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agrocolfabog@gmail.com
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Criollo E., Hernando; Silva P., Amanda; Delgado H., Hernando
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Balance de gases de efecto invernadero relacionado a sistemas convencionales y sostenibles de producción de frutas en la región del Altiplano de Pasto, Colombia

Hernando Criollo E.[1], Amanda Silva P.[2], and Hernando Delgado H.[2]

ABSTRACT

This research focused on the greenhouse gas (GHG) emissions and potential sinks associated with conventional and sustainable fruit production systems in the Highlands region of Pasto, Nariño, Colombia. 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 activities and the potential for soil C accumulation and biomass C fixation in all of the studied systems. The multivariate analysis showed that positive GHG balance emissions would be achieved in all sustainable fruit production systems, as compared to conventional fruit production systems with greater impact on (SS1): *Rubus glaucus* Benth. associated with *Acacia decurrens* trees and live coverage of kikuyu *Pennisetum clandestinum* grass. According to the results of this study, (SS1) showed the beneficial total GHG balance emission accounting for -21,079 kg of atmospheric CO_2eq ha^{-1} yr^{-1} divided into -4,587 kg CO_2eq ha^{-1} yr^{-1} and -17,102 kg CO_2eq ha^{-1} yr^{-1} due an annual soil and biomass C sequestration potential that could help offset its emissions (610 kg CO_2eq ha^{-1} yr^{-1}).

Key words: biomass C, climate change, mitigation practices, GHG emissions, potential sinks, soil C.

RESUMEN

Este trabajo se enfoca en las emisiones de gases de efecto invernadero (GEI) y los sumideros potenciales asociados a sistemas convencionales y sostenibles de producción de frutas en la región del Altiplano de Pasto, Nariño, Colombia. Basados en las metodologías del IPCC (2006), el balance de las emisiones anuales para un ciclo de producción media de 6 años incluyó las fuentes agrícolas y el consumo de gasolina relacionado con las principales actividades agrícolas y el potencial para acumular C en el suelo y fijar C en la biomasa en todos los sistemas estudiados. El análisis multivariado mostró que un positivo balance de emisiones de GEI puede ser alcanzada con todos los sistemas sostenibles de producción de frutales comparados con los sistemas convencionales de producción con gran impacto en (SS1): *Rubus glaucus* Benth. asociado con árboles de *Acacia decurrens* y cobertura viva de pasto kikuyo *Pennisetum clandestinum*. Basado en los resultados de este estudio, el sistema (SS1) mostró benéfico balance del total de las emisiones de GEI contabilizando -21,079 kg CO_2eq atmosférico por ha^{-1} por año, dividido en -4,587 kg CO_2eq ha^{-1} año^{-1} y -17,102 kg CO_2eq ha^{-1} año^{-1}, debido al potencial de secuestro anual de C en el suelo y la biomasa que puede contrarrestar en parte las emisiones del sistema (610 kg CO_2eq ha^{-1}año^{-1}).

Palabras clave: C de la biomasa, cambio climático, prácticas mitigadoras de GEI, potenciales sumideros, C del suelo.

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 shown 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 (Gerber *et al*., 2013).

Agricultural sources are responsible for 38.09% of Colombia´s GHG total emission (62 million t of CO_2 per year). The main partition of emission of GHG are 49.8% for CO_2, 30.1% for CH_4 and 19.1% for N_2O, being those two last gases mainly related to agricultural sources (Pedraza *et al.*, 2009).

Worldwide, the systems that are exposed to intensive uses has higher utilization of agricultural inputs as soluble fertilizers, mainly nitrogen and pesticides (Smith *et al.,* 1997; Lal, 2004; Tubiello *et al*., 2013), practices that results in direct and indirect GHG emissions (Lal, 2004).

Pesticide manufacturing represents about 9% of the energy used for arable crops (IPCC, 2006; Lal, 2004). It is assumed that due course all the carbon included in the

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[1] Grupo de Investigación Producción de Frutales Andinos, Faculty of Agricultural Sciences, Universidad de Nariño. Pasto (Colombia).

[2] Grupo de Investigación Innovacion en Sistemas Agricolas y Forestales (ISAF), Faculty of Agricultural Sciences and Natural Resources, Universidad de Los Llanos (Unillanos). Villavicencio (Colombia). asilvap@unillanos.edu.co

pesticide will be broken down and emitted to the atmosphere as carbon dioxide (IPCC, 2006).

Agroforestry systems can have a major effect on the productivity of fruit production systems, where nitrogen is often a limiting factor in production systems (Nair *et al.*, 2009). Agroforestry systems can substantially reduce the use of synthetic fertilizers through the biological nitrogen fixation (BNF) of leguminous tress (Nair *et al.*, 2009; Naranjo *et al.*, 2012).

Agroforestry is based on principles of sustainable production and diversification (Nair *et al.*, 2009; Naranjo *et al.*, 2012); an agroforestry system retains soil and biomass carbon stocks (Lal, 2011). Moreover, the soil carbon stock is related to management soil factors as land use, residue inputs of soil C and soil tillage practices (Albrecht and Kandji, 2003; IPCC, 2006).

Lal (2011) estimated that 89% of the agriculture sector's total GHG mitigation potential is from soil organic carbon (SOC) sequestration. Carbon sequestration has the potential to offset fossil fuel emissions by 0.4 to 1.2 gigatons of carbon per year (Lal, 2011).

The objective of this study is to estimate the GHG balance related to conventional and sustainable fruit production systems in the Highlands region of Pasto, Colombia, in order to identify the fruit production system that emits less GHG emissions and has greater potential to mitigation GHG emissions (soil and biomass C sequestration).

Materials and methods

Location and production systems

The systems considered in our study refer to the fruit production located in the highlands region of Pasto, state of Nariño, South-West Colombia. Geographical coordinates of 0°37' to 2º47'N and 79°03' to 76º47'W. It is one of the highest plateaus of the country located between 2,400 to 2,800 m a.s.l.

Three types of conventional fruit production systems were found in the various degraded areas of the Highlands region of Pasto, Colombia, were as follows:

Monoculture of *Rubus glaucus* Benth. (S1); monoculture of *Physalis peruviana* (S2) and monoculture of *Solanum quitoense* Lam. (S3). The cultivation of these systems had used the conventional type. On the other hand, three types of sustainable fruit production systems were found in the various areas of the highlands region of Pasto, were as follows: Agroforestry system of *Rubus glaucus* Benth. (SS1); agroforestry system of *Physalis peruviana* (SS2); agroforestry system of *Solanum quitoense* Lam (SS3). The cultivation of these systems had been associated with *Acacia decurrens* trees as living fence and live coverage of kikuyu *Pennisetum clandestinum* grass. In this study, data was collected from 20 actual farms for each one of the systems considered. Tab. 1 presents the details associated with the agronomic parameters of the fruit production systems considered in this study. All of the systems were run in a 06-year cycle (Tab. 1).

Characterization of production systems

Emission sources and sinks and amount of supplies

Table 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 this study.

Table 3 and Figure 1 present the agricultural supplies and fuel consumption due to agricultural activities conducted in each of the studied systems corresponding to variables from 1 to 8 and analysis de continuous variables in multivariate analysis.

Emission factors

N_2O from soil management and CO_2 from agricultural activities

The direct plus indirect emissions from N fertilizer applications and above ground residues were estimated by using the IPCC (2006) methodology. Emission factor regarding lime was assumed as 0.477 kg CO_2eq kg^{-1} (dolomite) (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 EF depends on the type of pesticide applied (Helsel, 1992) to control pests and diseases in all systems.

An emission factor considered as 2.33 kg CO_2eq L^{-1} of gasoline, under tropical conditions (IPCC, 2006).

Greenhouse gas emissions variables were expressed in CO_2 equivalent units to account for global warming potential of each gas in accordance with IPCC (2006), assuming a 100-year time horizon (298 for N_2O and 1 for CO_2) (Table 4, variables from 9 to 19).

TABLE 1. Land use historical of areas dedicated to fruit production systems in the Highlands region of Pasto, Colombia.

Agricultural characterization of the systems[1]		**Crop sequence of management in each year run in a 06-year cycle**					
	previous crop	**1**	**2**	**3**	**4**	**5**	**6**
S1	Pasture of kikuyu grass	Crop planting	Permanent crop of *Rubus glaucus*				
S2	Pasture of kikuyu grass	Crop planting	Monoculture crop		Crop planting	Monoculture crop	
S3	Pasture of kikuyu grass	Crop planting	Monoculture crop		Crop planting	Monoculture crop	
SS1, SS2, SS3	Introduction of sustainable fruits production systems each year similarly as explained above in fence permanent of *Acacia decurrens* and pasture						

Agronomic characterization	**Conventional systems**	**Sustainable systems**
Land use (FLU)	Continuous crop	Agroforestry[2]
Type of management system	Intensive	Sustainable
Tillage practices (FMG)	Conventional	Minimum
Residue inputs (FI)	Zero	High[3]
Living mulches	Zero	High
Practices for pesticides reduction		Biological control Plant pruning

(S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam. [1]The agronomic characterization was obtained directly in the production sites. [2]Agroforestry system combination of fruit production systems with shrubs of *Acacia decurrens* at a density of 400 trees per hectare as a living fence. [3]According to Giraldo *et al.* (1995), litter production of 407 trees per ha of *Acacia decurrens* is of 367 kg DM ha^{-1} yr^{-1}.

TABLE 2. Emission sources, greenhouse gases and sinks considered in each of the practices conducted in fruit production systems in the Highlands region of Pasto, Colombia.

Sources	**Conventional fruit production systems**	**Sustainable fruit production systems**
Emissions from soil management	N$_2$O from N syntethic fertilizer N$_2$O from N organic fertilizer	N$_2$O from N syntethic fertilizer N$_2$O from N organic fertilizer
	N$_2$O from pasture residues during soil tillage	N$_2$O from tree *Acacia decurrens* residues
Emissions from agricultural sources	CO$_2$ from lime use	CO$_2$ from lime use
	CO$_2$ from P and K use	CO$_2$ from P and K use
	CO$_2$ from pesticides use	CO$_2$ from pesticides use
	CO$_2$ from fossil fuel (Gasoline)	CO$_2$ from fossil fuel (Gasoline)
Potential to soil C sequestration Biomass C	Soil C sequestration ---------	Soil C sequestration Biomass C of permanent pasture and *Acacia decurrens*

TABLE 3. Annual amount of applied agricultural supplies, fossil fuel use (medium values for a 6 years cycle) for each fruit production systems in the Highlands region of Pasto, Colombia.

Farm variables	**Supplies**	**Amount (kg ha^{-1} yr^{-1})**						**Stadystical variables**		
		Conventional systems			**Sustainable systems**			**SD**[7]	**Min**[8]	**Max**[9]
		S1	**S2**	**S3**	**SS1**	**SS2**	**SS3**			
V1	N synthetic fertilizer	14	69[2]	100	----	37[2]	50	33.36	0	100
V2	N organic fertilizer	56[1]	----	----	56[1]	23[3]	75	32.68	0	100
V3	N from crop residues	30	59	59	22	22	22	16.74	22	59
V4	Lime	83	185	250	83	93	125	61.89	4	131
V5	P fertilizers	20	30	131	5	4	71	45.07	83	250
V6	K fertilizers	49	150	83	49	20	106	42.85	4	131
V7	Pesticides	18	8	44	-----	6	21	14.33	20	150
V8	Gasoline	61	78	78	45	45	45	---	---	---

(S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam. The amounts present were obtained directly in the production sites and supported by [1]Angulo (2006); [2]Silva *et al.* (2015) and [3]Angulo (2011).

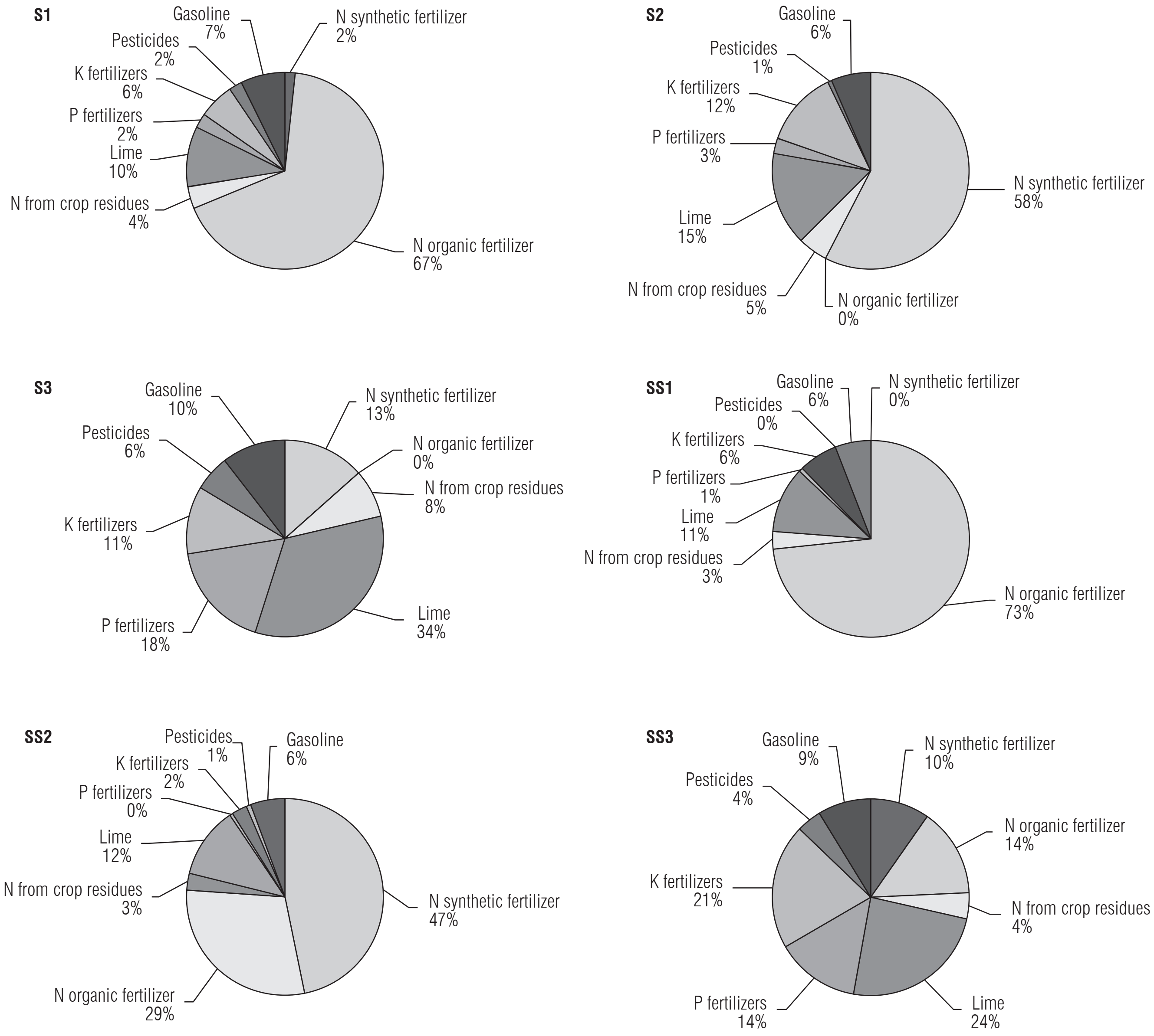

FIGURE 1. Diagram of annual amount of applied agricultural supplies and fossil fuel use (medium values for a 6-years cycle) for each fruit production systems in the Highlands region of Pasto, Colombia. (S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam.

Soil and biomass C pools

The estimative of potential sinks either in soil or in biomass is presented in Tab. 5 (kg CO_2eq ha^{-1} yr^{-1}) considering the 6-year cycle.

Reference values for the soil C stock in conventional S1, S2 and S3 fruit production systems of Highlands region of Pasto, Colombia, was based on soil analysis, being these 156.76, 51.84, 169.8 t C ha^{-1} in the top 30 cm layer. These values were used for estimating changes in final soil carbon stocks (V21) (Tab. 5) by converting from conventional to sustainable fruit production systems.

Ratios of gains/losses of soil C (V22) (Tab. 5) in the studied fruit production systems 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 climate and soil type in the specific region. Rates of gains/losses of soil C were multiplied by 3.66 to convert it from C to CO_2eq (V23) (Tab. 5).

TABLE 4. Farm variables related to total GHG emissions, considering each emission source (kg CO_2eq ha^{-1} yr^{-1}) in fruit production systems of Highlands region of Pasto, Colombia.

Farm variables	Supplies	GHG emissions kg CO_2eq ha^{-1} yr^{-1}						Statistical variables		
		Conventional systems			Sustainable systems					
		S1	S2	S3	SS1	SS2	SS3	SD[1]	Min[2]	Max[3]
V9	N_2O from N synthetic fertilizer	79	404	585	----	215	293	195.70	0	585
V10	N_2O from N organic Fertilizer	329	----	----	329	130	439	170.87	0	439
V11	N_2O from N crop residues	173	345	345	129	129	130	97.75	129	345
V12	N_2O from soil management	581	749	930	458	474	862	---	---	---
V13	CO_2 from Lime	40	88	120	39	44	59	29.81	39	120
V14	CO_2 from P fertilizers	4	6	26	1	1	14	8.90	1	26
V15	CO_2 from K fertilizers	7	22	13	7	3	16	6.39	3	22
V16	CO_2 from pesticides	75	58	200	------	33	86	62.48	0	200
V17	CO_2 from gasoline	141	181	181	105	105	105	---	---	---
V18	CO_2 from agricultural activities	267	355	540	152	186	280	126.96	152	540
V19	Total GHG emissions	848	1,104	1.470	610	660	1,142	299.47	610	1,470

(S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam. [1]Standard deviation, [2]Minimum [3]Maximum values of continuous variables.

TABLE 5. Total GHG balance emission of fruit production systems in the Highlands region of Pasto, Colombia.

Variables Farm	Components	Conventional			Sustainable			Stadystical variables		
		S1	S2	S3	SS1	SS2	SS3	SD[3]	Min[4]	Max[5]
20	Total GHG emission (kgCO_2eq $ha^{-1-1}yr^{-1}$)	848	1,104	1,470	610	660	1,142	299.47	610	1,470
21	Soil C final stock (t C ha^{-1})	138.33	44.58	130.85	180.51	74.64	188.25	52.10	44.58	188.23
22	Rate soil C gain/loss (t C $ha^{-1}yr^{-1}$)	-0.97	-1.21	-2.05	1.25	1.20	0.97	1.32	-1.05	1.25
23	Soil C sequestration[1] (kgCO_2eq $ha^{-1}yr^{-1}$)	3,559	4,440	7,523	-4,587	-4,404	-3,559	1,337	3,559	7,523
24	Biomass C fixation[2] (kgCO_2eq ha^{-1} yr^{-1})	----	----	-----	-17,102	-17,102	-17,102	8,551	0	17,102
25	Balance GHG emissions	4,407	5,544	8,993	-21,079	-20,846	-19.519	13,477	8,993	21,079

(S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam. [2]Negative values refer to gain in biomass C stock; [3]Standard deviation; [4]Minimum [5]Maximum values of continuous variables.

Accumulation rate of C in biomass was estimated only in sustainable fruit production system. The increase in biomass C stock was assumed as 4.5 t C ha^{-1} $year^{-1}$, considering the wood component, based on the IPCC (2006) methodology for Acacia ssp in South America. The accumulation rate of C in biomass of *Pennisetum clandestinum* grass of 0.16 t C ha^{-1} $year^{-1}$ was calculated of Giraldo *et al.* (2008); these rates were expressed in kgCO_2eq and related to (V24) variable (Tab. 5).

Total GHG balance

The results of total GHG balance emission (V25) considering the potential for soil C gain/loss and biomass C fixation are reported on Tab. 5.

Statistical analysis

A Principal Components Multivariate Analysis was performed in order to reduce the number of explanatory variables, using variables that were not collinear. A numerical classification of farms was then performed using cluster analysis method with the same variables identificated. All analyses were conducted with SAS® software.

Results and discussion

Correlation between variables

The correlation matrix description of emission sources and total GHG emissions variables under different fruit production systems of Highlands region of Pasto, Colombia indicated that the variables (V12) (CO_2 from agricultural activities), (V20) (total GHG emissions) and (V25) (GHG balance emissions) considered independently, demonstrated positive correlation with others variables. The (V12) variable (CO_2 from agricultural activities) was best explained by the (V4) variable (lime) (r= 0.95), the (V13) variable (CO_2 from lime) (*r*=0.95) and the (V14) variable (CO_2 from P) (*r*=0.90).

According to the Intergovernmental Panel on Climate Change IPCC (2006), 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 (IPCC, 2006). For instance, all C in lime is eventually released as CO_2 to the atmosphere (IPCC, 2006). Emission factors of phosphates and potassic fertilizers are associated with manufacturing, transportation, storage and application. On agroforestry systems, nutrient recycling is higher, reducing dependence on lime, phosphate and potassic fertilizers (Nair *et al.,* 2009).

On the other hand, the (V20) variable (total GHG emissions) was increased when increased the (V3) variable (N from crop residues) (*r*=-0.89) and the (V11) variable due to N_2O from N crop residues emissions (*r*=-0.88). Soil C losses in terms of CO_2 emissions can be as high as the annual C sequestration rates due to N_2O from N crop residues emissions occasioned by conventional tillage (La Scala *et al.*, 2008). N_2O is a gaseous by-product of nitrification that is ultimately released into the atmosphere (IPCC, 2006).

The variables that were highly correlated with the (V25) variable (total GHG balance emissions) were the (V22) variable (rates of gains/losses soil C) (*r*=-0.99) and the (V24) variable (biomass C fixation) (*r*=0.95).

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool, primarily mediated by plants through photosynthesis (Lal, 2011). Sustainable fruit production systems showed a large potential of sequestering carbon in soil and biomass, as observed by Giraldo *et al.* (2008) in an agroforestry system located in an Andean region of Colombia; which suggests the importance of the agroforestry fruit systems evaluated through on GHG mitigation.

Multivariate analyses

To make a distinction between the systems analyzed, principal components were generated (Factor 1 and Factor 2). The PCA considered the first two factors with a cumulative value of 66.84 % for the variables analyzed (Table 6) was negatively associated with the variables V1 (N synthetic fertilizers) (*r*=-0.93), V4 (lime) (*r*=-0.97), V9 (N_2O from N synthetic fertilizers) (*r*=-0.93), V13 (CO_2 from Lime) (*r*=-0.98), V18 (CO_2 from agricultural activities) (*r*=-0.93), and the V20 (total GHG emissions) (*r*=-0.95), being the most sensitive variables in these analyses (Tab. 6). However, these variables can also be observed in the vector diagram, where the variables are closer to the axis of this factor to demonstrate that most can influence the distinction between the types of fruit systems evaluated (Fig. 3). Diagram generated for the projection vectors demonstrated that the (V22) variable (rate soil C gains/losses) (*r*=0.85) was that most positivity influence the distinction between the types of fruit production systems (Fig. 3).

Despite the huge potential for mitigation of GHG emissions, especially in sustainable fruit production systems, it is important to point that soil C accumulation could be lost rapidly, depending on the soil management decisions made at those sites. For instance, Conant *et al.* (2001) reviewed about 115 studies in 17 countries on the effects by conversion from agricultural crops to agroforestry system on soil C accumulation. This author considered values of soil C sequestration rates ranged from -0.2 to 3.0 t C ha^{-1} yr^{-1} respectively.

It could be concluded that better soil management is possible through the use of agroforestry systems as demonstrated also by Nair *et al.* (2009) and Giraldo *et al.* (2008).

TABLE 6. Correlation coefficients of the principal components analysis (factors 1 and 2) for the variables associated to GHG balance emissions related to conventional and sustainable fruit production systems in the Highlands region of Pasto, Colombia.

Variables	Factor 1	Factor 2
V1	-0.93	-0.03
V2	-0.35	0.91
V3	-0.89	-0.41
V4	-0.97	-0.04
V5	-0.87	0.49
V6	-0.58	-0.35
V7	-0.33	0.50
V9	-0.93	-0.03
V10	0.65	0.05
V11	-0.90	-0.41
V13	-0.98	-0.04
V14	-0.87	0.49
V15	-0.61	-0.31
V16	-0.90	0.37
V18	-0.99	0.09
V20	-0.95	0.20
V21	0.25	0.86
V22	0.85	0.22
V23	-0.75	0.19
V24	0.71	0.37
V25	0.78	-0.31

V1 = N synthetic fertilizer; V2 = N organic fertilizer; V3 = N from crop residues; V4 = Lime; V5 = P fertilizers; V6 =K fertilizers; V7 = pesticides; V8 = gasoline ; V9, V10, V11, V12 = N_2O emissions from N synthetic fertilizer, N organic fertilizer, N from crop residues, N from soil management; V13, V14, V15, V16, V17, V18 = CO_2 from lime, P fertilizers, K fertilizers, pesticides, gasoline, agricultural activities; V19, V20, V21, V22, V23, V24, V25 = Total GHG emission, Soil C final stock, Rate soil C gain/loss, Soil C sequestration, Biomass C fixation, Total balance GHG emissions.

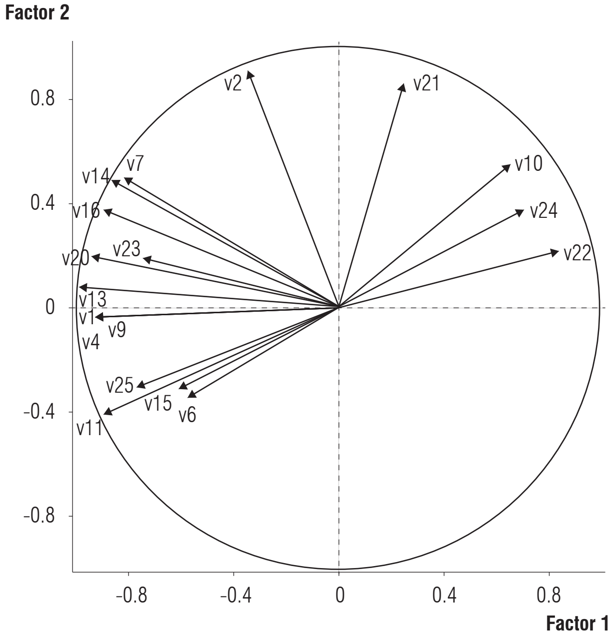

FIGURE 3. Diagram of the vectors projection of the variables associated to factor 1 and 2 of GHG balance related to conventional and sustainable fruit production systems in the Highlands region of Pasto, Colombia. V1 = N synthetic fertilizer; V2 = N organic fertilizer; V3 = N from crop residues; V4 = Lime; V5= P fertilizers; V6 = K fertilizers; V7 = pesticides; V9, V10, V11 = N_2O emissions from N synthetic fertilizer, N organic fertilizer, N from crop residues; V13, V14, V15, V16, V18 = CO_2 emissions from lime, P fertilizers, K fertilizers, pesticides, agricultural activities; V19, V20, V21, V22, V23, V24, V25 = Total GHG emission, Soil C final stock, Rate soil C gain/loss, Soil C sequestration, Biomass C fixation, Total balance GHG emissions.

For factor 2, the variables V2 (N organic fertilizer) (r=0.91) and V21 (Soil final C stock) (r=0.86) explained 16.9 % of the variation (Tab. 6). The increase in soil C stock is subject to greater amounts of crop residues returned to the soil (Albrecht and Kandji, 2003) and minimal soil disturbance (Johnson *et al.*, 2010) (Tab. 6).

The cluster analysis performed with the same variables as the principal components analysis identified three groups (Fig. 4).

The cluster analysis showed that the first cluster consisted of conventional (S3) and (S2) fruit systems, with no statistical differences; in the (S3) system, characterization with continuous variables of cluster or categories showed that the variables that had greater weight was total GHG balance emissions (V25) (4,407 kg CO_2eq ha^{-1} yr^{-1}) (P= 0.046) (Fig. 4), due to that has on its favor the highest soil C losses (V23) (P= 0.048) (7,523 kg CO_2eq ha^{-1} yr^{-1}) and an additional potential for GHG emissions (V20) (P= 0.037) equivalent to 1,470 kg CO_2eq ha^{-1} yr^{-1}, statistically equating to (S2) system (Figure 4) with total GHG balance emissions (V25) of 5,544 kg CO_2eq ha^{-1} yr^{-1}, further emissions would be expected according to our estimations due also to potential of soil C losses (V23) and total GHG emissions (4,404 and 1,104 kg CO_2eq ha^{-1} yr^{-1}) (V20).

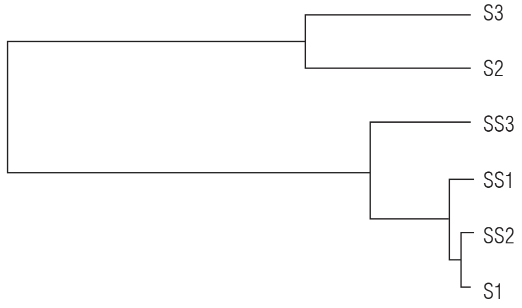

FIGURE 4. Hierarchical cluster analysis GHG balance related to fruit production systems in the Highlands region of Pasto, Colombia. (S1) = Monoculture of *Rubus glaucus* Benth.; (S2) = Monoculture of *Physalis peruviana*; (S3) = Monoculture of *Solanum quitoense* Lam.; (SS1) = Agroforestry system of *Rubus glaucus* Benth.; (SS2) = Agroforestry system of *Physalis peruviana*; (SS3) = Agroforestry system of *Solanum quitoense* Lam.

The multivariate analyses also showed that N from the synthetic fertilizers (V10) significantly influenced the formation of this cluster (P= 0.029). The use of N synthetic fertilizers in agriculture in Colombia is 137 kg ha^{-1}, almost double the intensity in South American, with an average of 74 kg ha^{-1} (World Bank, 2008), resulting in higher direct and indirect N_2O emissions (Smith *et al,* 1997).

The formation of the cluster 2 as showed in Fig. 5, agroforestry system of *Rubus glaucus* Benth. (SS1) can neutralize higher emissions (-21,079 kg CO_2eq ha^{-1} yr^{-1}) (V25), as according to our results has, in addition to the higher potential soil C accumulation (-4,587 kg CO_2eq ha^{-1} yr^{-1}) (V23) and lower total GHG emissions (610 kg CO_2eq ha^{-1} yr^{-1}) (V20), results from this study are compared with relevant studies of Naranjo *et al.* (2012). It was statistically similar to agroforestry system of *Physalis peruviana* (SS2) (Fig. 4) accounting for total GHG balance emission reduction of -20,846 kg CO_2eq ha^{-1} yr^{-1} (V25).

But in turn the agroforestry system of *Physalis peruviana* (SS2) was statistically equals to monoculture of *Rubus glaucus* Benth. (S1) (Fig. 4), although it is a system that does not neutralize GHG emissions but if it emits less GHG to the atmosphere (4,407 kg CO_2eq ha^{-1} yr^{-1}) than the other two conventional (S2) and (S3) fruit production systems

The cluster analysis in Fig. 4 showed an intermediate cluster to the agroforestry system of *Solanum quitoense*

Lam. (SS3) system, accounting for a total GHG balance emissions reduction of -19,519 kg CO_2eq ha^{-1} yr^{-1} (V25); statistically it may be equal to sustainable fruit production (SS1) and (SS2) systems, but also to the conventional fruit production (S1) system.

It is important to point that differences in management practices by adoption from conventional (S1) monoculture of *Rubus glaucus* Benth. to sustainable (SS1) agroforestry system of *Rubus glaucus* Benth. could significantly affect subsequent trends in increases of soil carbon accumulation and potential for mitigation of the GHG emissions.

Conclusion

Sustenaible fruit production systems (agroforestry) have the potential to offset GHG emissions, representing an important alternative to the recovery of degraded areas of conventional fruit production systems in Highlands region of Pasto, Colombia because they are able to maintain biomass C and soil organic matter through the addition of litter and crop residues in the soil.

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