SÃO PAULO STATE UNIVERSITY – UNESP
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GREENHOUSE GAS BALANCE IN THE CONVERSION FROM EXTENSIVE PASTURE TO OTHER AGRICULTURAL SYSTEMS IN ANDEAN REGION OF COLOMBIA

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2015

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Thesis presented to the Faculty of Agricultural and Veterinary Sciences – UNESP, Campus of Jaboticabal, as part of the requirements for obtaining the title of Doctor of Agronomy (Soil Science).

2015

P258g

Parra, Amanda Silva

Greenhouse gas balance in the conversion from extensive pasture to other agricultural systems in Andean region of Colombia / Amanda Silva Parra. – – Jaboticabal, 2015

xi, 36 p. : il. ; 28 cm

Tese (doutorado) - Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, 2015

Orientador: Newton La Scala Junior

Banca examinadora: Gener Tadeu Pereira, Glauco de Souza Rolim, Marcelo Valadares Galdos, Débora Marcondes Bastos Pereira Milori

Bibliografia

1. Carbon sequestration in soil and biomass. 2. GHG mitigation. 3. Milk production scenarios. 4. Global warming. 5. Climate Change. 6. Grassland. 7. Trees. I. Título. II. Jaboticabal-Faculdade de Ciências Agrárias e Veterinárias.

CDU 631.433.3

Ficha catalográfica elaborada pela Seção Técnica de Aquisição e Tratamento da Informação – Serviço Técnico de Biblioteca e Documentação - UNESP, Câmpus de Jaboticabal.

unesp **UNIVERSIDADE ESTADUAL PAULISTA**
CAMPUS DE JABOTICABAL
FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS DE JABOTICABAL

CERTIFICADO DE APROVAÇÃO

TÍTULO: GREENHOUSE GAS BALANCE IN THE CONVERSION FROM EXTENSIVE PASTURE TO OTHER AGRICULTURAL SYSTEMS IN ANDEAN REGION OF COLOMBIA

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Aprovada como parte das exigências para obtenção do Título de DOUTOR EM AGRONOMIA (CIÊNCIA DO SOLO) , pela Comissão Examinadora:

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Data da realização: 08 de abril de 2015.

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Amanda Silva Parra – borned November 01, 1965 in Florence city, Caquetá state, Colombia. In 1990, she graduated from Agronomy Engineer and later in 2005 from Project Management Specialist at Nariño University in Colombia. In 2006, she received her title from Magister in Agricultural Science emphasis Soil Science at Colombia National University. She was agronomy university Professor for The Nariño University in Colombia. In 2011, she made the admission in Brazil at The Faculty of Agricultural and Veterinary Sciences of São Paulo State University, Jaboticabal Campus and in April 2015, she received her title from Doctor in Agronomy in Soil Science. Recently, she made the admission at Llanos University in Colombia as professor of Agronomy in Soil Science. She pretend to continue research related to soil CO_2 emissions.

Be the change that you wish to see in the world.

Seja a mudança que você quer ver no mundo.

Mahatma Gandhi

I DEDICATE

God first, his indescribable love.

To my Professor Dr. Newton to be part of this important process in my life.

This is for you, Luis Carlos and for you Andres Felipe. Thanks for always being there for me.

I dedicate this to my mother Carmen and my father Esteban, both have done so many things for me that I do not where to begin. Thank you very much.

I dedicate this to Hernando Criollo Escobar and his mother for her endless support; for all the love my son Luis Carlos.

To my sister Judith and her husband Guillermo Guerrero Urrutia, who always communicate with me and gave me strength to continue.

To my beautiful sisters Betty and Nancy, and their families for being part of my life and always give strength in this long way.

To my brothers Esteban and Fernando, and their families because they always knew understand my ideals.

My family and other friends unconditional of Colombia and Brazil.

To all women of the world, we are different in customs, races, religions, but we are equal in our ideals.

Thank very much, do not be afraid to take a big step.

ACKNOWLEDGEMENTS

I wish to sincerely thank my supervisor, Prof. Dr. Newton La Scala Junior. I am appreciative for her guidance and support over the last two years.
I would like to extend a very special thank you to Dr. Eduardo Barretto de Figueiredo, for his time and constructive comments on this thesis.
I wish to sincerely thank you to M.Sc. Ricardo Oliveira de Bordonal. For all their help in this research.
I am especially grateful to my dear friend M.Sc. Mara Regina Moitinho, for all their help in this research. Your friendship is there every day; that is why it is so important.
I would also like to thank my committee member of qualification, Prof. Dr. José Carlos Barbosa, Prof. Dr. Jose Marques Junior, Prof. Dr. Gener Tadeu Pereira, and Prof. Dr. Glauco de Souza Rolim.
I would also like to thank my committee member of defense, Dra. Débora Marcondes Bastos Pereira Milori, Prof. Dr. Gener Tadeu Pereira, Prof. Dr. Glauco de Souza Rolim and Dr. Marcelo Valadares Galdos Pereira for helping me with the construction of this research.
I will forever be indebted to the group with whom I worked in Brasil: Risely Ferraz de Almeida, Clariana Valadares, and Elienai Ferreira, Daniel de Bortoli Teixeira, Telmo Mendes. Thank them from the bottom of my heart.
I would also like to extend my sincerest gratitude to the families of Prof. Dr. Newton La Scala Junior and Maria Jose Servidore Trizòlio, who helped me with my child Andres Felipe. For all the hope and faith that I received from them.
I am so grateful to have been able to work in the company of Shirley Ap. Martinelli de Souza.
Finally, to Nariño University in Colombia and UNESP in Brazil, for being part of this process.

SUMMARY

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GREENHOUSE GAS BALANCE IN THE CONVERSION FROM EXTENSIVE PASTURE TO OTHER AGRICULTURAL SYSTEMS IN ANDEAN REGION OF COLOMBIA

ABSTRACT – The challenge of agricultural sector is to reduce emissions and increase food production, taking into account environmental aspects. In Andean zone of Colombia, there is a growing need to develop GHG (greenhouse gas) mitigation techniques associated to milk production. This work focuses on the GHG emissions and potential sinks associated to milk production scenarios in the Andean zone of Colombia. The scenarios considered were: conventional agriculture of *Pennisetum clandestinum* in rotation with potatoes (PRP), improved pastures of *Lolium multiflorum* (IP) and silvopastoral system of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens* (SPS). Based on the IPCC (2006) methodologies, the annual emission balance for a 6-year production cycle included agricultural sources and gasoline consumption related to the main agricultural phases in field, and the potential for soil C accumulation and biomass C fixation in all studied scenarios. Lower GHG emissions were estimated in PRP scenario (3,864 kg CO_2eq ha^{-1} yr^{-1}), but this presents the lower milk productivity. The higher GHG emissions were observed in IP scenario (7,711 kg CO_2eq ha^{-1} yr^{-1}), which presented the highest milk productivity and a considerable potential for soil C accumulation, that could help into the offset of its emissions. But SPS scenario, which has a milk productivity close to IP, presented the highest potential to offset GHG emission (4,878 kg CO_2eq ha^{-1} yr^{-1}) due to soil C accumulation plus biomass C fixation in trees.

Keywords: carbon sequestration in soil and biomass, climate change, GHG mitigation, global warming, grassland, milk production scenarios, trees

BALANÇO DE GASES DE EFEITO ESTUFA NA CONVERSÃO DE PASTAGEM EXTENSIVA PARA SISTEMAS AGROPECUÁRIOS NA REGIÃO ANDINA DA COLÔMBIA

RESUMO – O desafio do setor agrícola é reduzir as emissões e aumentar a produção de alimentos, tendo em conta os aspectos ambientais. Na zona andina da Colômbia, há uma crescente necessidade de se desenvolver técnicas de mitigação de GEE (gases de efeito estufa) associados à produção de leite. Este trabalho considera as emissões de GEE e os potenciais sumidouros de carbono associados aos cenários de produção de leite na zona andina da Colômbia. Os cenários considerados foram: agricultura convencional de *Pennisetum clandestinum* em rotação com batatas (PRP), pastagens melhoradas de *Lolium multiflorum* (IP) e sistema silvipastoril de *Pennisetum clandestinum* em consórcio com *Acacia decurrens* e *Trifolium repens* (SPS). Com base nas metodologias do IPCC (2006) e considerando-se um ciclo de produção de 6 anos, o balanço anual das emissões compreende as fontes agrícolas e o consumo de gasolina relacionadas com as principais fases de produção agrícola, e o potencial de acúmulo de C no solo e a fixação de C na biomassa em todos os cenários estudados. Menores emissões de GEE foram estimados no cenário de PRP (3.864 kg CO_2eq ha^{-1} ano^{-1}), porém apresenta uma menor produtividade de leite. As maiores emissões de GEE foram observadas no cenário IP (7.711 kg CO_2eq ha^{-1} ano^{-1}), que apresentou uma maior produtividade de leite e um potencial considerável para o acúmulo de C no solo, que poderia ajudar na compensação das emissões. No cenário SPS, que tem uma produtividade de leite próximo de IP, apresentou o maior potencial para compensar as emissões de GEE (4.878 kg CO_2eq ha^{-1} ano^{-1}) devido ao acúmulo de C solo e a fixação de C na biomassa em árvores.

Palavras-chave: sequestro de carbono no solo e na biomassa, mudanças climáticas, mitigação de GEE, aquecimento global, pastagens, cenários de produção de leite, árvores

CHAPTER 1 – General considerations

1.1 Introduction

Grasslands are the largest ecosystems in the world with an estimated area of 52.2 million km^2, corresponding to around 40% of the total land in the world (REYNOLDS; FRAME, 2005), while pasture areas in Colombia are estimated around 33.9% of the country total area (IGAC, 2003).

Worldwide, dairy farms produced about 730 million tonnes of milk in 2011, from 260 million dairy cows. India is the world's largest producer and consumer of milk. New Zealand, the European Union's 28 member states, Australia, and the United States are the world's largest exporters of milk and milk products (FAO, 2012). Throughout the world, there are more than 6 billion consumers of milk and milk products.

Cattle in Colombia reached in the year 2013 23.5 million of heads, but the production of milk, based in dairy cattle, was around 6,617 million of litters (FEDEGAN, 2013). During several decades, kikuyo (*Pennisetum clandestinum* Hoest) pasture has been the baseline scenario of the dairy sector production system in Colombia as well as in Andine Zone of Colombia (LAREDO; MENDOZA, 1982; GUERRERO, 1998). The Savannah Túquerres in Nariño has 9,745 heads of dairy cattle with an average production of 12.9 million liters of milk $year^{-1}$ occupying 16,000 hectares (SOLARTE; MARTINEZ; BURGOS, 2006), predominating extensive systems of *Pennisetum clandestinum* grass (2,800 meters above sea level), associated to conversion from forest around 50 years ago. Those areas, nowadays, could be considered as degraded, being kept with Holstein mostly (SOLARTE; MARTINEZ; BURGOS, 2006).

In the last years it has emerged other alternatives to avoid the problems related to pasture degradation (SOLARTE; MARTINEZ; BURGOS, 2006). The most common systems converted is the conventional agriculture of *Pennisetum clandestinum* in rotation with potatoes, which pasture is generally managed extensively (SILVA et al., 2010). Most recently, silvopastoral systems (SPSs) have been adopted in Andean zone of Colombia, being scaled up to regional levels.

Several research groups in Colombia have sustained the adoption of silvopastoral systems in order to adapt to and/or mitigate the GHG effect (CARULLA; LASCANO, 1994; HOLMANN et al., 2003; GIRALDO et al., 2003; MEDINA et al., 2008; APRAEZ et al., 2012). Certainly, the adoption of those agricultural systems replacing extensive pasture would impacts on soil (BILOTTA; BRAZIER; HAYGARTH, 2007) and biomass C reservoirs (NARANJO et al., 2012), affecting the GHG balance in several ways due to their sources associated to each of those production systems (VAN DER NAGEL; WAGHORN; FORGIE, 2003; ERNST; SIRI-PRIETO; CANO, 2005; ECKARD; JOHNSON; CHAPMAN, 2006; THORNTON; HERRERO, 2010; NARANJO et al., 2012).

Colombia has presented its National Communication of Climate Change to the United Nations Framework Convention on Climate Change (UNFCCC), based on its National GHG Inventories (GALEANO et al., 2009). Considering GHG emissions of land use and land use change Colombia was responsible for 0.41% of global emissions associated to this source in year 2000 (GALEANO et al., 2009). In the year of 2004 agricultural sources were responsible to 38.09% of Colombia´s GHG total emission, being mostly due to enteric fermentation and manure, those two sources only corresponded to 96% of agricultural activities emission. When added emissions associated to land use change and conversions from natural areas to agriculture, the total contribution jumps to 52.54%, more than half of the country´s GHG emissions. On that year, 2004, the partition of emission in main the GHG were 49.8% to CO_2, 30.1% to CH_4 and 19.1% to N_2O, being those two last gases mainly related to agricultural sources.

1.2 Objective

The objective of this study is to estimate the GHG balance associated to the conversion of extensive pasture to three different milk production scenarios in the Andean region, Colombia.

1.3 Literature review

1.3.1 On the GHG emission and sinks in agriculture

The anthropogenic contribution on global warming is mainly due to additional emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere (STEINFELD et al., 2006; IPCC, 2007), being those also associated with agricultural sources and activities (FLYSJÖ et al., 2011). Following we describe the main sources and sinks associated to agriculture, take into account the estimations presented in this work.

1.3.1.1 Methane from enteric fermentation and manure management

In general, the primary source of methane (CH_4) emissions from dairy cattle production is enteric fermentation, the only GHG emissions of concern resulting from enteric fermentation is CH_4 (PRIMAVESI et al., 2004; MORGAVI et al., 2010). The amount of methane emitted is related primarily to the gross energy (GE), which is the amount of energy (MJ day^{-1}) that an animal needs for maintenance and for activities such as growth, lactation, and pregnancy (IPCC, 2006). It is also dependent on methane conversion factor, the percent of gross energy in feed which is converted to CH_4. GE and Ym (Methane conversion factor) depend on feed digestibility and both factors define the methane emission factor (MEF) (IPCC, 2006). Digestibility of food is mainly related to neutral detergent fiber (NDF) and acid detergent fiber (ADF), Approximately 5% of the variation in the proportion of gross energy is lost as CH_4 and could be explained by the digestibility of dietary energy (JOHNSON; JOHNSON, 1995).

According Hassan (2011), the highest CH_4 emissions is from enteric fermentation from lactating cows, and those emissions are significantly higher than those from bulls, dry cows, heifers and calves. Changes in CH_4 emission factors (MEF) depending on different management of production systems were also observed by this author.

When animal productivity is increased, the absolute amount of CH_4 per animal also increases, but the CH_4 emission per unit of animal product decreases (O'HARA; FRENEY; ULIATT, 2003). Livestock management feeding practices, can reduce CH_4 emissions from enteric fermentation by 1-22% for dairy cows and this effect varies depending also on management of the animals (THORNTON; HERRERO, 2010).

Manure management also emits CH_4, as a result of microbial action of methanogens (anaerobic processes) (IPCC, 2006). CH_4 emissions from manure management should be lower when manure is deposited naturally on grassland, as it decomposes aerobically, with oxygen (IPCC, 2006).

The amount of manure produced annually for each type of animal is available as the amount of volatile solids (VS) production and the maximum amount of methane able to be produced from that manure (IPCC, 2006). Production of volatile solids (VS) can be estimated based on feed intake and digestibility (IPCC, 2006). The Intergovernmental Panel on Climate Change (IPCC, 2006), presents for dairy cattle sector, in Latin America, emission factor of CH_4 from enteric fermentation (Tier 2) as 72 kg CH_4 head^{-1} year^{-1} and by manure management of 1 kg CH_4 head^{-1} year^{-1}.

1.3.1.2 Nitrous oxide emission from manure and soil management

The source of NH_3 emission from manure management is the N excreted by livestock (dung and urines) (IPCC, 2006). Typically, more than half of the N excreted by livestock is in urine, and between 65 and 85 % of urine-N is urea and other readily mineralized compounds (JARVIS et al., 1995).

Several transformations from manure management occur via combined nitrification and denitrification of N contained in the manure (N_2O direct emissions) (PRIMAVESI et al., 2004; IPCC, 2006; SAGGAR et al., 2007). The indirect N_2O emissions occur via volatilization of N in forms of NH_3 and NOx (IPCC, 2006). Nitrification is the biological oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-), with N_2O being a by-product (IPCC, 2006). Denitrification is the biological reduction of nitrate to gaseous nitrogen (N_2), with N_2O being an obligatory intermediate (IPCC, 2006).

Grazing ruminants utilize relatively little of the N in feed (WHITEHEAD, 1995) 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. Other researchers have shown that the addition of tannin in diet reduces the losses of N by urine and N retention by the animal (DE KLEIN; ECKARD, 2008).

Mora (2001) obtained on farms of low, medium and high level of input use, 1.33, 1.20 and 1.94 kg N_2O head^{-1} yr^{-1} from manure, being the larger emissions of GHG corresponded due to higher inputs. Naranjo et al. (2012) in Tropical conditions of Colombia estimated N_2O emissions from manure management (dung and urines) in beef cattle 355 kg CO_2eq ha^{-1} yr^{-1} in degraded pastures, 961 kg CO_2eq ha^{-1} yr^{-1} in improved pasture and 1,230 kg CO_2eq ha^{-1} yr^{-1} for silvopastoril systems of Acacia and *Eucalyptus tereticornis* Sm. In tropical conditions, between 0.21 to 2.87 kg N_2O head^{-1} year^{-1} were emitted due manure management (MESSA, 2009).

According to the World Bank (2008), in 1988 the use of N fertilizers in grasslands in Colombia was 137 kg ha^{-1}, being almost double in intensity as compared to the South American with average of 74 kg ha^{-1}, resulting in higher direct and indirect N_2O emissions. Silva et al. (2010), in Andean zone of Colombia, showed that N deficiencies usually limit productivity at the short term and affect *Pennisetum clandestinum* grass yield.

Silvopastoral systems can substantially reduce the use of synthetic fertilizers through biological nitrogen fixation (BNF) of leguminous tress (NARANJO et al., 2012), which in turn, reduces the consumption of fossil fuels in the production of fertilizers. Biological nitrogen fixations (BNF) in silvopastoral systems contribute significantly to the nitrogen nutrition and pasture productivity (MURGUEITIO et al., 2011). Silvopastoral systems can 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 (NARANJO et al., 2012).

N_2O emissions associated with management practices increase the availability of N on soil (PASSIONATO et al., 2003; ALVAREZ, 2005; PAVELEY et al., 2008); which may reduce benefit brought by increased sequestration of SOC in these systems (URQUIAGA et al., 2010).

1.3.1.3 Carbon dioxide emission from agricultural activities

Lime application in agriculture is an emission source of CO_2, due to limestone dissolved in soil cations (Ca and Mg), exchanged for hydrogen ions (H^+), colloid soil, forming bicarbonate ($2HCO_3$), which can transform into CO_2 and H_2O (IPCC, 2001). According by the Intergovernmental Panel on Climate Change (IPCC, 2006) all C in lime is eventually released as CO_2 to the atmosphere.

Agricultural lime is commonly applied to soils in the Andean zone to increase soil pH (GUERRERO, 1998) and aglime includes crushed limestone ($CaCO_3$) and crushed dolomite (Mg-Ca $(CO_3)_2$) (GUERRERO, 1998). The IPCC (2006) 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 (GUERRERO, 1998). According to Intergovernmental Panel on Climate Change (IPCC, 2006), 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 (NAIR et al., 2009).

Pesticide manufacturing represents about 9% of the energy use of arable crops, less for spring crops and more for potatoes and about 3% of the 100-year Global Warming Potential (GWP) from crops (IPCC, 2006; SMITH et al., 2007). It is assumed that due course all the carbon included in the pesticide will be broken down and emitted to the atmosphere as carbon dioxide (IPCC, 2006).

1.3.1.3.1 C fixation in biomass

Carbon storage in forest and agroforestry systems ranges from 10 to 40, 20 to 150 and 30 to 200 Mg C for boreal, temperate and tropical forest ecosystems, respectively (DIXON; TURNER, 1991). Young trees have high growth rates but contain relatively little C, while mature trees present higher C content (COOPER, 1983). Land-use change in forest ecosystems of tropical latitudes is a major CO_2

source, but the range of emissions estimates is around 1.6 ±1.0 Pg C annually (COOPER, 1983). Forest ecosystems can be net sources or sinks of CO_2, depending on dominant biological or physical factors, including: state of the soil and vegetation (system undisturbed, disturbed or recovering); harvesting, deforestation, reforestation of trees; environmental conditions; environmental pollution and no pollution (BROWN, et al., 1992). The IPCC (2006) believes that the semiannual and annual crops around the C accumulated is lost during harvest and therefore are not C sinks.

The ability of silvopastoral systems for carbon capture, if focuses on biomass, both aerial and root (NAIR et al., 2009) is performed by means of the total biomass in inventory systems, expressing the values in tons of carbon per hectare using a fraction of carbon as 0.5 % fraction of carbon in dry matter (IPCC, 2006).

According Kimaro et al. (2007), after a 5 year fallow period with *Acacia auriculiformis* and variations of species the carbon fixed in biomass of Acacia sp. fall within the range of values of 1.50–6.55 t C ha^{-1} yr^{-1} and coincided with values reported by Nair et al. (2009). Continuous maize (*Zea mays* L.) cropping systems were included as controls.

1.3.1.3.2 C sequestration in soil

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of SOC (IPCC, 2001).

Total C in terrestrial ecosystems is approximately 3,170 gigatons (1 Gt is equivalent to 1 petagram, equivalent to 1 billion metric tons). Of this amount, nearly 80% (2,500 G ton) is found in soil (LAL, 2008). Globally, soil systems contain up to three or more C than above-ground biomass (560 GT) (DIXON; TURNER, 1991). The soil is considered the main temporary reservoir ecosystem of C (LAL, 2008), presenting on average 4.5 times more C than the C in biota and 3.3 times more than the atmosphere (LAL, 2004), being considered an important component increase and reduction of CO_2 in the atmosphere (LAL, 2004).

Estimates presented by Lal (2004) suggested that 400-800 Mt C yr^{-1} (equivalent to about 1,400-2,900 Mt CO_2eq yr^{-1}) could be sequestered in global agricultural soils with a finite capacity saturating after 50 to 100 years.

In general, increased C accumulation is associated with a land use factor (FLU), related the type of land use, an input factor (FI) which is related to the input of C in soil, and a tillage factor related to the kind and frequency of tillage applied (FMG) (IPCC, 2006).

The literature is rich with examples where conservation practices can be used to mitigate and adapt to climate change, the increase in C stocks is subject to greater amounts of crop residues returned to the soil and minimal soil disturbance (WANG et al., 2010; JOHNSON; EDWARDS; MASERA, 2010). Regarding soil C sequestration (CARVALHO, 2009) found a soil accumulation rate of 0.46 t C ha^{-1} yr^{-1} was determined in Brazil pasture area, in a pasture not degraded with no restrictions of fertilization in a fertile soil.

Conant et al. (2001) reviewed about 115 studies in 17 countries on the effects of grazing management on soil organic matter. This author considered values of soil C sequestration rates ranged from -0.2 to +3.0 t C ha^{-1} yr^{-1}, showing that fertilization of pasture, proper animal management, the use of productive species, conversion of agricultural crops in permanent pasture, the presence of legumes and the use of irrigation increased C accumulation in the soil.

Silvopastoral systems represent an important alternative to the recovery of degraded areas of *Pennisetum clandestinum* in Andean zone as those are able to maintain soil organic matter and nutrient cycling through the addition of litter and root residues into the soil (GIRALDO; BOLIVAR, 2004). Giraldo et al. (1995), showed litter production of 367 kg DM ha^{-1} yr^{-1} with 407 trees per ha of *Acacia decurrens.* There is a large potential of sequestering carbon in soil (GIRALDO; ZAPATA; MONTOYA, 2008).

Reis (2007), evaluating the interference of Ipê Felpudo trees on pastures, verified larger amount of C stored in the SSP, 2.43 t C ha^{-1} stored in the litter, 13.9 t ha^{-1} C in the biomass and 53.1 t C ha^{-1} in the soil, totaling 69.53 t ha^{-1} C compared to 61.08 t C ha^{-1} found under monoculture grass. Kimaro et al. (2007) have also found increases in soil C stocks after a 5 year fallow period, organic C in the top 0–15 cm soil depth under *A. nilotica*, *A. polyacantha* and *A. mangium,* significantly higher (21.6–25.6 t C ha^{-1}) than the organic C (13 t C ha^{-1}) in the continuously cropped soils.

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CHAPTER 2 – On the greenhouse gas balance in three milk production scenarios in the Andean region of Colombia

2.1 Introduction

The agricultural sector represents a significant source of greenhouse gas (GHG) worldwide due to direct and indirect emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Estimates have pointed that agriculture contributes to the enhanced GHG effect by emitting around 7.1 Gt of CO_2eq, or ~18% of total global anthropogenic GHG emissions (STEINFELD et al., 2006).

Approximately 14,000 hectares in the Savannah of the city of Túquerres in southern Colombia are intended for grazing dairy cattle in extensive systems of *Pennisetum clandestinum* (SOLARTE; MARTINEZ; BURGOS, 2006), being currently on degradation (SILVA et al., 2010), and with low forage diversity and low productivity (SILVA et al., 2010). On those areas, crop and livestock production are closely linked to the traditional mixed conventional agricultural system, characterized by degraded pastures of *Pennisetum clandestinum* in rotation with potatoes (GUERRERO, 1998), or are changed completely each year for planting improved pastures of *Lolium multiflorum* (BERNAL, 1994).

Conventional agricultural systems have been adopted intensively with high utilization of agricultural inputs such as soluble fertilizers, mainly nitrogen (SMITH, TAGGART; TSURUTA, 1997; OENEMA et al., 1997; McGRATH et al., 1998) and pesticides (BOUL et al., 1994), which also results in direct and indirect GHG emissions (ROBERTSON; PAUL; HARWOOD, 2000; SAGGAR et al., 2007).

But the recent adoption of silvopastoral systems has been reported as resulting in positive aspects when compared to conventional systems in Andean areas, with increases in milk productivity (CORREA; PABON; CARULLA, 2008; AGUILAR et al., 2009), efficient use of N through biological fixation (MEDINA; OROZCO; DIAZ, 2008) and potential for soil sequestration and biomass C fixation (GIRALDO; ZAPATA; MONTOYA, 2008) including GHG mitigation (GRAINGER et al., 2009).

Despite all the efforts, there is still some resistance to adopt silvopastoral systems in the tropics (FEDEGAN-CIPAV, 2010; FAO, 2010). The objective of this work was to estimate the GHG emission sources and sinks related to conventional agriculture, improved pasture and silvopastoral production systems in the Nariño region, Colombia.

2.2 Materials and Methods

2.2.1 Production scenarios and location

Our database is related to the real production scenarios applied in the Andean Zone of Colombia, considering 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: pastures of *Pennisetum clandestinum* in rotation with potatoes (PRP); 2) improved pastures of *Lolium multiflorum* (IP); and 3) silvopastoral system represented by pastures of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens* (SPS). All scenarios run in a 06-year cycle (Figure 2.1), with PRP having a crop sequence of potatoes, pasture and animal grazing in first and fourth years, with pasture and animal grazing in other years. In the case of IP scenario, animal grazing in pasture in considered in all cycle. But in the case of SPS scenario, animal grazing with pasture associated with Acacias would run in all years during the 6-year cycle.

The systems considered in our study refer to the milk production located in the Andean region, city of Túquerres, state of Nariño, South-West Colombia. Those pasture areas are placed at around 3,070 m above sea level in geographical coordinates of 1°05′14″N 77°37′08″W. It is one of the highest plateaus of the country exceeding 2,900 meters above sea level, with an average temperature of 8-12ºC, annual rainfall averages around 900 mm and weather classification of *Dfb*, according to the Köppen climate classification, microtherm no dry weather station (KÖPPEN 1948).

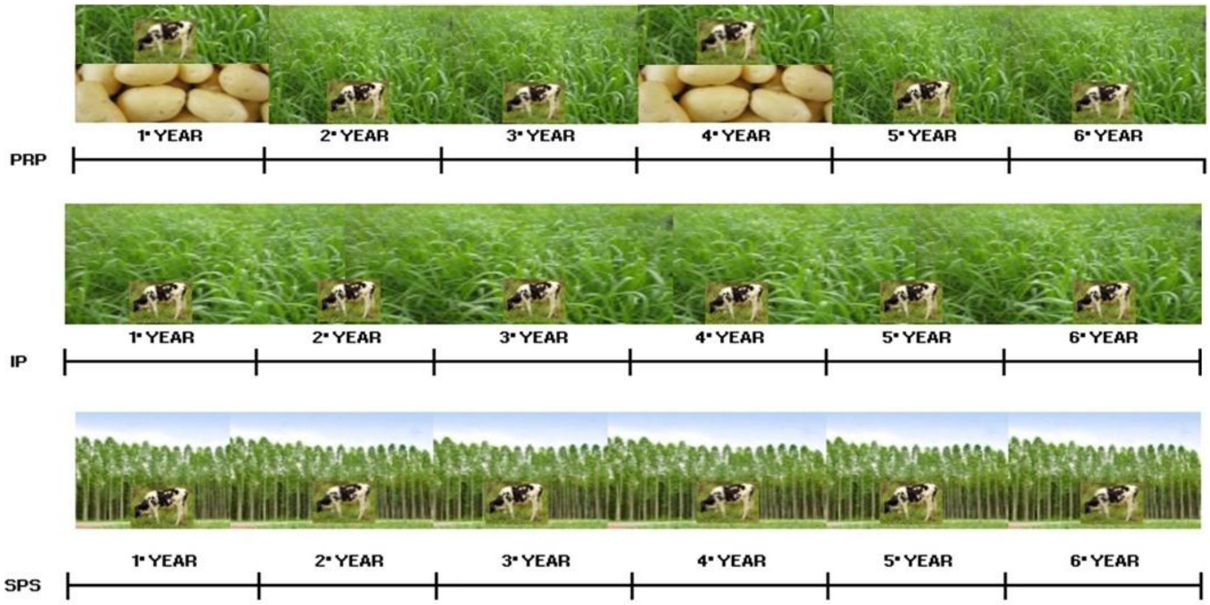

Figure 2.1. Schematic representing the main aspects associated with the 6-year cycle of the 03 production scenarios considered: PRP: conventional agriculture: pastures of *Pennisetum clandestinum* in rotation with potatoes. IP: improved pastures of *Lolium multiflorum* and SPS*:* silvopastoral system represented by pastures of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens.*

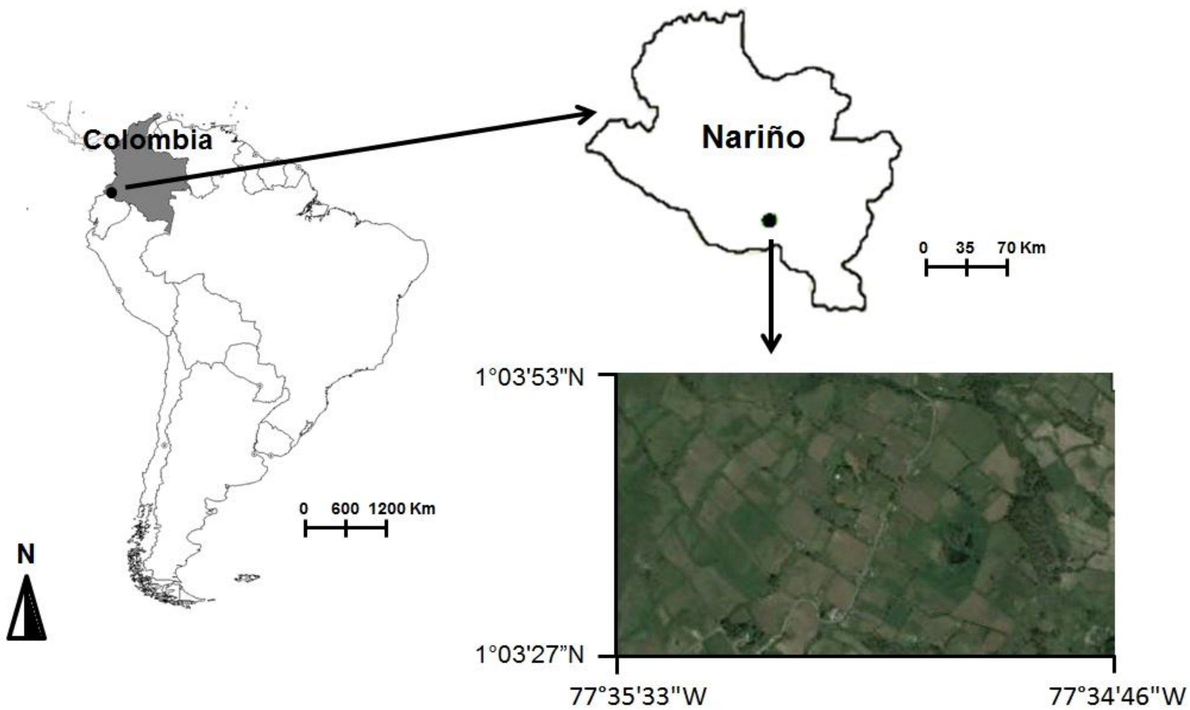

Figure 2.2. Close photo of the pasture area and location of the studied scenarios located in Túquerres city, Nariño state, Colombia.

2.2.2 Characterization of production systems

Table 2.1 presents the details associated to the zootechnical and agronomic parameters of the production scenarios of Andean region considered in this study. The crop sequence considered in the scenario PRP is potatoes in monoculture with two cycles per year, conventional soil tillage, high input of fertilizers and pesticides, high residues production (GUERRERO, 1998), followed by pasture of *Pennisetum clandestinum*, extensive systems with degraded pastures using 02 years for grazing production (GUERRERO, 1998), low input of fertilizers and having low milk productivity, with rotational grazing of animals every 90 days (BERNAL, 1994). Around 10% of pastures with *Pennisetum clandestinum* (1,400 ha) are used in the Andean zone of Colombia for dairy cattle (SOLARTE; MARTINEZ; BURGOS, 2006). The intensification applied in unfertilized rotations of pastures in PRP had to be sustained through the extraction of soil reserves.

Table 2.1. 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 zoo technical and agronomic parameters.

Agricultural characterization of the systems[1]	Sequence 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 *Pennisetum clandestinum* with *Acacia decurrens* and clover					

Zoo-technical characterization[1]	PRP	IP	SPS [2]
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}) [3]	0.5	1.5	1.5
Production (liter of milk $animal^{-1}$ day^{-1})	10	18	17
L of milk ha^{-1} yr^{-1}	1,825	9,855	9,308

[1] Extracted from Guerrero (1998), Bernal (1994), Solarte, Martinez and Burgos (2006), Fedegan-CIPAV (2010). [2] 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. [3] AU for 650 mature weights lactating cow (kg).

In the scenario IP, the agronomic characteristics are intensive system with high grass production, high residues production from pasture which is replanted every year (BERNAL, 1994), using conventional tillage, with high demand for N fertilizers and concentrates as animal supplementation and high productivity of milk, rotational grazing of animals every 45 days (BERNAL, 1994). Around 1,500 ha are converted to this production system in Andean region, Colombia (SOLARTE; MARTINEZ; BURGOS, 2006).

Silvopastoral system, SPS scenario, is characterized by introduction of grass species with higher productivity in 06 years consecutively with *Acacia decurrens,* which fodder of leaves and stems are used as grazing feeding (GIRALDO; ZAPATA; MONTOYA, 2008; GIRALDO; BOLIVAR, 2004). The trees are used as fence surrounding pasture area in arrangement of 1 m apart, resulting in a total of 400 trees ha^{-1} (GIRALDO; BOLIVAR, 2004). This system also includes soil management by subsoiling (NOREÑA, 2011) and planting of clover forage legume (SANCHEZ; VILLANEDA, 2009). Biological N_2 fixation in SPS displaces synthetic N fertilizer use (NARANJO et al., 2012), with stocking rate lower than in intensive silvopastoral systems (FEDEGAN-CIPAV, 2010; NARANJO et al., 2012) and rotational grazing of animals every 60 days (Table 2.1).

2.2.3 Emission sources and sinks and amount of supplies

Table 2.2 presents the sequence of sources and potential sinks related to the main greenhouse gases (CO_2, CH_4 and N_2O) associated to each of the production systems under analysis in our study.

Table 2.2. Emission sources and respective greenhouse considered in each on the systems related to the 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 manure N_2O from urine and dung on pasture.	CH_4 from enteric fermentation. CH_4 from manure N_2O from urine and dung on pasture.	CH_4 from enteric fermentation. CH_4 from manure N_2O from urine and dung on pasture.
Emissions from soil management	N_2O from N fertilizer. N_2O from crop residues and pasture renewal.	N_2O from N fertilizer. N_2O from residues of pasture renewal.	N_2O from N fertilizer. N_2O emissions from residues of Acacia leaves
Emissions from Agricultural sources.	CO_2 from lime use. CO_2 from potassium and phosphorus use. CO_2 from pesticides use CO_2 from concentrates CO_2 from fossil fuel (Gasoline).	CO_2 from lime use. CO_2 from potassium and phosphorus use. CO_2 from pesticides use CO_2 from concentrates CO_2 from fossil fuel (Gasoline).	CO_2 from lime use. CO_2 from potassium and phosphorus use. CO_2 from pesticides use CO_2 from concentrates CO_2 from fossil fuel (Gasoline).
Potential to soil C sequestration Biomass C	Soil C sequestration	Soil C sequestration	Soil C sequestration *Acacia decurrens* and *Pennisetum clandestinum*

Table 2.3 presents the agricultural supplies and fuel consumption due to agricultural activities conducted in each of the studied systems.

Table 2.3. Annual amount of agricultural supplies applied and fossil fuel use (medium values for a 6-years cycle) for each agricultural systems studied. PRP: Conventional agriculture, IP: Improved pasture and SPS: Silvopastoral system.

Supplies[(1)]	Amount		
	PRP	IP	SPS
N synthetic fertilizer (kg N ha^{-1} yr^{-1})	65[a]	120[b]	50[c]
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[d]	1000[e]	166[f]
P fertilizers (kg ha^{-1} yr^{-1})	40[a]	24[b]	60[g]
K fertilizers (kg ha^{-1} yr^{-1})	30[a]	50[c]	50[g]
Concentrated (kg ha^{-1} yr^{-1})	406	2,190	2,068
Pesticides (kg ha^{-1} yr^{-1})	24	10	---
Gasoline (L ha^{-1} yr^{-1})	282	93	53

[(1)] Data from Guerrero (1998) and Bernal (1994). [a]1,500 kg 13-26-6 PRP (Guerrero, 1998), during two years (potato seeding) in cycle of 6 years. [b] 400 kg $ha^{-1}yr^{-1}$ of 30-6-0 (Guerrero, 1998) each year in IP, [c]50 kg $ha^{-1}yr^{-1}$ (Guerrero, 1998), 50 kg $ha^{-1}yr^{-1}$(Guerrero, 1998), [d] 2 t ha^{-1} before of potatoes seeding, [e]1 t ha^{-1} yr^{-1} (Guerrero, 1998), [f]1 t ha^{-1} in all cycle. [g] for native pastures in consortium with clover. Some of the amounts presented were obtained directly in the production sites.

2.2.4 On the emission factors

2.2.4.1 CH_4 and N_2O from enteric fermentation and manure management

To estimate emission associated to CH_4 by enteric fermentation it was applied the equations proposed by the IPCC Tier 2 methodology IPCC (2006), Chapter 10 (Table 10.3), used to estimate daily gross energy (GE) intake for dairy cattle with 412, 302 and 298 MJ $head^{-1}$ day^{-1} for milk production in PRP, IP and SPS scenarios, respectively. GE depends on the food digestible energy (DE%) considered in our study 65, 70 and 72%, for PRP, IP and SPS, respectively, and those resulted in a CH_4 enteric emission factor of 90, 79 and 59 kg CH_4 $head^{-1}$ yr^{-1} for PRP, IP and SPS, respectively.

CH_4 derived from manure management was based on the estimated on the amount of volatile solid (VS) excretion in manure, which was considered here as 5.3, 5.1 and 4.7 kg DM $head^{-1}$ day^{-1}, in PRP, IP and SPS, respectively. Those also resulted in distinguished methane emission factor associated to manure for each of the studied scenarios as 1.5, 1.4 and 1.3 kg CH_4 $head^{-1}$ yr^{-1} for PRP, IP and SPS, respectively. Values of VS were estimated based on feed intake and digestibility of food.

N_2O emission associated to manure management was estimated by also taking account the annual average N excretions as 18.4, 75.1 and 40 kg Nexc $head^{-1}$ yr^{-1} for PRP, IP and SPS, respectively, resulting in emission factor of 0.4, 4.3 and 2.3 kg N_2O $head^{-1}$ yr^{--1} , for those scenarios.

2.2.4.2 N_2O from soil management and CO_2 from agricultural activities

The direct plus indirect emissions from N fertilizer application and above ground residues were estimated by using IPCC (2006) methodology. Emission factor regarding lime was assumed as 0.477 kg CO_2eq kg-1 (dolomite) in PRP, IP and SPS (IPCC, 2006). Emission factors associated with the manufacturing, transport and storage of potassium and phosphate fertilizers were 0.2 kg CO_2eq kg-1 for P and 0.15 kg CO_2eq kg-1 for K, as proposed by Lal (2004). For pesticides, the emission factor depends on the type of pesticide applied (HELSEL, 1992) to control pests and diseases in PRP and IP (LAL, 2004). The amount of commercial feed concentrate used in each of the systems corresponds to 1 kg per 4.5 liters of milk produced (BERNAL, 1994). The EF used was 0.59 kg CO_2eq kg-1 of concentrate (HASSAN, 2011).

Fossil fuel used in the agricultural machinery in Andes Colombia is usually gasoline, with an emission factor considered as 2.33 kg CO_2eq L^{-1} of gasoline, under tropical conditions (HASSAN, 2011). All emissions values were converted to CO_2 equivalent following the individual global warming potentials for a period of 100 years, using 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007), in 100 years.

2.2.4.3 Soil and biomass C pools

Reference value for the soil C stock in extensive pastures of Andes, Colombia, was based on data from Silva et al. (2010), being this 147.9 ton ha^{-1} in the top 30 cm layer. This value is considered 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. Ratio of gains/losses of soil C in the studied scenarios were estimated by using specific methodology proposed by IPCC (2006), which takes into account 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 low inputs) those factors take into account also climate and soil type in the specific region.

Accumulation rate of C in biomass was estimated in SPS only. The increase in biomass C stock was assumed as 4.5 t C ha^{-1} $year^{-1}$, considering the wood component, based on IPCC (2006) methodology for Acacia ssp in South America.

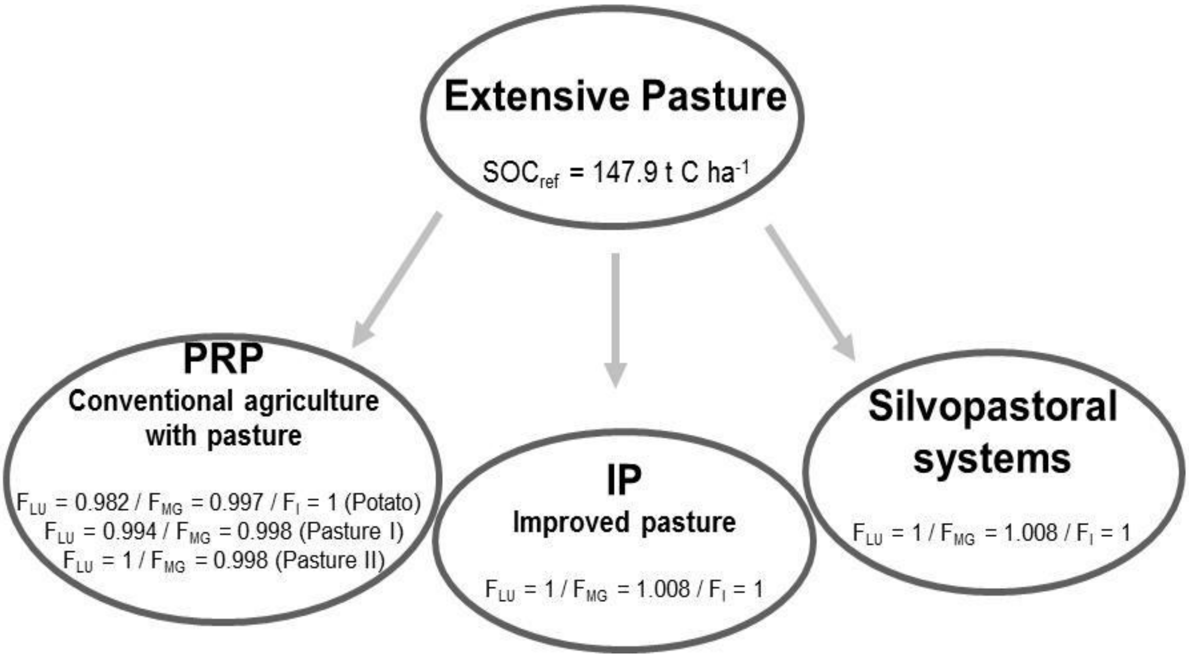

Figure 2.3. Representation of the main aspects (SOC reference and stock change factors) considered for estimations of soil C gain/losses (changes) in the conversion from extensive pasture to the studied scenarios.

2.3 Results and Discussion

2.3.1 GHG emissions

Table 2.4 presents the estimative of GHG emissions (in kg CO_2eq ha^{-1} yr^{-1}) in each of the studied scenarios (PRP, IP and SPS) in CH_4 and N_2O from animal and pasture management, N_2O from soil management and CO_2 from agricultural activities. In all production systems, the highest emissions were estimated as coming from CH_4 of enteric fermentation, 1,125, 2,963 and 2,213 kg CO_2eq ha^{-1} yr^{-1}, corresponding to 31, 38 and 45% of total GHG emission in PRP, IP and SPS scenarios, respectively (Figure 2.4). The second highest emission source varies among scenarios, in PRP this is in CO_2 related to fossil fuel use, in IP it is N_2O from cattle´s dung and urines, while in SPS it is related to the CO_2 concentrate used to feed cattle. Those emissions corresponds to 18, 17 and 25% of total GHG emission in PRP, IP and SPS scenarios, respectively (Figure 2.4). The third higher emission sources were also dissimilar in scenarios studied (Figure 2.4), those were associated to N_2O emissions from synthetic fertilizer in PRP and N_2O emission from dung and urines in IP and SPS, corresponding to 11, 16.9 and 14% of the total emissions in their respective scenarios (PRP, IP and SPS).

Total GHG emission differs mostly between IP and PRP scenarios, with highest and lowest emissions of 7,711 and 3,684 kg CO_2eq ha^{-1} yr^{-1}, respectively. This difference of 4,027 kg CO_2eq ha^{-1} yr^{-1} is mainly due to the contrasted cattle intensity in production systems (0.5 x 1.5 stocking rate, Table 2.1) as this comes from CH_4 in enteric fermentation and CO_2 from concentrates, in feed of cattle. As an intermediate total GHG emission, SPS scenario resulted in 4,878 kg CO_2eq ha^{-1} yr^{-1}, which is smaller than IP but higher than PRP total emissions.

Hence, a lower CH_4 emission from enteric fermentation per head would be achieved in IP compared to PRP due to a better feed digestibility, being higher this source in Table 2.4 just due to the stocking rate (0.5 x 1.5, PRP x IP). This assertion is supported in Primavesi (2004), which shows that the efficiency of grass utilization, individual animal performance and production per hectare is largely determined by improved management practices.

Table 2.4. GHG emissions, considering each emission source (kg CO_2eq ha^{-1} yr^{-1}), related to conventional agriculture (PRP), improved pasture (IP) and silvopastoral system (SPS) in the Andean region of Colombia.

Sources	PRP	IP	SPS
CH_4 and N_2O emissions from animal and pasture management			
CH_4 from enteric fermentation	1,125	2,963	2,213
CH_4 from manure management	19	53	49
N_2O from dung and urines on pasture	105	1,286	686
N_2O emissions from soil management			
N_2O emissions from synthetic N fertilizer	403	745	310
N_2O from organic fertilizer	200		
N_2O 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	1,292	1,220
CO_2 from pesticides use	188	50	---
CO_2 from due fossil (Gasoline).	657	216	124
Total GHG	3,684	7,711	4,878

GHG emissions related to the stocking rates in each agricultural systems, 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.

When comparing SPS and IP emission sources, it is possible to observe that the reduction of the total emissions comparing those scenarios comes from different sources. For instance, our calculation of CH_4 emissions from enteric fermentation in scenario PRP related to low efficiency of grass utilization, rotational grazing practices with potatoes, grass digestibility of 65%, gross energy of 412 MJ $head^{-1}$ day^{-1} resulted in an emission factor of 90 kg CH_4 $head^{-1}$ yr^{-1} that associated with stocking rate of 0.5 AU ha^{-1} yr^{-1}, result 1,125 kg CO_2eq ha^{-1} yr^{-1} (Table 2.4). CH_4 emissions from enteric fermentation due animal and pasture management of *Lolium multiflorum* for milk production in the scenario IP, related to intensive grazing, higher grass digestibility of 72% and gross energy of 302 MJ $head^{-1}$ day^{-1} account for a higher share of emissions of 2,963 kg CO_2 eq ha^{-1} yr^{-1} (Table 2.4) (47%), even related to alower emission factor of 79 kg CH_4 $head^{-1}$ yr^{-1} , but influenced by higher stocking rate of 1.5 AU ha^{-1} yr^{-1}.

From SPS, silvopastoril system, the adoption of animal and pasture management of *Pennisetum clandestinum* and *Trifolium repens* with browsing of leaves of *Acacia decurrens* for milk production with better feed digestibility of 75%, gross energy of 298 MJ head^{-1} day^{-1} resulted in significant lower emission of 53 kg CH_4 head^{-1} yr^{-1} that associated with stocking rate of 1.5 AU ha^{-1} yr^{-1}, corresponded to an emission of 2,213 kg CO_2 eq ha^{-1} yr^{-1} (Table 2.4). Our results point out to a high contribution of CH_4 from enteric fermentation in milk production systems in Andine zone of Colombia.

In addition, Apraez et al. (2012) showed the impact of a diet with *Acacia decurrens* for the reduction of enteric methane emissions, which is rich in tannins. A similar trend was observed by Hess et al. (2002) that indicated tannins in many legumes species to be associated with reduced of methane production, up to 50%, compared with traditional single pasture diet.

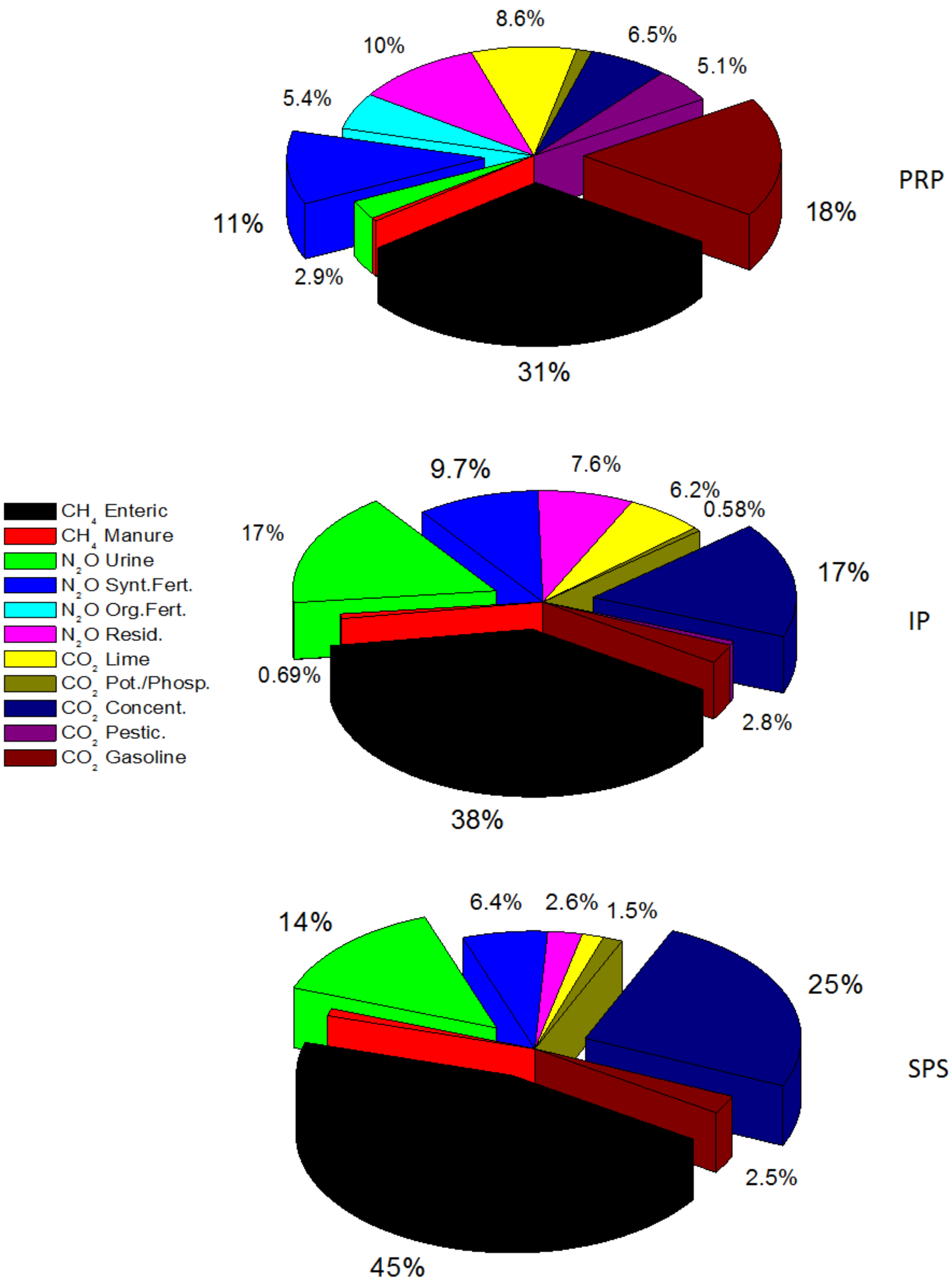

Figure 2.4. Percentage of estimated GHG emission related to distinguished sources in production scenarios PRP, IP and SPS.

2.3.2 Potential sinks

The estimative of potential sinks either in soil or in biomass is presented in Figure 2.5 (kg CO_2eq ha^{-1} yr^{-1}) considering the 6-year cycle. Our estimation indicates a reduction in soil C stock in extensive pasture to PRP from 147.9 to 138.95 t C ha^{-1}, which results in a soil C loss of 8.95 t C per hectare in the 6-year period. Mean annual value of this loss, when converted to CO_2eq would represent an emission of 5,471 kg CO_2eq ha^{-1} yr^{-1} (Figure 2.5).

On the other hand, a conversion of extensive pasture to IP system ranged from 147.9 to 154.99 t C ha^{-1}, which represents a soil C sink of 7.09 t C ha^{-1} over the 6-year cycle. This gain corresponds to a potential for soil C accumulation of 4,342 kg CO_2eq ha^{-1} yr^{-1}. Likewise, SPS scenario presented the same potential for soil C accumulation of 7.09 t C ha^{-1} (6 years) which resulted in the same CO_2 sink (negative) value (Figure 2.5).

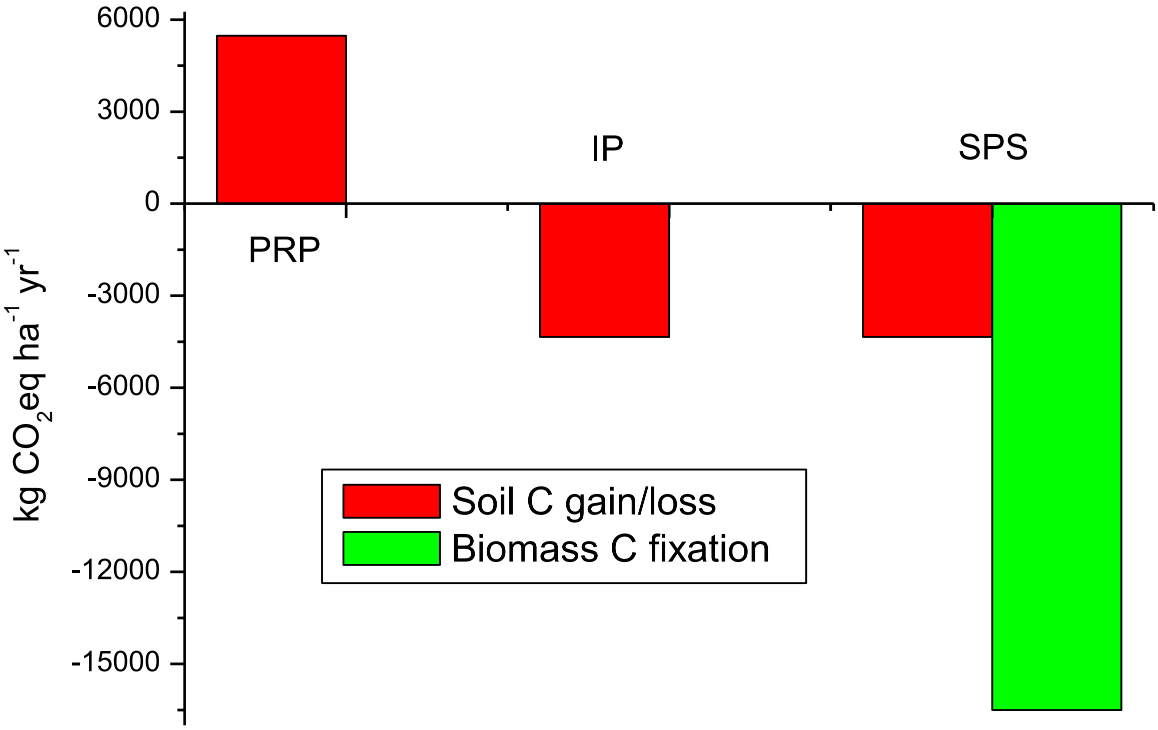

Figure 2.5. Potential C sinks in soil and biomass (kg CO_2eq ha^{-1} yr^{-1}) in studied scenarios.

The system that presented the better potential for GHG mitigation was SPS, as according to our results has, in addition to the potential soil C accumulation, the *Acacia decurrens* trees that have the potential to absorb 16,500 kg CO_2eq ha^{-1} yr^{-1} (Figure 2.5).

2.3.3 Discussion on the GHG balance, considering potential sinks

The results of total GHG emission considering the potential for soil C gain/loss and biomass C fixation are reported on Table 2.5. The PRP scenario presented the lowest GHG emission (3,684 kg CO2eq ha^{-1} yr^{-1}), but also it is important to point that this scenario presents the lowest milk production (1,825 L ha^{-1} yr^{-1}). Despite in this scenario potato is also produced; further emissions would be expected according to our estimations due to potential soil C losses (5,471 L ha^{-1} yr^{-1}).

The IP scenario resulted in the highest GHG emission (7,711 kg CO_2eq ha^{-1} yr^{-1}) but, on the other hand, has on its favor the highest milk productivity (9,855 L ha^{-1} yr^{-1}) and an additional potential for soil C accumulation equivalent to 4,342 kgCO_2eq ha^{-1} yr^{-1}.

Comparing our three studied scenarios, SPS combines two important strategies in order to mitigate the GHG emissions. The potential soil C accumulation, which is equal to IP scenario, plus a potential biomass C accumulation of 16,500 kg CO_2 ha^{-1} yr^{-1}, which is even higher than the expected soil C accumulation.

Table 2.5. Total GHG emission (in kg CO_2eq $ha^{-1}yr^{-1}$) taking into account the potential for soil C gain and biomass C fixation for PRP, IP to SPS considering the three studied scenarios.

Components	Unit	PRP	IP	SPS
Total GHG emission	kg CO_2eq $ha^{-1}yr^{-1}$	3,684	7,711	4,878
Soil C gain/loss[(1)]	kg CO_2eq $ha^{-1}yr^{-1}$	5,471	-4,342	-4,342
Biomass C fixation[(1)]	kg CO_2eq $ha^{-1}yr^{-1}$	---	---	-16,500

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.*[1] Negative values mean sink or soil carbon accumulation, converted to CO_2eq. Mean values for a 6-year cycle. [1]Negative values refer to gain in soil C stock.

In a recent report, FAO (2010) estimated for South America intermediate levels of GHG emission between 3 and 5 kg CO_2eq kg^{-1} of fat and protein corrected milk. The world average would represent a value of carbon footprint associated to milk close to 2.4 kg CO_2eq kg^{-1} of milk.

Despite the huge potential for mitigation of the GHG emissions, especially in SPS scenario, it is important to point that soil C accumulation could be lost rapidly depending of the soil management decision taken on those sites. For instance, La Scala et al. (2006) presents huge emissions induced by tillage events that are to the potential soil C accumulation in southern Brazil. Additionally, the use of *Acacia* wood after harvest, or even leaving those as living fence, determines the potential for biomass C fixation to turn a long-life C pool, or sequestration.

Therefore, silvopastoral systems represented by pastures of *Pennisetum clandestinum* in consortium with *Acacia decurrens* and *Trifolium repens* (SPS), in Andean zone, is an interesting system that has a potential to offset GHG emissions associated to milk production. Here we point out the need for further experimental studies on those sites to validate the potential C sinks in soil and biomass of that region.

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