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Low-carbon economy for the agricultural sector of the Colombian Orinoquia: An opportunity for bioenergy production

Economía baja en carbono para el sector agropecuario de la Orinoquia colombiana: una oportunidad para la producción de bioenergía

David Arturo Munar-Flórez[a, e], Clara Inés Caro-Caro[b], Nidia Elizabeth Ramírez-Contreras[c], Jesús Alberto García-Núñez[d]

RESUMEN

En el futuro, la oferta de alimentos, energía, tierra y recursos sostenibles será uno de los mayores retos de la humanidad. El cambio climático afecta el ambiente, impacta negativamente la producción agrícola y aumenta el riesgo de la extinción humana. A esto se agrega el actual modelo de producción de alimentos, por lo general ineficiente en el uso del suelo y la producción en toneladas por hectárea. Si este modelo de producción continúa, aumentarán las emisiones de gases de efecto invernadero a la atmósfera, lo que intensificará los efectos del cambio climático. Alimentos y energía deberían ser producidos con cero emisiones, mediante la descarbonización del sector agrícola y la aplicación de un modelo de economía baja en carbono. Este artículo presenta una compilación de literatura sobre el concepto de 'economía baja en carbono' y analiza su aplicación en la Orinoquia colombiana, resaltando la oportunidad de producir bioenergía con bajas emisiones de GEI. La mitigación del cambio climático y su adaptación en la Orinoquia fundamentan el desarrollo de una economía baja en carbono en la producción agrícola y el uso de la tierra.

PALABRAS CLAVE: cambio climático, calentamiento global, agricultura, bioenergía, Orinoquia

ABSTRACT

In the future, the supply of sustainable food, energy, land, and resources will be one of humanity's greatest challenges. Climate change affects the environment, impacts agricultural production negatively, and increases the risk of human extinction. Added to this is the current food production model, which is generally inefficient in terms of land use and production in tons per hectare. If this production model continues, greenhouse gas emissions into the atmosphere will increase, intensifying the effects of climate change. Both food and energy should be produced with zero emissions, through the decarbonization of the agricultural sector and the application of a low-carbon economy model. This article makes a compilation of literature on the concept of a 'low-carbon economy' and analyzes its application in the Colombian Orinoquia, highlighting the opportunity to produce bioenergy with low GHG emissions. The mitigation and adaptation to climate change in the Orinoquia are key to the development of a low-carbon economy in agricultural production and land use.

KEYWORDS: climate change, global warming, agriculture, biomass energy, Orinoquia

a Universidad de los Llanos, Maestría en Gestión Ambiental Sostenible. Centro de Investigación en Palma de Aceite, Programa de Procesamiento. Villavicencio, Colombia. ORCID Munar-Flórez, D. A.: 0000-0001-5750-534X

b Universidad de los Llanos, Instituto de Ciencias Ambientales de la Orinoquia Colombiana, Grupo de Investigación Gigas. Villavicencio, Colombia. ORCID Caro-Caro, C. I.: 0000-0003-1589-6535

c Centro de Investigación en Palma de Aceite, Programa de Procesamiento. Villavicencio, Colombia. ORCID Ramírez-Contreras, N.E.: 0000-0003-0659-1879

d Centro de Investigación en Palma de Aceite, Programa de Procesamiento. Villavicencio, Colombia. ORCID García-Núñez, J. A.: https://orcid.org/0000-0002-6551-610X

e Autor de correspondencia: david.munar@unillanos.edu.co

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Introduction

Population growth, demand for resources, and consumerism lead to the loss of species, environmental contamination, and the impact on the resilience of natural landscapes (Ballester et al., 2006; González et al., 2003; Lau et al., 2011; Samaniego, 2008). These difficulties are associated with dependence on fossil fuels, one of the causes of global warming and climate change (Gupta & Gaur, 2019; Rabbani et al., 2018). Thus, the transition to renewable energy sources is a priority for the decarbonization of the economy (Nikkhah et al., 2020; Paschalidou et al., 2018; Röder et al., 2020). In addition, the increase in demand for food and bioenergy has conditioned land use and increased greenhouse gas (GHG) emissions (Godfray, 2015), which —together with the inefficiency of current production systems— leads to the search for sustainable low-carbon production models (Ramírez-Contreras et al., 2021).

The environmentally sensitive approach —with low GHG emissions— and obtaining bioenergy to decarbonize the economy turn the Orinoquia (Casanare, Vichada, Meta and Arauca) into a strategic region with potential for the Low Carbon Economy (LCE) (Alam et al., 2019; Lal, 2004; Nayak et al., 2019), as it has a large part of Colombia's untouched agricultural frontier and soils suitable for the establishment of energy crops such as oil palm and sugarcane (Ramírez-Contreras et al., 2021). However, regional transformation and development must prevent social and environmental risks. The altillanura[1]1 has a projected 80% increase in its agricultural frontier (Devia Acosta & Piñeros Lizarazo, 2021; Departamento Nacional de Planeación, DNP, 2014), but with no sustainable implementation, it could lead to the intensification of social conflict, a decline in regional welfare and the repetition of failed experiences such as those of Urabá and the Colombian Pacific (Andrade et al., 2014).

When the agricultural expansion is inevitable, it is relevant to manage landscape transformation, minimizing impacts on environmental values and increasing territory resilience (Bustamante & Rojas, 2018; Folke, 2006). Agricultural expansion should maximize economic gains and reduce hits on the Orinoquia and its conserved landscapes through the valorization of agricultural production and biodiversity conservation (Andrade-Pérez et al., 2013; Mastrangelo et al., 2015) to achieve a balance of the socio-ecological system (Ramírez-Contreras et al., 2022). With this description, this article aims to identify the benefits of the future application of the LCE model in the Colombian Orinoquia oriented to food production and the establishment of energy crops with low GHG emissions.

Materials and methods

The literature was reviewed to identify and analyze the application of the LCE model in the Orinoquia, according to studies published in Web of Science and technical research works available on the official web pages of the Institute of Hydrology, Meteorology and Environmental Studies, IDEAM, the Ministry of Environment and Sustainable Development and the Rural Agricultural Planning Unit, UPRA. The article explains the concepts of climate change and global warming as well as the anthropogenic causes of climate change, followed by the situation in the Colombian Orinoquia, ending with the LCE proposal and bioenergy production for that region.

Climate change and global warming

Climate change is a natural or anthropogenic modification due to atmospheric composition alteration (Intergovernmental Panel on Climate Change, IPCC, 2019). Anthropogenic activities unbalance the composition and amount of GHGs in the atmosphere and are thus responsible for increasing the greenhouse effect (Białecki & Stanek, 2017). The dominant anthropogenic causes are the change in the uses of the earth's crust (agriculture, livestock, and deforestation), the population explosion, socio-economic development, the production and consumption regime, and industrialization (Useros Fernández, 2013).

1 The *altillanura* is a part (half) of the Eastern plains of Colombia, which is a little higher than the rest of the plains. Only a little (maybe 50 mts), so it will never be a plateau.

Global warming is an effect linked to human activities that stems from the increase in GHG emissions (carbon dioxide [CO_2], methane [CH_4], water vapor [H_2O], ozone [O_3], and nitrous oxide [N_2O]) (IPCC, 2014). Since the industrial revolution, a progressive increase in the planet's average temperature and the concentration of GHGs has been observed (Figure 1). Atmospheric CO_2 concentration rose from 280 to 379 ppm; CH_4 changed from 715 to 1774 ppb, and N_2O from 270 to 320 ppb between 1750 and 2016 (Białecki & Stanek, 2017; Robbins, 2016; Singh & Singh, 2017). Industrialized countries committed through the Kyoto Protocol to stabilize anthropogenic GHG emissions, mitigate and report them (United Nations Framework Convention on Climate Change, UNFCCC, 2008) and, recently, the United States, the European Union, and Brazil pledged to achieve zero emissions by 2050 at COP26-2021.

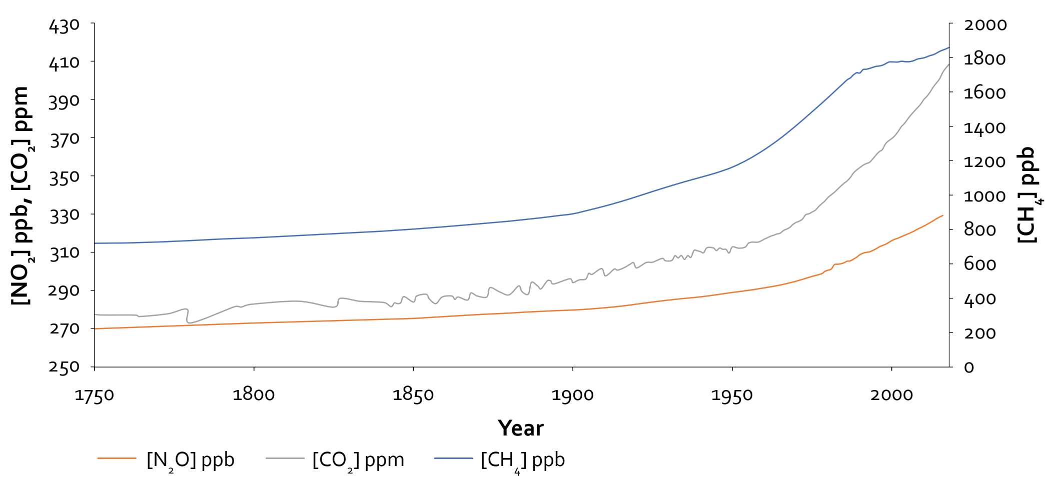
Climate change adaptation and mitigation will set the path for ecosystem resilience, human well-being, and sustainable development (DNP et al., 2016). Climate change challenges society to converge between politics, science, economic interests, and responses through the exercise of governance (Gómez-Lee et al., 2021); therefore, inaction or actions by economic sectors can lead to loss of biodiversity, risks to human society and eventually a temperature increase of up to 5 °C (Fróna et al., 2021; IPCC, 2022ab).

For 2019, total global emissions were 59 GtCO-2eq: the energy sector contributed 33.9%; industry 23.7%; AFOLU 22.0%; transport 14.7%, and energy use in buildings was 5.6% (Figure 2).

Anthropogenic causes of climate change

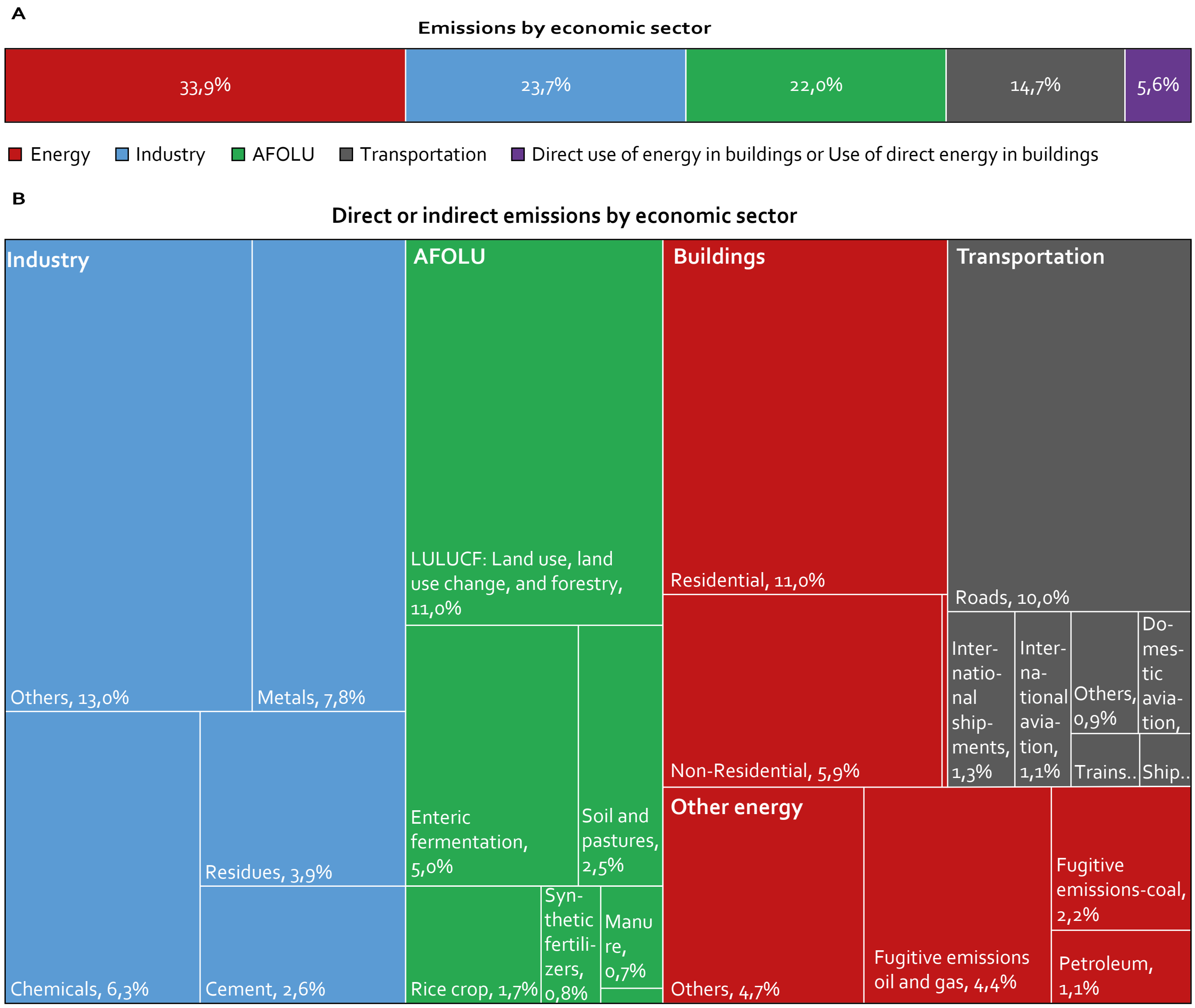
Using fossil fuels remains the basis of industrialization (Londoño-Pulgarin et al., 2021). In recent decades, the transportation and goods and services sectors have relied intensively on the consumption of oil, natural gas, and coal (Wood & Roelich, 2019), fossil fuels that accelerate climate change and influence global economic crises through price volatility and reserve depletion (le Billon, 2001; Maher, 2018). Obtaining 1 MBTU of diesel power emits 74.14 kg CO_{2eq} (United States Environmental Protection Agency, US EPA, 2022). If fuels with low GHG emissions, such as palm biodiesel or hydrogen, were used, carbon footprints of -679.6 kg CO-$_{2eq}$/kg and 1.45 kg CO_{2eq}/kg, respectively, would be obtained (Ramírez-Contreras et al., 2020; Yadav & Banerjee, 2020). The search for energy sources with low GHG emissions and alternatives to fossil fuels are fundamental to achieving Low Carbon Economies (LCEs).

Figure 1. Increase in global GHG concentrations in the atmosphere



Note. From Ritchie et al., 2020.

Figure 2. Global (direct and indirect) GHG emissions by economic sector in 2019



Note. Taken from IPCC, 2022.

The preservation of forests and their soils (recognized as carbon sinks) is paramount for climate change mitigation (Anderson-Teixeira & DeLucia, 2011; Budiharta et al., 2018); for example, a tropical forest is capable of absorbing 255 t C/ha, compared to 33 t C/ha of cropland (Castanheira et al., 2014); thus, when a forest is intervened, it becomes a source of emissions. Deforestation accounts for 12% of global anthropogenic GHG emissions (4.4 Gt CO_{2eq}/yr) (Jackson & Decker Sparks, 2020). The United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD+) Program protects forest biomes, promotes natural carbon sequestration in developing countries, and identifies low-carbon sustainable development pathways (United Nations, UN-REDD, 2020). In Colombia, 52% of the surface is covered by forests, distributed as follows: 66.9% in the Amazon; 17.8% in the Andes; 8.8% in the Pacific; 3.6% in the Orinoquia, and 2.9% in the Caribbean. It is estimated that between 1990 and 2016 Colombia lost six million hectares of forest and for the period 2018-2021 deforestation reached 701 840 ha (Ministry of Environment and Sustainable Development & IDEAM, 2018, 2020).

Climate change impacts agriculture by altering temperature, precipitation, soil quality, pest regimes, and seasonal growth patterns (Hertel & Rosch, 2010). Likewise, agriculture contributes significantly to GHG emissions (Figure 2), whose principal sources include CO_2 from deforestation, CH_4 from rice cultivation, CH_4 from enteric fermentation, and N_2O from excessive use of nitrogen fertilizers (Ritchie et al., 2020). Climate change challenges society to seek alternatives to ensure future food and the planet's energy security (Amadu et al., 2020; de Moraes Sá et al., 2017). Thus, a low-carbon and resilient agriculture is achieved through good low-carbon practices that promote the efficient use of resources and carbon sinks (International Center for Tropical Agriculture, Spanish: CIAT, et al., 2018; Peñuela et al., 2019; Rodríguez Borray et al., 2019).

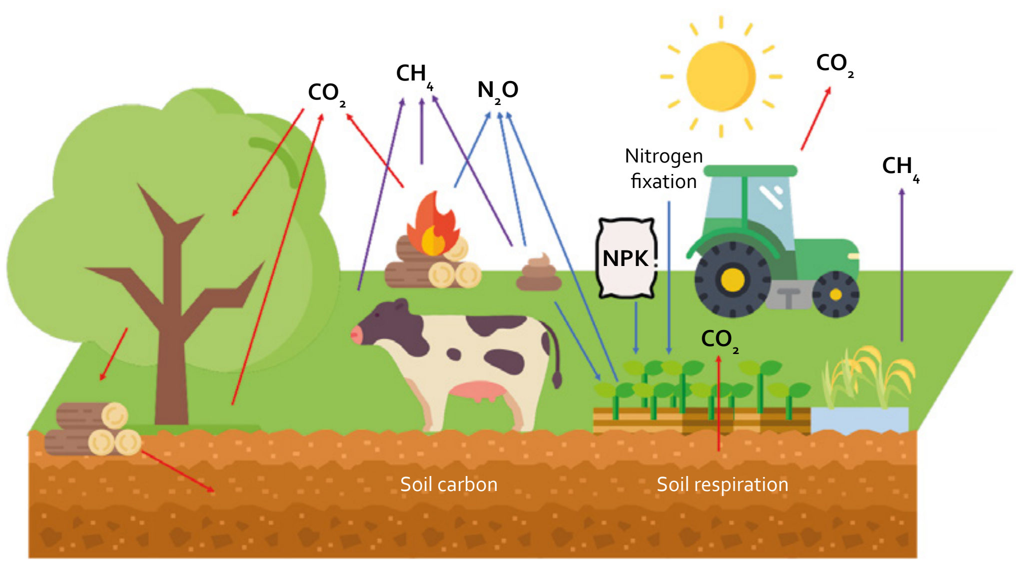
Greenhouse gas emissions in the agricultural sector and the Colombian Orinoco region

The pressure on land and the increase in GHG emissions caused by the demand for food and other raw materials threaten natural resources and production (Ramírez-Contreras et al., 2021). Inadequate land use -and population growth demanding areas for increased food production, fresh water, materials, and fuels- contribute to climate change (IPCC, 2014). Likewise, the life cycle of an agricultural product generates GHG emissions; these are assumed to be a 'legitimate' environmental cost for agricultural production, but this trend will increase the loss of biodiversity and accelerate the effects of climate change on the planet (IPCC, 2014). By 2050, agricultural expansion, demand for agrochemicals, water pollution, and conversion of forests to pastures are expected to simplify ecosystems, leading to loss of ecosystem services and biodiversity and damage to human health (Stavi & Lal, 2013).

In the agricultural sector, N_2O and CH_4 emissions increase global warming like no other, compared to CO_2 emissions. Nitrogen fertilizers produce N_2O, which, when not assimilated by plants, is volatilized or lost by leaching or runoff (Paustian et al., 2006). CH_4 emissions come from biomass combustion, flooded crops, enteric fermentation, and degradation of manure and organic residues, whereas CO_2 emissions derive from biomass combustion, organic matter degradation, and biological processes inherent to living beings (Figure 3).

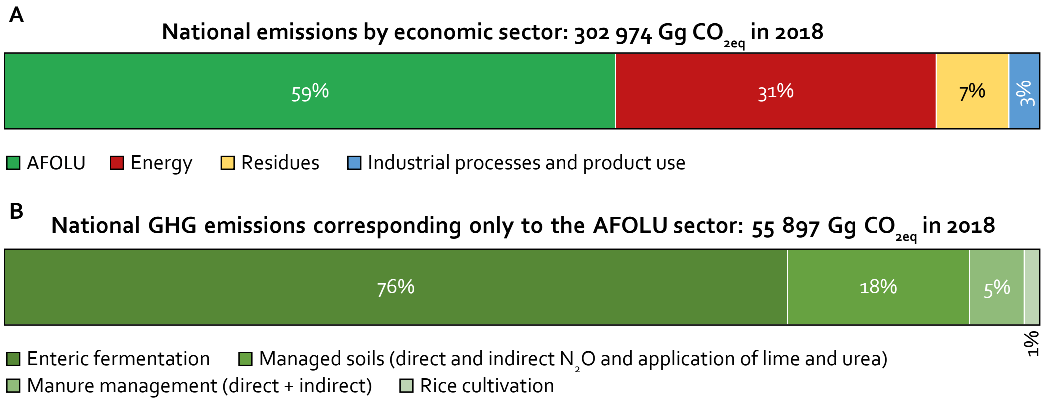
Processes such as photosynthesis store CO_2 in plants and soil (GHG removals); thus, plant biomass and soil form carbon sinks (Paustian et al., 2006) (Figure 3). Through changes in vegetation cover and land use, stored carbon is released, and CO_2 emissions to the atmosphere increase (Budiharta et al., 2018; DeFries et al., 2004; Henson et al., 2012). Worldwide, the AFOLU sector contributed 22% of global GHG emissions in 2019 (see Figure 2).

Figure 3. Principal sources of greenhouse gas emissions/absorptions and processes in managed ecosystems



Note. Adapted from Paustian et al. (2006).

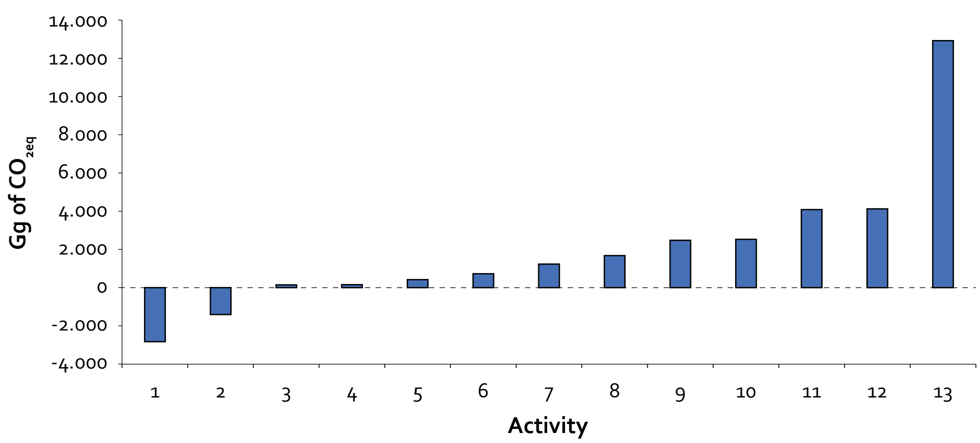
Figure 4. Sectoral share of GHG emissions in Colombia



National GHG emissions corresponding only to the AFOLU sector: 55 897 Gg CO_{2eq} in 2018

Note. Taken from IDEAM et al. (2021).

Figure 5. GHG emissions and removals of the Orinoquia by activity for 2012



Note. GHG emissions and removals in the Orinoquia by activity 2012: 1. natural forest regeneration; 2. carbon storage; 3. electricity; 4. fires; 5. fertilization; 6. firewood removal; 7. land transportation; 8. replanting of permanent crops; 9. fugitive-oil; 10. manure management; 11. fuel burning in refineries; 12. enteric fermentation, 13. deforestation. Taken from IDEAM et al., 2016.

In Colombia, total GHG emissions were 302 974 Gg CO_{2eq} in 2018 (equivalent to 0.5% of global emissions), with the AFOLU[2] sector contributing 59% (Figure 4 [a]). In this activities, the top emission sources included enteric fermentation, managed soils, manure management, and rice crops (Figure 4 [b]).

For 2012, the Colombian Orinoquia (departments of Arauca, Casanare, Meta, and Vichada) contributed 34 311 Gg CO_{2eq}: 81% of these emissions correspond to the AFOLU sector (agriculture, livestock, forestry, and land use change); 18.2% to the energy sector; 1% to waste, and 0.2% to IPPU (industrial processes) (CIAT et al., 2018; Ideam et al., 2016). These emissions are associated with deforestation, livestock, fossil fuel burning, fugitive emissions, and permanent crop replanting (Figure 5). This last activity also removes GHG by storing carbon in biomass and soil. In the region, livestock farming is one of the predominant sources of GHGs due to the (a) conversion of natural ecosystems to grazing land, which subtracts carbon stocks from biomass and soil; (b) enteric fermentation; (c) use of fertilizers for pasture management; (d) production of feed for livestock, and (e) waste production and manure management (Stavi & Lal, 2013). This analysis proposes that GHGs removal, the planting of permanent crops, forest lands, and permanent

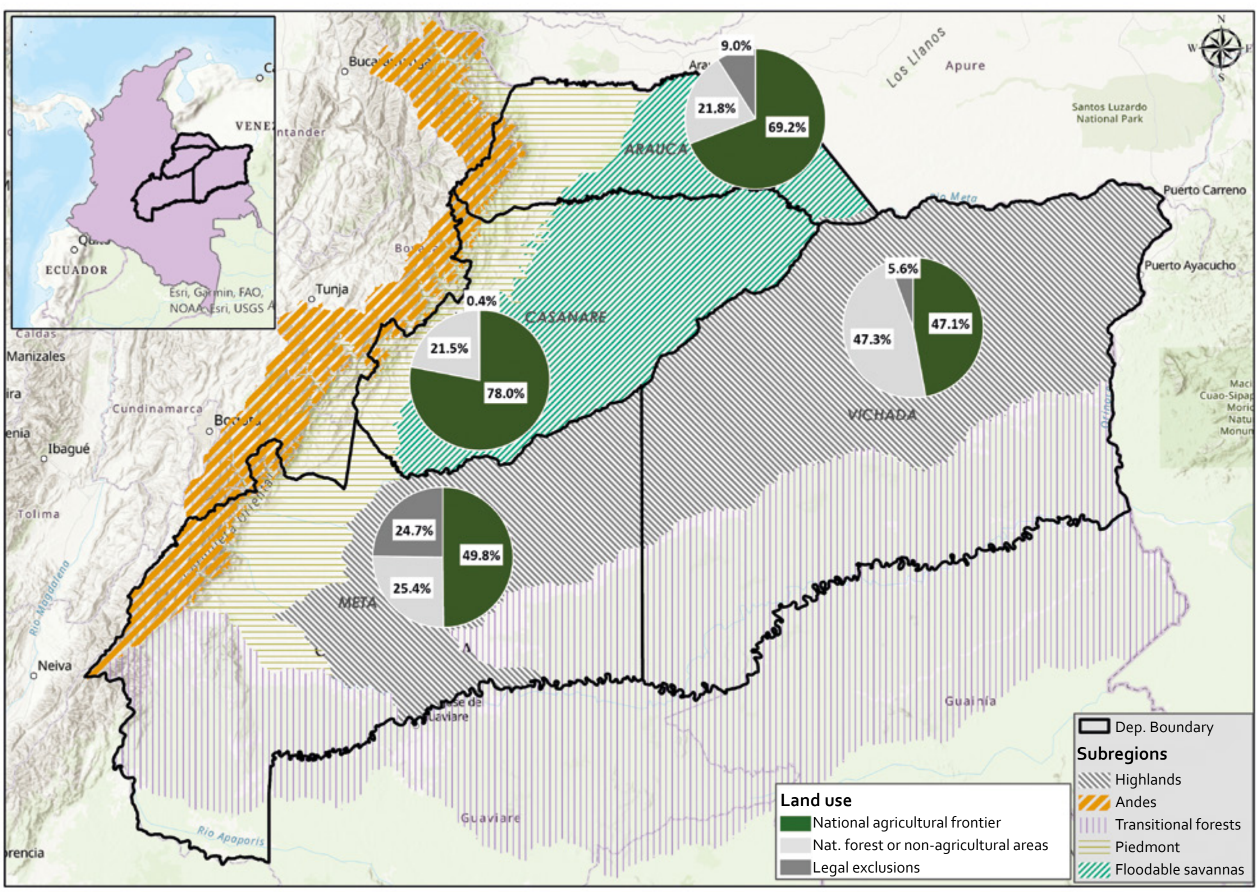
2 Agriculture, Forestry, and Other Land Use.

pastures, and the regeneration of natural forests contribute (IDEAM et al., 2016; Vásquez-Cerón et al., 2019).

The Colombian Orinoquia, or Eastern plains, is made up of four departments (Arauca, Casanare, Meta, and Vichada); it has 8 rainy months and 4 dry months and comprises 13 watersheds belonging to the Orinoco macro-basin. These conditions enable it to provide ecosystem services in its strategic areas (Caro-Caro et al., 2016). It has an area of 25.4 Mha and about 9.9 Mha with legal exclusion. It currently has 15.5 Mha of the agricultural frontier, with the use of 7 Mha (90% in grazing and 10% in crops) (Ramírez-Contreras et al., 2021) (Figure 6). Transitory crops such as rice, corn, plantain, soybean, and cassava and permanent crops such as oil palm dominate the region. Livestock farming is also vital as a socioeconomic and cultural activity (Vásquez-Cerón et al., 2019). The agricultural sector in Orinoquia contributed 10.2% to the GDP of this economic activity in 2020, maintaining around this value during the last 15 years. For 30 years, the Orinoquia has had an average annual deforestation rate of 40 000 hectares. In 2018, the Orinoquia concentrated 6.1% of the country's total deforestation figure with 57 640 ha (López et al., 2020; Rozo-López et al., 2021).

There is a global commitment to reduce GHG emissions and avoid a 1.5°C increase in global temperature. Colombia proposed to reduce GHG emissions by 51% by 2030 (United Nations Climate Change, 2020). For this purpose, the Ministry of Environment and Sustainable Development has settled the Colombian Low Carbon Development Strategy (ECDBC) and plans to cut GHG emissions caused by deforestation and forest degradation and to conserve and increase CO_2 sequestration (REDD+).

Figure 6. Landscapes and departments of the Orinoquia in Colombia



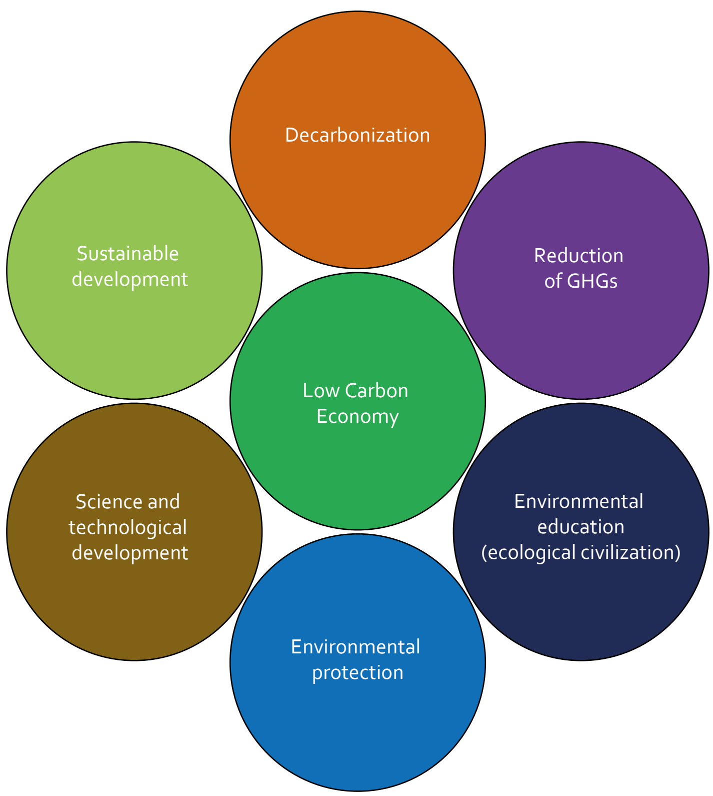
The Ministry of Environment and Sustainable Development (2023) has conducted prospective GHG mitigation studies of the Colombian agricultural sector using the Carbon calculator 2050 tool; these studies project decreasing the average consumption of meat and milk (205 g and 2. 9 l per person per week) to fulfill this objective, entailing that six million hectares should be managed as silvopasture systems, 241 793 ha should be rehabilitated as pastures, the diet of the livestock herd should be upgraded (at least 30%), and rational grazing practices should be adopted in 10% of the livestock area. Better practices are also expected to be implemented in 42% of the country. As for energy, a 35% increase in land dedicated to first-generation energy crops is projected, and 100% of the biogas generated from waste treatment will be used. Regarding deforestation, the objective is reduced to 0% from 2040 and aims to protect 34 million hectares accumulated in commercial reforestation between 2010 and 2050 (Ministry of Environment and Sustainable Development, n. d.).

Low Carbon Economy for the agricultural sector in the Colombian Orinoco region

LCE belongs to the priority issues to achieve sustainable development through technological innovation, industrial transformation, development of new energy sources, and reduction of energy consumption and GHG emissions, aimed at achieving social development and environmental protection (Yun, 2016; Zhai et al., 2014). Agricultural development of an LCE would reduce the impact of production systems on nature and promote sustainable development. Low-carbon agriculture is possible through investment in research and development, efficient use of resources, and social awareness of the role of agriculture and human activities in climate change (Figure 7) (Xiong et al., 2016).

FAO calculates that LCE could offset 80% of GHG emissions from agriculture; for example, the rational use of fertilizers could reduce 30% of agricultural emissions (Zhai et al., 2014). LCE is

Figure 7. Significant concepts within the low-carbon economy model



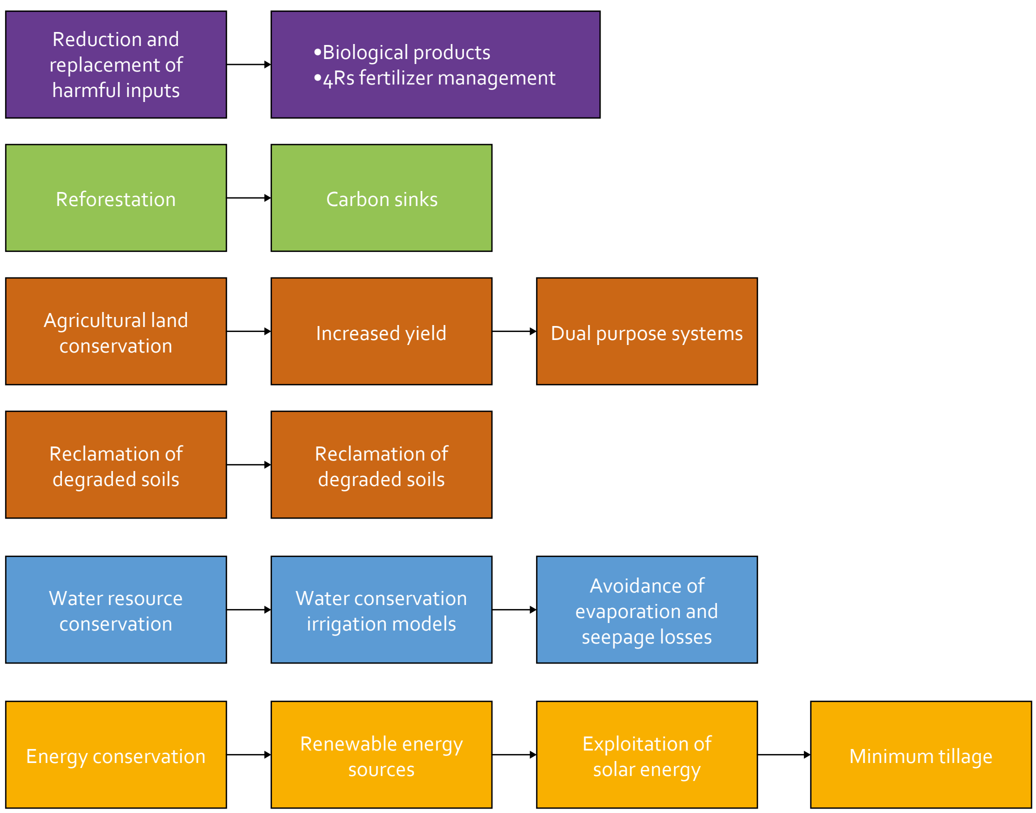
Note. Author's elaboration.

achieved with increased investment in science and technology and the promotion of research and development in the different eco-economic sectors. Additionally, the agricultural industry must receive sound technical assistance for effectively transferring and adopting practices and technologies (CIAT et al., 2018). Research and development are cornerstones within LCE because they enable technical and scientific studies on soil conservation, care of water resources, reduction of synthetic fertilizer and pesticide use, efficient energy disposal, and application of circular economy models (Yang et al., 2019) (Figure 8). Likewise, the leadership of governmental entities is essential to foster environmental education —focused on the risks of climate change, its mitigation, and influence on productive systems— and the generation of compensation mechanisms for carbon sinks and payment of ecosystem services for the reduction of GHG emissions (Xiong et al., 2016).

Bioenergy production in the Orinoquia

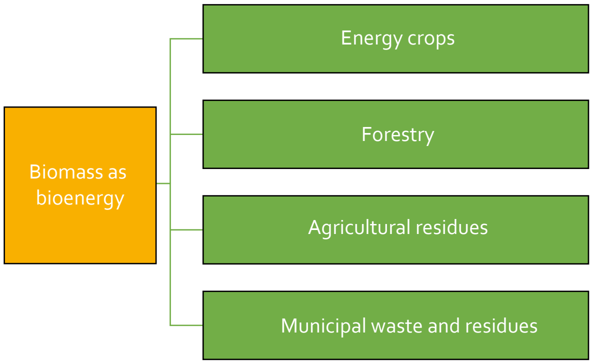
Bioenergy plays a role when transiting to an LCE and meeting GHG mitigation targets (Younis et al., 2021). This source stems from biomass from energy crops, agricultural residues, and municipal waste (Paschalidou et al., 2018) (Figure 9). This energy type can provide electricity, heat, and fuel. About 70% of renewable energy comes from biomass worldwide (Röder et al., 2020). Energy crops represent significant biomass sources for biogas, biodiesel, and bioethanol. For choosing the energy source, energy (fossil fuel consumption in the supply chain) and GHG (life cycle GHG emissions) studies need to be developed to compare their performance against fossil sources (Nikkhah et al., 2020). Furthermore, other impacts on the environment and society should be evaluated, such as water, soil, and air pollution, in addition to the displacement of populations due to the contamination of their territories (Nazir et al., 2020).

Figure 8. Guidelines for achieving a low-carbon economy



Note. Author's elaboration.

Figure 9. Bioenergy from biomass

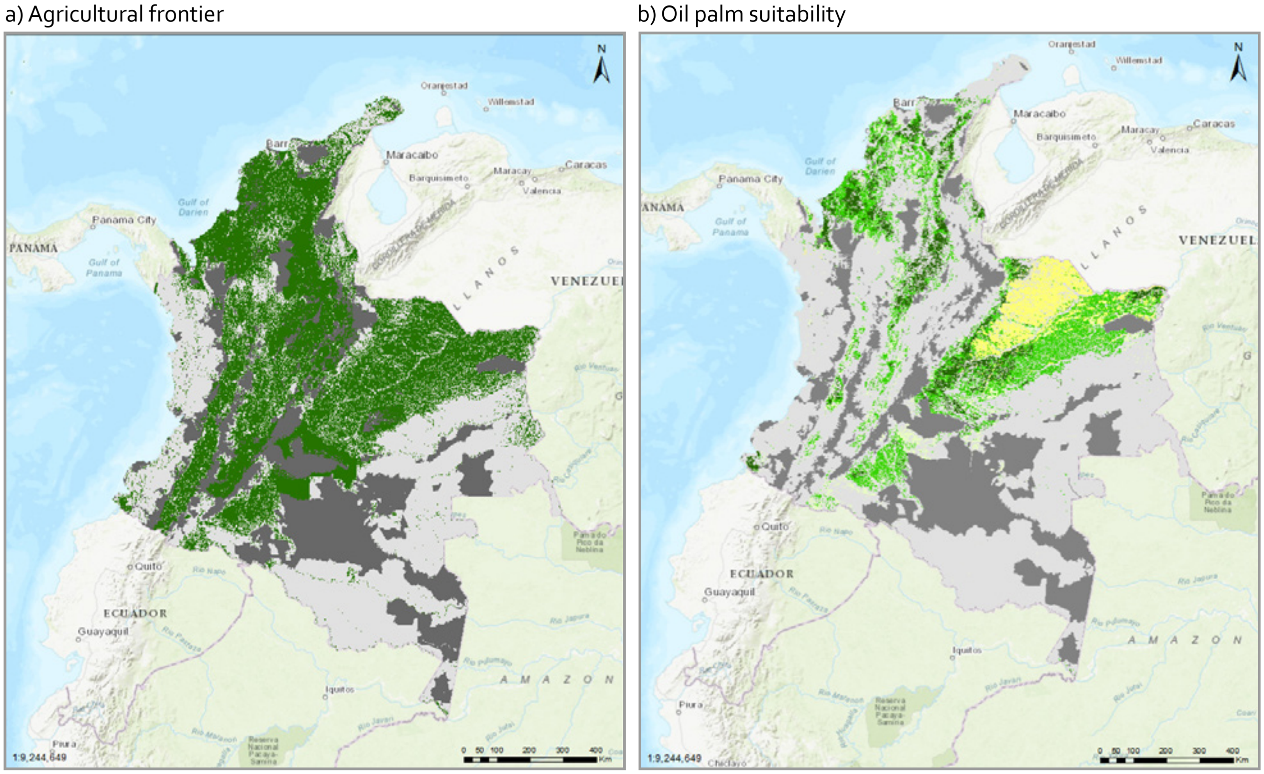


Note. Author's elaboration.

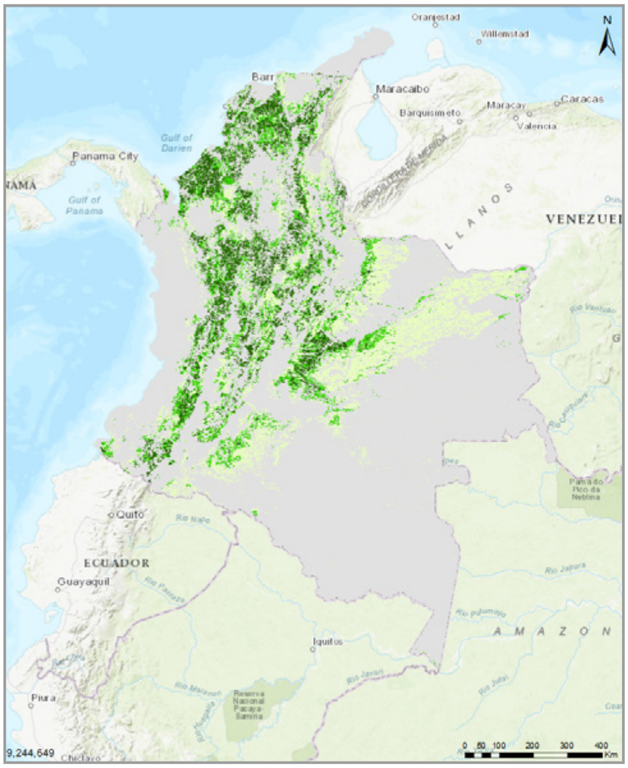
The depletion of fossil fuel reserves entails the search for new sources of energy capable of decarbonizing the economy. Thus, policies are currently being promoted to stimulate the production of energy crops; many countries have allocated part of their land (cultivated and unproductive) to the obtention of biofuels (Palacio-Ciro & Vasco-Correa, 2020). In this context, between 2002 and 2010, Colombia added the agro-industrial side of the policy agenda, focusing on bioethanol production from sugarcane and biodiesel from palm oil (Jiménez, 2012). Figure 10 shows the country's agricultural frontier emphasizing on the suitability of oil palm, sugarcane, and forestry energy crops. Colombia registers 39 million hectares (Mha) of the agricultural frontier, corresponding to 34.7% of its surface, with 6.3 Mha in farming use and nearly 22 Mha in livestock activity (Buitrago & Cadena, 2019). Much of the unused agricultural frontier is in the Orinoquia; the region offers an extensive proportion of soils with potential for oil palm cultivation, followed by agroforestry — mainly in Meta and the plains foothills—in addition to lands with suitability for sugarcane in the same department (Figure 10 [e]) (UPRA, 2018). (Figure 10 [e]) (UPRA, 2018). However, much of the Orinoquia soil is destined for extensive livestock farming, contrasting with its low participation in the national economy (1.3% of GDP) (Ministry of Agriculture and Rural Development, 2018).

Figure 10. Maps of the agricultural frontier and zoning of energy crops in Colombia

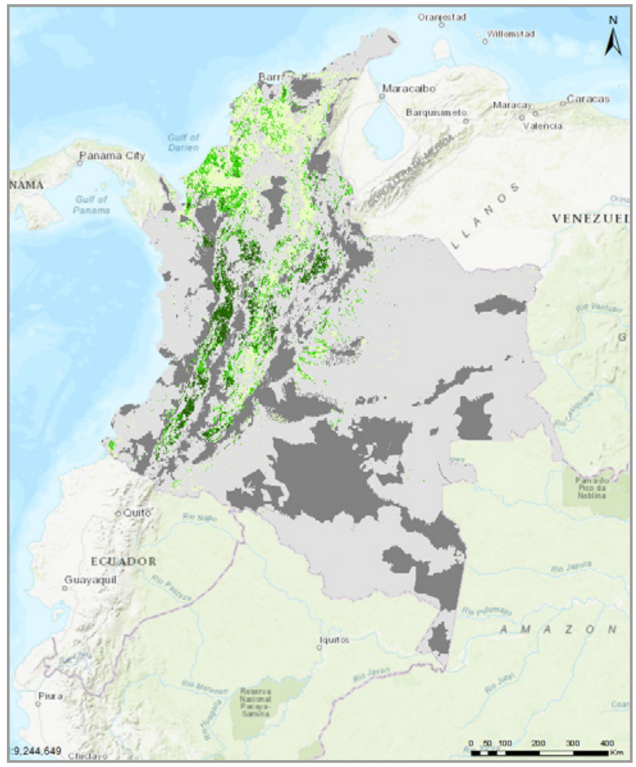
a) Agricultural frontier b) Oil palm suitability



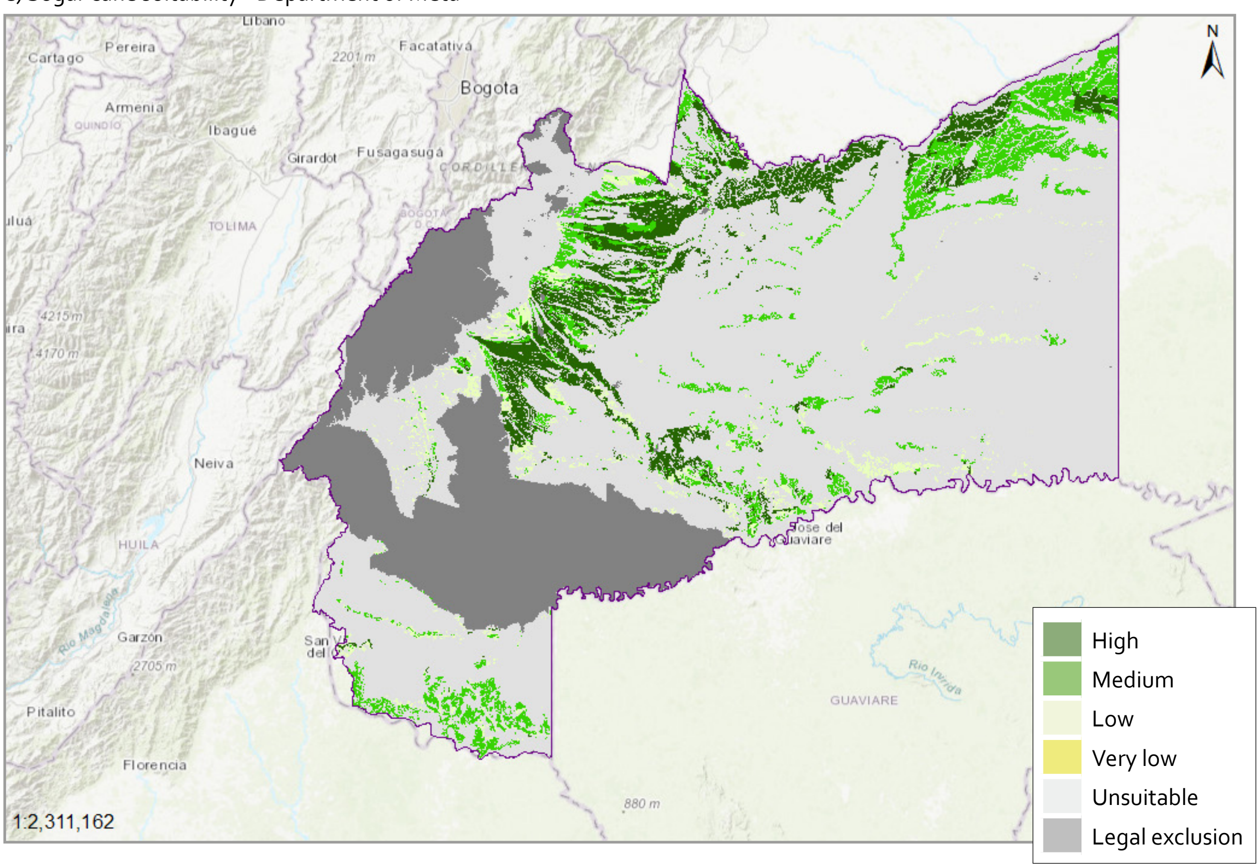
c) Suitability for forestry plantations



d) Sugar cane suitability



e) Sugar cane suitability - Department of Meta



Note. Taken from UPRA, 2022.

Colombia is the world's fourth largest producer of palm oil, with 559 582 ha planted and production of 1.5 million tons of crude palm oil in 2019 (Federación Nacional de Cultivadores de Palma de Aceite, FEDEPALMA, 2020); in turn, the Orinoquia has 229 695 ha (41% of the area planted in the country) (FEDEPALMA, 2020). In sugarcane, during 2013-2017, Colombia ranked 15th in world production, with low participation (1.3 % of the total) (ASOCAÑA, 2019): out of 25 million tons of sugarcane milled in 2018, 2.3 million t of sugar, about 467 million liters of bioethanol (471 000 t of sugar equivalent) and 1702 GWh of electricity generation from sugarcane bagasse were produced (ASOCAÑA, 2019). The Orinoquia maintains 27 133 ha of sugarcane cultivation, predominantly in the department of Meta (AGRONET, 2019; ASOCAÑA, 2019; Lacerda Bezerra & Ragauskas, 2016).

It is assumed that the palm oil sector in the region holds the potential to produce 34 154 TJ/year of energy using all of its biomass (Table 1). This agribusiness outputs palm oil and energy that could be harnessed for the country's decarbonization strategy (biodiesel, biogas, biomethane, cogeneration). Table 2 contains some agricultural and livestock wastes that, under circular economy models, would correspond to efficient use to extract bioenergy. Thus, it is possible to count different products: (a) from chemical processes such as transesterification or hydrotreating, biofuels based on vegetable oils such as palm oil would be obtained; (b) from gasification and pyrolysis processes, products with energy value, and (c) from biological processes such as fermentation and anaerobic degradation, bioethanol or biomethane (García-Núñez et al., 2016). Therefore, the central regional production chains (rice, banana, oil palm, corn, etc.) (Table 3), under a circular economy approach, would reduce the region's and the country's dependence on fossil fuels.

Additionally, in the Orinoquia, energy could be gained from non-conventional sources such as solar. This Colombia's region clusters photovoltaic capacity where the average radiation is 4.5-5 kWh-m-2 (Ruíz López et al., 2020). Indeed, the Orinoquia counts on resources that will permit it to expand the country's energy supply to unconnected areas and vulnerable populations.

Table 1. Energy potential of the products and by-products of the palm oil supply chain in the Orinoquia

Product	Quantity (t/year)	Calorific value (MJ/kg)	Energetic potential (TJ/year)
Produced fruit	3 106 366	n. a.	n. a.
Crude palm oil	704 381	31,40	22 118
Kernel	108 498	26,26	2849
Palm kernel oil	43 030	19,22	827
Palm kernel cake	63 011	21,91	1381
Conrncob	165 367	18,18	3006
Fiber	56 132	18,20	1022
Cuesco	42 476	18,72	795
Biogas*	95 091 435 (m^3)	22,68 (MJ/m^3)	2157
		Total	34 154

Note. Data from Fedepalma, 2021; Ramírez-Contreras et al., 2015, 2020.

Table 2. Energy content of agricultural and livestock waste

Origin of the waste	Product	Type of waste	Calorific value (MJ/kg)
Agricultural residues	Sugarcane	Crop residues	4,89
		Bagasse	10,97
	Panela sugarcane	Bagasse	10,97
		Crop residues	4,89
	Coffee	Pulp	3,59
		Vegetal culm	17,26
		Stalks	13,53
	Corn	Stubble	9,83
		Corncob	10,40
		Capacho*	15,17
	Rice	Chaff	3,58
		Husk	14,48
	Banana	Rachis	0,43
		Shoot	0,56
		Rejection	1,76
	Plantain	Rachis	0,43
		Shoot	0,56
		Rejection	1,76
Livestock waste		Bovine	0,85
		Poultry	8,47
		Swine	1,54

Note. Adapted from Guzmán (2002).
* Translator's note: Tropical plant of the cañacoro genus with edible fruit

Non-conventional sources, such as biomass and solar, will bring efficient environmental responses and financial solutions to conventional energy sources (Ruíz López et al., 2020; Rodríguez-Urrego & Rodríguez-Urrego, 2018).

Masum et al. (2021) reviewed the economic and environmental feasibility of producing electricity from eucalyptus in the Colombian Orinoquia. The research was undertaken to alleviate GHG emissions from the Colombian energy sector and provide electricity to the population in areas without interconnection; they found lower energy production costs with biomass ($92/MWhe) compared to diesel ($280/MWhe). Among others, this research suggests the possibility of obtaining bioenergy in the Orinoquia thanks to the availability of land for planting energy crops, such as forestry, with a low risk of deforestation. In 2021, the electric power generation plant with 100% eucalyptus was inaugurated in the municipality of Puerto Carreño (Vichada), with a 4 MW capacity, 50 000 t CO_{2eq} reduceable annually, and renewable electricity supply to its 18 000 inhabitants (ASORINOQUIA, 2021). Electricity production through biomass represents less emissions than diesel, between 81% and 87%. Moreover, since it is an economically viable production, it benefits populations without interconnection (Masum et al., 2021).

Although bioenergy holds the potential to replace fossil fuels with a source of low GHG emissions, its promotion must be careful to prevent collateral impacts on the environment. Using bioenergy raises questions related to the following issues:

§ the medium- and long-term effects of the establishment of energy crops

§ the impact on food supply, food prices, and global nutrition

§ the cost of decarbonization of the economy (Paschalidou et al., 2018)

Given the accelerating growth of the global population, with about 85% of humanity at the poverty line (income less than 30 USD/day) and about 10% hungry, allocating the soil resource and food crops for bioenergy production may exacerbate these difficulties. Moreover, competition for soils could lead to deforestation, destruction of ecosystems, and loss of biodiversity (Gao et al., 2011; Liu et al., 2014; Rosillo-Calle, 2012). However, strategies permitting the production of biofuels with low risk for land use change, low GHG emissions, limited use of fossil fuels, and sustainable forms of production for crops and livestock can mitigate these impacts (Gerssen-Gondelach et al., 2017; Ramírez-Contreras et al., 2022; Ramírez-Contreras et al., 2021; van der Hilst et al., 2012). Additionally, governments can ensure the balanced use of soils and implement policies that protect food production (Fresco, 2006). Therefore, LCE and agriculture intensification (livestock) become essential to meet the population's food demand and energy consumption (Ramírez-Contreras et al., 2022).

Table 3. Top agricultural products of the Orinoquia (Arauca, Casanare, Meta, and Vichada)

Product	Production (t)	Planted area (ha)	Production participation (%)	Average yield (t/ha)
Rice	1 393 679	249 306	26%	5
Plantain	1 296 690	67 432	24%	14
Oil palm	936 578	280 668	17%	3
Corn	572 277	102 017	11%	3
Cassava	212 812	14 655	4%	13
Soybeans	191 658	65 132	4%	3
Watermelon	161 629	5580	3%	23
Pineapple	138 431	4135	3%	31
Sugar cane	117 954	12 766	2%	9
Citrus	113 035	8127	2%	15

Note. Production, planted area, and average yields for 2019. DANE: Encuesta Nacional Agropecuaria, ENA, 2019; author's elaboration.

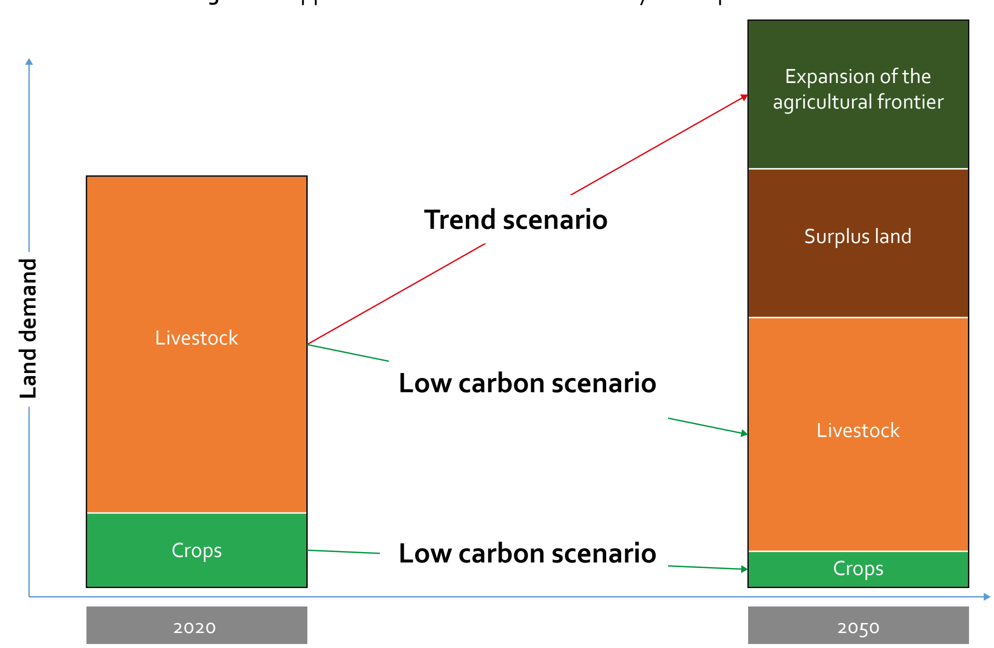
With the sustainable diversification of agricultural systems and the application of appropriate low-carbon practices, it is possible to reduce future soil demand to meet population needs (Godfray, 2015; Ramírez-Contreras et al., 2022; Ramírez-Contreras et al., 2021) (Figure 11). Through an LCE, biofuels with low carbon footprints, reduced risk of indirect land use change (ILUC), and low deforestation hazard and expansion into non-intervention areas are achievable (Gerssen-Gondelach et al., 2017; van der Hilst et al., 2012).

The Orinoquia has extensive areas with medium and high suitability for oil palm cultivation (UPRA, 2018). It is also an ideal region for sugarcane cultivation, providing approximately 2 million ha for its production without irrigation (Rueda Ordóñez et al., 2018). Nonetheless, the promotion of bioenergy should include benefits such as rural employment generation, energy independence, environmental sustainability, and global warming mitigation, as well as considering the dynamics generated with food and energy crops related to food security, ILUC, water resource management, loss of biodiversity and inflation in the prices of regular inputs (Bano & Arshad, 2018; International Institute for Applied Systems Analysis, IIASA, 2009; Koizumi, 2015; Liu et al., 2014; Ramirez-Contreras et al., 2022; Ramirez-Contreras et al., 2021; Subramaniam et al., 2020).

Ramírez-Contreras et al. (2021) projected the behavior of GHG emissions of the biggest production chains in the Colombian Orinoquia through low, medium, and high trend scenarios based on the sustainable intensification of production for the year 2030 (Figure 11). They found that good agricultural practices make it possible to increase food availability and supply-demand through efficient land use. By increasing the productivity of agricultural and livestock systems, especially livestock, soils are freed up for growing food and energy crops. Food and biofuels would be produced under this strategy with lower GHG emissions, zero deforestation, no intervention in pristine areas, and low ILUC irrigation. Thus, Colombia would meet the Paris Agreement goals of 20% emissions reduction by 2030. Besides, with the sustainable intensification of regional agriculture, GHG emissions will be mitigated by 120% for the best scenario proposed (energy crop oil palm).

In the case of oil palm, it is possible to apply good low-carbon practices (GLCPs) to reduce GHG emissions. Table 4 presents some LCBPs applied to the palm oil supply chain and their co-benefits related to biodiversity protection, reduction of water

Figure 11. Application of Low-Carbon Economy for surplus land



Note. Obtained through the sustainable intensification of agricultural production systems; adapted from Ramírez-Contreras et al., 2021.

consumption, application of circular economy models, and efficient resource management. Ramírez-Contreras et al., 2022 and Ramírez-Contreras et al., 2021 include some BPBC and state that an extension of the low efficiency of the production systems by 2030 will involve 93% of the current areas with natural vegetation to supply the demand for food until that year. Moreover, improving productivity frees up surplus land for energy crops without transforming areas of natural vegetation. It entails the reduction of GHG emissions, making efficient use of water resources, favoring biodiversity in areas with natural vegetation, and improving the regional economy.

On sustainable intensification of production chains in the Orinoco region, Ramírez-Contreras et al.(2021) stated that livestock is the principal contributor to land surpluses. The Colombian stockbreeding sector is an inefficient productive system, covering 78% of the area for agricultural purposes. In coordination and articulation with the territorial stakeholders, the Government should plan and implement sustainable production, mitigate the environmental impacts of agro-activities, improve the regional economy, and promote the well-being of the communities.

LCE allows for Climate-Smart Agriculture (CSA) based on three pillars: (a) sustainable

Table 4. Good Low Carbon Best Practices (GLCP) for GHG reduction in cultivation and processing plants in the palm oil supply chain

Practice	Component	Reduction point	GHG reduction potential	Co-benefit
Cultivate in previously inter-ventilated areas or without forest cover	Prevent deforestation of high-carbon areas	Land use change	High	(+) Biodiversity
	Planting in degraded areas		High	Restoration
	Avoidance of planting on soils with high carbon content		High	(+) Biodiversity
Implement agroforestry systems	Incorporation of trees in crops and hedges	Mitigation	Medium	(+) Biodiversity
Efficient use of fertilizers and amendments	Management of doses, sources, type of fertilizer, time, and location of application	Manufacture, transport, and use of fertilizers	Medium	(–) Eutrophication
	Nitrification inhibitors and the use of slow-release fertilizers		High	
	Organic fertilizers		Medium	
	Establishment of cover crops		Medium	
Increasing the productivity of the mill	Continuous improvement of the industrial process	Fruit processing	High	Optimization of industrial process
	Reduction of water consumption		Medium	Reduction of effluents
	Raw material quality		High	Reduction of oil losses
	Training of plant personnel		Low	Good manufacturing practices
	Energy and environmental performance indicators		High	Monitoring and efficient use of industrial services
Efficient use of biomass	Compost production and use of POME (palm oil mill effluents)	By-product management	High	Circular economy and application of biorefinery models
	Cogeneration of energy with residual biomass and biogas	By-product management	High	Fossil fuel dependencies
	Alternative uses of biomass	By-product management	Medium	Bioeconomy

Note. Adapted from Chaparro-Triana et al., 2020; Ivanova et al., 2020.

increase in agricultural productivity; (b) adaptation to climate change, and (c) reduction of GHG emissions as long as possible (Forero & González, 2020). CSA is vital to promote the Sustainable Development Goals (SDGs), including the elimination of hunger and the fight against climate change, particularly in developing countries (Amadu et al., 2020). Adopting good practices within the framework of CSA can influence crop yields, bringing them closer to those of conventional experiences or increasing them (Amadu et al., 2020; Liang et al., 2021; Ramborun et al., 2021); indeed, it is reported that appropriate applications boosted crop yields by 53% compared to those where they were not used (Amadu et al., 2020), so they need to be intensified in production systems and delinked from the increase in GHG emissions through the adoption of Good Low-Carbon Practices (GLCP).

Conclusions

There is sufficient and ample evidence of the relationship between climate change, global warming, and GHG emissions from anthropogenic sources. For this reason, it is necessary to propose approaches that separate economic growth from the increase in GHG emissions. The LCE promotes sustainable development and the reduction of GHG emissions; therefore, it constitutes a mitigation strategy against climate change. Applying LCE in the agro-sector reduces the expansion of the agricultural frontier, deforestation, and the intervention of pristine areas. It also contributes to productivity and environmental protection. Thus, LCE in regions such as the Colombian Orinoquia represents an opportunity for establishing energy crops in tandem with food production. The surplus land provided by the increased yields of the production chains will make it possible to obtain bioenergy with low GHG emissions, low ILUC risk, and production chains with zero deforestation or deforestation. In addition, it emerges as a strategy for decarbonizing the country's economy and contributes to meeting the goals agreed in the Paris Agreement. Although this type of model makes it possible to mitigate climate change, it is necessary to work in synergy with the reduction of society's consumption patterns, as well as with the care of water, soil, air, and biodiversity resources, since if the current dynamics continue, the implementation of strategies or measures to mitigate this problem will not be sufficient.

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Authored contributions

Munar-Flórez, D. A.: conceptualization, methodology, draft writing, and formal analysis. Caro-Caro, C. I.: methodology, conceptualization, and supervision. Ramírez-Contreras, N. E.: conceptualization and supervision. García-Núñez, J. A.: supervision.

Conflicts of interest

The manuscript was prepared and reviewed exclusively by the authors, who declare that they have no conflict of interest that could jeopardize the validity of the results presented here

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