Food and Agriculture
Organization of the
United Nations

Global Soil Organic Carbon Sequestration Potential Map

GSOCseq

Colombia

National Report v.1.0 2021

Pillar 4
Working
Group &
INSII

GLOBAL SOIL PARTNERSHIP

Colombia: Soil Organic Carbon Sequestration Potential National Map

National Report. Version 1.0. Year: 2021

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Executive summary

One of the many factors that have caused the global climate crisis is soil degradation. This is induced by deforestation of natural areas, poor soil management practices, an increase in agricultural areas, among other reasons. This has generated a direct impact on the Soil Organic Carbon (SOC) stock, which is deteriorating. In Colombia, in addition to the reasons stated above, agricultural practices produce erosions that degrade the soils and in the most serious cases generates desertification. According to the reasons stated, the main objective of this work is to identify the first approximation of the sequestration potential of SOC from agricultural soils, through the implementation of national data sets, under the approach of FAO-GSP Technical Specifications and Country Guidelines for Global Sequestration Potential Map v1.0. This result is presented on a map with a resolution of 1 km^2. The evolution of the SOC stock was estimated under a scenario of business-as-usual practices (BAU) for 20 years (2020-2040), and three scenarios with sustainable management measures (SSM), which include inputs of 5% (SSM1), 10% (SSM2) and 20% (SSM3) of organic matter, thus estimating the absolute sequestration of COS. The differences between the BAU scenario and the SSM scenarios are calculated with this information. The results show that the second average COS in the BAU scenario decreased at a rate of -0.022 t C ha^{-1}.yr^{-1}, between 2020-2040; In contrast to the projections of the SSM scenarios, it showed a positive evolution with 0.040, 0.102, and 0.225 t C ha^{-1}.yr^{-1} for SSM1, SSM2 and SSM3, respectively. On the relative sequestration rate (RSR) there is an average increase of 0.062 t C ha^{-1}.yr^{-1} for SSM1, 0.124 t C ha^{-1}.yr^{-1} for SSM2, and 0.247 t C ha^{-1}.yr^{-1} for SSM3, which indicates that in any organic matter scenario the increase in C is positive. The results (maps) are available in the GSOCseq Data Platform hosted in the GloSIS Global – Global Map Services portal management by FAO (http://54.229.242.119/GloSIS/).

Abbreviations

C - Carbon

SOC - Soil organic carbon

BAU - Business as usual

SSM - Sustainable soil management

RSR - Relative sequestration rate

ASR - Absolute sequestration rate

1. Introduction

According to National Agricultural Survey (DANE, 2020), Colombia has 5,311,977 ha of crop areas planted with the following distribution: agro-industrial crops 2,186,389 ha, cereals 984,859 ha, tree crops 716,501 ha, tubers/plantains 574,770 ha, fruit 505,164 ha, vegetables 288,212 ha, and other crops 56,083 ha. However, the top five crops planted in Colombia are coffee (839,661 ha), rice (555,183 ha), oil palm (546,085 ha), yellow corn (327,744 ha), and plantain (304,600 ha). These crops have different soil management practices, many of them aim at improving yield and production.

Soil is a non-renewable resource on human time scales. Its vulnerability to degradation depends on complex interactions between processes, factors, and causes occurring at a range of spatial and temporal scales (Lal, 2015). In terms of the degradation process, Colombia has 45,379,058 ha (39.8% of the total area of the country) with some degree of erosion (IDEAM and UDCA, 2015), and 14,476,939 ha (12.7% of the total area of the country) with susceptibility to salinization ranged from medium to very high (IDEAM et al., 2017).

There is depletion of the soil organic carbon (SOC) pool. However, its quantification is not available yet. There is general agreement that the technical potential for sequestration of carbon in soil is significant, and some consensus on the magnitude of that potential (Sommer and Bossio, 2014; Paustian et al., 2019). Thus, last decade one of the main achievements in Colombia was the development of the National Soil Organic Carbon Map by IGAC under the consultative and participatory process of the Global Soil Organic Map (FAO and ITPS, 2018). The mapping method included regression-kriging, a spatial interpolation technique that combines a regression of the dependent variable (target variable) over the predictors with kriging of the prediction residuals. The map had values ranging from 10 to 264 $t.ha^{-1}$.

The country has generated guidelines to estimate biomass-carbon at the national and sub-national level (Yepes et al., 2011) and they incorporate a protocol of analysis in soils. Nevertheless, the country has not carried out a soil organic carbon (SOC) sequestration potential map yet. On a global scale, there have been approaches such as the works developed by Morais et al. (2019) and Zomer et al. (2017). In this last project, Zomer et al. (2017) demonstrated where carbon might be sequestered, and how much. They also showed if, through improved practices and management, they could increase SOC on agricultural land in a generally accepted moderate to optimistic amount, based on the medium and high sequestration scenarios by Sommer and Bossio (2014). The national analysis of SOC on available cropland soils indicated the following average results for Colombia: Current state 99 $t.ha^{-1}$, after 20 years medium sequestration scenario 110 $t.ha^{-1}$, after 20 years high sequestration scenario 120 $t.ha^{-1}$ and annual incremental in medium scenario 0.52 $t.ha^{-1}$ and high scenario 1.06 $t.ha^{-1}$. The agricultural area was considered at 30,359 km^2.

At the local scale, the approaches have been directed to analyze stocks in different land use. Amézquita et al. (2004) worked in carbon sequestration in pastures, silvopastoral systems, and forests in tropical Andean hillsides and humid tropical forests. In hillsides, total soil carbon stocks values range from 86 $t.ha^{-1}$ (mixed forage bank) to 162 $t.ha^{-1}$ (*Bracharia decumbens* pasture). Both estimates are based on the fixed soil mass method. In the case of humid tropical forests, the pastures *Brachiaria humidicola* and *Brachiaria decumbens* obtained higher total soil carbon stock values than silvopastoral systems and forests. Similar results were obtained by Mosquera et al. (2012) in Amazonia, when they evaluated the effect of land use change on SOC in a flat and a sloping landscape, the carbon contents and stocks of primary forest, degraded pasture, and four improved pasture systems. In both areas, there were wide differences between stocks under the various treatments. Stocks ranged from 104 to 137 t.ha^{-1} in the flat area and from 94 to 153 t.ha^{-1} (1 m equivalent depth) in the sloping area.

Vasquez and Macías (2016) studied the relationship of the different land uses with the contents and forms of carbon in six soil and climate zones in northern Magdalena. In different crops combined with forest, the following total soil carbon stocks were obtained at 20 cm depth: coffee 78.1 t.ha^{-1}, oil palm 37.6 t.ha^{-1}, banana 32.1 t.ha^{-1}, mango 58.0 t.ha^{-1}, temperate fruit 36.6 t.ha^{-1} and vegetables 36.9 t.ha^{-1}. Another important area in Colombia is the paramo ecosystem because it helps mitigate climate change due to the availability to sequestrate more carbon in the soil concerning other ecosystems (Zimmermann et al., 2010). Montes-Pulido et al. (2016) estimated SOC at different soil depths and soil used in the Sumapaz paramo, in the district of Cundinamarca. For potato (*Solanum tuberosum* L.) crops, the averages SOC sequestration were: 119 t.ha^{-1} to 25 cm, 83 t.ha^{-1} to 50 cm, and 71.8 t.ha^{-1} at soil depths below 50 cm. However, in a larger study, Gutierrez et al. (2020) estimated the SOC in paramo ecosystem soils in Colombia in the first 30 cm of depth, in an area of 1,469,980 ha. The predictive modeling technique Random Forest was used to obtain the model, using 44 environmental covariates and 390 soil profiles. The estimated SOC oscillated between 22 and 338 t.ha^{-1} and this was related to the coverage and use of the soil and the climatic conditions (temperature and precipitation).

In the Orinoco region, Silva Parra (2018) generated a multivariate analysis of the modeling of the SOC stocks and soil carbon losses rates and/or soil gains in productive systems of High plains and other lower mountains. They formed three distinct groups: the first with improved pastures and coffee agroforestry systems associated with plantain and legumes, the second with rice and pineapple monocultures, and the third with an agroforestry system (rubber and leguminous cover crops) and silvopastoral system (*Acacia mangium* and improved pastures). The silvopastoral system was the system with the highest productive gain rates (2.64 t C ha^{-1}.yr^{-1}), followed by the coffee agroforestry system associated with plantain and legumes (2.37 t C ha^{-1}.yr^{-1}). The pineapple monoculture had the highest loss rates (-2.35 t C ha^{-1}.yr^{-1}). The estimated 20-year SOC stocks oscillated between 34.8 and 116.64 t.ha^{-1} at 30 cm depth.

On the other hand, Paustian et al. (2019) mentioned that in general, agricultural soils degrade according to their pre-agricultural condition and therefore have a capacity for SOC stocks to be rebuilt if managed appropriately. An extensive body of research has shown that land management practices can increase SOC stocks on agricultural lands with practices including the addition of organic manures, cover cropping, mulching, conservation tillage, fertility management, agroforestry, and rotational grazing (Zomer et al., 2017). In Colombia, soil management practices have been used to increase the SOC stock. However, the most used ones corresponded to traditional practices of integrated soil management, such as managed grazing, rotation of crops, and introduction of earthworms and native species (Ordoñez et al., 2015). Chatterjee et al. (2018) developed a meta-analysis about changes in SOC stock across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions, including the lowland humid tropics region (LHT). They indicated that the contribution of agroforestry systems compared to agriculture or pasture was higher by +26% in LHT, a typical region in Colombia.

Giving the context mentioned above, the main aim of this study was to evaluate SOC sequestration, the national distribution, and the results with different sustainable soil management (SSM) practices. SOC sequestration potential after the adoption of SSM practices under specific conditions was expressed in different ways depending on the definition of SOC baseline stocks and time towards a new equilibrium state. The study was developed by applying the FAO approach (FAO, 2020). The main result contained a SOC potential sequestration map for Colombia at 1 km^2 spatial resolution using the best available national data. The institutions involved in the process were: Colombian Corporation for Agricultural Research – AGROSAVIA, Institute of Hydrology, Meteorology and Environmental Studies – IDEAM, Agustin Codazzi Geographic Institute – IGAC, Ministry of Environment and Sustainable Development of the Republic of Colombia – MADS, Ministry of Agriculture and Rural Development of the Republic of Colombia – MADS, Ministry of Foreign Affairs of the Republic of Colombia, and Food and Agriculture Organization of the United Nations – FAO, Office in Colombia.

2. Methods

2.1. Study area

Colombia is located in the northwest of South America (American tropic), with a total continental and insular area of 1,141,748 km^2, including the San Andrés, Providencia, and Santa Catalina Archipelago in the Caribbean Sea and the Malpelo, Gorgona, and Gorgonilla islands in the Pacific Ocean. It is the third largest country in South America, behind Brazil and Argentina, and 26th in the world.

Due to the country's location, it is influenced climatologically by the atmospheric circulation of the Caribbean Sea, Pacific Ocean, and the Amazon basin, "an island between three oceans" (Snow, 1976 cited by Poveda, 2004), the orographic barrier of the three branches of the Andes Mountain range (Western, Central and Eastern) with altitudes up to 5,400 meters above sea level, the valleys within them, the plains of the Caribbean and the Orinoquia regions, and the Sierra Nevada de Santa Marta. All of this encourages the formation of several highly complex regional and local climates (Poveda, 2004). Therefore, the annual average rainfall varies between ~ 500 mm.yr^{-1} in the extreme north (La Guajira desert), to more than 11,000 mm.yr^{-1} in the western side that corresponds to the Colombian Pacific. Likewise, the average annual temperature varies according to the orography: elevations above 4,000 meters above sea level, present average temperature ~ 6 °C, while at sea level it is higher than 28 °C; the annual average temperature varies little during the year. However, the daily variation can be greater than 20 °C (IDEAM, 2015).

According to IDEAM (2015a), Colombia has 29,594,382 ha in agricultural land (25.9% of total area), with the following distribution: 22.3% in croplands and 77.7% in grazing lands. A study developed by IGAC (2012) indicated that the country has 19.3% of the area suitable for croplands, 13.3% in grazing lands, and 3.6% in agroforestry. However, the same study showed that underuse is 13.1% of the total area, while overuse is 15.6%. In 2018 UPRA designed the agricultural frontier for the country and identified that it corresponds to 34.4% of the total national area.

On the other hand, the country has eleven predominant soil classes (Figure 1), with marked differences in soil type between each of the natural regions.

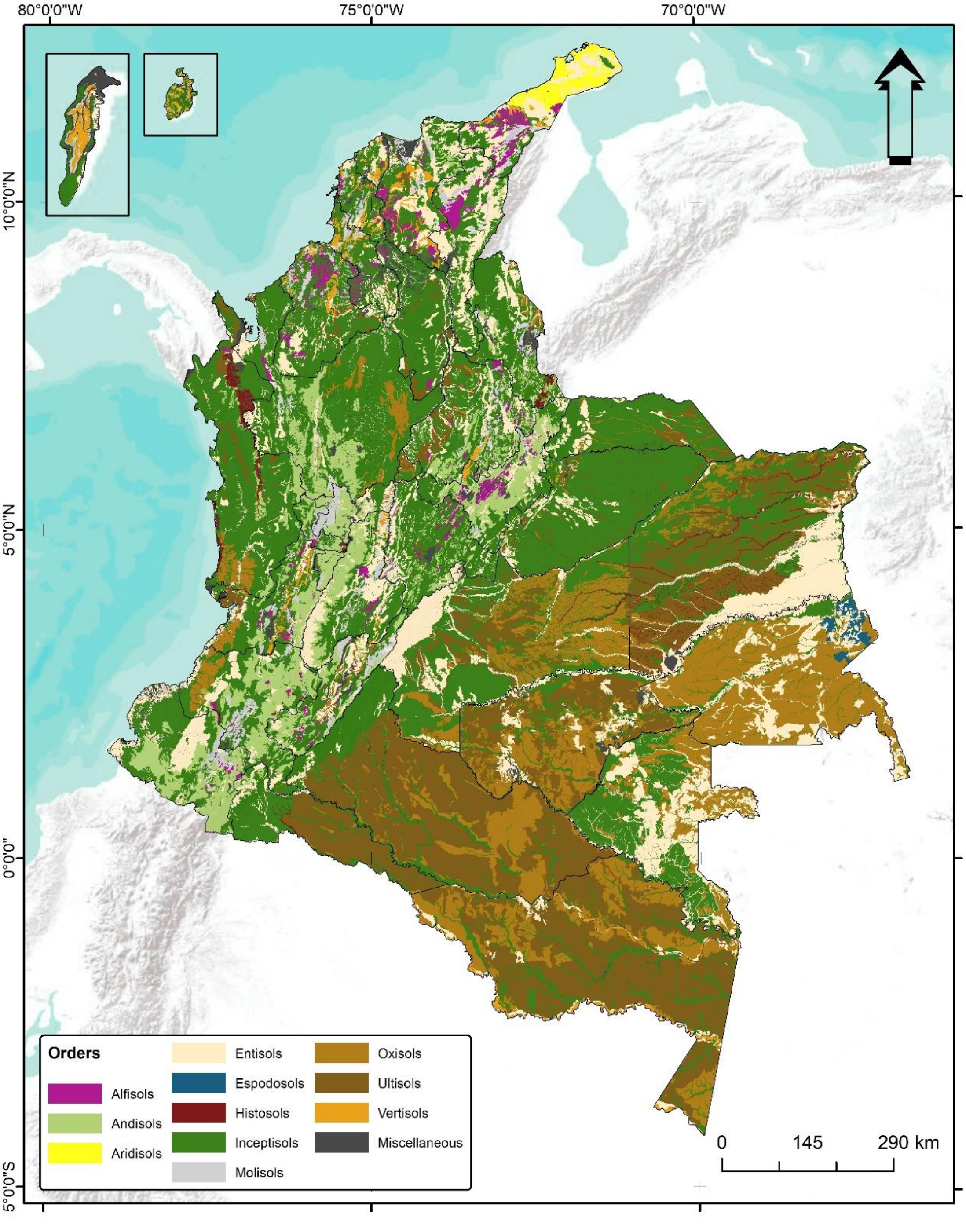

Figure 1. *Dominant soil orders of Colombia (IGAC, 2015).*

According to IGAC (2015), Inceptisols are predominant in most of the country, especially in the Pacific region, southern Caribbean, and northern Orinoquia, while Ultisols, Entisols, and Oxisols, dominate much of the Amazon, the Orinoquia and part of the foothills of the Eastern and Central Mountain ranges. Espodosols only predominate in the extreme east of the country, on the border with Venezuela. In the Andean region, which presents the highest elevations, the Andisols and Inceptisols dominate, and to a lesser extent, the Molisols, which dominate an important area of the valleys of the Cauca and Magdalena rivers, together with the Entisols. Likewise, towards the northeast of the

Andean region, there is the presence of Alfisols, Entisols, and Histosols, the latter dominating an important portion of the north of the Pacific region. The Caribbean region presents a mosaic of soil types, mainly of Inceptisols, Entisols, and Aridisols (predominant only in the La Guajira peninsula). To a lesser extent, Alfisols, Molisols, Vertisols, and Ultisols, dominate a large part of the Caribbean savannahs that are mainly dedicated to livestock activity. Finally, in San Andres and Providence Islands, there are Inceptisol, Vertisol, and Molisol soil types.

Due to the above aspects (types of soils, climate, orography, among others), the country presents a wide variation in the range of SOC stocks (0-30 cm), between 10 and 264 t C ha^{-1}, with a total accumulated of 6.24 Pg (FAO and ITPS, 2018). The highest values are concentrated in the Andean region, while the lowest are in the Caribbean and Orinoquia regions.

2.2. General Methodology

The applied methodology is based on the guide "Technical specifications and country guidelines for Global Soil Organic Carbon Sequestration Potential Map (GSOCseq)" proposed by FAO in 2020. This methodology consists of the application of the RothC model (Coleman and Jenkinson, 1996, cited by FAO 2020a), where the accumulation of Soil Organic Carbon (SOC) is estimated for a standard layer of 0-30 cm of mineral soils projected for 20 years (period 2020-2040). The SOC stock models in 2040, were performed in four scenarios: the first under current land management (business as usual-BAU), while the remaining three were performed through standard scenarios, which incorporated Sustainable Soil Management (SSM) in organic matter percentages of 5%, 10% and 20% for SSM1, SSM2, and SSM3, respectively. Next, the differences between SOC stock in 2020 (T0) and 2040 (T20) under BAU and the SSM scenarios were estimated, through the absolute difference maps and the relative difference maps, respectively.

Modeling was carried out at points where land use belonged to agricultural land, extracted from the analysis of three periods of land cover classification: 2000-2002, 2003-2009, and 2010-2012 according to the CORINE Land Cover methodology CLC (see 2.3.3., Land use and land use change data).

The RothC model was run in three phases: 1. Long spin–up (Equilibrium), 2. Warm-up (Short spin–up) for and 3. Forward modeling. For the Long spin-up phase, it was run 1000 years, where it ran iteratively to reach the equilibrium to SOC pools, considering the partition of four active compartments: Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO), Humified Organic Matter, and a small amount of Inert Organic Matter (IOM); the equilibrium was reached based in the environmental context, derived of climatic conditions for the period 1980–2020, clay content and land use for the year 2000 and Carbon inputs (C). For the Warm-up phase, it includes the effects of climatic conditions from 2000-2020 and the adjustment of C input year to year. For the third phase, the SOC stocks were estimated between 2020-2040 adjusted C inputs for the BAU scenario and estimated the percentual increase between BAU and SSM scenarios, which considered strategies to increase carbon inputs. The C inputs in all phases used the SOC stock map generated in 2017 and updated in 2019 by IGAC (see: 2.3.2. Soil data sets).

All the processing was based on the routines from GitHub directory (https://fao-gsp.github.io/GSOCseq/index.html) FAO (2020), which was done in R version 4.0.2 (R core team, 2021), under Lenovo® workstation with Intel® Xeon® CPU E5-2630 v4 @2.20 GHz. (2 processors) and 24 GB of RAM.

2.3. Input data layers

2.3.1. Climatic data sets

The precipitation and mean temperature layers were obtained from the interpolation of 3,073 and 800 daily climatic series respectively, added on a monthly scale, from the IDEAM national hydrometeorological network; (http://dhime.ideam.gov.co/atencionciudadano/). Hence, 418 daily climatic series were used, added on a monthly scale, of maximum and minimum temperature in Celsius degrees, mean relative humidity in percentage, hours of bright sunshine in and wind speed in m.s-1 to calculate the reference crop evapotranspiration (ETo) with the FAO Penman-Monteith method (Allen et al., 2006). All the information, periods 1981-2000 and 2001-2020, was subjected to quality control, verifying the statistical and physical coherence (spatial and temporal) of each climatic series (Corpoica, 2015). The spatial interpolation of the variables: precipitation and evapotranspiration, expressed in mm, was carried out through the Inverse Distance Weighted IDW (Shepard, 1968), while for the mean temperature, expressed in Celsius degrees, the altitudinal gradient was used (Fries et al., 2012). The resulting layers have a spatial resolution of 1-km (~ 0.0090 degrees).

2.3.2. Soil data sets

The original SOC stock map was made by IGAC during FAO's regional training workshop on Digital Soil Organic Carbon Mapping, offered in 2017. The latest version of this map was updated in 2019. This map was created using information from 4329 soil profiles, collected between 1980 and 2012, in soil surveys (scale 1:100.000) made by IGAC. All profiles were harmonized calculating the carbon stock in a standard layer from 0 to 30 cm depth. The spatial distribution (1 km resolution) of the SOC stock (t C ha^{-1}) was predicted using the Regression Kriging model. The resulting SOC stock map presented an RMSE value of 0.6705 and a ME value of -0.0023 t C ha^{-1}.

The clay content map was created following two different methodologies depending on geography. For insular areas, the soil survey cartographic units (IGAC, 2001) were analyzed, and a unique clay content value was estimated doing a weighted average for each soil profile. After that, soil cartographic units were rasterized at 1 km resolution. For continental areas, the clay content map was made using 4203 harmonized and transformed (additive log transform) soil profiles at three standard depths (5, 15, and 30 cm) (Varón-Ramírez and Araujo-Carrillo, 2021). The data was divided into two sets: the first to train the algorithm (75% of total samples) and the second to validate the model (25% of total samples).

The model prediction for each standard depth was built using MACHISPLIN algorithm (Brown, 2021). The external validation demonstrated boundary adjustment parameters for RMSE values of 15.13, 14.36, and 15.73, and ME values of -1.0, -0.3, and -0.5 at 5, 15, and 30 cm, respectively. These three maps were integrated into a unique map (0-30 cm) using the methodology proposed by Hengl et al. (2017). For Colombian soils, clay contents between 0 and 82% were found. The highest clay contents were found in the Caribbean, Andean, and Orinoquia regions.

2.3.3. Land use and land use change data

Since 2000, Colombia has represented its land cover through the CORINE Land Cover -CLC methodology. CLC includes a consolidated land cover report for the entire country, at 1:100,000 scale (vector representation) and with intersectoral work. Three periods were analyzed: 2000-2002, 2003-2009, and 2010-2012 (IDEAM, 2021). However, the country does not have land use maps, so a protocol was adapted to reclassify land cover categories to land use. The protocol followed the work developed by UPRA and IGAC (2015), and the FAO Land Cover Classification System (FAO, 2021). According to the National Legend of Land Cover (IDEAM, 2010), level 3 of the legend presented 55 categories, which were adjusted to thirteen land use classes. In this manner, three land use maps were made as input data layers. Figure *2* shows the land use classes for the 2010-2012 period.

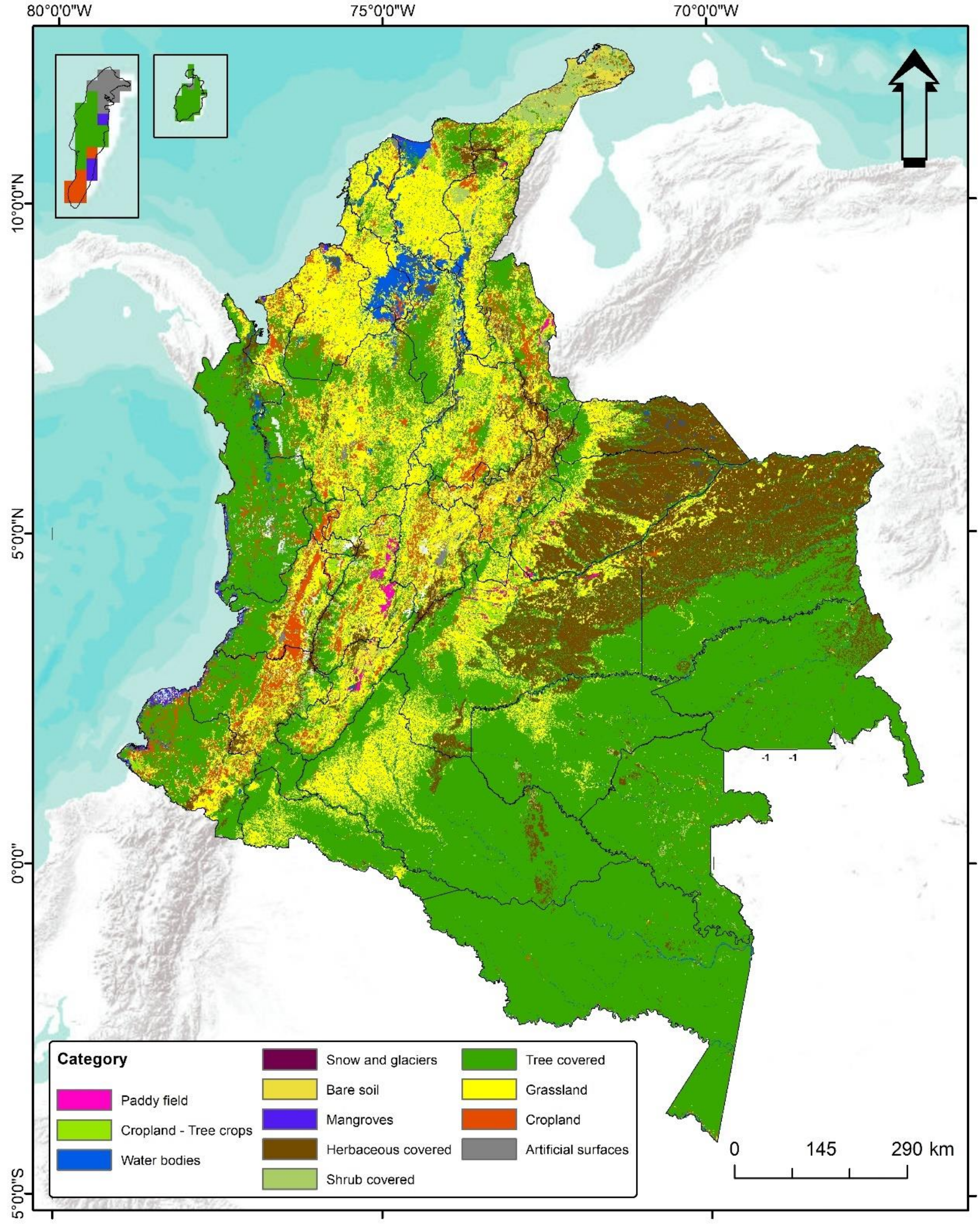

Figure 2. *Land use classes for the 2010-2012 period. Adapted from CLC 2010-2012 (IDEAM, 2021).*

2.3.4. Land management, C inputs, and scenarios

Land management, C inputs, and scenarios were applied according to the methodology proposed by FAO-GSP. So, standard C input increase scenarios (+5, +10, and +20%) were used, because the country has not produced enough local data to standardize the C input increase. Similarly, the NPP estimation, the residue quality, and the monthly vegetation cover followed the methodology indicated above.

2.4. Model/s performance evaluation

Unfortunately, local results from different management practices on SOC stocks are not available for the entire agricultural lands of the country. Some specific experiences about management practices were indicated in the introduction section. However, we considered that they are not representative of performance evaluation.

2.5. Uncertainties

The selected approach to estimate uncertainties considered minimum and maximum values (corresponding to the limits of a 95% confidence interval) of a set of predefined input parameters, considered to have the greatest influence in RothC modeling results (initial SOC, Carbon inputs, and soil and climatic variables). For each scenario map, we produced an uncertainty map of one standard deviation expressed in percentage with regards to the predicted value of each scenario.

3. Results

3.1. Summary and spatial prediction of SOC sequestration rates in Colombia

SOCT0 (the year 2020) had a mean value equal to 48.56 t C ha^{-1} and a standard deviation equal to 27.71 t C ha^{-1}. This stock ranged between 8.57 and 280.57 t C ha^{-1}. In the case of BAU, the mean value was 48.12 ± 27.28 t C ha^{-1}. This result indicated a SOC negative evolution for the BAU scenario. However, in the other scenarios, the SOC evolution was positive. In SSM1 the mean value was 49.36 ± 27.79 t C ha^{-1}, in SSM2 was 50.59 ± 28.31 t C ha^{-1} and SSM3 was 53.06 ± 29.35 t C ha^{-1}. The maximum value was predicted in the SSM2 scenario (294.82 t C ha^{-1}), while the minimum value was predicted in the SSM3 scenario (0.01 t C ha^{-1}).

Regarding spatial prediction of SOC sequestration rates, the results of Absolute Sequestration Rates (ASR) and Relative Sequestration Rates (RSR) were similar for different scenarios. For example, the national average ASR for the SSM1 scenario was 0.040 t C ha^{-1}.yr^{-1}, while the national average RSR was 0.062 t C ha^{-1}.yr^{-1}. For the SSM2 scenario, ASR was 0.102 t C ha^{-1}.yr^{-1} and RSR was 0.124 t C ha^{-1}.yr^{-1}. In the case of the SSM3 scenario, ASR was 0.225 t C ha^{-1}.yr^{-1} and RSR was 0.247 t C ha^{-1}.yr^{-1}. In general terms, the SSM3 scenario had the highest rate. The paddy field land use was the highest average ASR. However, cropland had the highest average RSR. It is possible to see more information in Table 1.

Table 1. *Average absolute sequestration rate (ASR) and relative sequestration rate (RSR) for each SMM scenario and land use group*

Land use	**Area (km^2)**	**Average ASR (t C ha^{-1}.yr^{-1})**			**Average RSR (t C ha^{-1}.yr^{-1})**		
		SSM1	**SSM2**	**SSM3**	**SSM1**	**SSM2**	**SSM3**
Cropland	33,465	0.016	0.086	0.226	0.070	0.140	0.280
Grazing land	171,045	0.040	0.106	0.239	0.067	0.133	0.267
Tree crop	8,817	0.024	0.089	0.219	0.065	0.130	0.260
Paddy field	2,901	0.182	0.224	0.308	0.042	0.084	0.168

Land use	Area (km^2)	Average ASR (t C ha^{-1}.yr^{-1})			Average RSR (t C ha^{-1}.yr^{-1})		
		SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Other agricultural land uses[1]	96,856	0.046	0.097	0.198	0.051	0.101	0.203
Average all land uses	**313,084**	**0.040**	**0.102**	**0.225**	**0.062**	**0.124**	**0.247**

[1] Other agricultural land uses refer to some areas covered with shrubs and herbaceous.

Table *2* indicates the absolute difference in SOC stocks for the SSM1, SSM2, and SSM3 scenarios. Also, it indicates the relative difference for the same scenarios.

Table *2*. *Absolute and relative differences in SOC for each SMM scenario and land use group*

Land use	Area (km^2)	Absolute differences in SOC (t C ha^{-1})			Relative differences in SOC (t C ha^{-1})		
		SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Croplands	33,465	0.310	1.711	4.512	1.401	2.802	5.603
Grazing lands	171,045	0.793	2.126	4.789	1.333	2.667	5.330
Tree crops	8,817	0.480	1.781	4.382	1.301	2.602	5.203
Paddy fields	2,901	3.635	4.476	6.158	0.841	1.682	3.364
Other agricultural land uses[1]	96,856	0.926	1.940	3.968	1.014	2.028	4.056
Average all land uses	**313,084**	**0.800**	**2.036**	**4.507**	**1.236**	**2.473**	**4.943**

[1] Other agricultural land uses refer to some areas covered with shrub and herbaceous.

In the case of the natural regions of Colombia, the Pacific region had the highest average ASR for the SSM2 and SSM3 scenarios and the highest average RSR for all scenarios. The insular Caribbean region had the lowest ASR and RSR average. It is important to say that the area of the insular Caribbean region is exceptionally low concerning the total area of the country. In the continental area, the Caribbean region had the lowest ASR and RSR average (Table *3*).

Table *3*. *Average absolute sequestration rate (ASR) and relative sequestration rate (RSR) for each SMM scenario and natural region*

Natural region	Area (km^2)	Average ASR (t C ha^{-1}.yr^{-1})			Average RSR (t C ha^{-1}.yr^{-1})		
		SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Amazon	22,527	0.072	0.145	0.292	0.074	0.147	0.294
Andean	118,068	0.027	0.104	0.259	0.077	0.155	0.309
Caribbean	56,878	0.032	0.079	0.173	0.047	0.094	0.189
Insular Caribbean	4	-0.093	-0.036	0.078	0.057	0.114	0.228
Orinoquia	111,162	0.051	0.100	0.198	0.049	0.098	0.196
Pacific	4445	0.071	0.167	0.359	0.096	0.192	0.384
Average all region	**313,084**	**0.040**	**0.102**	**0.225**	**0.062**	**0.124**	**0.247**

ASR and RSR maps are represented in Figure *3* and Figure *4*, respectively.

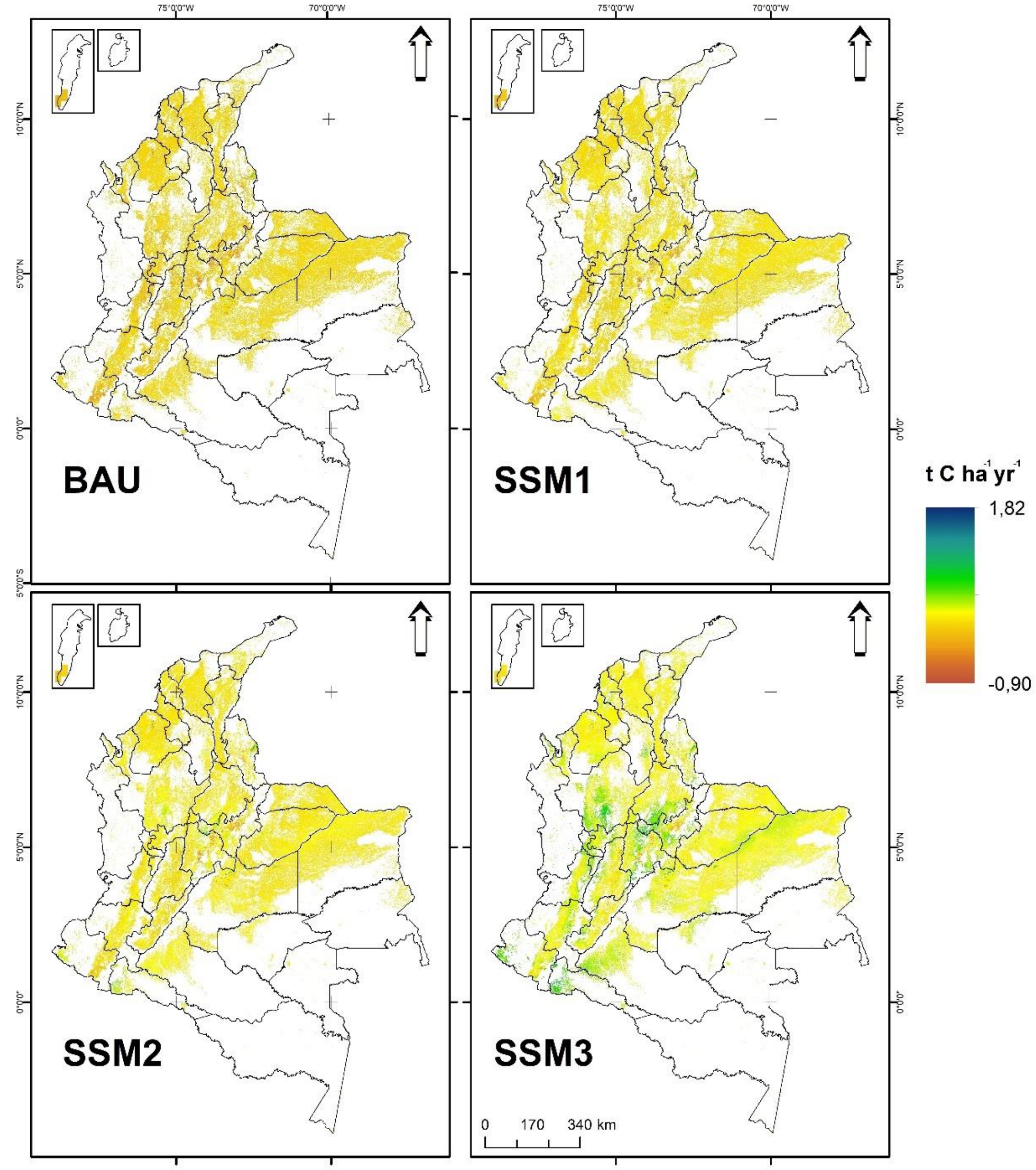

Figure *3. Absolute SOC sequestration rates (ASR) for Business as usual (BAU) model and three hypothetical scenarios of SOC gains (SSM)*

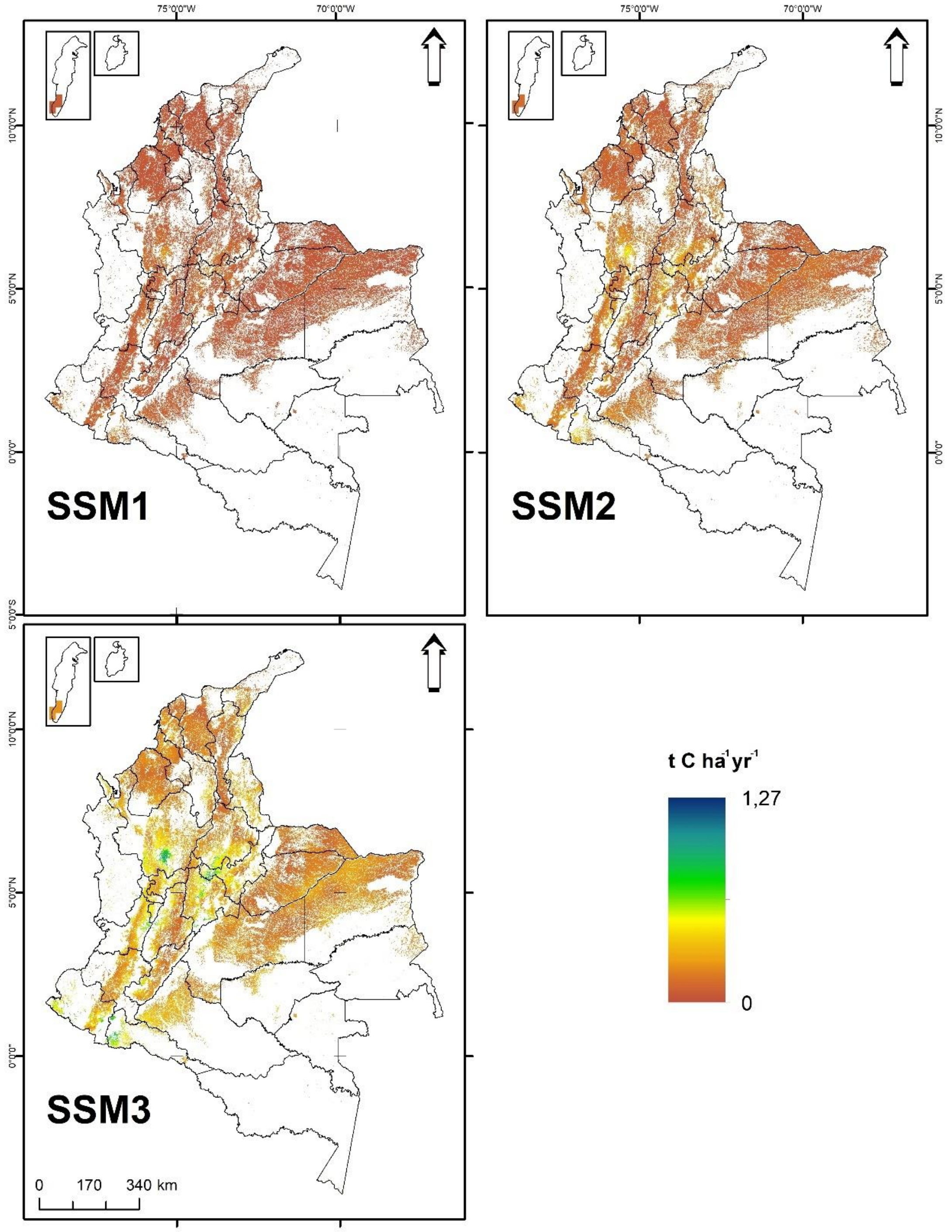

Figure 4. *Relative SOC sequestration rates (RSR) for three hypothetical scenarios of SOC gains (SSM)*

3.2. Model performance evaluation

This section was not completed because validation datasets are not available. We are looking forward to obtaining data and new information to evaluate the performance of the model in the near future, nevertheless, the comparison will depend on the degree of research on these topics.

3.3. Uncertainties

The mean uncertainty estimated and standard deviation for ASR were: BAU 15.60 ± 0.66%, SSM1 18.64 ± 1.07%, SSM2 18.72 ± 1.09%, and SSM3 18.88 ± 1.13% (Figure 5). In general, the mean uncertainty estimated for ASR ranged from 9.0 to 21.9%. In the case of RSR, the mean uncertainty estimated, and standard deviation were: SSM1 18.81 ± 1.16%, SSM2 18.88 ± 1.17%, and SSM3 19.04 ± 1.20% (Figure 6). The mean uncertainty estimated for RSR ranged from 8.3 to 22.4%. The uncertainties for ASR and RSR were remarkably similar in their statistics and spatial distribution. SSM3 had more uncertainty than other scenarios.

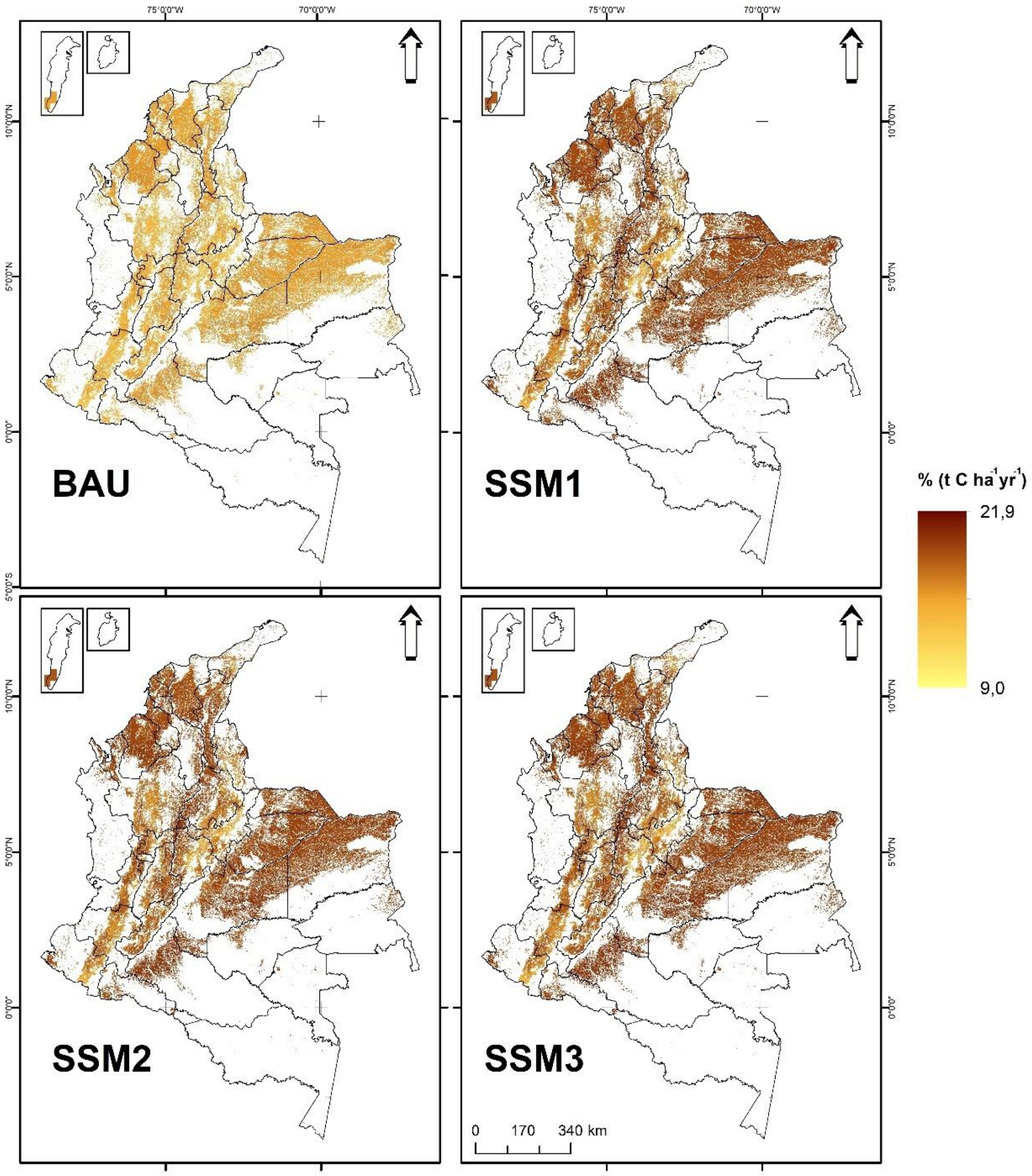

Figure 5. *Uncertainty absolute SOC sequestration rates (ASR) expressed in percentage for Business as usual (BAU) model and three hypothetical scenarios of SOC gains (SSM)*

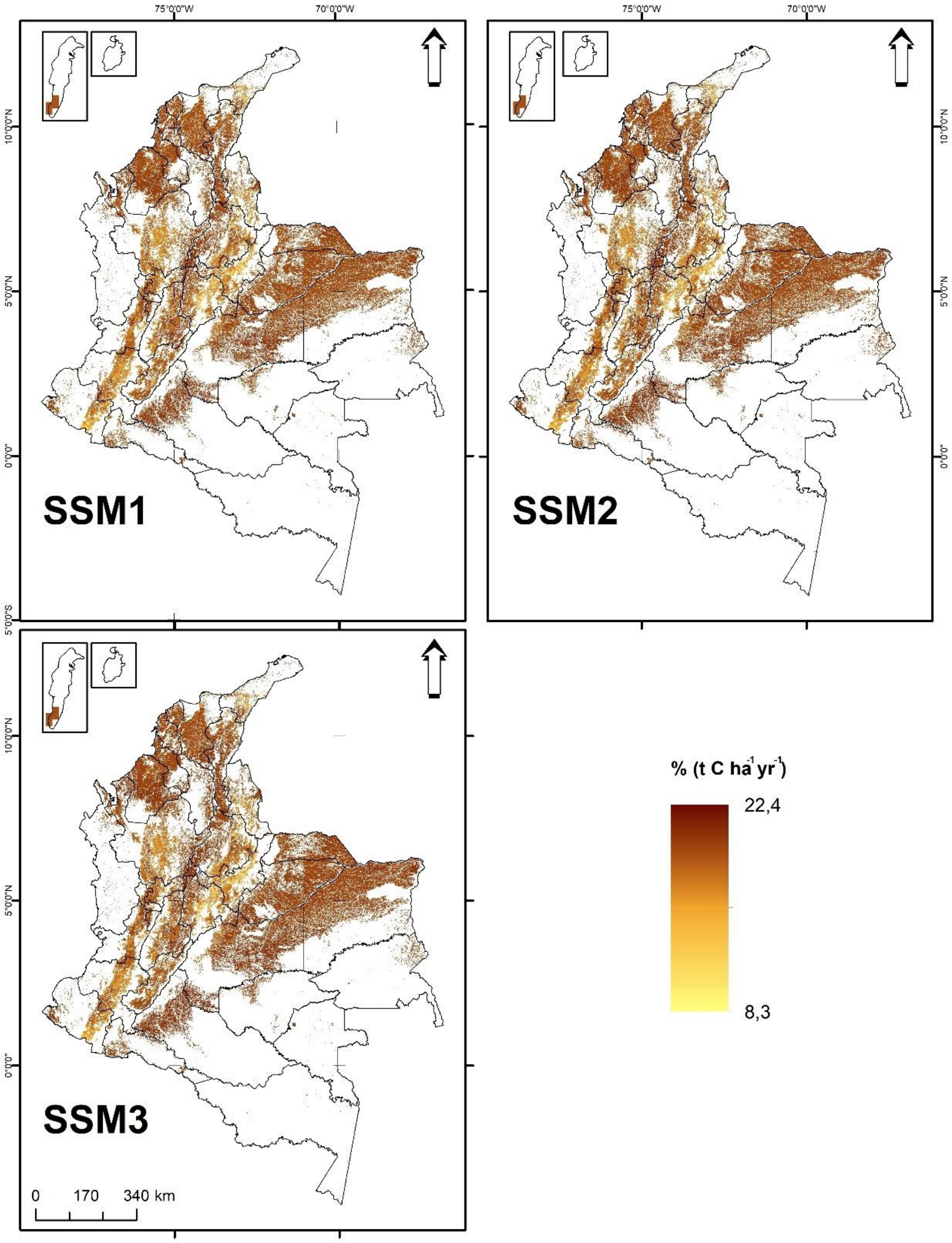

Figure 6. *Uncertainty of relative sequestration rates (RSR) expressed in percentage for three hypothetical scenarios of SOC gains (SSM)*

4. Discussion and relevant considerations

This study represents a national effort to identify agricultural production systems in different regions and environments that have the potential to increase or decrease SOC. The current SOC stock (t C ha^{-1}) in Colombian agricultural soils is lower than in other regions in the world. After 20 years (2040) under business-as-usual practices, the Colombian soils will be a CO_2 emitter. Addressing this problem, the Andean region is identified as the area with the highest potential to sequester CO_2, especially through improved management of croplands and grazing lands. At both the regional and national levels, these results give landowners a new tool for the conservation, management, and use of their properties.

The average SOCT0 for Colombian agricultural soils was 48.55 t C ha^{-1}. This value is less than the SOCT0 reported by Zomer et al. (2017) for all available cropland soils in South America (76 t C ha^{-1}), Central America (87 t C ha^{-1}), and globally (81.61 t C ha^{-1}). By land use, the highest SOCT0 was presented by the use of croplands (62.39 t C ha^{-1}) located mainly in the western Andes Mountains, and the lowest for other land uses (36.05 t C ha^{-1}), especially herbaceous cover situated in the Orinoquia region (Figure 1).

At the national scale, agricultural soils under current practices and management (Business as usual) are releasing CO_2. The average ASR BAU for the total area (313,084 ha) showed a negative value (-0.022 t C ha^{-1}.yr^{-1}). By land use category, the largest emissions were found for croplands (10.69% of the total area), tree crops (2.81% of the total area), and grazing lands (54.63% of the total area) with ASRBAU values of -0.055, -0.041, and -0.027 t C ha^{-1}.yr^{-1}, respectively. In contrast, the paddy soils are currently a net sink with an ASRBAU of 0.14 t C ha^{-1}.yr^{-1}. However, this use corresponds to less than 1% of the total agricultural area.

The average ASR for low (SSM1), medium (SSM2), and high (SSM3) SOC sequestration scenarios in all land use showed a positive balance after 20 years of simulation (0.040, 0.102, and 0.225 t C ha^{-1}.yr^{-1}, respectively). For grazing lands, the average ASR values for all scenarios were less than reported by other studies, where specific management practices, such as increased temporary pasture duration (0.1 to 0.5 t C ha^{-1}.yr^{-1}), and improved pastures (0.2 t C ha^{-1}.yr^{-1}) in France (Arrouays et al., 2002), and renovated pastoral hilly land in New Zealand (0.6 t C t C ha^{-1}.yr^{-1}) (Schipper et al., 2014) were implemented. For croplands, values obtained for all scenarios were less than the ASR reported for specific management practices, such as no soil tilling in the UK (0.31 t C ha^{-1}.yr^{-1}) (Powlson et al., 2012), reducing the use of summer fallow in Canada (0.3 t C ha^{-1}.yr^{-1}) (VandenBygaart et al., 2011) and converting land use from cropping to pasture in France (0.49 t C ha^{-1}.yr^{-1}) (Minasny et al., 2017).

The national average RSR for all SOC sequestration scenarios was higher than the national average ASR values, due to the negative balance of the BAU scenario. These positive RSR values imply that the implementation of improved management practices, even in the least impactful scenario, has a sink effect in all land uses in Colombian soils. In a regional analysis, the highest RSR values were found in the Andean region, specifically in southern Antioquia, north-western Cundinamarca, western Boyaca, and southwestern Santander districts (Figure *2*). In these places, there are mountain landscapes with altitudes between 1000 and 3000 MASL, high contents of SOC stock (> 100 t C ha^{-1}), clay contents between 10 and 40%, and high percentages of croplands and grazing land. On the other hand, the lowest RSR values were found in Orinoquia and the Caribbean region; each of these have common landscapes: the former has hills and coastal plains, and the latter has hills, valleys, and pediments. Also, these regions present altitudes less than 1000 MASL, SOC stock less than 50 t C ha^{-1} and herbaceous or grazing lands.

Additionally, it is important to underline that a specific national map was built to represent each RothC model input. Climatic, soil, and land use maps were constructed and harmonized by a Colombian interdisciplinary team. Because of this concern, these results are a very close approximation to the potential SOC sequestration in agricultural soils in Colombia. However, the maps showed need to be interpreted and associated with their uncertainty maps (Figure 5 and Figure 6), where the highest percentages imply a high variation in SOC predictions. Therefore, the Andean region has more reliable predictions than Orinoquia and the Caribbean region.

Under soil conservation policies that improve the SOC sequestration, Colombian soils can revert the current emissions of CO_2 in 2040. This potential SOC sequestration identification of agricultural production systems in different regions and environments is a tool to promote and implement public policies and research priorities to reduce the environmental impact of agricultural activities. Nevertheless, uncertainty maps need to be analyzed according to the error percentage. Finally, to improve these results some strategies such as improving soil sampling densities, exploring other digital soil and climate mapping models, and adding other explanatory covariates could be implemented in these areas.

5. Acknowledgments

We acknowledge the following institutions and dependencies: Colombian Corporation for Agricultural Research – AGROSAVIA, Research, and Development Office and Sustainable Intensive Production Department; Institute of Hydrology, Meteorology and Environmental Studies – IDEAM, Office of the Deputy Director of Meteorology and Office of the Deputy Director of Ecosystems and Environmental Information; Agustin Codazzi Geographic Institute – IGAC, Office of the Deputy Director of Agrology; and Food and Agriculture Organization of the United Nations – FAO, Office in Colombia, project CAEP II.

6. Data availability

The maps are available at two repositories: the first is the GloSIS Global – Global Map Services portal management by FAO (http://54.229.242.119/GloSIS/), in the data catalogue: GSOCseq – Global Soil Organic Carbon Sequestration Potential Map. The second is the *Colombia en Mapas* portal management by IGAC (https://www.colombiaenmapas.gov.co/), in the sustainable development section, climate change subsection. In both services, users can download the maps in editable formats.

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