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Assessment of Sustainability in Livestock Systems in the Amazonian Piedmont, Colombia*

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Abstract

This research aimed to suggest an assessment of sustainability in livestock systems in the Colombian Amazonian Piedmont. The variables benefit-cost ratio (*BCR*) of the production systems and the carbon stored (C_S) in the aerial biomass (B_a) of trees in pastures were used to construct the sustainability indicator. The percentage of productive soil and the number of heads of cattle were used as inputs. The sample consisted of 37 farms. The indicator was obtained with the non-parametric Data Envelopment Analysis method. The results showed that 8% of the production systems were on the sustainability threshold, and the remaining 92% had the potential for improvement, specifically through increased *BCR*, efficient use of productive land, and increased

Keywords

Sustainability indicator, ecosystem services valuation, carbon storage, data envelopment analysis

JEL classification

C61, D22, Q56

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carrying capacity. It was concluded that the sustainable farms had an average *BCR* of 2.3 and registered an average C_S in B_a of 2.14 $t{\cdot}ha^{-1}$, using 13.6% of the extension of the farm as productive soil.

Valoración de la sostenibilidad en sistemas ganaderos en el piedemonte amazónico colombiano

Resumen

Esta investigación tuvo por objetivo proponer una valoración de la sostenibilidad de los sistemas ganaderos del piedemonte amazónico colombiano. Para construir el indicador de sostenibilidad se usaron las variables razón beneficio costo (RBC) de los sistemas productivos y el carbono almacenado (C_A) en la biomasa aérea (B_a) de árboles en pasturas. El porcentaje de suelo productivo de la finca y el número de cabezas de ganado se utilizaron como insumos. La muestra fue de 37 fincas. El indicador se obtuvo mediante el uso del método no paramétrico Análisis Envolvente de Datos. Los resultados mostraron que el 8 % de los sistemas productivos estaban en la frontera de la sostenibilidad y el 92 % restante tenían un potencial de mejora, específicamente en aumentos en la RBC, el uso eficiente del suelo productivo y el aumento en la capacidad de carga. Se concluyó que las fincas sostenibles tuvieron una RBC promedio de 2,3 y registraron un promedio de C_A en B_a de 2,14 $t{\cdot}ha^{-1}$, empleando un 13,6 % de la extensión de la finca como suelo productivo.

Palabras clave

Indicador de sostenibilidad, valoración de servicios ecosistémicos; almacenamiento de carbono, análisis de envolvente de datos

Introduction

Population growth and current forms of production and consumption have generated the environmental crisis that resulted in climate change, loss of biodiversity, and overexploitation of natural and environmental resources (Constanza et al., 2017). In response, the focus on sustainability emerged as a development criterion by which the productive or consumption units guarantee the satisfaction of human needs in the socioeconomic and environmental aspects, based on the conservation of natural capital and the ecosystem balance (World Commission on Environment and Development [WCED], 1987). Current world policy has focused on these aspects to raise the so-called sustainable development goals –SDG– (Naciones Unidas, 2018).

For this reason, the assessment of sustainability in different sectors and contexts is a tool for the construction of environmental policy, in accordance with potential improvements for production units, and constitutes a baseline to strengthen communities with programs oriented towards sustainable development (Quiroga, 2007).

The Amazon is a strategic ecosystem that has been gradually reduced as a result of both colonization and the agricultural expansion to implement inefficient production systems, which fragment forests and, therefore, the ecosystem services that they sustain (Phillips et al., 2016). After the oil industry and its derivatives that emit about 85% of the Greenhouse Gases (GHG), the agricultural sector is responsible for emitting between 14 to 18% of the GHG, in essence methane (CH_4), dioxide carbon (CO_2), and nitrous oxide (N_2O), and this is primarily attributed to the enteric fermentation of cattle (Ritten et al., 2012). This environmental problem has been persistent, due to the economic representativeness of the agricultural sector in the regional economy, and it has result in high environmental costs (Brown et al., 2005; Gerber et al., 2013).

From this point of view, the rural production systems in the Amazon should be evaluated for changes in soil use and coverage, not only in terms of its financial profitability, but also for the achievement of its socio-economic goals, improvements in settler quality of life and social welfare, and environmental impacts generated, in order to decide if it should evolve with a focus on sustainability (Peña-Venegas & Cardona-Vanegas, 2010).

> “The rural production systems in the Amazon should be evaluated for changes in soil use and coverage, not only in terms of its financial profitability, but also for the achievement of its socio-economic goals, improvements in settler quality of life and social welfare, and environmental impacts generated”.

Theoretical references

Evaluating the sustainability of Latin America has mainly involved the construction of indicators developed by the Economic Commission for Latin America and the Caribbean –ECLAC–, the Inter-American Development Bank –BID– and the World Bank –BM–, among others (Pardo-Rozo & Sanjinés-Tudela, 2014). For the agricultural sector, indicators of biodiversity, deforestation, species depletion, carbon footprint, water footprint, quality of life, poverty, human development, environmental impact, and other forms of sustainability measurement have been developed. These include the Framework for the Assessment of Natural Resource Management Systems incorporating Sustainability Indicators (MESMIS), capital and life analysis (Sepúlveda et al., 2005; Schuschny & Soto de la Rosa, 2009). However, these indicators are partial, while the assessment of sustainability demands an integral indicator that consolidates socioeconomic and environmental dimensions (Muñoz, 2007; Cecchini et al., 2018; Heidari et al., 2021).

In the Colombian Amazon, studies have been carried out to diagnose and monitor environmental problems, as well as to seek alternatives for agricultural development that are more environmentally viable (Ramírez et al., 2004; Ramírez et al., 2013; Instituto Amazónico de Investigaciones Científicas SINCHI, 2015). However, it is important to evaluate the sustainability of the farm systems and understand the potential for improvement in the Colombian Amazonian piedmont.

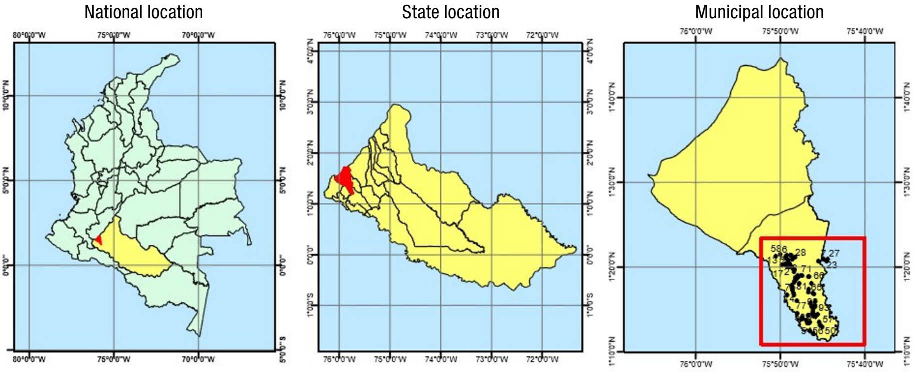
Valorization of sustainability is a crucial process for measuring the effectiveness of local administrations and sectoral policies for rural development, aiming to protect and conserve indispensable resources with strategies developed in Colombia to mitigate and adapt to climate change (Álvarez et al., 2013). Such methods must integrate the potential of ecosystem services (Balvanera et al., 2017), which can add value to the land and strengthen production processes (Millennium Ecosystem Assessment, 2005; Ruíz & Bello, 2014; Toledo et al., 2018).

Methods

The study was developed in the towns of Belén de los Andaquíes (1º 24’59” N, 75º52’22”W) in the Amazon piedmont of the state of Caquetá (Colombia) (Figure 1). The topography of the sector is undulated with altitudes between 250-530 m (Sistema de Información Ambiental Territorial – Amazonia Colombiana

[SIAT-AC], 2018). The climate is characterized by presenting, on average, 3758 mm of annual precipitation, 25.8°C of average temperature, and 4.3 *h·day*$^{-1}$ of sun light (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2020).

Figure 1. Production units of the mine in Belén de los Andaquíes, Caquetá, Colombia



*The points indicate the number of farms
Source: own work.

Of the 297 properties in the area, 37 were randomly selected , considering the proportion of farm operation and size (Hernández et al., 2014). These agricultural systems of the Amazonian piedmont had the following characteristics: i) areas with traditional livestock, agricultural, and forestry practices, ii) areas with presence of traditional systems but updated with policies for transition to sustainable systems and the promotion of ecotourism, iii) areas with locations connecting spaces between national and municipal natural parks, iv) area with water and biodiversity richness, and v) area with potential for the establishment of economic incentive compensation systems for ecosystem services (Ramírez et al., 2012; Ramírez et al., 2013).

The primary information was collected directly from the producers, through a structured survey with questions about socioeconomic and environmental aspects. The variables to estimate the sustainability indicator were the benefit-cost ratio (*BCR*) of the production systems, the carbon stored (C_S) in the aerial biomass (B_a) of trees in pastures, the percentage of productive farm soil, and the number of heads of cattle.

Valorization of sustainability considers the Benefit Cost Ratio (BCR) as a socio-economic variable because of the financial viability of all the production activities that are carried out on the farm. This data demands the construction of cash flows for each production unit, which incorporate both the dynamics of the income and costs reported by the producer (according to market prices) and the quantity of products versus the costs of production factors (labor, land, and capital). The benefit-cost ratio was calculated from the quotient between the net present value of the incomes and the net present value of the costs (Castro-Rodríguez et al., 2008). The opportunity interest rate (OIR) used to discount cash flow was 12 % for social projects (DNP, 2018). It was compared to the Internal Return Rate (IRR), another financial criterion for decision-making (Castro-Rodríguez et al., 2008).

The C_S was used as a variable of the environmental dimension of sustainability. The C_S is a strategic ecosystem service in mitigation and adaptation to climate change. The carbon stored data were taken from the study by Pardo-Rozo et al. (2021). This study established temporal sampling plots of 500 m^2 in pastures with trees on each farm. In total, there were 40 plots (2 ha). Then, all trees with a trunk diameter at breast height (dbh) > 10 cm, located in the plots, were measured. The stored carbon (C_S) per hectare was estimated based on the model (Equation 1) of IPCC (2006). An estimate of the aerial biomass (B_a) was performed using an allometric model (Equation 2) and wood density value (ρ) for tropical forests, of 0.6 $g{\cdot}cm^{-3}$ (Álvarez et al., 2012).

$$C_S = B_a \cdot 0{,}47 \text{ (Equation 1)}$$

$$B_a = e[2.406 - 1.289 \cdot \mathrm{Ln}\,(Dbh) + 1.169 \cdot (\mathrm{Ln}(Dbh))\hat{}2 - 0.122 \cdot (\mathrm{Ln}\,(Dbh))\hat{}3 + 0.445\ \mathrm{Ln}\,(\rho)]$$
$$\text{(Equation 2)}$$

The CO_2 carbon equivalent ($CO_{2\ eq}$) was estimated according to the model (Equation 3) suggested by IPCC (2006).

$$CO_2\ eq = C_S \cdot [44/12] \text{ (Equation 3)}$$

With the above data, the sustainability indicator was estimated using the data envelopment analysis (Data Envelopment Analysis –DEA–), a resource for linear programming to build a synthetic indicator from partial data (Coll & Blasco, 2006; Quiroga, 2007). This approach is used to integrate variables of different sustainability dimensions to determine if the farms have been able to maximize the benefits in economic, social, and environmental terms with the lowest number of inputs (García-Cornejo et al., 2020; Nandy et al., 2021).

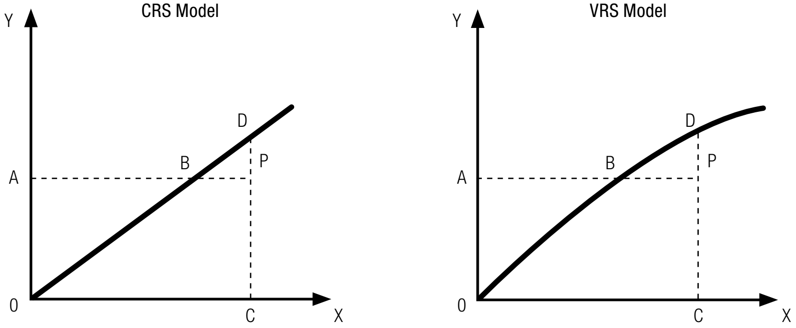
The sustainability indicators are calculated using the Frontier Analyst program, which sets efficiency rates between 0 and 1 for each property. Farms that obtained a score equal to one (1) were considered sustainable (efficient) because they present an optimal relationship between products (socioeconomic and environmental variables) and inputs (percentage of productive income from cattle and cattle heads). Farms with less than one (1) score are considered unsustainable (inefficient). For sustainable livestock farms, a border was built to define each farm's improvement potential with respect to the different sustainability variables. The potential for improvement is associated with reduced inputs and increased products that farms, with a score below 1 must obtain to be considered sustainable. This information allowed for comparing farms and elucidating policies and programs aimed at sustainability.

The mathematical model was aimed at maximizing a product (U) and simultaneously minimizing inputs (V) to build a scenario that allowed each observation unit to be compared against its optimal potential. It was started from N farms that used a certain number of inputs (I) to produce products (P) in a certain period (t). Matrices X of inputs (of order I x 1) and matrix Y of products (of order P x 1) were taken for the i-th farm, and both were confirmed by the data observed from the agricultural farms, assuming constant returns for scale. The BCR and C_S were used as outputs, while the percentage of productive farm soil and the number of heads of cattle were used as inputs. The technical efficiency of a given farm was estimated using the following linear programming expression:

Objective function: $Max\ U,V\ (X_i\ ,\ Y_i)$
Subject to the restrictions: $VX_i = 1$
$UY_i - VX_i \leq 0$
And: $i = 1,2, \dots N$
$U, V \geq 0.$

where, U is a vector of P x 1 optimal products to be found (the weight of the *output*), V is a vector of I x 1 that represents the optimal combination of inputs to be found (the weight of the *input*), X_i represents the inputs of the i-th evaluated farm, Y_i represents the products of the i-th evaluated farm, and N is the number of decision-making units (DMU), in this case, 40 farms. This DEA approach corresponds to a product-oriented model. However, the input-oriented model was also explored. The existence of constant returns at scale (CRS model) and variable returns at scale (VRS) were considered. Thus, the output-oriented efficiency ratio is measured between CP/CD, and in the input-oriented approach, it is constructed between the AB/AP ratio (Figure 2).

Figure 2. Product-oriented (CP / CD) and input-oriented (AB / AP) technical efficiency representations with constant returns (CRS model) and variable returns at scale (VRS model)



Source: adapted from Gamarra (2004).

Scale efficiency (*SE*) was obtained from the quotient between the model's score with constant returns θ_{CRS} and the model with variable returns θ_{VRS} (in each orientation). *SE* is used to identify which DMUs were operating on an optimal scale. The analyses were carried out with the VRS models (Coll & Blasco, 2006). One of the advantages of this linear programming method is that it allows for treating and involving many variables of different nature (economic, social, and environmental), which are measurable in different units (some monetary and others in quantities) with values that can be continuous or discreet.

Additionally, the method allows for identifying the distance between the score calculated for each farm and the optimal sustainable score. That is, it identifies the potential improvements, the values that define how many resources (products or inputs) must be increased or decreased to reach the efficiency threshold (or, sustainability threshold in this case).

Results

Socio-economic aspects of producers in livestock systems

The farm size under study was 2000 *ha* (100%), with 1506.5 *ha* (75.3%) used as pasture for livestock. The farms under study were mainly small and medium-sized (Table 1), had an average extension of 54.1 *ha* with a minimum of 8 *ha* and a maximum of 178 *ha*, and were between 5 and 60 km from the municipal seat of Belén de Los Andaquíes (Colombia). The 37 farms under study were inhabited by a total of 140 people, representing 3.3% of the municipal rural population, and 89% were male. Households were made up of four people, on average, with a maximum of seven, and there was an average of two children per household. 80% of the producers were between the ages of 21 and 60. 33% of the producers did not have any education diploma; 26% did not finish primary school, but they know how to read and write; 7% did not carry out any study; 65% had educational qualifications, and only 2% are professionals.

According to land tenure, 87% of those surveyed were owners, 10% were on a lease, and 3% lived on the properties as family homes. 95% of the heads of the household were active on their farms, and 5% were pensioners. The average monthly income of the families was COP 732,000 (USD 216.3), observing a minimum of COP 100,000 (USD 29.5) and a maximum of COP 3,000,000 (USD 886.5). The average monthly expenditures per household (in aspects related to food, health, transportation, education, clothing, and unforeseen events) was COP 673,200 (USD 198.9), noting a minimum of COP 185,000 (USD 54.7) and a maximum of COP 4,650,000 (USD 1,374).

38% of the farms were subsistence economies because their profits were zero or they reported annual losses, presenting an RBC between 0-1. 22% were simple economies, characterized by few possibilities for capital accumulation or technological investment (their profits were positive, with RBC> 1, but without a culture of saving or investment to expand production). 40% were characterized as capital accumulation economies that generated RBC > 3 and had a culture of savings and investment. 85% of the farms employed family labor, while only 15% employed external labor. 82% of the farms were considered family production systems, and the remaining 18% were semi-commercial production systems.

Table 1. Classification of the farms under study according to their size

Classification	Range (*ha*)	Frecuency	Average size (*ha*)	Relative %
Microfarm	3 – 10	3	8.6	8.1
Minifarm	11 – 20	5	16.2	13.5
Small farm	21 – 50	14	40.9	37.9
Medium farm	51 – 100	12	73.8	32.4
Medium-Large farm	≥ 100	3	160.1	8.1
Total		**37**	**54.1**	**100.0**

Source: own work.

Financial and economic aspects of production systems

90% of the farms had milk production systems, and 10% were dual-purpose (meat and milk). Regarding the minority, 26.6% of the farms reported pig farming activities, 30% reported poultry meat, and 35% produced field and barn eggs, while only 2% of the producers developed aquaculture activities. The most profitable production systems were, in decreasing order: dairy farming, rubber production (*Hevea brasiliensis* Muell Arg.), palm oil (*Elaeis guineensis* Jacq.), and cocoa (*Theobroma cacao* L.). The latter barely managed to reach the social discount rate (SDR) for the rural sector (12%), which means that the producer decides whether to reinvest the money in agricultural activity or to instead put it into the financial system (Table 2).

Table 2. Profitability indicators for rural production systems in the Caquetá Amazon piedmont considering the main economic activities

Economic activity	BCR	*IRR* (%)
Rubber (*Hevea brasiliensis* Muell Arg.)	1.9	16.3
Cacao (*Theobroma cacao* L.)	1.4	11.9
Palm oil (*Elaeis guineensis* Jacq.)	1.5	16.7
Livestock systems	2.1	17.4

BCR: benefit-cost ratio; IRR: annual effective internal rate of return

Source: own work.

According to the main economic activity, 36% of the production systems under study were agroforestry; 29% were purely livestock systems (bovine livestock with minor bird and swine species); 16% were combined agricultural units (cattle and crops); 10% were bovine livestock systems, and 9% were forest systems.

Environmental Aspects

Among the environmental aspects, the abundance of superficial and underground water resourcesoth stood out (Alcaldía de Belén de Los Andaquíes, 2020). 20% of the farms had access to water bodies, such as streams and wetlands, and 78% had creeks and streams on the properties. 83.5% of the production units were supplied from underground water sources through the construction of reservoirs. 54% of the producers stated that they had permanent water availability during dry periods. 24% considered the supply at a medium level in these periods, and the remaining 22% considered the level of water availability in dry periods low, which could affect their agricultural production activities, but not their domestic ones. With the results of the sampling plots (Table 3), the aerial biomass immersed in the 2000 *ha* of existing pastures was estimated at 15,600 $t\ C_S$ and 57,200 $t\ CO_2$.

Table 3. Dasometric measurements of trees in pastures and estimates based on data collected in temporary sample plots in the Amazonian piedmont of Caquetá

Parameter	Mean	Standard Error
Average *Dbh* (*cm*)	15.90	(1.67)
Average B_a ($t \cdot individual^{-1}$)	0.38	(0.10)
Average B_a ($t \cdot ha^{-1}$)	4.6	(1.19)
Average C_S ($t \cdot ha^{-1}$)	2.14	(0.11)
Average CO_2 ($t \cdot ha^{-1}$)	7.85	(0.08)
Abundance (*individual·ha*$^{-1}$)	12.00	(2.33)

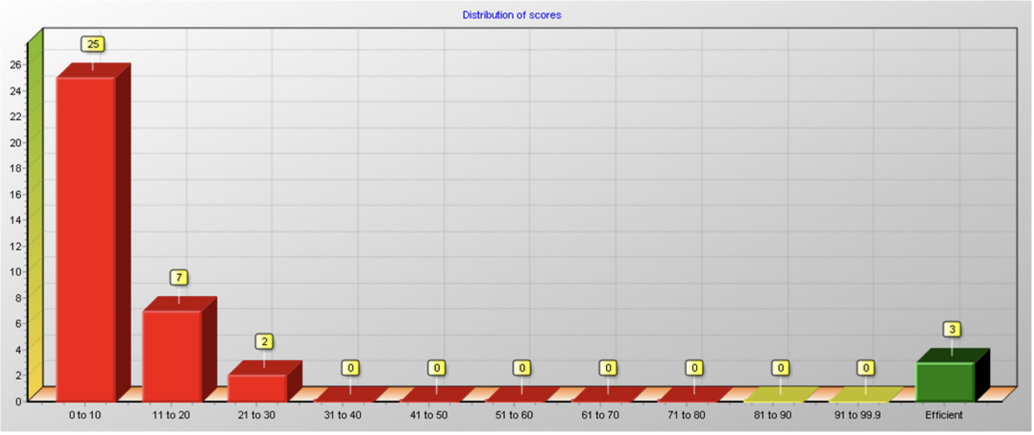
Dbh = diameter at breast height; Ba = Aerial Biomass; CS = Sequestered Carbon

Source: own work.

Input-oriented model with constant returns at scale (CRS)

The challenge was to minimize the inputs (head of cattle as a percentage of production area) to produce a given level of products (C_S in B_a and *BCR*), given the assumption of constant returns at scale. The result will be the same as the primary problem of maximizing outputs at a certain level of inputs with constant returns to scale. The distribution of the inefficiency (non-sustainability) scores was mostly concentrated between 0 and 30 (Figure 3), and only 3 efficient or sustainable farms were found (8.1%).

Figure 3. Distribution of model inefficiency scores with constant yields oriented to inputs (CRS input) for the properties under study in the Amazon piedmont (Caquetá, Colombia)

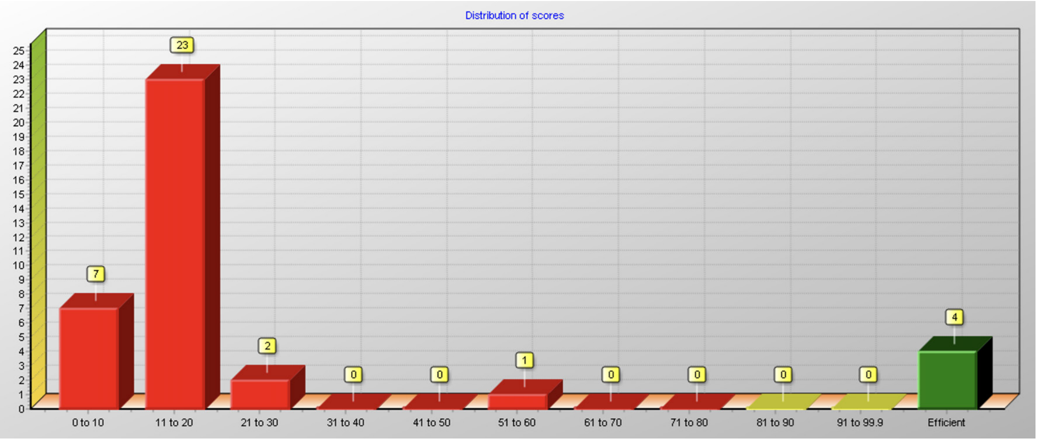


Source: author own elaboration using Frontier Analyst software.

Input-oriented model with variable returns at scale (VRS)

The challenge was to minimize the inputs to sustain a given level of outputs. The distribution of the inefficiency (non-sustainability) scores was concentrated between 3 and 40 (Figure 4), and only showed 4 efficient farms (11%).

Figure 4. Distribution of input-oriented model inefficiency scores with variable returns to scale (VRS input) for the properties under study in the Amazonian piedmont (Caquetá, Colombia)



Source: author own elaboration using Frontier Analyst software.

Scale Efficiency (*SE*)

With the sustainability scores of the previous models, the SE was calculated from the quotient between the model's score with constant returns and the model with variable returns in each orientation (Table 4). The sustainable farms (with SE = 1) presented an average BCR of 2.3, an average C_S of 3.64 $t{\cdot}ha^{-1}$, and only 13.6% of its extension as a production area. These output values for the sustainable farms were higher than the average output of the sampled group's total farms. Likewise, the average values of sustainable farm inputs were lower than those of unsustainable farms.

The sustainable farms had areas between 40-60 ha (small farms) with forest cover and were located at an average altitude of 260 meters above sea level. The predominant production activity in 58% of these farms was dairy farming with minor species (pigs and chickens), while 28% were rubber forest systems, and the remaining 14% were agroforestry systems. 100% were farms with their own land tenure and were managed by family systems. The average annual profit of these farms was COP $17.65 million (USD 5,215.4) with a minimum of COP 10,650,000 (USD 3,146.9) and a maximum of COP 25,300,000 (USD 7475.9). The three sustainable farms defined the data envelopment analysis (sustainability threshold) and marked the difference between the different dimension attributes that defined sustainability (social, economic, and environmental aspects) (Figure 5).

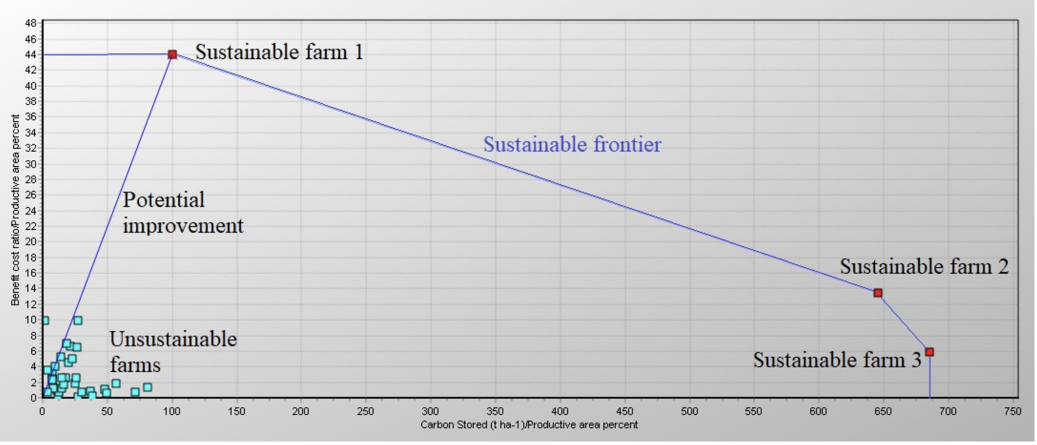
Table 4. Descriptive statistics of sustainability scores for input-oriented models (under constant and variable returns to scale) and efficiency at scale for farms in the Amazonian piedmont

Parameter	θ_{CRS}	θ_{VRS}	θ_{SE}
Average Sustainability Score	21.50	30.20	0.67
Standard Deviation	0.25	0.29	
Mínimum	3.10	8.30	
Average Unsustainable Farm Score	14.60	21.70	0.65
Number of Sustainable Farms*	3 (8%)	4 (11%)	3 (8%)
Number of Unsustainable Farms *	34 (92%)	33 (89%)	34 (92%)

θ_{CRS}: scoring efficiency at scale with constant returns. θ_{VRS}: efficiency score at scale with variable returns. SE: Scale efficiency. *: those farms whose efficiency score was equal to 1 were considered sustainable, while the others had potential for improvement towards sustainability

Source: own work.

Figure 5. Threshold of sustainability in the input-oriented model with constant returns at scale (Benefit Cost Ratio: CBR, Carbon Stored CS)



Source: author own elaboration using Frontier Analyst software.

Potential improvements for unsustainable farms

The present values for production area represented 86% of the total extension of unsustainable farms, where the negative sign for the improvements (%) indicates an underutilization of this resource (Table 5). Similarly, the production unit must increase its profitability, and the tree capacity to serve as carbon sinks can be improved.

Table 5. Potential improvements in the farms under study in the Amazon piedmont (Caquetá, Colombia)

Units	Current Value	*Input* CRS*		*Input* VRS**	
		Target	Improvement (%)	Target	Improvement (%)
Percentage Area Production	86.0	6.4	-39.7	12.1	-84.6
Carbon in Pastures	18.8	19.2	+47.9	25.0	+126.6
Cost-Benefit Ratio (RBC)	1.9	2.0	+2.2	3.9	+384.0

*: CRS = Input-oriented model with constant returns at scale. **: VRS = Input-oriented model with variable returns at scale.

Source: own work.

Sustainable farms use less land and obtain both higher production and better BCR. Thus, they are more efficient in managing their resources and show that this is possible without impairing the capacity of carbon sequestration service that is stored in trees.

Discussion

The results found in this research were consistent with those reported by Zúñiga-González et al. (2015), who evaluated productivity using the DEA in dual-purpose agricultural systems of 17 Latin American countries, including countries in the Amazon basin (Bolivia, Brazil, Colombia, Ecuador, and Peru). The authors concluded that livestock is one of the activities with the highest GHG emissions, mainly methane gas (CH_4), produced from bovine enteric fermentation processes. Likewise, they highlighted the importance of forested farm areas in the reported technical and environmental efficiency scores. They concluded that the valorization of loss or gain of B_a and C_S helps to promote action to face climate change by reducing of greenhouse emissions and preserving carbon sinks.

In Colombia, Gamarra (2004) evaluated the efficiency of livestock and obtained an average score of 60, a value higher than that obtained in the present investigation, yet, this value was calculated without considering environmental factors. However, the sustainability assessments by Calderón-Cuartas & Flórez-Yepes (2015) and Figueroa-Lucero (2016) found that, similar to this study, sustainability depends on variables of a social, economic, and environmental nature. Conservation of ecosystem services and the financial profitability of livestock are productivity factors that play a fundamental role in the sustainability of Colombian agricultural farms. Although forests are major carbon sinks (Amézquita et al., 2008), the C_S ecosystem service can be enhanced in pastures (Ritten et al., 2012) due to the magnitude of the areas used for grazing.

Local milk production (4 $L{\cdot}cow^{-1}{\cdot}día^{-1}$) is considered low compared to the regional average (4.6 $L{\cdot}cow^{-1}{\cdot}día^{-1}$) and the national average in specialized dairy (5.6 $L{\cdot}cow^{-1}{\cdot}día^{-1}$) evidenced in the study area highlights the need to generate specific adaptations of the production systems to the edaphic, topographic, hydrological, and climatic conditions of the Amazon piedmont landscape. These would help increase production and reduce the impacts on ecosystem services to protect biodiversity in endangered forests and rural soils, as Liebig et al. (2017) proposed.

The tree density in pastures found in this study (12 $\text{trees}{\cdot}\text{ha}^{-1}$) is within the range of 2-20 $\text{trees}{\cdot}\text{ha}^{-1}$ found by Trujillo et al. (2012) and close to the 17 $\text{trees}{\cdot}\text{ha}^{-1}$ reported by Rojas-Vargas et al. (2019) for traditional pastures of the Colombian Amazonian landscape. Likewise, the results for the ecosystem service associated with trees in pastures found in the present study were consistent with the reports by Rojas-Vargas et al. (2019) and Calderón et al. (2016) for pastures in the Caqueteña Amazon (Colombia).

The low profitability of the average livestock farms in the Amazon piedmont (compared to the national average) and the low establishment of trees in pastures (which represent low levels of carbon stored in aerial biomass) resulted in high inefficiency. The sustainability indicator found from the integration of the economic and environmental technical efficiency index showed the predominance of unsustainable agricultural systems in the area (92% of the farms).

The above resulted in potential improvements related to the use of productive land, increased carbon storage capacity in aerial biomass in pastures, and increased profitability. In this regard, Trujillo et al. (2012) and Gutiérrez et al. (2012) argue that pastures are areas in which one of the strategies can be implemented to mitigate the impacts of livestock systems productivity. The so-called trees scattered in pastures help to increase milk production because the shade, foraging provisions, and fruits improve the animals' thermal comfort and reduce heat stress. These factors increase feed consumption and reduce the animal's energy expenditure while contributing to the storage of carbon.

In addition, Fajardo & Facundo-Vargas (2014) demonstrated that farms in the Amazonian landscape with sustainable production systems (SPS) —such as agroforestry arrangements— are more profitable than traditional systems. Furthermore, they stated that the transition to SPS per hectare requires higher investment and costs in the first two years but is recoverable in the third year. This demonstrates that agroforestry systems are competitive and had comparative advantages with traditional systems. Other authors, such as Grassauer et al. (2021), mention eco-efficiency as an approach to managing livestock systems, a concept that takes up variables related to the concept of sustainability.

In this sense, pastures present an opportunity for adaptation toward sustainable systems by stablishing scattered trees in pastures (Álvarez et al., 2013). These can potentially be used on unsustainable farms in the Colombian Amazon piedmont to improve their SE (Pardo-Rozo et al., 2020). These strategies must be accompanied by efficient business management in the field, which maximizes the economic benefits for producers and preserves the balance of the ecosystems that intervene in the production processes.

Another factor to consider that strengthens sectoral sustainability is the social context. The area under study presents limitations to development caused by the levels of poverty evidenced by low education, low production technology, and, therefore, low productivity and profitability (Pardo-Rozo et al., 2019). These effects suggest fewer possibilities for transitioning from current productive units to commercial levels. Such a transition would require production diversification, a change in the mentality of producers toward the incorporation of environmentally friendly productive alternatives (Pardo-Rozo et al., 2020), and the establishment of a policy toward the sustainable development of the rural sector. These factors could promote the comparative advantages of the Colombian Amazon piedmont in terms of natural resources, ecosystem services, biodiversity, and food security (Van Riper et al., 2017).

The sustainability of the rural economy in the Colombian Amazon piedmont can be improved if respect for ecosystem services is enhanced, and these methods are incorporated into the estimation of the production profitability. This proposal for an industry sustainability assessment can serve as the basis for developing an environmental policy that contributes to mitigating climate change from the Colombian Amazon.

> "The sustainability of the rural economy in the Colombian Amazon piedmont can be improved if respect for ecosystem services is enhanced, and these methods are incorporated into the estimation of the production profitability".

Conclusions

Sustainability is a multidimensional concept that involves socioeconomic and environmental variables. The research integrated variables from each dimension of sustainability to evaluate agricultural systems in the Amazonian piedmont. The sustainability indicator calculated using the DEA optimized the relationship between the benefit-cost ratio, the carbon storage in aerial biomass in pastures, and the capacity of the livestock production areas of each farm. 8% of the sustainable farms are agroforestry systems, which combine livestock activity with rubber and palm forestry production. These operations demonstrate that economic growth is possible while conserving environmental resources. 92% of the livestock systems were not sustainable because these production units can still improve the carrying capacity, milk productivity, and profitability, as well as improve their function as carbon sinks by using pasture trees. Because forests only occupy 9% and pastures represent more than 80% of rural production soil use, the establishment or conversion towards sustainable production systems is viable (such as agroforestry systems, living fences, and pastures with trees, among others). Sustainability is a principle, a guiding criterion, capable of being materialized, valued, and evidenced in the farming sector in vulnerable landscape areas like the Amazonian piedmont.

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