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An Initial Approximation to the Simulation of Soil CO_2 Emissions Using the IPCC Methodology in Agricultural Systems of Villavicencio

Una aproximación inicial a la simulación de emisiones de CO_2 del suelo usando la metodología del IPCC en sistemas agropecuarios de Villavicencio

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ABSTRACT

At a global level, the agricultural sector has represented the largest source of greenhouse gas (GHG) emissions. Our research hypothesizes whether it is possible to faithfully define the effect of soil management factors on modeling soil carbon organic (SOC) sequestration and reducing soil CO_2 emissions in different agricultural systems across three zones of Villavicencio (Colombia) by applying the Tier-1 IPCC process-based model. Agroforestry systems (AFS) are typically found in zone 1, and intensive croplands (CL) in zones 3 and 4. Soil CO_2 emissions rates are calculated according to the current IPCC guidelines for national GHG inventories. Root-mean square error (RMSE, RMSE/n), R^2, and Nash-Sutcliffe efficiency (NSE) are measured to assess model performance. In zone 1, 7-year coffee-based agroforestry stored higher SOC, neutralizing -10,83t CO_2 eq ha^{-1} $year^{-1}$ than 25-year soybean/corn crop rotation in zone 3, with emissions of 2,56t CO_2 eq ha^{-1} $year^{-1}$. The agricultural systems of zones 3 and 4 turned out to be greater emitters, with 7 223 and 3 889t CO_2 eq $year^{-1}$, respectively, which could increase if CL continues to adopt agricultural practices that encourage full tillage. The beneficial effects of AFS on stored SOC are identified via field observations and correctly reproduced by RMSE evaluation.

Keywords: climate change, carbon sinks, land use, tillage

RESUMEN

A nivel mundial, el sector agropecuario ha representado la mayor fuente de emisiones de gases de efecto invernadero (GEI). Nuestra investigación hipotetiza si es posible definir fielmente el efecto de los factores de manejo del suelo en el modelado del secuestro de carbono orgánico del suelo (COS) y la reducción de las emisiones de CO_2 del suelo en diferentes sistemas agropecuarios para tres zonas de Villavicencio (Colombia) aplicando el modelo basado en procesos de nivel 1 del IPPC. Los sistemas agroforestales (AFS) se encuentran típicamente en la zona 1, y los sistemas intensivos de tierras de cultivo (CL) en las zonas 3 y 4. Las tasas de emisiones de CO_2 del suelo se calculan de acuerdo con las directrices actuales del IPCC para los inventarios nacionales de GEI. Se evalúan el error cuadrático medio (RMSE, RMSE/n), el R^2 y la eficiencia de Nash-Sutcliffe (NSE). En la zona 1, el sistema agroforestal de café de 7 años almacenó más COS, neutralizando -10,83t CO_2 eq ha^{-1} $año^{-1}$ que el cultivo de soya/maíz en rotación de 25 años de la zona 3, con emisiones de 2,56t CO_2eq ha^{-1} $año^{-1}$. Los sistemas agropecuarios de las zonas 3 y 4 resultaron ser más emisoras, con 7 223 y 3 889t CO_2 eq $año^{-1}$ respectivamente, lo cual puede aumentar si el CL continúa adoptando prácticas agrícolas que incentiven la labranza convencional. Los efectos benéficos de los AFS sobre el COS almacenado se identifican mediante observaciones de campo y se reproducen correctamente mediante la evaluación del RMSE.

Palabras clave: cambio climático, sumidero de carbono, uso del suelo, labranza

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Introduction

Globally, agricultural-use land occupies about 40-50% of the land surface and generates about 10-12% of the total global anthropogenic emissions, *i.e.*, 5,1-6,1G t CO_2-eq per year (IPCC, 2006). Land uses in the study area (Villavicencio) are characterized mainly by conversion from grassland to continuous croplands, which causes a large degradation of soil organic matter (SOM) (Silva, 2018; Silva and Orozco, 2018), mainly due to conventional tillage (García *et al.*, 2018). Greenhouse gas emissions are influenced by the type of land used, especially by the types of crops and/or pastures in diverse environments (Mangalassery *et al.*,

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2014; Chambers *et al*., 2016; Lal, 2018). The effects of land use on the emission of CO_2 are dominated by the type of tillage and/or pasture management (IPCC, 2006; Haddaway *et al*., 2017; Behnke *et al*., 2018; FAO, 2018). Land use may have direct and indirect effects on soil carbon stocks, and these changes may be conditioned to meet the social needs of farmers, such as the production of food, energy and fossil fuel, water supply, and crop residues management, in order to achieve higher productions in the short term (Popp *et al*., 2017; Nyambo *et al*., 2020). Several studies applying IPCC models to different extents corroborate that different soil management practices and types of tillage increase soil CO_2 emissions (IPCC, 2006; Cardinael *et al*., 2018; Lal, 2018; Parra *et al*., 2019). As an option for reducing soil CO_2 emissions, conservation practices have increased in many parts of the world, aiming to also increase production and sustainable development (Ogle *et al*., 2019). Agroforestry systems with trees and crops in interactive and simultaneous cultivation have been regarded as a key cropping practice for improving the productivity of agroecosystems and reducing soil CO_2 emissions (Nair, 2012; Feliciano *et al*., 2018). This can be seen in Figure 1.

Figure 1. (a) Cocoa-based agroforestry including *Acacia mangium* trees; (b) silvopastoral system of *B. decumbens* pasture with *Acacia mangium* in the study area (Villavicencio, Colombia). The capacity of soils and biomass in agroforestry systems to store C depends on several factors, including local edaphic and climatic conditions, previous land use, tree density and species, harvesting and pruning practices, and management activities (Nair, 2012).
Source: Authors

In general, the transition from cropland to an agroforestry system is beneficial to soil organic carbon (SOC) (Cardinael *et al*., 2018). The accumulation of SOC due to the sequestration of carbon in the soil is certainly one of the major benefits of agricultural systems, as it is effective in helping to mitigate the increase in atmospheric CO_2 concentrations (Lal, 2018). For example, in the southeastern USA, conservation tillage, combined with intensive crop rotations that include cover crops, can sequester an average of 1 700 lb of CO_2 each year, *i.e.*, 464 lb of C per acre (Franzluebbers, 2015). There are various methods to estimate soil CO_2 emissions from agriculture, ranging from simple Tier 1 methods (IPCC, 2006; Ogle, 2004; Parra *et al*., 2019) to complex process-based models that simulate the changes in soil carbon with some detail (Tiers 2 and 3) (FAO, 2018), although this relation is even more complex under the influence of climate change in tropical zones. Cardinael *et al*., (2018), applying a Tier 1 IPCC methodology, validated that the mean SOC storage rate (± confidence intervals) for croplands converted to agroforestry systems was 0,75±0,19 t C ha^{-1} yr^{-1}, while the mean SOC loss rate for forests converted to agroforestry systems was -1,15±1,02 t C ha^{-1} yr^{-1}, in all regions, climates, and agroforestry systems taken together. The mean SOC change rates for the conversion from grasslands to agroforestry systems were not significantly different from zero (0,23±0,25 t C ha^{-1} yr^{-1}). In this sense, by employing soil management practices, agricultural lands can both sequester soil carbon and reduce GHG emissions (IPCC, 2006). Nemo *et al*., (2017) showed a variant of Tier 1 testing with the 2 RothC model (IPCC, 2006), which is used to simulate the interaction between GHG emissions, growth, and grazing in managed grasslands, where the C-input was adjusted so the equilibrium C matched the measured total SOC at the end of the spin-up period. This variant is useful for grassland systems in which the plant-derived carbon input is the most uncertain parameter, as well as the one to which the model is most sensitive (Poeplau, 2011). These types of approaches have been used to estimate C sequestration potentials in grasslands, as well as the potential effects of pasture management on SOC and stock changes on global, national, and regional scales (Henderson *et al*., 2015; Chambers *et al*., 2016; Novaes *et al*., 2017; FAO, 2018; Parra *et al*., 2019). Our specific objectives were the following: (1) to test the performance of the IPCC Tier 1 ensemble approach to simulate soil CO_2 emissions; (2) to quantify differences in soil CO_2 emissions between agricultural systems and zones across the Villavicencio area by modeling and measuring SOC according to the effect of soil management practices as a first approximation to national inventories; and (3) to assess the performance of the IPCC Tier 1 approach with parameters such as the RMSE, the Nash-Sutcliffe efficiency (NSE), and R^2.

Material and methods

The Tier 1 IPCC model

The Tier 1 IPCC model is designed to simulate change in SOC stocks by assigning a reference SOC stock value, which varies depending on climate and soil management factors. To run the simulation, the Tier 1 model requires input parameters regarding the soil management factors (inputs). In this regard, (i) FLU is related to land use (long-term cultivated, paddy rice, perennial/tree crop, set aside); (ii) FMG characterizes the tillage regime (full, reduced, no tillage) for croplands, as well as different pasture management types for grasslands; and (iii) FI describes the carbon input level (low, medium, high without manure, high with manure). These factors come with individual error ranges (between ±5 and ±50%) and must be defined according to climatic conditions (IPCC, 2006). The main parameters (inputs) for modeling SOC changes (outputs) are presented in Figure 2.

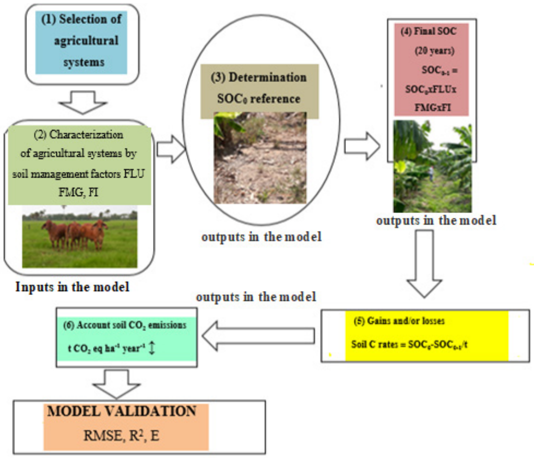

Figure 2. Methodological steps to simulate soil CO_2 emissions with the Tier 1 IPCC methodological approach (input and outputs) in the model
Source: Authors

Study site and empirical data

To parameterize the IPCC model, empirical data on local agricultural systems of Villavicencio were used. This area is located in the Meta Piedmont in Eastern Colombia, 4°8′31,2′′N and 73°37′35,9′′E, and it covers an area of ~1 328 km^2 within the sectoral soil analysis (Alcaldía de Villavicencio, 2012). In this study, three zones of agricultural vocation were selected (Figure 3, Table 1).

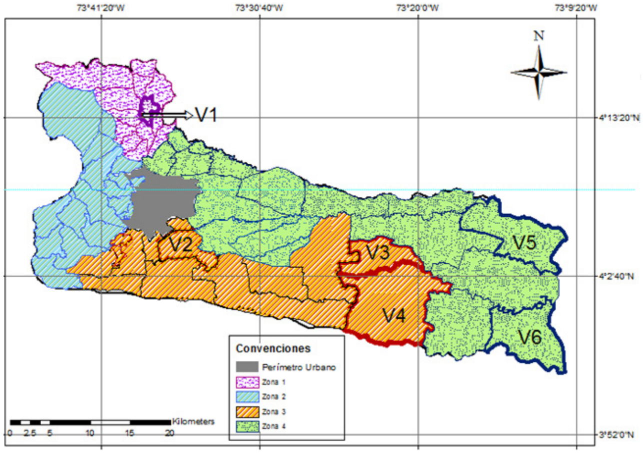

Figure 3. Map of the location of the sampling sites in the Villavicencio area: zone 1 includes Puente Abadía locality (V1); zone 3 comprises three localities: Barcelona (V2), Pompeya Alto (V3), and Pompeya Bajo (V4); and zone 4 has two localities: Indostant (V5) and Porvenir (V6).
Source: Authors

Soils are predominantly acid (Department of Agriculture, 1996). The criterion for the agricultural systems' (land uses) selection was area representativeness. Six agroforestry systems (AFS) were selected in zone 1, 23 in zone 3, and 21 in zone 4. These comprised AFS, croplands (CL), pasture types in different states of degradation, non-degraded pastures (NDP), and moderately degraded pastures (MDP), with different times of use. More information about the collected agricultural systems in each zone is provided in Table 2.

Table 1. Agro-ecological characteristics of the sampling localities, Villavicencio (Colombia).

Zones	Locality	Latitude Longitude	Meters above sea level, Climatic condition, mean annual rainfall (mm), mean temperature (°C)
Zone 1	Puente Abadía	4°10′42′′, 4°17′33′′ N. 73°36′24′′ 73°46′21′′E	800-2 000 Tropical humid 3856 20
Zone 3	Barcelona Pompeya Alto Pompeya Bajo	3° 56′ 15″ 4° 11′ 5″ N. 73° 10′ 00″ 73° 46′00″ E	500-220 Tropical humid 2 850 24
Zone 4	Indostat Porvenir	4°01′04′′ 4°10′00′′ N. 73°13′55′′ 73°37′10′′ E	400-225 Tropical humid 2 850 24

Adapted from Alcaldía de Villavicencio (2012). Typical hapludox (Department of Agriculture, 1996).
Source: Authors

The criteria for the characterization of agricultural systems were evaluated *in situ* by monitoring soil management factors (IPCC, 2006). For this stage, site information was employed, where land use transitions included information from five years before the implementation of the current agricultural system, which were often reported to have been assessed via the IPCC Tier 1 methodology (Table 3).

The identified soil management factors identified contrasted with the default values in Chapters 5 and 3 (*Cropland* and *Grasslands*, Tables 5.5 and 3.4.5) of the IPCC document (2006), which were used as input data for the model. Default values for FLU, FMG, and FI higher than 1,0 correspond to SOC storage, while those lower than 1,0 correspond to SOC loss.

Field measurements for model parameterization

To allow for a standardized analysis compatible with the IPCC guidelines, soil samples were collected (n=150) from the upper 0-30 cm layer (IPCC, 2006). Soil sampling was carried out for four months between January and April 2018 in the study area. The sieved soils were further milled to 0,25 mm in order to measure the initial physical-chemical soil analysis. Bulk density was determined from a core sample (Department of Agriculture, 1996).

The soil organic carbon content before (SOCinitial) in the soil samples was determined according to Walkley and Black (Department of Agriculture, 1996). Initial SOC stocks (SOC_0) were determined via Equation (1), as follows:

$$SOC_0\ (\text{t C ha}^{-1}) = SOC\ (\%) * (\rho b * 100) * d\ (m) \tag{1}$$

where SOC_0 is the mean of initial soil C stocks (t C ha^{-1}); ρb is the bulk density (g cm^{-3}); and d denotes a depth of 0,30 m. In the model parameterization, the dynamics of SOC were projected to 20 years, in sufficient agreement with empirical

Table 2. Basic information on agricultural systems and the area in the data collection site, Villavicencio (Colombia)

Land use categories	Agricultural system definition	Author
	Agroforestry systems, zone 1 (n = 1 115 ha), zone 3 (n = 1 115 ha), zone 4 (n = 1 317 ha)	
Shadow systems (SS), zone 1	Coffee and/or cocoa shrubs with multi-purpose shade species.	Nair (1985)
Agrisilvicultural systems (AS), zone 1	Simultaneously growing crops of coffee and cocoa involve trees, cover on the same piece of land, mainly leguminous.	Nair (1985)
Homegarden (HG), zones 3, 4	Perennial crops of citrus and livestock –all managed in the same piece of land.	Huai and Hamilton (2009)
Improved fallow (IF), zones 3, 4	Continuous cropping of fruits such as papaya and banana with limited or no fertilizer application to enrich the soil within a shorter time, in comparison with natural fallow.	Nair (1985)
	Pasture types, zone 3 (n = 32,244 ha), zone 4 (n = 2,725 ha)	
Improved pasture	Grassland sustainably managed with moderate grazing pressure and receiving at least one improvement (*e.g.*, fertilization, species improvement, irrigation, mainly applied as SP).	IPCC (2006)
Non-degraded pasture, zone 3	Non-degraded and sustainably managed grassland, but without significant management improvements.	
Moderately degraded pasture zone 4.	Overgrazed or moderately degraded grassland, with somewhat reduced productivity (relative to the native or nominally managed grassland) and receiving no management inputs.	
	Silvopastoral systems, zone 4 (n = 2,906 ha), zone 4 (n = 136 ha)	
Silvopastoral system (SP), zones 3, 4	Improved pasture of Brachiaria associated mainly with *A. mangium*, including agroforestry practice that integrates livestock, forage production, and forestry in the same land management unit.	Nair (1985)
	Cropland, zone 3 (n = 15,109 ha), zone 4 (n = 4,607 ha)	
Cropland (CL), zone 3, 4	Area that has been continuously managed, mainly with rice and crop rotation (CR). Long term cultivated land between corn, soybean, and rice.	IPCC (2006)

Source: Authors

SOC measurements regarding observed and default values (FLU, FMG, FI) in each field plot (50 selected agricultural systems x 3 replicates = 150 samples). The model inputs required a total of three default values per agricultural system characterized, for a total of 450 parameters in the model, from which a mean was taken for each agricultural system, for a total of 150 data.

Model validation

To evaluate the accuracy of our model parameterization, the model performance was evaluated with four widely used quantitative methods, *i.e.*, the R^2 (squared correlation coefficient), which is described in Equation (2); the RMSE (root mean squared error) (Equation (3)) and RMSE/n (Moriasi *et al.*, 2007), a measurement of accuracy calculated as the differences between model-predicted and measured SOC values; and the (E) (model performance efficiency) (Nash-Sutcliffe, 1970), which evaluates the degree of closeness between modeled and observed data (Ludwig *et al.*, 2011) (Equation (4)). These indicators were analyzed with $P < 0,005$. The statistical analysis was performed using Infostat v. 17.0 for Windows.

$$R^2 = 1 - SS/res/SStot \tag{2}$$

where: $SSres = \text{sum}\,(Oi - Pi)^2$ and $SStot = \text{sum}\,(Oi - Omean)^2$; Oi = observed values (known results); Pi = expected values or unknown results.

$$RMSE = \text{Square root of} \sum (Oi\text{-}Pi)^2/n \tag{3}$$

The RMSE ranges from 0 to 100. At an ideal fit, the RMSE is equal to zero. A lower RMSE is better.

The Nash-Sutcliffe model efficiency coefficient E was calculated as follows:

$$E = 1 - \sum (Oi - Pi)^2 / \sum (Oi - \bar{O})^2 \tag{4}$$

where $\bar{O}$ is the observation mean. A higher E is better, and it can be expressed as a percentage when multiplied by 100 (Smith and Smith, 2007). A linear regression of the simulated SOC (yPi) and observed SOC (xOi) time-series data was performed (Equation (5)):

$$YPi = IPi + spi \cdot xOi \tag{5}$$

which resulted in a slope sPi, an intercept IPi, and the coefficient of determination R^2. In this sense, only the agricultural systems with the best fit in the model were graphed.

Model application to simulate soil CO_2 emissions

After validation, the Tier 1 IPCC model was used to simulate the current SOC initial stock changes in order to assess the effect of soil management factors on SOC final stocks (Equation (6)).

$$SOC_{0\text{-}1}\,[tC\ ha^{-1}] = SOC_0 * FLU * FMG * FI \tag{6}$$

Table 3. Characterization of agricultural systems five years before land use transitions and current land uses with soil management factors related to each zone studied, Villavicencio (Colombia)

Land use **5 years before/F_{MG}**	**Land use** **change/F_{MG}/F_I level/ID ($F_{LU_}F_{LU}$time)**
6 5 4 3 2	1 **Agricultural systems, zone 1**
--- Coffee crop / HG fruit trees/chicken / DP Brachiaria/NT	AS coffee/MT/L/ASCf_1
----------------------Agrisilvicultural coffee/NT------------------	SS of coffee/NT/H/ AFCf_7, SSCf_5
	SS of cocoa/NT/H/ SSCc_5
---------------Cocoa crop/NT-----------------IP *Brachiaria*/FT	AS cocoa/MT/H/ ASCc_2
----------------Cocoa crop/NT-----------------------------IP/FT----	AS cocoa/NT/H/ ASCc_4
Agricultural systems, zone 3	
--SP (*Brachiaria dictyoneura* pasture + *Acacia mangium*) /IP-	SP (*B. decumbens* and *A. mangium*+kudzu *P. phaseloides*) /IP/H/ Sp_8
-SP (*B. dictyoneura* + *A. mangium*) /IP-/ -----Brachiaria/NDP-	SP (*B. decumbens* + *A. mangium*) /IP/M/ Sp_3
-------------------SP/IP--------------------/ -----Brachiaria/NDP--	SP (*B. decumbens* + *A. mangium*) /IP/M/ Sp_1
--------------------------IP *B. dictyoneura*/NDP--------------------	*B. decumbens*/ND/H/ NDP_26
------- *B. dictyoneura*/NDP/ -------*B. dictyoneura*/MDP-----	*B. decumbens*/ND/H/ NDP_15
-IF banana/NT-/ banana/MT-/ rice/MT-/ ----rice crop/FT-------	IF banana/MT/M/ IFB1_2
	IF banana/MT/M/ IFB_2
---IF banana/NT--/ ---------corn/soybean/NT----------------------	IF banana/FT/L/ IFB_1
------------------------IF citrus/NT------------------------------------	IF citrus/FT/L/ IFCi_7
--------IF citrus/NT----------/ -----------rice crop/FT-------------	HG citrus/NT/M/ HGCi_2
----citrus crop/NT-/ ---------------rice crop/FT---------------------	HG citrus/MT/M/ HGCi_1
-IF citrus/NT--/ -------------rice crop/FT--------------------------	IFCitrus crop/MT/M/ IFCi_1, IFCi1_2
-------------------------Citrus crop/FT-------------------------------	HG citrus/NT/M/ HGCi_5
-----------------------Agrisilvicultural cocoa/NT-------------------	SS of cocoa/NT/H/ SSCc_6
-----------papaya crop/FT---/ ----------corn/soybean/MT---------	IF papaya/NT/M/ IFP_3
--papaya/FT---/ -----------rice/soybean/MT------------------------	IF papaya/NT/M/ IFP_1
----------------------Continuous rice crop/MT----------------------	Continuous rice crop/FT/L/ CLR_29
----------------------Rice/corn/MT------------------------------------	Rice/corn/FT/M/ CRR/C_27
-----------------------Rice crop/FT------------------------------------	Rice crop/FT/L/ CLR_23
-----------------------CR rice/soybean/MT---------------------------	CR rice/soybean/FT/L/CRR/S_25
rice/soybean/FT/ -------------rice/soybean/MT--------------------	CR rice/soybean/FT/L/ CRR/S_28
-----------------soybean/corn/FT------------------------------------	CR soybean/corn/FT/L/ CRS/C_25
Agricultural systems, zone 4	
--------------------Papaya crop/MT-----------------------------------	IF papaya/MT/M/IFP_6
--papaya--/MT-------------------------/ Brachiaria/MDP-----------	IF papaya//NT/H/IFP_3
--HG citrus/NT-----/ ---------------Brachiaria/MDP---------------	HG citrus with herb/MT/HGCi_2
---------------------------Citrus crop/NT------------------------------	HG citrus with herb/NT/H CLC_20, HGCi_15
	HG citrus with legume/NT/HGCi_6, HGCi_10
----------------------------HG citrus/NT------------------------------	AS citrus/NT/H/ASCi_26
----------------------------------Pasture *B. decumbens*/NDP--------	SP *B. decumbens*+*A. mangium*/IP/H/SP_1
-----------------------------Pasture *B. dictyoneura*/MDP------------	Pasture *B. decumbens*/MD/M/MDP1_16, MDP_29
------------------Pasture *B. decumbens*/MD-------------------------	Pasture *B. dictyoneura*/MD/M/MDP_16
-------Banana crop/MT---------------------------Brachiaria/MDP-	IF banana crop/MT/M/IFB1_3
-----IF banana crop/NT-----------------/ ---*B. decumbens*/MDP-	IFBanana crop/MT/M/IFB_3
--banana crop/MT--/ -------*B. decumbens*/MDP------------------	IFBanana crop/FT/L/IFB_1
--rice/MT--/ -------------crop rice/FT------------------------------	Continuous crop rice/FT/L/CLR_32
-------------------------------Crop rice/FT----------------------------	Continuous crop rice/FT/L/CLR_18, CLR_25, CLR_20
-------------------------------Crop rice/MT--------------------------	Continuous crop rice/MT/M/CLR_14
-----Crop rice/MT----------------------------------Crop rice/FT---	Continuous crop rice/MT/M/CLR_24

Legend: NT No tillage: Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. FT Full tillage: Substantial soil disturbance with full inversion and/or frequent tillage operations (within year). MT Minimum tillage: Including primary and/or secondary tillage, but with reduced soil disturbance (usually shallow and without full soil inversion). AFS: Agroforestry system; SS: Shade system; AS: Agrosilvicultural system; SP: Silvopastoral system; NDP: Non-degraded pasture; MDP: Moderately degraded pasture; CL: Continuous and/or Intensive Cropland; L: Low input; M: Medium input; H: High input.
Source: Authors

where SOC_{0-1} is the mean of the final soil C stocks (t ha-1) over the next 20 years, (SOC_0) = SOCinitial Stock (t ha^{-1}); and FLU, FMG, and FI are the default values for soil management (IPCC, 2006). SOC stock changes in the top soil (0-30 cm) over a period of 20 years were calculated as follows (Equation (7)):

$$\Delta SOC\ [t\ C\ ha^{-1}\ year^{-1}] = (SOCfinal-SOCinitial)/T \quad (7)$$

where: ΔSOC = losses and/or gains in SOC rates, T = default time for transition between equilibrium SOC values (20 years). ΔSOC can be converted to atmospheric CO_2 stored in or emitted from the soil by multiplying the tons of C by 44/12 (the ratio of molecular weight for CO_2 and C) (IPCC, 2006).

Results and discussion

Rates of gains/losses of soil C and soil CO_2 emissions for each agricultural system

A significant limitation for model validation was that the change in SOC stock was equated with CO_2 emissions, as only input variables had an assigned probability distribution within each default value, depending on the soil management factor identified, without considering other input factors. The observed SOC storage rates regarding the conversion from pasture for coffee-based agroforestry (AFCf_7) in zone 1 were higher than those of the conversion of rice/corn crop rotation for improved banana fallow (IFB_2) of zone 3 (Table

Table 4. Simulated gains and losses of SOC rate data (outputs in the model) considering IPCC default values for soil management factors (inputs in the model) in agricultural systems, Villavicencio (Colombia)

Land use_ time use	Default values $F_{LU}xF_{MG}xF_I$ (inputs in the model)	Gains/losses of SOC rates t C ha^{-1} yr^{-1} (outputs in the model)	Land use_time use	Default values $F_{LU}xF_{MG}xF_I$ (inputs in the model)	Gains/losses of SOC rates t C ha^{-1} yr^{-1} (outputs in the model)
Zone 1			Zone 3		
ASCf_1	1,12	+0,91	CRR/C_27	0,55	-0,40
SSCf_7, SSCf_5	1,35	+2,96 +0,92	CLR_23	0,44	-0,57
SSCc_5	1,35	+0,70	CRR/S_25, CRR/S_28	0,50 0,44	-0,49 -0.63
ASCc_2	1,35	+1,05	CRS/C_25	0,44	-0,70
ASCc_4	1,35	+1,43	Zone 4		
Zone 3			IFP_6	1,15	+0,73
Sp_8	1,29	+0,92	IFP_3	1,35	+0,63
Sp_3	1,16	+0,15	HGCi_2	1,22	+0,58
Sp_1	1,17	+0,11	HGCi_20, HGCi_15	1,12 1,12	+0,36 +0,24
NDP_26	1,10	+0,10	HCic_6, HGCi_10	1,35 1,35	+1,15 +1,51
NDP_15	1,10	+0,12	ASCi_26	1,35	+1,17
IFB1_2	1,21	+0,43	SSP_1	1,29	+0,92
IFB_2	1,22	+0,08	MDP1_16, MDP_29	0,96 0,96	-0,02 -0,03
IFB_1	0,92	-0,06	MDP_16	0,97	-0,04
IFCi_7	1,12	+0,33	IFB1_3	1,15	+0,21
HGCi_2, HGCi1_1	1,26 1,22	+0,43 +0,26	IFB_3	1,22	+0,31
IFCi_1, IFCi1_2	1,21 1,22	+0,26 +0,26	IFB_1	0,92	-0,12
HGCi_5	1,21	+0,30	CLR_32	0,55	-0,18
SSCc_6	1,35	+0,41	CLR_18, CLR_25, CLR_20	0,44 0,44 0,44	-0,59 -0,62 -0,07
IFP_3, IFP_1	1,21 1,22	+0,30 +0,20	CLR_14	0,55	-0,55
CLR_29	0,50	-0,46	CLR_24	0,55	-0,47

Legend: AS: Agrisilvicultural system; SS: Shade system; SP: Silvopastoral system; NDP: Non-degraded pasture; IF: Improved fallow; HG: Homegarden system; MDP: Moderately degraded system; CL: Cropland; CR: Crop rotation; Cf: Coffee; Cc: Cocoa; B: Banana; Ci: Citrus; P: Papaya; R: Rice; S: Soybean; C: Corn; F_{LU}: land use factor; F_{MG}: pasture management and/or tillage regime in cropland (full, reduced, no tillage); F_I:carbon input level (low, medium, high without manure, high with manure).

Source: Authors

4) –levels: ΔSOC = AFCf_7 = 2,96 t C ha^{-1} $year^{-1}$ and IFB_2 = 0,08 t C ha^{-1} yr^{-1}, accounting for a neutralization of -10,83t CO_2eq ha^{-1} $year^{-1}$ in AFCf_7, which was due to default values FLU, FMG, and FI in the simulations that demonstrated potential mitigation.

The mean stock change factor (default value, ± confidence intervals) was 1,19±0,10 for grassland converted to agroforestry (Cardinael *et al.*, 2018). Poeplau *et al.*, (2011) demonstrated that conversion from grasslands to agroforestry systems did not improve SOC stocks. However, this work agrees that the returns of organic material (leaf litter) in coffee-based agroforestry systems is higher than in the monoculture of coffee as, demonstrated by Zaro *et al.*, (2020). In general, the transition from cropland to an agroforestry system is beneficial to SOC (Lu *et al.*, 2015), as demonstrated in the simulated IFB_2. The results in Table 4 also show that the effect of pasture management on gains/losses of soil C rates varied substantially between NDP_15 compared to the MDP1_16 of zones 3 and 4 (Table 4) –levels: ΔSOC = NDP_15 = 0,12 t C ha^{-1} $year^{-1}$ and MDP1_16 = -0,02 t C ha^{-1} $year^{-1}$. These values are in line with those reported by Silva and Orozco (2018) in degraded pastures of Ariari, Meta, Colombia. Typically, in the model-integrated soil management factors, NDP demonstrated better pasture management than MDP. Several previous studies also showed that many pasture techniques have been applied to mitigate GHG emissions from agriculture (Jadan *et al.*, 2015; Parra *et al.*, 2019). A plausible adoption rate of 30% for improved deep-rooted legumes associated to Brachiaria pastures in Cerrado, Brazil, represented a mitigation potential of -29,8 t CO_2-eq yr^{-1} to the atmosphere (Thornton and Herrero, 2010). However, belowground C-inputs from exudation and root sloughing from C4 grasses are high in Brachiaria pastures, forming the base for soil organic matter buildup in these systems (Anderson-Teixeira *et al.*, 2016). Moreover, elements from agricultural systems (the impact of pasture management and grazing on growth and yield) need to be included in the modeling in order to allow predicting future food security (Van *et al.*, 2018). The responses of our predictions showed that the adoption of silvopastoral systems SP_1 and SP_8 stemming from pastures by farmers of zone 3 resulted in a significant absorption of soil CO_2 emissions (Table 4) –levels: -3,37 and -3,39 t CO_2 eq ha^{-1} $year^{-1}$, respectively. In the tropical zone of Colombia, Parra *et al.* (2019), using the Tier 1 IPCC approach (2006), showed that a silvopastoral system had the highest potential for offset GHG emissions (-4,8 t CO_2eq ha^{-1} $year^{-1}$) due to soil C accumulation plus biomass C fixation in Acacia trees. Soil C sequestration by the world's grasslands could offset up to 4% of global GHG emissions (IPCC, 2006). This research showed that 34% of the agricultural systems evaluated (7 and 10 out of the 23 and 21 agricultural systems of zones 3 and 4) turned out to be CO_2eq emitters, mainly due to CL and MDP (Table 4). Default emission factors used in the Tier 1 IPCC model can be further sources of uncertainty, as they may not be representative of SOC changes and, in many cases, they can under- or overestimate soil CO_2 emissions and/or absorptions (FAO, 2018; Silva and Orozco, 2018). Soil C losses rates differ considerably between continuous the crop rotation of soybean/corn CRS/C_25 including FT of zone 3 and the MDP *B. decumbens* MDP1_16 with MT of zone 4 (Table 4) –levels: ΔSOC = CRS/C_25 = -0,70 and MDP1_16 = -0,02 t C ha^{-1} yr^{-1}. In fact, easily decomposable materials are fully or partially depleted, and the microbial population and decomposition rate of litter materials decline due to full tillage (Lal, 2018). Reduced tillage and 'no till', residue incorporation, improving soil biodiversity, and mulching enhance the sequestration of carbon in the soil. NRCS conservation practices can be expected to sequester approximately 0,07 to 0,96 t C ha^{-1} yr^{-1} due to improved soil management in croplands (Chamber *et al.*, 2016).

Representativeness of soil CO_2 emissions by each category of land use and each zone across the Villavicencio area

The simulated total of contributions regarding emission and/or neutralization of soil CO_2 across the Villavicencio area, zone 1 (comprising AFS), account for -5 416 t CO_2eq yr^{-1} (Figure 4, Table 5) (-4,86 t CO_2eq ha^{-1} yr^{-1} * 1 115 ha), which is possibly due to a high SOC initial state (Table 5) and a higher default value used in the simulation. This is shown in Table 4.

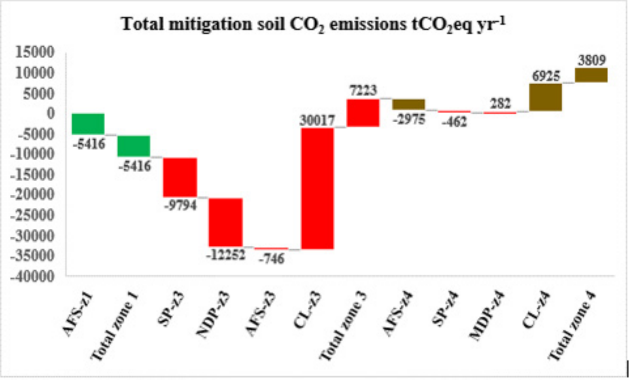

Figure 4. Contribution of soil CO_2eq emissions and sinks in each land use category and zone across the Villavicencio area, which was computed (SOC rates tC ha^{-1} yr^{-1} x area (#ha) x 3,65) based on the changes in SOC storage reported in Table 4. Soil CO_2 emissions are negative in the face of stored SOC and positive with released SOC. Legend: AFS: agroforestry systems; SP: silvopastoral systems; NDP: non-degraded pastures; CL: cropland; MDP: moderately degraded pasture; z: zone.
Source: Authors

Silva (2018) found that the SOC initial state has the greatest impact on emissions dynamics. Numerous studies across the globe demonstrate that the use of integrated practices such as AFS can increase soil C gains by 10-60%, thus reducing the carbon emissions associated with the residue inputs by 20-50% (Nair, 2012). For example, a cocoa AFS has the capacity to sequester about 3 t C ha^{-1} $year^{-1}$, with a reduction of 11 t CO_2eq ha^{-1} $year^{-1}$ (Jadan *et al.*, 2015). On the other hand, zone 3 showed the highest soil CO_2 emissions across the Villavicencio area, followed by zone 4, due to the contributions of CL (Figure 4), *i.e.*, 7 223 t CO_2eq yr^{-1}, and 3 809 t CO_2eq yr^{-1}, respectively. As shown in Table 5, the lowest initial SOC stocks mostly appear in the continuous CL of zones 3 and 4, where there is no land use transition between rice crops and crop rotation and soils are frequently disturbed by full tillage. Soil conservation practices such as crop rotation can fix a large amount of soil organic C and achieve a balance in C storage as long as full tillage is not performed (IPCC, 2006). Efforts for the mitigation of soil CO_2 should focus mainly on zones 3 and 4, adopting more sustainable soil management practices. In a study by Silva (2018), conversion from rice monoculture or crop rotation would increase the soil C stock by about of 12,3 t C ha^{-1} in 20 years, equivalent to 0,61 t C ha^{-1} yr^{-1}, which would reduce emissions by 2,27 t CO_2eq ha^{-1} $year^{-1}$. In zone 3, the contribution of NDP to the mitigation of emissions (-12 252 t CO_2eq yr^{-1}) (Figure 4) is more influenced by the area planted (ha) than by the rates of soil C gains per year (Table 5). However, the time reference of the NDP does not usually pose a challenge. This change is usually fast –soon after the introduction of the new practice– and eventually stabilizes when a new equilibrium is close by (FAO, 2018). The silvopastoral systems of zone 3 and 4 stemming from the conversion of NDP showed an apparent SOC storage (Table 4) and neutralizations of -9 794 and -462 t CO_2 eq yr^{-1}, respectively (Figure 4). MDP contributed with 7,40% of the total emissions of zone 3 (Figure 4). Converting degraded grassland to silvopastures could increase SOC stocks ((Mangalassery *et al.*, 2014). Silvopastoral systems are agricultural strategies that can act positively for the potential mitigation of soil CO_2 emissions (Parra *et al.*, 2019). As pointed out by the FAO (2018), there is a significant lack of rigorous data on C sequestration in silvopastoral systems, since a large amount of the root inputs (FI) of trees can be incorporated into these systems.

Model validation analysis

Among all zones, zone 3 was the best reproduced by the model (Table 5) –levels: RMSE = 3,96 t C ha^{-1}, RMSE/n = 0,05 t C ha^{-1}, Nash-Sutcliffe E= 0,33. The levels for zone 4 were (Table 5): RMSE = 10,95 t C ha^{-1}; RMSE/n = 0,17. In the agricultural systems of zone 1, a clear assessment of the source of deviations between the simulated and measured SOC data was difficult (Table 5) –levels: RMSE = 29, RMSE/n = 1,61 (Figure 5a). The modeled SOC accounted for 111,66 t C ha^{-1} over the entire measurement (86,47 t C ha^{-1}) (Table 5), which implies an overestimation of 29,13% by the model.

This is possibly related to several factors, mainly the high input factor (FI) due to manure application in these systems. Many controversies continue to arise as to the fact that conversion from pasture to AFS does not improve SOC stocks (Poeplau *et al.*, 2011; Cardinael *et al.*, 2018). Fujisaki *et al.* (2015) found slightly higher SOC stocks in grasslands than in forests. In this sense, more precise simulation

Table 5. Representativeness of soil CO_2 emissions by category of land use in each zone across the Villavicencio area and relationships of observed and simulated SOC data with statistical analysis R2, RMSE, RMSE/n, and model efficiency E.

Current land used by each zone	**Area (ha)**	**SOC_0 Obs. t C ha^{-1}**	**SOC_{0-1} Sim. t C ha^{-1}**	**R^2**	**E**	**RMSE t C ha^{-1} (n=150)**	**RMSE/n t C ha^{-1}**	**SOC Rates t C ha^{-1} yr^{-1}**
				Agricultural systems, zone 1				
AFS	1 115	86,47	111,66	0,90	0,21	29,0 (n=18)	1,61	+1,32
Total, zone 1	1 115	86,47	111,66	0,90	0,21	29,0 (n=18)	1,61	
				Agricultural systems, zone 3				
SP	2 906	29,18	36,65	0,85	0,21	10,28 (n=9)	1,14	+0,39
NDP	32 244	19,42	21,55	0,73	0,10	12,14 (n=6)	2,02	+0,11
AFS	757	25,47	30,58	0,96	0,51	5,73 (n=36)	0,15	+0,26
CL	15 109	19,73	9,43	0,95	0,31	10,48(n=18)	0,58	-0,54
Total, zone 3	51 016	23,45	24,55	0,94	0,33	3,96(n=69)	0,05	
				Agricultural systems, zone 4				
AFS	1 317	50,60	62,31	0,98	0,22	14,69(n=33)	0,44	+0,61
SP	136	58,80	76,36	0,96	0,16	9,52 (n=3)	3,17	+0,92
MDP	2 725	17,90	17,36	0,74	0,13	10,58 (n=9)	1,17	-0,02
CL	4 607	15,71	7,87	0,95	0,41	9,64 (n=18)	0,53	-0,41
Total, zone 4	8 785	35,75	40,97	0,96	0,26	10,95(n=63)	0,17	

Legend: The *RMSE* unit is the amount of t C ha^{-1} standard deviations of the residuals (prediction errors). *E* is the Nash-Sutcliffe model efficiency. *AFS*: Agroforestry system; *SP*: Silvopastoral system; *ND*: Non-degraded pasture; *MDP*: Moderately degraded pasture; *CL*: Cropland.
Source: Authors

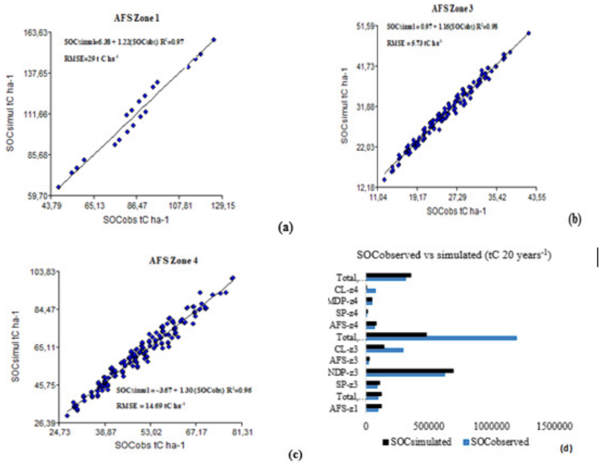

Figure 5. a) Relationship between observed and simulated SOC for AFS, zone 1; b) relationship between observed and simulated SOC for AFS, zone 3; (c) relationship between observed and simulated SOC for AFS, zone 4; d) relationship between observed and simulated SOC (tC 20 years^{-1}) for the agricultural systems in Table 5 (total ha). Legend: AFS: agroforestry systems; SP: silvopastoral systems; NDP: non-degraded pastures; CL: cropland, MDP: moderately degraded pasture; z: zone.
Source: Authors

models must be elaborated which consider the monitoring of soil C stocks from previous systems. The main difficulty to properly assess SOC changes in agroforestry systems compared to other land uses is spatial heterogeneity (Cardinael *et al.*, 2018). However, there were stronger and more significant R^2 between the SOC_0 and SOC_{0-1} for all of the AFS than for the NDP and MDP in zones 3 and 4 (Table 5). In global Tier 1 IPCC models for simulating grasslands, the model ensemble is highly uncertain, partly due to the difficulty in characterizing diverse grassland systems (Ogle *et al.*, 2004). The linear regression of the simulated and observed SOC data shows a better fit for the AFS of zone 3 (Figure 5b) –levels: R^2 = 0,94, SOCsimulated = 0,97+1,16, SOCobserved, $P < 0,005$– that for those in zones 1 and 4 (Figures 5a, 5b, and 5c). An adjustment of these parameters with local data may be required to improve estimations (Figure 5d), as supported by FAO (2018). AFS management options targeting increases in leaf litter inputs could be a promising strategy to increase the SOC content. The SP of zones 3 and 4 differ considerably in terms of RMSE and RMSE/n (Table 5) –levels; RMSE = 9,52t C ha^{-1} and RMSE = 10t C ha^{-1}, respectively–, but the RMSE/n was higher in zone 4 due to a lower number of samples (Table 5). One significant limitation in assessing the suitability of process-based models can be the small number of datasets used. The livestock farmers of zone 3 and 4 can influence root biomass and thus SOC inputs by grazing management, as well as the plant species composition (Henderson *et al.*, 2015). The Nash-Sutcliffe efficiency (E) coefficients supported the results of the statistical analysis conducted for the RMSE values. The mean values of said coefficients for the AFS of zone 3 was equal to 51% (Table 5). The continuous cropland system (CL) also demonstrated a better match between the modeled and measured SOC contents (Figure 5d), especially in zone 3, where the value of the positive Nash-Sutcliffe E coefficient reached 31% (Table 5). However, the NDP of zone 3 showed a low model E in predicting SOC changes, as well as a higher deviation in the observed and measured SOC (Table 5) –levels: E = 10%, RMSE/n = 2,02 t C ha^{-1}–, probably because the pastures exhibited a greater degree of SOC degradation variability. The uncertainty of SOC models for grazed grassland will likely be large, probably larger than that for models applied to croplands (FAO, 2018). Certainly, in all possible combinations of the observed FLU, FMG, and FI default values in the calibration, the inclusion of AFS in zones 3 and 4 yielded the best results.

Conclusions

As climate change research becomes more and more relevant, agroforestry system (AFS) models can play a major role in understanding the interplay between environmental change, SOC, and the functioning of these systems. In this sense, GHG simulations across Villavicencio zones showed that the highest removals took place in the AFS of zone 1 (-5 416 t CO_2 eq yr^{-1}). However, the better matches for AFS (between observations and simulations) were obtained in zones 3 and 4 in comparison with zone 1 (RMSE/n = 0,05, 0,17, and 1,61 t C ha^{-1}). In zone 1, there may be an overestimation of the modeled SOC in AFS. Our simulation analyses clearly indicate that a pathway for the reduction of soil CO_2 emissions is possible through a wide-scale adoption of different types of AFS that can optimize soil management factors for increased SOC. Silvopastoral systems (SP) have gained large attention during the last decades due to their SOC accumulation and should be considered to improve Moderately Degraded Pastures (MDP). In zones 3 and 4, the potentially significant negative impacts on soil CO_2 emissions (7 223 and 3 809 t CO_2 eq yr^{-1}, respectively) are due to SOC losses in Intensive Cropland (CL), which account for 30 017 and 6 925 t CO_2 eq yr^{-1}. In this sense, in CL, the reduction of soil CO_2 emissions can generate a large portion of the needed mitigation through the adoption of cropping rotation and soil management practices such as minimal tillage and higher above-crop residues. AFS are important Factor Land Use (FLU) to incentive low-carbon footprint agriculture, as a plan by the Colombian Government to reach its GHG emission reduction targets.

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Author contributions

D. Y. G. R., conceived the idea, did the background research, collected the data, developed the workflow, and performed the assessment. *C. L. L.*, and *A. S. P.*, supervised the research and provided critical feedback. *D. Y. G. R.* and *A. S. P.*, led the drafting process and wrote the main part of the manuscript, to which all authors contributed.

Conflicts of interest

The authors declare any type of conflict of interest.

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