ from concentrates in cattle feed. With an intermediate total GHG emission, SPS scenario resulted in 4878 kg CO₂-eq ha⁻¹ year⁻¹, which is lesser than that of IP but higher than PRP total emissions.

Table 4 GHG emissions related to conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS) in the Andean region of Colombia, according to each emission source (kg CO₂eq ha⁻¹ yr⁻¹) considered herein

Sources	PRP	IP	SPS
CH ₄ and N ₂ O emissions from animal and pasture management			
CH ₄ from enteric fermentation	1125	2963	2213
CH ₄ from manure management	19	53	49
N ₂ O from dung and urines on pasture	105	1286	686
N ₂ O emissions from soil management			
N ₂ O emissions from synthetic N fertilizer	403	745	310
N ₂ O from organic fertilizer	200		
N ₂ O from above-ground residues	384	585	126
CO ₂ from agricultural activities			
CO ₂ from lime use	317	476	79
CO ₂ from potassium and phosphorus use	46	45	71
CO ₂ from concentrates	240	1292	1220
CO ₂ from pesticides use	188	50	–
CO ₂ from due fossil (Gasoline)	657	216	124
Total GHG emissions	3684	7711	4878

GHG emissions related to the stocking rates in each agricultural system, 0.5 AU ha⁻¹ yr⁻¹ in PRP, 1.5 AU ha⁻¹ yr⁻¹ in IP and SPS. Mean values for 6-year cycle

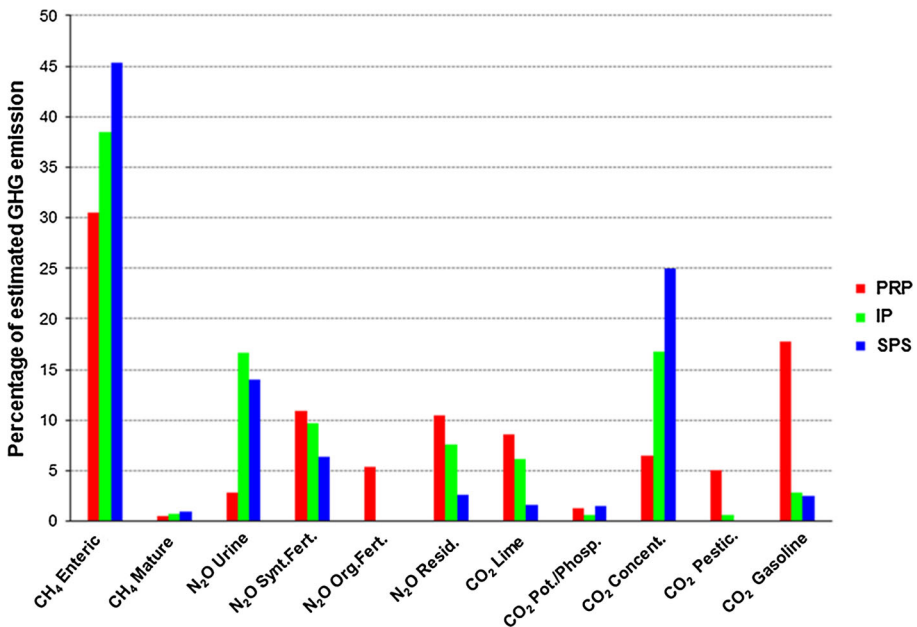


Fig. 3 Percentage of estimated GHG emissions for each source of the assessed production scenarios: conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS)

Hence, a lower CH₄ emission from enteric fermentation per head would be achieved in IP rather than in PRP, due to a better feed digestibility found in improved pasture conditions, as listed in Table 4. This assertion is supported by several studies (Primavesi et al. 2004, Figueiredo et al. 2017b), which showed that the efficiency of grass utilization,

individual animal performance and production per hectare is largely determined by improved management practices.

When comparing SPS and IP emission sources, it could be observed that the reduction of the total emissions results from the different sources. For instance, our calculation of CH₄ emission from enteric fermentation in the PRP scenario is related to low efficiency of grass utilization, rotational grazing practices with potatoes, grass digestibility of 65%, and gross energy of 412 MJ head⁻¹ day⁻¹, which resulted in an emission factor of 90 kg CH₄ head⁻¹ year⁻¹ that was associated with a stocking rate of 0.5 AU ha⁻¹ year⁻¹, resulting in 1125 kg CO₂-eq ha⁻¹ year⁻¹ (Table 4). CH₄ emissions from enteric fermentation due to animal and pasture management of *L. multiflorum* for milk production in the IP scenario were related to intensive grazing, higher grass digestibility of 72%, and gross energy of 302 MJ head⁻¹ day⁻¹, which accounted for a higher share of emissions of 2963 kg CO₂-eq ha⁻¹ year⁻¹ (47%) (Table 4), and was even related to a lower emission factor of 79 kg CH₄ head⁻¹ year⁻¹, but was influenced by higher stocking rate of 1.5 AU ha⁻¹ year⁻¹.

From the SPS scenario, the adoption of animal and pasture management of *P. clandestinum* and *T. repens* with browsing of leaves of *A. decurrens* for milk production with better feed digestibility of 75% and gross energy of 298 MJ head⁻¹ day⁻¹ resulted in significantly lower emissions of 53 kg CH₄ head⁻¹ year⁻¹. When associated with a stocking rate of 1.5 AU ha⁻¹ year⁻¹, it corresponded to an emission of 2213 kg CO₂-eq ha⁻¹ year⁻¹ (Table 4). Our results point out to a high contribution of CH₄ from enteric fermentation in milk production systems in the Andean zone of Colombia and the importance to the management of improved pasture areas, resulting in higher feed digestibility and lower associated GHG emissions. In addition, Apraez et al. (2012) showed the impact of a diet with *A. decurrens* rich in tannins on the reduction of enteric methane emissions. A similar trend was observed by Hess et al. (2002), who indicated tannins in many legume species to be associated with reduction of methane production (e.g., up to 50%) compared with traditional single pasture diet.

3.2 Potential C sinks

The estimations of potential sinks either in soils or in biomass for all assessed scenarios are presented in Fig. 4 (kg CO₂-eq ha⁻¹ year⁻¹) considering a 6-year cycle. Our estimation indicates a reduction in soil carbon stock in extensive pasture of PRP system from 147.9 to 138.95 Mg C ha⁻¹, which results in a soil carbon loss of 8.95 Mg C ha⁻¹ in the 6-year period. Mean annual value of this loss, when converted into CO₂-eq, would represent an emission of 5471 kg CO₂-eq ha⁻¹ year⁻¹ (Fig. 4).

On the other hand, a conversion of extensive pasture to IP system resulted in carbon stock ranging from 147.9 to 154.99 Mg C ha⁻¹, which represents a soil carbon sink of 7.09 Mg C ha⁻¹ over the 6-year cycle. This gain corresponds to a potential for soil carbon accumulation of 4342 kg CO₂-eq ha⁻¹ year⁻¹. Likewise, the SPS scenario presented the same potential for soil carbon accumulation of 7.09 Mg C ha⁻¹ (6 years), which resulted in the same CO₂ sink value. The system that presented the better potential for GHG mitigation was SPS. As according to our results, it has, in addition to the potential for soil carbon accumulation, the trees *A. decurrens* that have the potential to absorb as much as 16,500 kg CO₂-eq ha⁻¹ year⁻¹ (Fig. 4).

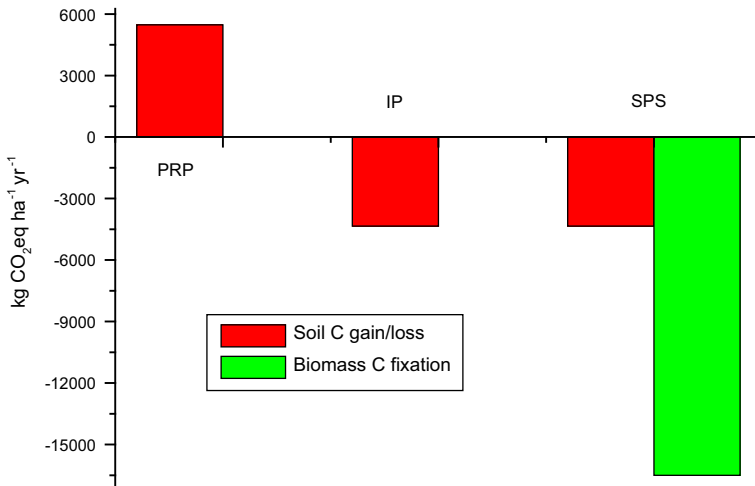


Fig. 4 Potential C sinks or emissions from soils and biomass (kg CO₂eq ha⁻¹ yr⁻¹) for each evaluated production scenario: conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS)

3.3 Discussion on the greenhouse gas balance, considering total emission and potential sinks

In a recent report, FAO (2010) presented intermediate levels of GHG emissions between 3 and 5 kg CO₂-eq kg⁻¹ of fat- and protein-corrected milk for South America. The world average would represent a value of carbon footprint associated with milk production as close to 2.4 kg CO₂-eq kg⁻¹ of milk. In this study, however, only the GHG balance was considered for the assessed production systems instead of carbon footprint of milk production. The results of GHG balance are listed in Table 5, considering the total GHG emissions as well as the potential for soil carbon gain/loss and biomass carbon fixation. The PRP scenario presented the lowest GHG emission (3684 kg CO₂-eq ha⁻¹ year⁻¹), but also presented the lowest milk production (1825 L ha⁻¹ year⁻¹). Although potato is produced in this scenario, further emissions would be expected according to our

Table 5 GHG balance (in kg CO₂eq ha⁻¹yr⁻¹) considering the total GHG emissions and the respective potential for soil carbon accumulation and biomass carbon fixation of each evaluated scenario (PRP, IP and SPS)

Components	PRP	IP	SPS
Total GHG emissions	3684	7711	4878
Soil C gain/loss ^a	5471	- 4342	- 4342
Biomass C fixation ^b	-	-	- 16,500
GHG balance	9155	3369	- 15,964

PRP conventional agriculture with pastures of *Pennisetum clandestinum* in rotation with potatoes, IP improved pasture of *Lolium multiflorum*, SPS silvopastoral systems represented by pastures of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens*. Mean values for a 6-year cycle

^a Negative values indicate soil carbon accumulation and positive soil C losses (converted into CO₂eq)

^b Negative values refer to gain in biomass C reservoirs

estimations because of soil carbon losses (5471 kg CO₂-eq ha⁻¹ year⁻¹), leading to the highest GHG balance of 9155 kg CO₂-eq ha⁻¹ year⁻¹ in relation to the other assessed scenarios of milk production.

The IP scenario resulted in the highest GHG emission (7711 kg CO₂-eq ha⁻¹ year⁻¹), but also presented the highest milk productivity (9855 L ha⁻¹ year⁻¹) and an additional potential for soil carbon accumulation equivalent to 4342 kg CO₂-eq ha⁻¹ year⁻¹. In this scenario, total GHG emissions were partially offset by the soil carbon accumulation and therefore resulted in GHG balance of 3369 kg CO₂-eq ha⁻¹ year⁻¹. Comparing the three assessed scenarios, the results showed that SPS merged two important strategies to mitigate the GHG emissions from milk production, such as the potentials for soil carbon accumulation (4342 kg CO₂-eq ha⁻¹ year⁻¹) and for biomass carbon accumulation (16,500 kg CO₂-eq ha⁻¹ year⁻¹), which is even higher than the expected for soil carbon accumulation. Both soil and biomass carbon sinks in the SPS scenario completely offset the total GHG emissions of milk production and thereby resulted in GHG balance of -15,964 kg CO₂-eq ha⁻¹ year⁻¹ (Table 5).

Despite the huge potential for mitigation of GHG emissions, especially in the SPS scenario, it is important to highlight that soil carbon accumulation could be lost rapidly depending on the soil management decision taken for these sites. For instance, La Scala et al. (2006) reported significant emissions induced by intensive tillage operations in southern Brazil. Additionally, the use of *Acacia* wood after harvest, or even leaving those as living fence, can effectively contribute for the potential of biomass carbon fixation to turn into a carbon pool with prolonged longevity, or sequestration.

4 Conclusions

The conversion of conventional agriculture areas to a more intensive pasture or silvopastoral system for milk production increased total GHG emission per unit area, but also reduced the GHG emission per unit of product (kg CO₂eq per kg of milk), as a result of a more efficient production system and higher yields. Although the IP has showed a higher milk production compared to all assessed systems, the SPS presented the lowest GHG emission per unit of milk produced. Silvopastoral system represented by pastures of *P. clandestinum* in combination with *A. decurrens* and *T. repens* (SPS) showed to be a promising integrated system that has the potential to offset GHG emissions associated with milk production, which could contribute for the development of a more sustainable milk production system. However, it is also important that these management systems be considered along with economic and social aspects. This study supports the conclusion that the intensification of dairy cattle production leads to a reduction in GHG emissions per unit of product in the Andean zone of Colombia. Further, the great advantage of intensification is not only associated with GHG mitigation, but also in the reduction in land needed to produce the same quantity of product. Our findings appear as good indicator of the main sources of GHG emission in the dairy cattle production in both extensive and intensive systems in Colombia and could contribute to a better understanding of the Colombian milk production chain in the context of sustainability. However, there exists a need for additional experimental studies to further comprehend the potential carbon sinks in soils and biomass in the Andean region of Colombia.

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