

From rural Family Production to Climate Mitigation: An Ecological-Economic Approach to Measuring CO₂ Emissions in the Chico Mendes Extractive Reserve

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Abstract

The urgency of reversing environmental degradation and advancing global warming has mobilized the international community and scientific research. The drastic reduction of CO₂ emissions is the primary measure to mitigate this crisis. This study aims to present a theoretical-analytical proposal for measuring CO₂ emissions in rural family production in the Amazon rainforest. The research was built on ecological economics principles from the co-production perspective and the social reproduction of rural family production in the Chico Mendes Extractive Reserve in Acre, Brazil. The proposed methodology systematizes the calculation of environmental impact in terms of carbon emissions and resource consumption, based on quantitative metrics, from information on 1) data on operations carried out, with details in terms of the use of labor and 2) data on materials and inputs in the production process. A case study was used as a reference. The results indicate a very low environmental impact in using inputs and materials, with zero effect on using family labor in production processes. This confirms nature's co-productive nature in the search for zero net carbon emissions. Thus, this approach can contribute to disseminating a new vision that seeks to position rural family production as part of the solution and opportunities in the transition to low-carbon production systems that respect the ecological balance of ecosystems.

Keywords

Climate Change, Environmental Impact, Sustainability, Brazilian Amazon

1. Introduction

Brazil is considered a player in the discussion on reducing Greenhouse Gas (GHG) emissions, such as carbon dioxide (CO₂). To maintain its leading role and reduce deforestation, the transition to a low-carbon economy and, subsequently, climate neutrality (net zero) are being sought. To this end, researchers worldwide have scientifically demonstrated that the worsening of environmental threats is due to anthropogenic action intensified by the current model of production and consumption [1].

The Paris Agreement¹, signed in 2015, established a historic milestone in the fight against climate change. Unlike the Kyoto Protocol, it requires all countries to contribute to reducing GHGs. Recognizing the need for global and equitable action, the document set ambitious but flexible targets, taking into account the capacities and realities of each nation. Actions to reduce CO₂ emissions began in 2020, and the core goal was to curb the increase in global temperature by 1.5°C compared to the pre-industrial era [2].

However, the greenhouse effect intensifies due to the increased concentration of GHGs in the atmosphere, resulting in a rise in the Earth's average temperature. According to the sixth report of the Intergovernmental Panel on Climate Change (IPCC), the average temperature of the Earth's surface will increase by 1.1°C between 2011 - 2020, compared to the average temperature of 1850 - 1900. The research confirms that human influence on the climate is unequivocal, and the temperature increase could exceed 1.5°C by 2040, especially in a scenario of highly high GHG emissions. Furthermore, global temperatures could rise between 3.3°C and 5.7°C in a carbon-intensive emissions scenario by 2100 [3].

Humanity is getting further and further away from meeting the goals of the Paris Agreement. The Copernicus Global Climate Report revealed that 2024 was the hottest year, exceeding the historical limit of 1.5 degrees of warming. Average global temperatures were around 1.6°C above the pre-industrial period. The constant increase in GHG emissions continues to be the principal agent of climate change [4].

According to [5], the world has already crossed six of the nine planetary boundaries due to the climate crisis. This will likely result in irreversible damage to biodiversity and ecosystems, and tens of millions of people will be exposed to dangerously high temperatures. To [6], if the world continues on the projected trajectory, by 2030, around two billion people will be outside the "climate niche", *i.e.*, temperatures in which humans can flourish and reproduce socially. The study estimates that average temperatures of over 29°C will be faced, and, in a population

¹In one of his first acts in his second administration (2025-2028), the President of the United States of America (USA), Donald Trump, signed a decree notifying the United Nations (UN) of his intention to withdraw from the Paris Climate Agreement. The country is one of the largest emitters of GHGs. Leaving the Agreement for the second time casts doubt on global efforts to curb global warming. It carries significant weight, especially regarding finances, since the country contributes considerable sums to the climate fund. The decision will substantially impact the future of the Agreement, and the international community will need to mobilize even more forcefully to ensure that the global climate targets are met.

growth scenario, around 3.7 billion will be living outside the niche by 2090.

In this direction, ecological economists have demonstrated since the 1990s that high economic growth under current technical and cultural standards will lead the planet to environmental collapse [7] [8]. As a result, alternatives are being sought to the current linear production and consumption system—which is increasingly unsustainable—as it leads to both the exhaustion of natural resources and unsustainable waste production. For the development pattern to become sustainable, it is necessary to overcome three shortcomings of the current development model: high social inequalities, the trap of low income and low productivity, and growing environmental impacts [9].

In contrast to the dominant production model, rural family production manages some of the world's forests [10], with the potential to contribute to mitigating climate change, reducing carbon emissions, and keeping families in rural areas. For [11], the interaction between human beings and the environment has been the central theme of various studies, especially regarding how nature is appropriated in the Amazon Rainforest and how local populations have developed different survival and social organization strategies over time.

The Amazon rainforest is a fundamental biome for the planet's climate balance due to its vast extension, high provision of ecosystem services, and rich biodiversity. Its ability to absorb CO₂ from the atmosphere makes it an indispensable ally in the fight against climate change, directly influencing the global and regional climate [12].

Within the Amazon rainforest, specifically in the state of Acre, the Chico Mendes Extractive Reserve (Resex) stands out as a pioneer in the concept of a sustainable use conservation unit. The Chico Mendes Extractive Reserve was created in the mid-1990s and is an icon in the construction of solutions that keep the forest standing and, at the same time, create better living conditions for the people who live there. Based on the struggle of the rubber tapper movement, it has become a symbol of the recognition of the land rights of traditional communities in forest conservation, covering an area with significant non-timber forest products, such as rubber extraction and Brazil nut production [13].

By adopting measures that promote the sustainable use of natural resources and adding value to agroforestry products, rural family production, especially in the conservation units of the Amazon rainforest, has the potential to play a leading role in low CO₂ emission production models. When combined with forest conservation, this can contribute to climate change mitigation. In this way, using appropriate environmental technologies can generate positive impacts both in the present and guarantee effective sustainable development [11].

Considering the global problem of GHG emissions, this study aims to present a theoretical-analytical proposal for measuring CO₂ emissions in rural family production in the Amazon rainforest. The research was based on the principles of Ecological Economics from the perspective of production and the social reproduction of rural family production in the Chico Mendes Extractive Reserve in the

state of Acre.

This study is organized into five parts in addition to this introduction. The following section discusses the importance of the Amazon rainforest in the carbon balance and the vision of ecological economics. The third section reflects the particularities of Acre and the Chico Mendes Extractive Reserve. Then, it presents rural family production and the process of co-production with nature. The fourth topic presents the theoretical and analytical proposal for measuring CO₂ emissions in rural family production in the Amazon, discussing the results of a case study in the region, which validates the proposed methodology. Finally, there are concluding remarks, followed by references.

2. The Amazon Rainforest and the Carbon Balance: A Look from Ecological Economics

The Amazon rainforest, the largest tropical forest in the world, plays a fundamental role in regulating the global and regional climate. Given its magnitude, it acts as an essential carbon sink, absorbing CO₂ from the atmosphere, captured by the photosynthesis of its vegetation. The Amazon also helps to control atmospheric warming through the transpiration of its trees, moving the so-called “flying rivers” and currents of water vapor responsible for the rainfall in Brazil’s South and Southeast regions. However, this tremendous green carbon ecosystem, which provides invaluable ecosystem services to the planet, is under threat [12].

Reducing the carbon sink—the capacity of the Amazon rainforest to absorb carbon dioxide—has significant implications for the global climate. The study by [14] points out that the decrease in this sink leads to rising temperatures, changes in rainfall patterns, and increased carbon emissions. According to the authors, the risk of droughts and forest fires increases as the Amazon becomes hotter and drier. These events release large amounts of CO₂ into the atmosphere, transforming the forest from a carbon sink into a carbon source. In addition, soil respiration, a natural process that releases CO₂, also increases in hotter and drier conditions.

According to [15], deforestation is already threatening to turn the forest into an arid region, which emits more carbon than it absorbs. In addition to the direct emissions caused by burning, the forest traps the equivalent of almost a decade’s global GHG emissions in its trees, and the felling of trees is already affecting temperatures in the region. The dry season is three to four weeks longer in some areas south of the forest. The decrease in rainfall has increased the temperature by 2.5°C in the southeast of the Amazon, forcing trees to emit more carbon than usual to compensate for the imbalance.

According to [16], the negative synergies between deforestation, climate change, and the widespread use of fire indicate a tipping point (“point of no return”) for the Amazon system to transform into non-forest ecosystems in the eastern, southern and central Amazon, with 20% - 25% deforestation, and four degrees Celsius of global warming for degraded savannas in most of the central, southern and eastern Amazon. The authors point out that the most sensible way

forward is to rigorously contain deforestation and rebuild a safety margin against Amazon's tipping point by reducing the deforested area to less than 20%.

For [17], the increasing frequency of unprecedented droughts in 2005, 2010, 2015, and 2016 signals that the tipping point ("point of no return") is near. In simple terms, the Amazon rainforest can no longer withstand deforestation and needs to be rebuilt as the foundation of the hydrological cycle to continue to serve as a flywheel of the continental climate and an essential part of the global carbon cycle, as it has done for millennia. The good news is that a margin of safety can be rebuilt through immediate, active, and ambitious reforestation, particularly in the deforested regions, which represent 23% of the destroyed forest and are abandoned or occupied with extensive cattle breeding.

According to [18], if deforestation continues at the same rates as in recent decades and global warming significantly exceeds 1.5°C, the Amazon will exceed its tipping point, which could lead to more than 50% of the forest becoming highly degraded ecosystems. Furthermore, if the dry season continues to lengthen, the irreversible tipping point will be reached in 2050. In this case, between 50% and 70% of the forest would be degraded within 30 to 50 years. This would release more than 250 billion tons of CO₂ and lead to the extinction of thousands of species.

Given this scenario, Ecological Economics, as a field of study, points to the limits to economic growth related to the sustainable scale of production, the laws of thermodynamics, and the point of no return. For [19], the economic system cannot go against the Laws of Physics. The limitation is due to the law of entropy, which means no productive activity of transformation of matter and energy (first law of thermodynamics) is possible without irreversible entropic degradation that generates waste (second law of thermodynamics). Even so, reducing waste by increasing ecological efficiency is possible, but there are insurmountable entropic limits after a certain point [20].

Transformation requires energy and inevitably generates highly entropic waste. With the continuous growth of production, the economic subsystem must eventually exceed the capacity of the global ecosystem to sustain it. Thus, entropy is a one-way street of irreversible change, a continuous increase of disorder in the universe [21]. Inevitably, any resources transformed into helpful things must disintegrate, decay, decompose, or dissipate into something useless, returning in the form of waste to the support system that generated the resource.

According to [20], the total waste inevitably generated by the extraction, transformation, and consumption of natural resources in a given period, called "throughput", cannot exceed the Earth's carrying capacity and that zero growth is the only way to prevent this. Thus, estimating the sustainable scale of using natural resources is always necessary for Ecological Economics. For neoclassical environmental economics, the use scale is determined by the most efficient allocation, *i.e.*, the one that minimizes adjustment costs without considering long-term sustainability. Thus, for Environmental Economics, the goods and ecosystem services to be used (the scale) are treated as adjustment variables. For the Ecological Eco-

nomics, on the contrary, they should be treated as physical parameters of ecological sustainability, which should be adjusted to the non-physical variables of technology and individual preferences ([20], p. 81).

In short, ecological economics is not against using the energy capital resources available to humanity. The energy demands of the economic growth model and the technical impossibility of fully utilizing the flow of low entropy solar energy require that ever-greater portions of this stock be used. However, Ecological Economics criticizes the irresponsible use of these resources and disregards the finiteness of the physical base that sustains the economic system [7].

In this sense, ecological sustainability (strong sustainability) must be seen as the preservation of essential ecosystem services (irreplaceable by capital); even in the case of raw materials, they must be used with greater ecological efficiency to extend the time horizon of their availability, making it possible to maintain physical stocks of natural capital. It must be clear that biophysical limitations determine planet Earth's capacity for self-regulation. Exploiting natural resources is so intense that it is impossible to conceive of living in an unlimited ecosystem. It is, therefore, necessary to bring the growth of material and energy production to zero [20]-[22].

Any subsystem, such as the economy, must at some point stop growing and adapt to a dynamic equilibrium, something akin to a steady-state economy. Therefore, humanity needs to transition to a model of economic development that respects the physical limits inherent in the global ecosystem and guarantees its continued functioning in the future—in a finite biosphere; this requires new ways of thinking and productive practices that can be models of sustainability in the fight against climate change [20]-[23].

Undeniably, anthropization caused by unsustainable activities in the Amazon has already converted part of the forest into open areas, such as pastures. However, with reforestation, in the future, they will be transformed into secondary forest areas, which is a natural path when the slash-and-burn system takes place. This process is a traditional and financially accessible strategy for local producers, as it produces a large volume of ash, which increases its fertility when incorporated into the soil [12].

[24] indicate that slash-and-burn agriculture has been practiced for thousands of years in tropical forest areas. However, slash-and-burn agriculture's role in deforestation and other environmental and socioeconomic impacts is growing in academic literature and political debate. This process results from changes in land use, agricultural intensification, and population growth, which alter practices and compromise the sustainability of traditional farming systems.

In tropical forests such as the Amazon, where many wild plant species are inedible or challenging to collect, slash-and-burn agriculture has been an essential adaptive strategy for the region's subsistence economy [25]. Its practice involves a range of techniques that denote its diversified and itinerant nature, with the use of the energy capital of the forest being recomposed [24]. The study of [26] attested to the sustainability of these systems when practiced traditionally and under

low population densities, maintaining or even promoting local biodiversity and guaranteeing the livelihoods of many rural populations.

However, it is essential to emphasize that, historically, rural family production uses the forest in a slash-and-burn system. In an ideal world, deforestation should not occur, but given the need for small farmers to grow food, anthropization is crucial to the livelihoods of local populations. The system is carried out by rural family production responsibly and within a sustainable use scale, that is, through a minimum scale to provide food “precisely through the ancestral form of slash-and-burn agriculture” ([27], p. 21).

Family farmers use firebreak techniques—strips of land without vegetation that prevent the spread of fire—to prevent and fight fires [28]. Slash-and-burn agriculture is associated with crop rotation, and the “*aceiro*”² restricts burning to a specific point. At the same time, the local population maintains control of the fire for a particular purpose, unlike arson and out-of-control fires. Therefore, the key element is the low scale and the sustainable aspect linked to social reproduction, which does not effectively disrupt the system.

Carbon dioxide can be emitted immediately after the felling and burning process. However, in a short time, as the secondary forest advances, it tends to sequester carbon again. In this way, the slash-and-burn system allows the forest to regenerate. As a result, agricultural production and deforestation don’t have to go in the same direction. Agroforestry allows crop trees to grow alongside native vegetation, characterizing it as a sustainable source of income while at the same time restoring the native rainforest and combating climate change by capturing and storing carbon naturally [29].

According to [30], agroforestry systems (SAFs) are land use systems in which trees are consorted—simultaneously or sequentially—with herbaceous plants, shrubs, crops, and/or forage in the same place according to a predetermined spatial and temporal arrangement. According to the authors, there are several possible models and combinations for these systems, which are seen as interesting tools when it comes to reintroducing the tree component into the rural landscape, with ecological objectives such as improving landscape connectivity, rescuing native biodiversity, regenerating soil health, strengthening secondary forest and capturing carbon. The focus is on obtaining agricultural and forestry products, both timber and non-timber, to generate employment and income for rural populations.

Agroforestry systems are seen as an alternative for improving the sustainability and resilience of degraded landscapes. For [31], SAFs are suitable tools for enhancing the soil’s physical, chemical, and biological characteristics (increasing its fertility), controlling erosion, and improving water availability. In addition, the restoration of degraded landscapes using agroforestry systems can increase the resilience of rural communities to shocks, including droughts and food shortages, and help mitigate climate change. It also seeks to promote livelihoods for rural communities by providing a greater variety of food and forest products that in-

²“*Aceiro*” is a strip of land without vegetation used to prevent and fight forest fires.

crease food sovereignty.

For [18], although many scientists consider that the southern Amazon region has already passed the point of “no return”, the author believes that it is still possible to reverse the situation, but to do so, it is necessary to increase governance in the region; eliminate deforestation, degradation, and fire; and conserve and restore the forest by developing what is called a new socio-bioeconomy of standing forest and flowing rivers. In this direction, many deforested and degraded areas can be used for forest restoration and inclusive agroforestry systems, producing large quantities of native species and food.

In addition, following [32], socio-bioeconomics provides some fundamental criteria, characterizing it as a way to move away from the point of no return in the Amazon. The concept of socio-bioeconomics is rooted in local practices, culture, and principles such as equity. Activities that lead to the conservation and restoration of ecosystems increase cooperation and social participation, protect human and territorial rights, promote social benefits, and integrate diverse knowledge, such as scientific and traditional.

In this sense, sustainable use conservation units, such as Extractive Reserves (Resex), have emerged as the model for sustainable development in the Amazon, led by rural family production. According to [33], conservation units, as in the case of the Chico Mendes Resex in the state of Acre, emerged as a way of solving problems related to the struggle for land ownership in the Amazon region, as well as environmental issues arising from unsustainable activities such as timber production and extensive cattle ranching. According to the authors, despite the growth in deforestation seen in recent years, the Chico Mendes Resex maintains more than 90% of its forest cover and corroborates the thesis that protected areas act as barriers to the advance of deforestation, fulfilling their role of environmental protection.

The standing forest provides a livelihood for families, so its conservation is fundamental. In this respect, the co-productive character and the sustainable aspect of the rural family production lifestyle in the region are interrelated. This process, according to [34], resembles socio-ecosystems, which is an approach that considers the various human elements, including their systems of use and exploitation of natural resources, as part of the landscape, offering inspiring emerging properties for understanding people-nature relationships, the result of the combination of social systems and ecosystems.

3. The State of Acre and Resex Chico Mendes

The opening up of the Amazon for colonization since the 1970s has led to the expansion of cattle ranching, conflicts over land, and widespread deforestation. According to [35], Brazilian cattle production has grown more intensely in the Legal Amazon³. The authors point to the intensification of production in the region, given that the herd growth rate was between 5.6% and 15.68% higher in the

³The legal Amazon consists of the states in Brazil's northern region (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, and Tocantins), as well as Mato Grosso and Maranhão.

Legal Amazon than in the country, while the growth in cattle density (herd per km²) was between 11.11% and 21.47% higher. Cattle are the primary driver of deforestation in the Amazon, and the direct consequence is a reduction in primary forest areas.

The history of the rubber tappers' struggle in Acre to defend the forest is a milestone for the Brazilian environmental issue. By protecting a sustainable development model based on latex extraction, these workers demonstrated that it was possible to reconcile the local economy with conserving biodiversity and the environment. However, pressure from the expansion of the agricultural frontier and the rise of cattle ranching have led to a radical change in the regional scenario. Today, cattle ranching has spread across vast areas of the Acre Amazon, transforming the landscape and the local population's way of life with socio-environmental impacts [36] [37].

According to [38], the diversity of cattle ranching practices in Acre explains the region's varied economy. The author indicates that it is possible to find large ranchers and a range of livelihood strategies practiced by small landowners. In addition, some rubber tappers see cattle as part of their livelihood strategies, including forest extraction, slash-and-burn agriculture, and wage labor. These practices can change due to opportunities, limitations, and the scope of production for subsistence or trade.

Of the territories in the Amazon, Acre is particular because it has high densities of rubber trees and the Brazil nut tree relative to the territory. These are two species with productive potential within the forest-based economy. In addition, the state has many environmental protection parks and extractive and Indigenous reserves, which is an advantage for containing deforestation.

One of the essential expressions is the Chico Mendes Extractive Reserve, a federal conservation unit for sustainable use, managed by the Chico Mendes Institute for Biodiversity Conservation (ICMbio), granted for the sustainable use of extractivists spread over seven municipalities in Acre⁴, covering 970,570 hectares [13], located in the region most impacted by deforestation in the state, surrounded by large cattle ranches. Over thirty years, the protected area has lost over 6% of its forest cover. The management plan allows cattle farming but limits it to 15 hectares per property, which would yield a maximum of 45 head. However, the reality is different; many families have more than 100 cattle heads [39].

The creation of the reserve, the fruit of a historical struggle that cost Chico Mendes his life, is threatened by various illegal practices. The opening of new areas for grazing, illegal logging, and the irregular sale of plots of land are just a few examples of the problems plaguing the region. The decline in the competitiveness of the extractive economy, combined with the loss of the residents' identity with the movement that gave rise to the protected area, has led to replacing traditional activities, such as Brazil nut gathering and latex extraction, with cattle breeding.

⁴The municipalities are Assis Brasil, Brasília, Capixaba, Epitaciolândia, Sena Madureira, Rio Branco e Xapuri.

According to [27], cattle breeding has historically been present in the lives of the residents of the Chico Mendes Resex, but with a secondary role. The animal was seen as a valuable asset used to meet specific needs. Livestock farming took on a new meaning with the decline of extractive activities and the difficulties of selling forest products. The ease with which cattle could be sold for cash made this activity an attractive alternative for guaranteeing family income, in some cases becoming the primary source of livelihood for the reserve's residents.

However, [40] points to the economic unfeasibility of commercial beef cattle production, which is only valid as a store of value. The logic of commercial production, which requires more significant investment and the search for greater efficiency, conflicts with the reserve's environmental restrictions. The combination of extensive management and deforestation limits makes cattle ranching in the Chico Mendes Reserve economically unviable on a large scale.

The proliferation of branch roads in the region has intensified the threats to the forest, such as pressure for paving and illegal logging. This dynamic puts the environmental balance and the sustainability of extractivist activity at risk. Preserving extractivist culture and strengthening the extractivist production chain is a challenge that requires a joint effort from various actors. Through subsidy and incentive policies, government support is essential to guarantee the sustainability of extractive products, which can compete with other predatory activities.

In this context, ways are being sought to encourage low-carbon production alternatives that promote sustainable land use instead of the traditional, unsustainable capitalist mode of production. This leads to the exhaustion of natural resources. Nature-based solutions, such as forest conservation and the recovery of degraded areas, are Brazil's most significant advantages when it comes to positioning itself in the new economy of the 21st century. However, for this mission, it is essential to carry out a carbon balance appropriate to the productive reality of the social actors involved in the ecosystem.

Because of this, rural family production is fundamental in the discussion on climate change and the carbon balance—in the direction of keeping the forest standing as a carbon sink—and promoting a profitable rural family production model with quality of life for the local population and free from deforestation. This is a decisive step towards the future of the Amazon rainforest, based on a production model in which people and nature thrive together.

Rural Family Production in the Chico Mendes Extractive Reserve and Co-Production with Nature

Whatever the discussion on ways to promote ecological sustainability, it is essential to incorporate the role of rural family production, local communities, and indigenous peoples into the development process. For [10], rural family production and local communities manage most of the world's forests. Almost a quarter (1/4) of the global land area is occupied by indigenous peoples or local communities, such as small farmers, and these populations manage more than a fifth (1/5) of the tropical forest area. In the context of environmental justice, rural family land

use stands out for its management of forest areas and can play an essential role in helping to mitigate climate change.

For [41], rural family farming—which is conceptually a mode of production—regardless of the size and type of production system, manifests itself in the peasant way of life as an alternative to the capitalist production system, or more specifically, to industrial-scale agriculture that is intensive on finite natural resources. According to [13], the key issue in the coexistence of this alternative mode of production with capitalism is its interference in rural communities, whose logic of reproduction is based on extra-market values but with partial dependence on them. In the rural family production model, the reasons for reproduction go beyond economic efficiency and market logic. In other words, the driving force behind family production units is not the pursuit of profit but the social cost associated with the family's collective reproduction, which is not adequately incorporated into the market price mechanism.

The authors [13] defend that rural family production is a mode of production that works co-productively and interactively with nature; by respecting the ecosystem's biophysical limits, they promote local biodiversity and relevant socio-environmental services. In other words, the rural family production model is inherently sustainable because of the second law of thermodynamics (the law of entropy) acceptance, which can potentially solve socio-environmental problems, especially in rural areas.

From a sectoral perspective, rural family production has the potential to contribute to the process of sustainable regional development by strengthening co-production relationships with nature, respecting biophysical limits, and working within the boundaries of ecosystem resilience (carrying capacity) through a concern to preserve the environment, conserve the natural landscape, guarantee food security and strengthen local communities. It thus opposes the corporate production model by providing solutions to address environmental, social, and economic pressures. In addition, it aims to maintain the natural productive cycle, producing not only jobs and economic well-being but also social, ecological, and cultural benefits, with the potential to mitigate the effects of climate change through less dependence on fossil fuel-based inputs.

The social category is plural, complex, and heterogeneous and includes various particular dynamics that characterize the rural space. Beyond a production system, it is described as a way of life with actors, social reproduction, and its dynamics [42]. In these terms, the rural family production model has social, economic, and environmental advantages because it is more democratic, sustainable, and more efficient than the conventional form. Positioning itself as an environmentally prudent, socially just, and economically viable model of agriculture.

Rural family production is a way of life based on co-production (between people and nature). For these reasons, its carbon emissions tend to be very low and, in some cases, close to zero. Individuals ensure their social reproduction by using natural resources, and, at the same time, through the production process, they

conserve nature and preserve biodiversity. Thus, low CO₂ emissions indicate precisely how resilient the production system is. Because of this, the discussion about the carbon balance is emerging in rural family production, considering that it has all the elements to be characterized as Net Zero Carbon. The terminology refers to the commitment to zero direct and indirect emissions of greenhouse gases into the atmosphere, especially CO₂.

This commitment is part of a context of strong global mobilization, spearheaded by the UN through the Climate Convention (in favor of neutralizing net carbon emissions by 2050), which aims to limit global warming to a maximum of 2°C by the end of this century. The “net zero carbon emissions” commitment states that humanity depends on an unprecedented boost to clean technologies, which generally requires immediate and large-scale applications of the various technologies already available and ensuring the most outstanding possible energy efficiency. Therefore, there is a worldwide commitment to carbon neutrality to limit global warming, and national strategies and adaptation plans to alleviate the negative impacts of climate change are essential for a low-carbon and climate-resilient future [43].

The following section presents a theoretical and analytical proposal for measuring CO₂ emissions in diversified family production systems in the Amazon, aligning with ecological economics and eco-efficiency principles.

4. Theoretical-Analytical Proposal for Measuring CO₂ Emissions in Rural Family Production

The theoretical-analytical proposal considers the lack of protocols and technical coefficients to measure the degree of CO₂ emissions in diversified rural family production systems, particularly in the conservation units of the Amazon Rainforest. It is based on compilations of secondary data from scientific works and existing models available for estimating GHG emissions from the agricultural and land use sectors, such as the Intergovernmental Panel on Climate Change, which has developed a protocol for accounting for GHGs at a national level [44]; the Agricultural GHG Protocol method [45]; and the carbon balance in family agricultural production in the Amazon, within the framework of the Cocoa and Livestock Programs in the region of the Transamazon highway [46].

Due to the variety of land uses and management practices in the rural family production context, as in the case of the Chico Mendes Resex, it was necessary to make adaptations because these tools do not consider the primary sources and sinks of GHGs present in this type of production system. In this way, this proposal differs from other scientific studies in that it develops a specific carbon balance for rural family production in conservation units with sustainable land use, with the potential to be applied to other scales of production. It should be emphasized that the uniqueness of this theoretical-analytical proposal lies in its foundation, which is based on indicators built on almost three decades of field research in the Chico Mendes Resex [33], which gives it an unprecedented character concerning

other studies and methodologies.

The systematization offered is in harmony with the Brazilian government's national strategic agenda, which includes a sectoral policy for tackling climate change in the agricultural sector, the "Adaptation and Low Carbon Emission Plan for Agriculture—ABC+⁵". The ABC+ Plan is being implemented in the 2020 - 2030 cycle to promote adaptation to climate change and the control of GHG emissions in Brazilian agriculture, with an increase in the efficiency and resilience of production systems [47]. In this sense, more sustainable and resilient production systems are encouraged, capable of controlling GHG emissions, guaranteeing the supply of food and bioenergy in quantity and quality, and conserving natural resources. Agroforestry Systems (SAFs) stand out here as a strategy for dealing with the challenges of climate change [48].

The structuring of guidelines for determining the degree of carbon emissions in family production systems in conservation units in the Amazon rainforest is based on the importance of environmental impact assessment. It contributes to the sustainable management of projects and processes. This proposal is based on calculating environmental impact using quantitative metrics. Information is recorded using labor and input in the production process to structure it, quantifying the environmental effects of carbon emissions and resource consumption.

The data brings together two main types of information: 1) data on operations carried out, which contains details on working time in days and hours and the size of the batches worked on, and 2) data on materials, which is information on the quantity of materials used categorized by type of product and unit of measurement. The statistical procedure based on the median of the variables gathered was used to determine the environmental impact associated with the use of labor.

To collect the information, we used the database of the research project entitled "Socioeconomic Analysis of Basic Family Production Systems in the State of Acre"⁵, called ASPF, which has been active since 1996 and is currently coordinated by the Center for Applied Legal and Social Sciences (CCJSA) of the Federal University of Acre (UFAC), to carry out a socioeconomic diagnosis of rural family production units in the state of Acre. The object of the study is the extractivist families who live in the Chico Mendes Extractive Reserve and are part of an extractivist rural family production system in the Acre region [13]-[49].

The project conducts the field survey by sampling, following the criterion that the extractivist has resided in the "*colocações*" (family production units) for at least two years. The sample is defined based on three stages: 1) stratification of the area, 2) representativeness within each stratum, and 3) simple random sampling, totaling 10% of the production units. The median measures the central tendency to ensure representativeness since the population is heterogeneous and has extreme values. The information gathered was based on the local agricultural calendar, which runs from May of one year to April of the following year.

The relevant variables include **Man Day (HD)**, indicating the total number of

⁵See <https://aspf.wordpress.com/>.

days worked, adjusted according to the size of the plot; **Man Hour (HH)**, which represents the sum of working hours converted into HD when divided by 8 (eight hours of daily work—according to Brazilian labor legislation—CLT); and **Lot Size**: which refers to the volume or quantity of work carried out per plot. The GIAD (Aggregate Degree of Performance or General Environmental Impact Index) is the environmental result of the activities and materials used, described in a single number. **Table 1** shows a description of labor indicators.

Table 1. Labor indicators description.

(First) Weeding and cleaning the area	ID1
Beaconing/picketing/planting	ID2
Insecticide Application	ID3
Fungicide application	ID4
Formicide application	ID5
Herbicide application	ID6
Limestone application	ID7
Organic fertilization of holes	ID8
Planting seedlings	ID9
Replanting	ID10
(Second) Weeding and cleaning the area	ID11
Organic mulch fertilization	ID12
Fertilization with chemical top dressing	ID13
Application of natural defenses	ID14
Weeding	ID15

Source: authors' elaboration.

The GIAD calculation process involves the following steps: first, data is collected on the operations carried out in each activity to determine the environmental impact value based on the established criteria. Next, each operation's environmental impact values are added together. Finally, the total impact of the operations is divided by the total number of operations and inputs. This normalization adjusts the value to reflect the proportion of the environmental effects of the operations concerning the total batches surveyed, and the result becomes the GIAD for operations. The formula for calculating the total GIAD value for operations is as follows:

$$v_{\text{total}} = \text{Median}(\text{Median}(\text{Lot Size}) + \text{Median}(\text{HD})/8) / \text{Median}(\text{HH}) \quad (1)$$

Where:

- Median(HD)/8 —is the median of the Man Day values collected.
- Median(HH) —is the conversion of the Man Hour into a unit comparable to a Man Day.
- Median(Lot Size) —is the median of the lot sizes surveyed.

Environmental impact (quality) is classified based on ranges of values for v_{total} . For each range, an environmental impact value (ID) is assigned, ranging from 0 (low) to 13 (very high), as shown in **Table 2**.

Table 2. Performance indicators for operations in five categories.

Categories	Performance
Low	$v_{total} \leq 10$
Little low	$10 < v_{total} \leq 11$
Moderate	$11 < v_{total} \leq 12$
High	$12 < v_{total} \leq 13$
Very high	$v_{total} > 13$

Source: authors' elaboration.

The GIAD calculation for input data follows a very similar pattern. Data collection on the impact of inputs considers that each input category is assigned an environmental impact value based on the quantities consumed. Thus, all the values concerning the environmental impact of the inputs are added together to arrive at an overall total. **Table 3** describes input indicators.

Table 3. Input indicators description.

Input	Indicators
Seeds	ID16
Seedlings	ID17
Seedlings of native species-trees	ID18
Insecticide	ID19
Fungicide	ID20
Herbicide	ID21
Limestone	ID22
Chemical fertilization	ID23
Organic fertilizer	ID24
Rock dust	ID25
BioCharcoal	ID26
Natural Defensive	ID27
Biofertilizer Grout Kit (Virgin Lime, Copper Sulphate and Sulphur)	ID28
Motorized brushcutter (1 liter of gasoline per 2 hours of work)	ID29
Use of machinery to clear the area (hours rented or used per hectare)	ID30

Source: Authors' elaboration.

The total impact of inputs is calculated by calculating the GIAD for Inputs, which considers the division of the total number of operations and inputs. The value reflects the proportion of the environmental impact of inputs concerning the available data set. The environmental impact associated with inputs is also based on the median of the total quantities consumed, calculated for each input type. The formula for quantity calculation can be seen below:

$$\text{Quantity} = \text{Median (Quantity of Inputs)} \quad (2)$$

Thus, the impact of the inputs is classified based on quantity ranges, each range being associated with an environmental impact value (ID), ranging from 0 (low) to 60 (very high), according to **Table 4**.

Table 4. Performance indicators for operations in five categories.

Categories	Performance
Low	quantity \leq 30
Little low	30 < quantidade \leq 40
Moderate	40 < quantidade \leq 50
High	50 < quantidade \leq 60
Very high	quantidade > 60

Source: authors' elaboration.

Finally, to calculate the final GIAD, a sum Σ (GIADs of operations and inputs) is made, considering both elements' environmental impact. The result of this sum is the final GIAD, which reflects the total environmental impact, taking into account both operations and inputs. The mathematical formula for GIAD's determination is described as follows:

$$\text{GIAD} = \sum (ID_1 + ID_2 + \dots + ID_{30}) \times 10 \div 300 \quad (3)$$

Concerning the method of quantifying the degree of performance of each associated indicator, for the sake of comparison, all the values will be transformed to the decimal scale, with the final value of the degree of performance being the sum of the weighted values of the contexts of the labor and input indicators. In other words, the values obtained for each indicator will be transformed to a positive decimal scale. The indicators can be added within the two contexts and then weighed to get overall performance grade values for each production unit assessed⁶.

Therefore, the theoretical-analytical proposal for measuring CO₂ emissions in rural family production in the Amazon aligns with the Ecological Economics assumptions since nature-based solutions enhance the syntropic balance, marked by the preservation of energy in the environment and the maintenance of a sustainable scale of use of natural resources, allowing for their resilience. In this way, estimating CO₂ emissions can prove Resex Chico Mendes's commitment to envi-

⁶It is based on an adaptation of [50].

ronmental conservation, sustainable development, and the strengthening of extractivism.

Ecological Economics emphasizes the regeneration of ecosystems and the creation of a society that respects biophysical and ecological limits, promotes social justice, and guarantees the quality of life of traditional communities, both now and in the future. The theoretical-analytical proposal presents itself as a powerful tool for assessing the sustainability of agroforestry products, encouraging production practices that avoid the predatory use of natural resources and the generation of high entropy waste. In addition, it recognizes that rural family production, by providing decent work in harmony with the carrying capacity of ecosystems, contributes to ecological sustainability.

GIAD Application in Seringal Porongaba, Resex Chico Mendes

To validate the GIAD methodology, field research was carried out on five⁷ extractive production units in the Porongaba rubber plantation, part of the Chico Mendes Extractive Reserve in Epiaciolândia, Acre. This area is considered emblematic in the region of this conservation unit, as it faces extensive pressure for further deforestation, given its geographical location, close to cattle ranches, towns, and an international integration highway, where some production units already have environmental liabilities in terms of deforestation.

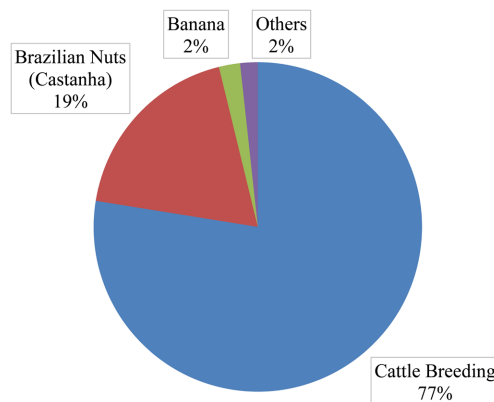


Figure 1. Income generation among families in Seringal Porongaba, Resex Chico Mendes, Acre—2022/2023. Source: Authors' elaboration.

The situation in this area can be explained precisely by the products that generate gross income in the production units surveyed since in the agricultural year surveyed, 2022/2023, around 77% of the families' gross income was generated by raising and selling cattle, as shown in **Figure 1**, whose activity is inherently unsustainable due to its extensive form of production.

Not by chance, the choice to raise cattle is highlighted by the median gross in-

⁷This study used a small nonrepresentative sample, and the results are limited to the analyzed scenario. So, it is not recommended to make generalizations to the entire Resex or other Amazonian contexts. Future studies, with a representative sample design, will seek to validate and deepen the theoretical-analytical proposal presented here.

come earned by the extractivists surveyed, around R \$4,000.00 per month, equivalent to 2.6 minimum wages/month in force in Brazil. However, this activity is not a productive alternative from a commercial point of view, given its extensive nature, since it is limited by the maximum size of deforestation, around 15 hectares per plot, allowed in the Chico Mendes Extractive Reserve management plan in line with the principles of this command-and-control policy in the region, which establishes a scale of sustainable use for the forest ecosystem.

In this way, ICMBio, responsible for the conservation units, has identified several areas with environmental liabilities beyond what is permitted by law, including three areas that are the subject of this study, to assess and embargo the areas involved in the environmental illicit activities. In partnership with ICMBio, some allotments are putting into practice the reforestation of open areas and implementing agroforestry systems to strengthen the sustainability of this development model in the region.

This study calculated the environmental impact of the labor, inputs, and materials used in the production process of the extractive placements surveyed since 2023. According to **Table 5**, the environmental result of the GIAD, based on the use of labor, inputs, and materials in the production processes per hectare (ha) in the extractive placements, indicates a low environmental impact, very close to zero. The GIAD for labor is precisely zero, demonstrating the co-productive nature of extractivism with nature. This symbiosis with the environment is also reflected in the low (or very low) environmental impact of the use of inputs and materials, characteristic of the ancestral entropic process of extractive activities for non-timber forest products, such as natural rubber and Brazil nuts, two critical commodities in the region.

Table 5. Aggregate Degree of Performance (GIAD) of labor, inputs, and materials used in the production process per hectare (ha) in Seringal Porongaba, Resex Chico Mendes, Acre—2022/2023.

Indicator	Period 2022-2023
GIAD for labor	0,0
GIAD for inputs and materials	0,82
Final GIAD	0,82

Source: authors' elaboration.

Properly valuing these commodities is essential for maintaining and strengthening the sustainable use of Extractive Reserves, such as Chico Mendes, by generating enough income to guarantee the social reproduction of families in the forest. According to Maciel *et al.* (2024), this has already been happening since 2019, with payment for socio-environmental services in the commercialization of native rubber from the Chico Mendes Extractive Reserve and other extractive regions in the Amazon becoming a sustainable, productive alternative to cattle farming or any other unsustainable activity from a socio-environmental point of view.

Thus, by achieving net zero carbon emissions, rural family production, particularly in direct-use conservation units such as RESEX, can help mitigate the impacts of climate change by properly managing primary or secondary forests.

5. Conclusions

The study aimed to present a theoretical-analytical proposal for measuring CO₂ emissions in rural family production in the Amazon rainforest. Based on ecological economics principles, the research was built from the productive perspective and the social reproduction of rural family production in the Chico Mendes Extractive Reserve in Acre.

The growing threat posed by rising GHG emissions and alarming projections of extreme weather events contributes to the urgent need to adopt a new development model that moves away from the current linear and unsustainable growth pattern. In this context, the transition to a low-carbon economy, which considers regional and cultural specificities, emerges as a pressing need, and rural family production represents a promising path in this direction, given its inherent co-productive characteristic with nature.

Climate mitigation strategies involve preserving and restoring degraded ecosystems, with reforestation as the primary strategy. The creation of Resex Chico Mendes results from the historic struggle of Amazonian rubber tappers against the invasion of their land and the search for agrarian reform that recognizes their rights and way of life. Led by Chico Mendes, the rubber tappers proposed an innovative model of environmental conservation that combines protecting the forest with guaranteeing the livelihoods of local communities through the sustainable use of natural resources.

The theoretical-analytical approach presented here provides indicators for assessing the carbon potential of Amazonian rural family production systems. This evaluation is fundamental for implementing mechanisms such as Payment for Socio-Environmental Services (PSSA), which remunerate producers for forest conservation through the multidimensional economic-ecological valuation of the services provided, including the socio-cultural and ecological dimensions. By providing an approach for measuring CO₂, these indicators can contribute to structuring Green Bonds and Carbon Credits, encouraging adopting sustainable practices in the region. It also improves producers' income and social reproduction and helps set a fair price for agroforestry products.

The results of the research carried out in this paper, based on a case study in the Porongaba rubber plantation within the Chico Mendes Extractive Reserve, corroborated the research hypothesis with the assertion of the co-productive nature of rural family production with nature, demonstrating the zero environmental impact of family labor in production activities within the forest, as well as the very low environmental impact of the inputs and materials used in production processes, close to zero, which highlights the ancestral aspect of sustainable forest management over time.

Thus, this theoretical-analytical proposal can be applied to rural family production in similar biomes and contexts, subject to adjustments as long as they are improved to take account of local specificities. Further research is, therefore, needed to validate and improve the approach and compare efficiency in different production systems.

In this sense, the next step in this research will be to evaluate the carbon balance of family production units (colocações) in the Chico Mendes Extractive Reserve, in partnership with the ASPF project, based on a statistically representative sample, whose socioeconomic information is expected to be collected in the second half of 2025, by the 2024/2025 agricultural period. The results will be evaluated and discussed in light of the evolution of the surveys carried out by the ASPF project over the last 28 years.

With its unprecedented applicability, it has the potential to contribute to the discussion about the role of rural family production in reducing CO₂ emissions. It also contributes to the global commitment to net zero carbon, signed in favor of carbon neutrality to limit global warming.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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