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AGRICULTURE AND CLIMATE CHANGE

ECO-EFFICIENCY OF THE MODELS OF AGRICULTURAL PRODUCTION OF HARD CORN AND ITS INFLUENCE ON CLIMATE CHANGE IN SHUSHUFINDI ECUADOR

ECOEFICIENCIA DE LOS MODELOS DE PRODUCCIÓN AGRÍCOLA DE MAÍZ DURO Y SU INFLUENCIA AL CAMBIO CLIMÁTICO EN SHUSHUFINDI ECUADOR

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Abstract

Eco-efficiency is defined as the quantity or economic value of a product by its environmental influence, and it identifies the sustainability of a system in socio-economic and environmental aspects. The objective of this research was to evaluate the ecoefficiency of three models of agricultural production of hard corn present in the Shushufindi canton, Ecuador. The models identified in the study were the conventional model (MC), semi-conventional (MS) and traditional (MT). The environmental influence was determined through two impact indicators contemplated in the Life Cycle Analysis, such as GHG emissions, according to the IPCC guidelines (IPCC, 2006a), and the water footprint (HH) through the components stated by Hoekstra et al., (2011). For the evaluation of ecoefficiency, the guidelines of Ribal et al. (2009) were considered, applying a non-linear programming optimization (LPG) model. GHG emissions per MC were 2926.92 kgCO_2eq ha^{-1} year^{-1} and an HH of 1157.86 m^3 ton^{-1}, MS contributed 1209.45 kg CO_2eq ha^{-1} year^{-1} and a HH of 1201.85 m^3 ton^{-1}, while the resulting MT emissions were 570 kg CO_2eq ha^{-1} year^{-1} and a HH of 1008.16 m^3 ton^{-1}, and it was determined that the MT is the most eco-efficient model with a value of 0.99. The results allowed to know the impacts associated to the models of agricultural production of maize, its contribution to the Climate Change (CC) in sensitive ecosystems like those of the Ecuadorian Amazon, so that in this way sustainable agricultural practices are implemented.

Keywords: Climate Change, greenhouse gases, water footprint, eco-efficiency, corn.

Resumen

La ecoeficiencia se define como la cantidad o valor económico de un producto por su influencia ambiental e identifica en términos socioeconómicos y ambientales la sostenibilidad de un sistema. El objetivo de esta investigación fue evaluar la ecoeficiencia de tres modelos de producción agrícola de maíz duro presentes en el cantón Shushufindi, Ecuador. Los modelos identificados en el estudio fueron el modelo convencional (MC), semi-convencional (MS) y tradicional (MT). La influencia ambiental se determinó mediante dos indicadores de impacto contemplados en el Análisis de Ciclo de Vida, como son las emisiones de GEIs, según las directrices del IPCC (2006a) y la huella hídrica (HH), a través de los componentes dados por Hoekstra et al., (2011). Para la evaluación de la ecoeficiencia se consideraron los lineamientos de Ribal et al. (2009), aplicando un modelo de optimización por programación no lineal (GLP). Las emisiones de GEIs del MC fueron de 2926,92 kgCO_2eq ha^{-1}año^{-1} y una HH de 1157,86 m^3 ton^{-1}, el MS contribuyó con 1209,45 kgCO_2eq ha^{-1}año^{-1} y una HH de 1201,85 m^3 ton^{-1}, mientras que las emisiones del MT fueron de 570 kgCO_2eq ha^{-1} año^{-1} y una HH de 1008,16 m^3 ton^{-1}. Se determinó que el MT es el modelo más ecoeficiente con un valor de 0,99. Los resultados permitieron conocer los impactos asociados a los modelos de producción agrícola de maíz y su contribución al Cambio Climático (CC) en ecosistemas sensibles como los que alberga la Amazonía ecuatoriana, para que de esta manera se implementen prácticas agrícolas sostenibles.

Palabras clave: Ecoeficiencia, GEIs, huella hídrica, Cambio Climático, maíz.

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1 Introduction

Among the agricultural production problems that have arisen are the environmental impact associated with the type and dose of fertilizers and plant protection, the use of machinery, irrigation systems, certified seeds, among others, which impact the water, soil and air resources. However, various options arise for establishing better agricultural practices that integrate environmental and economic aspects, promoting sustainability in agricultural production. In this sense, the concept of ecoefficiency originates, which is defined by Masuda (2016) as the quantity or value of the product by the environmental influence and "economic value/environmental impacts". In the case of eco-efficiency in agriculture, (Rodríguez, 2018) conceptualizes eco-efficiency as the capacity of a land-use system to be sustainable in economic, social and environmental aspects. In this context, greenhouse gases (GHG) are important factors of climate change (CC) because of their global warming potential (GWP) (IPCC, 2013). The increase in the GHG is associated with activities carried out by the economic sectors, such as the agricultural which has contributed to 24% of global emissions (IPCC, 2014). The IPCC (2015) reported that emissions from the global agricultural sector were 11.7 Gt CO_2eq. In the case of Ecuador, emissions in 2012 were 14 512.88 Gg of CO_2eq, corresponding to gases such as CO_2, CH_4 and N_2O from agricultural soils (46.37%), enteric fermentation (43.43%), rice cultivation (7.48%), manure management (2.34%) and the burning of agricultural waste (0.39%) (MAE, 2017). The increase in these GHG can cause serious ecological and economic changes, as well as unpredictable changes in climate systems (OMM, 2017).

Considering that the agriculture is one of the most demanding areas of GHG, in 2018 temporary crops accounted for 15.1% of Ecuador's total agricultural area, corresponding to 5.3 million hectares (INEC, 2019). Temporary crops with the greatest cropped areas are dry hard maize (40.7%), rice (32.1%) and potato (2.5%) (INEC, 2019). The agriculture present in the Ecuadorian territory has been replacing native ecosystems such as the moors and the forests, as evidenced between 2008 and 2014, where the expansion of the maize crop caused most of the change in land use with 42%, followed by cocoa (15.32%), African palm (14.5%) and coffee (11,18%) (Lasso, 2017). Besides, 80% of maize is used as raw matter in the industry for elaborating food for animals such as birds and pigs (Baca, 2016).

In Ecuador, Los Ríos is the province with the highest production of dry hard maize with 38.8% of the national total, corresponding to 602 thousand Tm and a planted area of 383 399 ha (INEC, 2019). According to data from the Continuous Agricultural Production and Surface Survey (ESPAC), maize production in Los Ríos in 2017 decreased by 4.88%, and an increase in maize production was observed in provinces that were not producers of this grain on a large scale, such as in the province of Sucumbíos, which had a total sown area of 1.99% of the national area equivalent to 7732 ha (INEC, 2017). In Shushufindi, agricultural maize production is made up of small and medium producers distributed throughout the territory. In parishes such as Central Shushufindi, Siete Julio and San Roque approximately 1018 ha of maize are planted (GAD Shushufindi, 2015).

Maize is traditionally grown under a family farming dynamic with crop rotation and association (GADP Limoncocha, 2015). On the other hand, the community production model is being replaced by a mechanized and industrial production model (Maza, 2015), and it is accompanied by technology containing certified seeds and inputs such as fertilizers, herbicides, insecticides, as well as machinery such as threshing, maize harvesters and tractors (GAD Provincial Sucumbíos, 2015; MAG, 2017; GADPR Siete de Julio, 2018). For all of the above, the objectives of the research are to characterize the agricultural models of hard maize present in Shushufindi; to estimate the emissions of GHG and freshwater consumption; and to determine the eco-efficiency of maize production models.

2 Methods

The investigation was based on the guidelines proposed by Ribal et al. (2009). The first step was to specify and characterize the scenarios or models to be studied. An environmental evaluation of the models was carried out using the Life Cycle Analysis (LCA), which includes two impact categories: Global Warming (GHG emissions) and Freshwater Consumption (water footprint). Additionally, an economic evaluation of these models was carried out through the K&K model developed by Kuosmanen and Kortelainen. Finally, the two previous evaluations were integrated using a non-linear GLP (Graphic Linear Optimizer) programming model to determine in this way which traditional, semi-conventional or conventional model is more eco-efficient in socio-economic and environmental terms.

2.1 Characterization and identification of models

Three agricultural maize models present in the study area were identified, the conventional model (CM), the semi-conventional model (SC) and the traditional model (TT). These models were characterized taking into account Martinez's attributes (Martínez, 2008) and other attributes suitable for the study as presented in Table 1.

In addition, CM, SC and TM models were georeferenced with the help of an unmanned aerial vehicle (UAV). The information was then processed in a GIS (ArcGIS ®), in which the location and area of the plots identified for each model was identified (Table 2). The geographical distribution of maize cultivation in Shushufindi was carried out using data provided by the SIPA inventory (Agricultural Public Information System) (Figure 1).

Once the models were identified, semi-structured interviews were conducted with the maize producers in order to collect information for socioeconomic and environmental factors, performing a convenience and consecutive sampling (non-probabilistic sampling).

Soil-root and biol samples were collected in the field for further analysis in the laboratory. The edaphological parameters analyzed in the samples were organic matter (OM), organic carbon (OC), pH, texture and humidity; and nitrogen (N), phosphorus (P) and potassium (K) were analyzed in biol. All samples were analyzed in certified laboratories (LABSU and AGROCALIDAD).

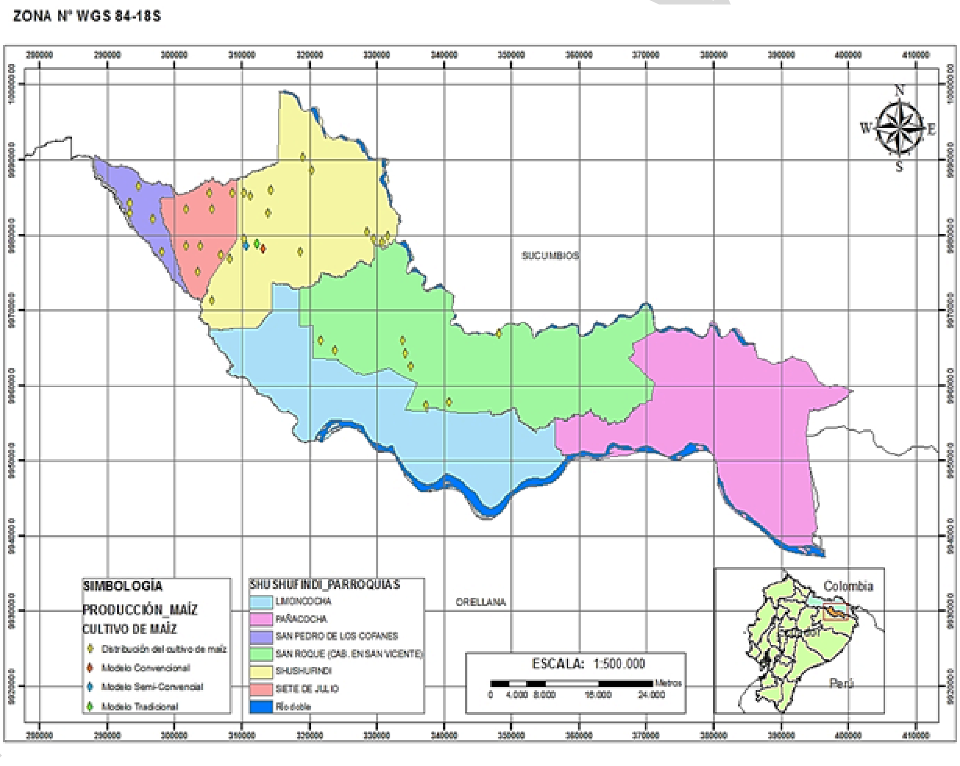


Figure 1. Geographical distribution of maize crops in the parishes of San Pedro de los Cofanes, Siete de Julio, San Roque, Shushufindi, and the location of study plots for each model CM, SM and TM. Source: Essential GPS data, georeferencing of drone Phantom 4 plots, National Information System (SNI), (GAD Shushufindi, 2015)

Table 1. Characterization of the maize production models in Shushufindi

Characterization Attributes	Scenario 1 Conventional model (CM)	Scenario 2 Semi-conventional model (SC)	Scenario 3 Traditional model (TM)
Energy	Predominates the use of fossil energy (gas and oil)	Predominates the use of fossil energy (gas and oil) – or alternatives (sun)	Use of renewable energy (sun). Less use of fossil fuel
Scale	Production area >1 ha	Plot of 0.5 ha area of 0.71 ha $\leq$ 1 ha	Plot as a production area
Objetive	Commerce	Self-consumption commerce	Self-consumption (Little or very Little to the commerce)
Workforce	Wage	Wage-family	Familiar - community
Diversity	Monocrop Low diversity	Monocrop – Associated Low diversity	Multicrop – High diversity
Productivity	"Irregular in the time, with high working productivity; low ecological and energetic productivity" (Martínez, 2008)	"Irregular in the time, with high working productivity; low ecological and energetic productivity" (Martínez, 2008)	"Regular in the time. High ecological-energetic productivity; low productivity at work" (Martínez, 2008)
Seed	Modified, hybrid	Cured	Creole
Machinery and tools	Large size agricultural machinery (destemmer, harvester, scythe)	Artisan agricultural machinery (artisan destemmer, scythe)	-There is not any use of agricultural machinery. -In this research, the producer used a scythe
Inputs	-Phytosanitary -Synthetic fertilizers	-Phytosanitary -Synthetic fertilizers	-Organic manure -Compost
Agricultural practice	-Without crop rotation	-There may or may not be crop rotation	-Crop rotation
Presence of pests	Yes	Yes	Yes-No
Pest control	Agro-chemical	Agro-chemical	Natural control
Wastes	-Incorporation of wastes, burning -Agro-chemical wastes	-Incorporation of wastes, burning -Agro-chemical wastes	-Incorporation of wastes -Production of organic wastes
Knowledge	Specialized, conventional science, standardized	Local-conventional	Local, traditional based in limited beliefs and knowledge and permacultural knowledge
Cosmovision	Market-based: "Nature is a separate system of society, whose richness must be exploited through science and technology" (Martínez, 2008)	Market-based	Eco-based: "Nature is a living and sacral identity. Nature is embodied in deity with whom the producer must dialogue during appropriation" (Martínez, 2008)

Source: (Martínez, 2008) Observations in the field and semi-structured interviews

Table 2. Description of the area and location of the research plots for each model studied

Type of production model	Sampled area		Location		
			X*	Y*	Place
(CM)	4	ha	310599	9978558	Atahualpa Route
(SC)	0.5	ha	310662	9978571	Los Ríos-Land Nº 11 Area belonging to the employee association of Shushufindi.
(TM)	0.15	ha	312274	9978832	Shushufindi Route-RICAAMA farm**

* Coordinates of the plots under study in UTM WSG 84 18S
** RICAAMA: Richness of the Amazon field – permacultural farm.

2.2 Environmental evaluation

The environmental influence was determined by the Life Cycle Analysis for Agriculture "LCA Agriculture" following the methodology of Arango et al. (2014) and the recommendations of Ramírez-Cando and Spugnoli (2016), Oliveral et al. (2016), Ramírez-Cando et al. (2017) and IHOBE (2009).

2.2.1 Limitations of the system to be evaluated

The system evaluated was limited from the agricultural production phase to the maize distribution phase. Inputs (resources, raw materials, inputs, transport, energy, etc.) and outputs (air emissions (GGG-GWP), water and soil, waste and by-products) are included, as observed in Figure 2.

2.2.2 Impact categories

The study considered two impact categories: global warming (kg CO_2 equivalents) and water consumption (m^3/ton), estimated through the water footprint.

a) **GHG emissions**

The IPCC 2006 guidelines for the AFOLU sector (IPCC, 2006a,b) were considered for estimating GHG emissions. In addition, the recommendations of the GHG protocol (WRI & WBCSD, 2011) and the guidelines taken from Agri-footprint (Durlinger et al., 2017a,b). were followed. It should be noted that the study considered sources of GHG emissions (E) with an impact of more than 1 % according to the "cut-off" IPCC criterion, as follows:

- E for the use of fuels and lubricants.
- E for fertilizers (organic-synthetic) N,P,K.
- E of CO_2 by the application of urea.
- E of N_2O by N applied on managed soils.
- E for the application of plant protection.
- E for maize seed.
- E because of the burning of agricultural waste.

GHG emissions were estimated using the general Equation given by (WRI & WBCSD, 2011) (Equation 1). Where *DA* represents the magnitude-amount of an input used in a place over a period of time and in a certain area, e.g. the amount of fuel used by the tractor. FE refers to the coefficients that quantify emissions or removals of a gas depending on activity data. The emission factors for the study were those determined by the IPCC and BioGrace (2011). GWP is the Global Warming Potential for CO_2 (1), CH_4 (25) and N_2O (298) gases for a 100-year time horizon (IPCC, 2007). It is important to mention that for comparative purposes, the activity data of the TM and SM models were extrapolated to one hectare.

$$kgCO_2eq/ha = DA * FE * GWP \qquad (1)$$

b) **Consumption of fresh water (water footprint WF)**

The components of Hoekstra et al., (2011) were used to measure green water footprint WF_{green} (precipitation) and gray water footprint WF_{gray} (freshwater pollution), thus allowing to know the total volume of fresh water used by maize crops in Shushufindi. It is important to mention that irrigation is not applied at the area under study due to the significant rainfall, so the blue water footprint WF$_{blue}$ (WF component) associated with precipitation was not evaluated. Using Equation 2 (Pérez, 2012), the WF of the maize crop was calculated for each agricultural production model studied.

$$WF_{crop} = WF_{green} + WF_{Gray} \left(\frac{m^3}{ton} \right) \quad (2)$$

Finally, CROPWAT 8.0 ® program developed by the Food and Agriculture Organization of the United Nations (FAO) and tabulations in EXCEL were used to calculate WF, followed by the Water Footprint Network (WFN) and FAO Water Footprint Assessment Manuals by Franke et al. (2013).

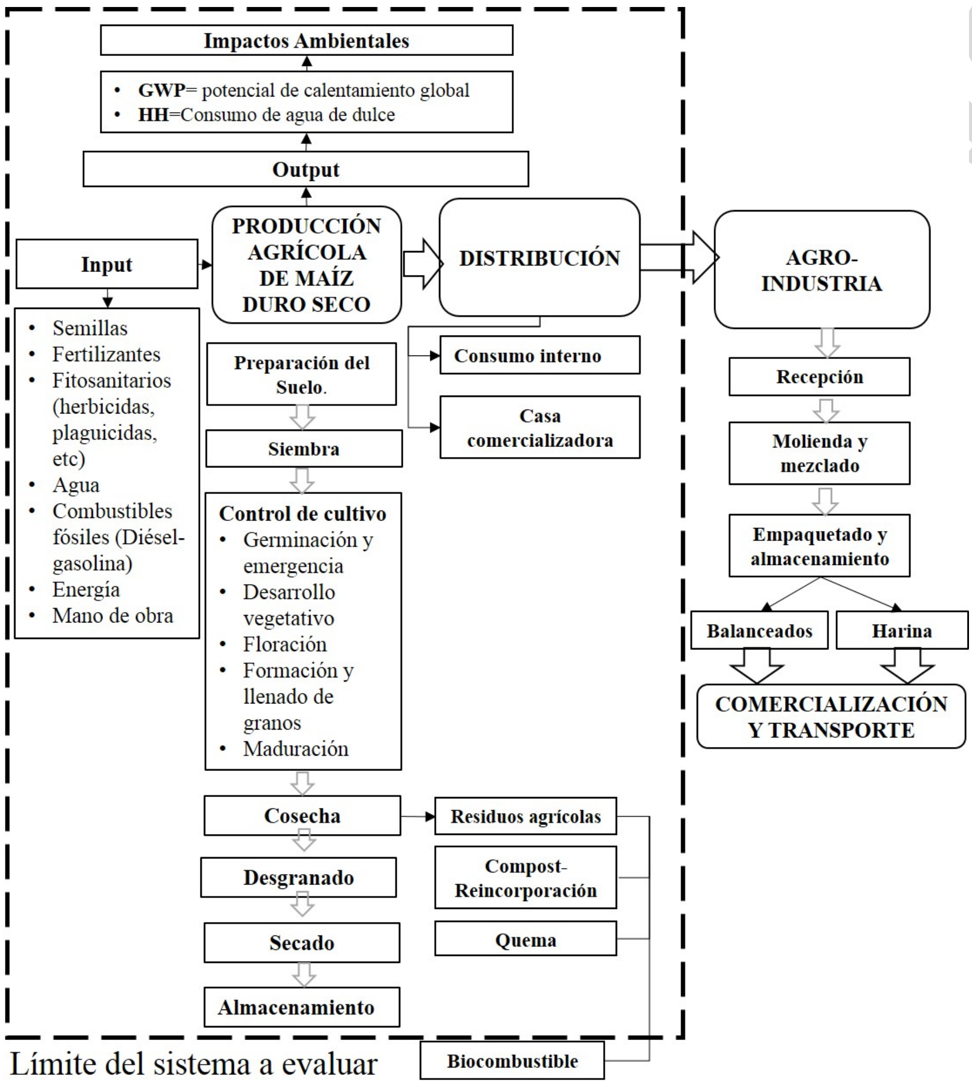


Figure 2. Limitations of the evaluated system - agricultural LCA of hard maize. The system evaluated ranges from maize production to distribution, excluding the agro-industry, marketing and transport phases.

2.3 Economic evaluation

K&K model developed by Kuosmanen and Kortelainen and described by Ribal et al. (2009) was applied. The partial accumulation of costs throughout the agricultural maize production process (seed, fuels, fertilizers, plant protection, wages, inputs, rental of machinery) was considered for each model analyzed ($ha/year). In addition, the profitability of maize production was quantified using Equations 3, 4 and 5, raised by Ayala-Garay et al. (2013).

$$\text{Profitability} = IT - CT \tag{3}$$

$$IT = P_y Y \tag{4}$$

$$CT = P_x X \tag{5}$$

Where IT is the total income $\left(\text{ha}^{-1}\right)$, CT is the total production cost, P_y is the market price of the crop Y ($\$/ton$), Y is the crop yield (ton ha^{-1}), P_x represent the price of the input or activity X (ton ha^{-1}) and X is the activity or input.

2.4 Ecoefficiency

Ecoefficiency was assessed using Rincón and Wellens (2011), as presented in Equation 6.

$$Ecoefficiency = \frac{Value\ of\ the\ product\ or\ service}{Environmental\ influence} \tag{6}$$

From Equation 6, (Ribal et al., 2009), propose a nonlinear programming model for m scenarios (CM, SC, TM models) and n impact categories (GHG-WF emissions) (Equations 7, 8, 9). This calculation was conducted in Microsoft Excel using the Solver application.

$$\underset{x}{maw} EE\ i = \frac{V_i}{w_1 \cdot z_{i1} + w_2 \cdot z_{i2} + \cdots + w_n \cdot z_{in}} \tag{7}$$

Subjected to:

$$\frac{V_1}{w_1 \cdot z_{i1} + w_2 \cdot z_{i2} + \cdots + w_n \cdot z_{in}} \leq 1 \tag{8}$$

$$\frac{V_m}{w_1 \cdot z_{m1} + w_2 \cdot z_{m2} + \cdots + w_n \cdot z_{mn}} \leq 1 \tag{9}$$

And $w_1, w_2, \ldots, w_n \geq 0$. Where V_i is the economic value added to scenary $i = 1 \ldots, m$ \$/ton, w_i is the weight of the environmental impact $j = 1, \ldots n$, z_{ij} is the environmental impact (gray footprint, green footprint and GHG) with $j = 1, \ldots, n$ by functional unit for the scenario $i = 1, \ldots, m$. The eco-efficiency index varies between 0 and 1, where value 1 will indicate that the scenario is eco-efficient (Ribal et al., 2009).

3 Results and discussion

3.1 Inputs y outputs

Table 3 presents the inputs and outputs of the models evaluated by taking into account laboratory results, interviews with producers and field observations.

3.2 Category of global warming

3.2.1 GHG Estimation of maize production models

The agricultural maize production model with the greatest contribution of GHG was CM with an estimated emission of approximately 2926.92 kg CO_2eq $\text{ha}^{-1}\text{year}^{-1}$, followed by SC emissions that emitted 1209.45 kg CO_2eq $\text{ha}^{-1}\text{year}^{-1}$, while TM emissions were lower with 570 kg CO_2eq $\text{ha}^{-1}\text{year}^{-1}$ (Table 4).

This study showed that TM emissions are 80% lower than those of CM and 57% lower than those of SC. Similarly, a study conducted by Eranki et al. (2019) reported that were 41% lower in an organic farming scenario emission than emissions from conventional agriculture.
Values of 145.32 (TM), 561.21 (SC) and 460.91 (CM) kgCO_2eq/ton (Figure 4-Table 6) were also reported, compared to the study conducted by Altuna et al. (2012) where the carbon footprint of maize was determined to be 514.76 kg CO_2 eq/ton of product, which is higher than other cereals such as wheat (380.87 kg CO_2eq/ton) and barley (297.75 kg CO_2 eq/ton). It is important to mention that regardless the model, SC and CM emissions are higher than those reported in Peru by mechanized maize production with 224 kg CO_2eq ton^{-1} (Morales et al., 2018).

3.2.2 Emissions from the use of fertilizers

Emissions from the application of fertilizers with NPK inputs were 54.26 (TM) and 4.49 (SC) kg of

CO_2 eq ha^{-1} $year^{-1}$ and 1032 (CM), kg of CO_2eq $ha^{-1}year^{-1}$. In addition, CM contributed to 133 kg of CO_2eq year/ha by fertilization with urea. Abrahão et al. (2016) reported that the main source of GHG emissions were the use of liquid fertilizers (69%) and 18% by the use of compound fertilizers, providing a carbon footprint for maize production of 1700 kg of CO_2eq year/ha.

Table 3. Inputs and outputs of the evaluated models

DESCRIPTION		QUANTITY			UNIT
Inputs*		**TM**	**SC**	**CM**	
Synthetic fertilizers	**10-30-10**	-	2	1088.62	$kg/ha\ year^{-1}$
	N	-	0.2	108.86	
	P	-	0.6	326.59	
	K	-	0.2	108.86	
	13-40-13	-	-	2	
	N	-	-	0.26	
	P	-	-	0.80	
	K	-	-	0.26	
	Thickener	-	4	-	
	N		0.33	-	
	P		0	-	
	K		1.16	-	
Biol	**Leachate of compost + urine**	16	-	-	$L/ha\ year^{-1}$
	N	8.96	-	-	$kg/ha\ year^{-1}$
	P	0.35	-	-	
	K	2.13	-	-	
Urea		-	-	181.82 / 83.64	$kg/ha\ year^{-1}$
Plant production		-	0.43	1.25	$kg/ha\ year^{-1}$
Fuels	Gasoline	6.28	22.75	9,46	$gal/ha\ year^{-1}$
	Diesel	-	-	29	
	Oil 2T	0.35	0.53	-	
Seed		48.38	45.36	40	$kg/ha\ year^{-1}$
Water	Irrigation	0	0	0	$m^3/ha\ year^{-1}$
Work		1366.67	552	121.68	$h/ha\ year^{-1}$
Outputs**					
Hard maize		3.92	2.40	6.35	$ton/ha\ year^{-1}$
Agriculture waste		4.49	3.16	7.28	

* **inputs:** Quantity of inputs, resources and energy employed by maize producers for the production of a maize hectare
** **outputs:** Quantity of by-products (maize) and agricultural wastes obtained in the production of a maize hectare
- Inputs not used by maize producers

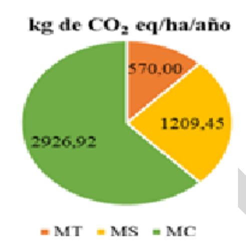
3.2.3 N_2O Emissions

The use of synthetic, organic fertilizers and the breakdown of stubble are responsible for significant N_2O emissions due to nitrification, denitrification, leaching-volatilization and runoff processes in the soil. These emissions were 443.93 (TM), 234.72 (SC) and 1279.81 (CM) kg of CO_2 eq ha^{-1} $year^{-1}$; CM is the model with the greatest contribution of emissions emitted to the atmosphere.

3.2.4 Emissions from the use of fossil fuels

Emissions from the use of fossil fuels (gasoline, diesel and lubricants) by agricultural machinery such as tractor, combine, threshing and transportation) had an emission contribution to the atmosphere of 406.49, 196.30 and 54.88 kg CO_2eq ha^{-1}year^{-1} for CM, SC and TM models, respectively. Figure 5 shows the percentage and kg of CO_2eq ha^{-1} year^{-1} emitted by the machinery used in each model studied.

Table 4. Total emissions from the models studied.

TOTAL OF GHG EMISSIONS	Agricultural production models of hard maize			
	TM	SC	CM	
kg of CO_2 eq/ha/year	570.00	1209.45	2926.92	
Contribution % of GHG	13	27	60	
kgCO_2eq/ton	145.32	561.21	460.91	

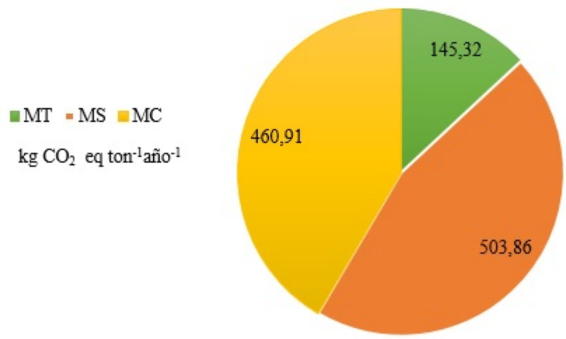


Figure 3. GHG emissions by the studied models (kg CO_2eq ton^{-1} year^{-1})

3.2.5 Emissions from phytosanitary

Agricultural production models reported emissions from phytosanitary applications of 9.48 kg of CO_2 eq ha^{-1} (SC) and 60.34 kg of CO_2 eq ha^{-1} year^{-1} for the CM model, while TM did not report emissions from this source, since the producer does not apply any type of plant protection. According to research conducted by Morales et al. (2018), the use of pesticides in mechanized maize crops contributed to 205 kgCO_2eq ha^{-1}, being higher than those estimated in the present study. Table 5 presents the contribution of GHG emissions from each phytosanitary system used by CM and SC models.

3.2.6 Emissions from the seed input

The use of seeds contributed to 2.97 %, 1.18 % and 0.48 % for TM, SC and CM models, respectively, corresponding to emissions of 16.93 (TM), 15.88 (SC) and 14 (CM) kg of CO_2eq ha^{-1} year^{-1}, and similar to those reported by Abrahão et al. (2016), that contributed to 3 % to emissions.

3.3 Water footprint

3.3.1 Water footprint of the crop (WFcrop)

Maize WFcultivation was 1008.16 (TM), 1201.85 (SC) and 1157.86 (CM) m^3/ton (Figure 6), showing a higher impact on CM and SC models, as the volume of fresh water used directly or indirectly to produce maize is very high compared to TM. In SC, 1153.75 m^3/ton of WFgreen was obtained, higher than TM with 1 008.16 m^3/ton of WFgreen. On the other hand, the conventional model had a green footprint of 599.69 m^3/ton, which depended on the performance (ton/ha) presented by the conventional model compared between the SC and TM models.

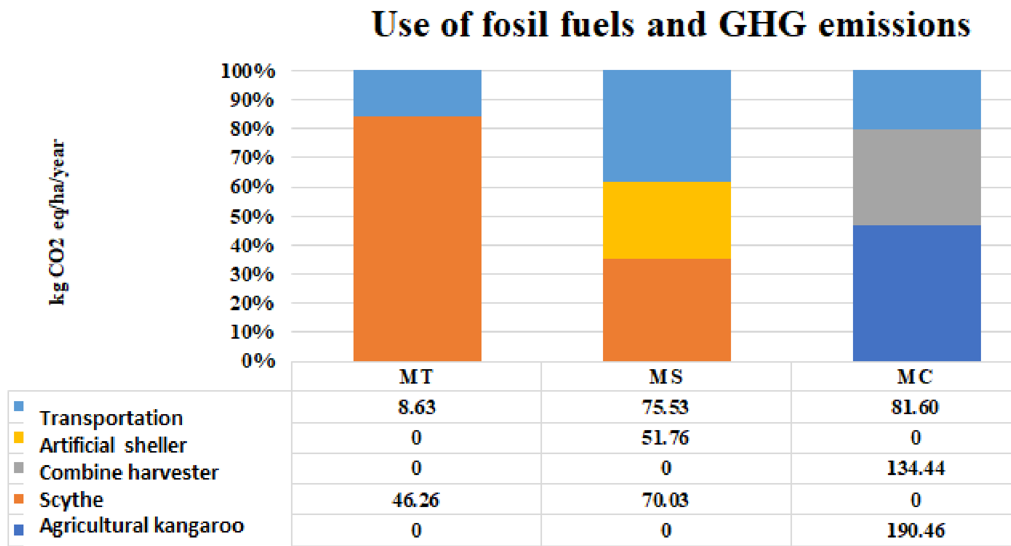


Figure 4. Participation of GHG by machinery and transport.

Table 5. GHG emissions by phytosanitary

Phytosanitary		**Quemante (Herbicide)**	**TEJO (insecticide)**	**NOSTOC (Herbicide)**	**Total of emissions**
		kg de CO_2eq ha^{-1} $year^{-1}$			
Model	CM	27.425	32.91	-	60.34
	SC	-	8.78	0.7	9.48

The WFgreen of the maize crop in Sucumbíos was 2073 m^3/ton according to Pérez (2012); this footprint is higher than the estimated in the three models analyzed in the present study. In addition, Romero et al. (2016) reported that the average green footprint represents 60 % of the total agricultural footprint (820.24 m^3/ton) in maize crops in Colombia, and green WF represents 52 % compared to CM.

As for the gray footprint, this was 48.10 and 558.17 m^3/ton for SC and CM, respectively. For its part, TM did not report gray WF values because no synthetic or phytosanitary fertilizer was used. In the province of Sucumbios, Pérez (2012) reported a gray footprint of 330 m^3/ton for the cultivation of maize, which is smaller than the gray footprint of the CM of this study, because this model has a high consumption of agricultural inputs such as fertilizers and plant protection.

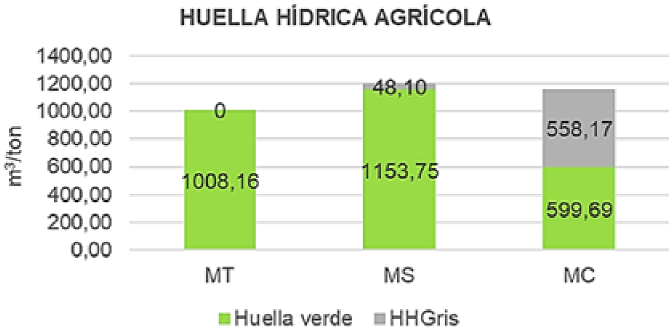


Figure 5. WFcrops of the maize production models in Shushufundi.

3.3.2 Economic evaluation

Table 6 presents the cost balance for the maize production by model studied, and it shows that maize production is unprofitable due to the high costs of agricultural inputs, with very low profits.

3.4 Ecoefficiency

The weights for each impact category were 1 for gray footprint, 0.41 for green footprint, and 0.92 for GHG emissions (Table 7). The traditional model is the most eco-efficient model in environmental and economic terms with 0.99 eco-efficiency.

Table 6. Cost balance for the maize production in the studied model

Model	**TM**	**SC**	**CM**
		($/ha year^{-1})	
Incomes	863.00	756.00	2100.00
Costs	312.95	521.21	1712.85
Seed	0.00	100.00	176
Fuels	23.45	27.71	12.35
Fertilizers	0.00	8.00	286.00
Phytosanitary	0.00	64.00	84.00
Wages	270.00	240.00	540
Inputs	9.50	12.50	34.50
Rent of machinery	10.00	69.00	580.00
Profitability	550.05	234.79	387.15

Eco-efficiency is influenced by the hotspots or critical points that each impact category has (green footprint, gray and GHG emissions); for this reason, the WFgray category has greater weight, due to the high use of synthetic and phytosanitary fertilizers used by SC and CM models. For the GHG emissions category, the hotspot is influenced by the high consumption of nitrogen fertilizers, which generates significant N_2O emissions from managed soils. These two components double their weight (importance for a more efficient management of the process), with respect to WFgreen, considering that the GHG and WFgray have their greatest influence from the use of fertilizers. This hotspot is the first to be taken into account to improve the ecoefficiency of conventional crops or combined maize production systems.

It is important to mention that ecoefficiency is relative to the models studied, i.e., there may be other agricultural practices that make the models more environmental and socio-economic efficient (Ri-

Table 7. Ecoeficiencia de los modelos de producción de maíz

Impact categories (Z)	WFgray	WFgreen	GHG Emissions
Weight (W)	W_1	W_2	W_3
	1	0.41	0.92
max. EE	0.999999617		
Ecoefficiency of agricultural production models			
$\mathbf{EE}_{SC}$	0.24		
$\mathbf{EE}_{CM}$	0.32		
$\mathbf{EE}_{TM}$	0.99		

bal et al., 2009).

4 Conclusions

Using the eco-efficiency index, it was possible to determine that the most economic and environment sustainable model of agricultural maize production is the traditional TM model, since it showed an eco-efficiency of 0.99. This high ecoefficiency is due to the fact that this model does not depend on inputs such as plant protection and synthetic fertilizers which are expensive. In addition, the use of these agrochemical inputs has a significant environmental impact on the environment, as evidenced by the different categories of impact.

Although the TM model is more eco-efficient, it is very little used by the producers, because it demands more working hours and low yield (Table 3) compared to a conventional model (Pinzón and Ramírez, 2019); which does not satisfy the economic demand. However, this type of TM model is more environmentally friendly, since it does not require technology but instead it uses unmodified creole seeds from the previous crop and do not need any plant protection or chemical fertilizers. Finally, this model preserves family farming, and sustainable agricultural practices such as crop rotation for pest control, as well as a vision for permaculture (Pinzón and Ramírez, 2019).

Finally, the results made it possible to know the impacts associated with agricultural maize production models and their contribution to Climate Change (CC) in sensitive ecosystems such as those of the Ecuadorian Amazon, so that sustainable agricultural practices can be implemented.

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