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To cite this version:

Darlena Caroline da Cruz Correa, René Poccard-Chapuis, Vincent Blanfort, Jean-Luc Bochu, Philippe Lescoat. Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia. Pastoralism: Research, Policy and Practice, 2025, 15, pp.14461. ⟨10.3389/past.2025.14461⟩. ⟨hal-05225618⟩

HAL Id: hal-05225618
https://hal.inrae.fr/hal-05225618v1

Submitted on 27 Aug 2025

Odessa centre | Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 25 July 2025
DOI 10.3389/past.2025.14461

Check for updates

OPEN ACCESS

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RECEIVED 07 February 2025
ACCEPTED 16 June 2025
PUBLISHED 25 July 2025

CITATION
Corrêa DCdC, Poccard-Chapuis R, Blanfort V, Bochu J-L and Lescoat P (2025) Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia.
Pastoralism 15:14461.
doi: 10.3389/past.2025.14461

Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia

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Greenhouse gas (GHG) emissions and energy use are important parameters in the development of sustainable livestock systems. On-farm management practices can maximise energy efficiency and reduce gas emissions, however, these practices have yet to be identified and characterized. This study evaluated the eco-efficiency of cattle farming, considering a combination of the energy balance and GHG emissions from 33 farms in the Brazilian Amazon (Paragominas - Pará), using a diagnostic tool adapted to the region. The farms represented the diverse production systems operating in the area, distinguished by their activity (dairy, breeder, breeder-fattener and fattener), degree of intensification, and agrarian situation (corresponding to the farm's geographical location and social and economic inclusion in the municipality). Energy efficiency on beef cattle farms is on average 16.29 GJ/t live weight (min = 1.74 GJ/t, max = 43.01 GJ/t), and on dairy farms 2.74 GJ/1000 L (min = 0.17, max = 6.48), i.e., respectively 46% and 40% lower than the figures reported by studies conducted in metropolitan France. Improved grazing enhances natural resources by optimising the use of forage biomass, which has a positive impact on energy efficiencies. The purchase of young animals and fertilisation account for a high percentage of energy consumption, with fuel constituting the major part of the direct energy consumed. GHG emissions are on average 17.40 teqCO_2/t live weight (min = 6.13, max = 40.85), similar to those of metropolitan France (14 teqCO_2/t). When emissions from livestock and storage by forests and pastures over 20 years of age are taken into account, farms have a positive carbon balance. The deforestation levels of each farm over the past 20 years have a strong impact on this balance sheet, which can make it negative.

This study highlights the effectiveness of the method in identifying systems and practices that could help farms achieve greater sustainability in terms of energy use and GHG emissions.

KEYWORDS

environmental impact, efficiency, livestock production, livestock emissions, ecological intensification

Introduction

Livestock expansion in the Amazon, and GHG emissions

Between 2000 and 2021, global meat production increased by 53%, reaching 357 million tons in 2021, which included 73 million tons of beef (FAOSTAT, 2023). During this period, Brazil was the second leading producer in the world, boasting a cattle herd of nearly 239 million head, with about 43% of that held in the Legal Amazon (IBGE, 2023). Defined by Law No. 1,806 of 6 January 1953, the Legal Amazon comprises the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins, and part of Maranhão. Created for regional planning and development purposes, it includes biomes beyond the Amazon rainforest, such as parts of the Cerrado savanna and a small part of Pantanal wetland (Brasil, 1953), according to the map by Tyukavina et al. (2017).

Despite contributing only 9% to the national Gross Domestic Product (GDP), the Legal Amazon was responsible for approximately 52% of Brazil’s greenhouse gas (GHG) emissions in 2020 (IPS Amazônia, 2023). In 2023, the Land Use, Land Use Change and Forests (LULUCF) sector was responsible for the largest share of gross GHG emissions in Brazil, corresponding to 46% of the national total. In the same year, 98% of the emissions attributed to the LULUCF sector originated from deforestation, and 65% of this amount was specifically due to deforestation in the Amazon (Seeg, 2024).

The agricultural and livestock sector is the second largest emitter of GHG in Brazil, contributing approximately 28.5% of the nation’s total emissions, with 62% of this figure originating from enteric fermentation of the herd (MCTI, 2022). To reconcile animal production with environmental impacts, strong measures, such as support for research, incentives for efficient and regenerative management, and the adoption of innovative practices, must be adopted to facilitate reductions in GHG emissions from livestock (FAO, 2017) and fossil energy use. The relationship between livestock systems and environmental issues related to land use is complex and often analysed in a simplified way, which can compromise the understanding of their impacts on sustainability. Although livestock farms use extensive areas of land, their effect is not inherently negative; rather, it is contingent on factors such as the type of production system, herd and pasture management, underlying biome where grazing takes place, and the governance of grazed land (Manzano et al., 2024). In Brazil, with contrasting biomes such as rainforests with no strong evolutionary history of grazing, and savannas with sustained strong presence of wild megaherbivores until recently, such complexity is crucial to understand sustainability.

In Brazil, the ecological intensification of cattle farming is widely cited as a means to achieve sustainable agriculture and livestock production. By intensifying grazing production systems, it is possible to increase production without increasing land extension while also contributing to ecosystem services (Cardoso et al., 2020; Cardoso et al., 2017; Palermo et al., 2014). On the other hand, the intensification of production systems affects energy consumption on livestock farms, mainly due to increased inputs. To achieve sustainable livestock production, the environmental impacts of livestock systems, including those generated by the consumption of fossil energy, must be reduced. This can be accomplished by developing systems in which the energy outputs from animal production exceeds the energy inputs. Such an approach also has the potential to reduce GHG emissions (Pérez Neira et al., 2014).

According to Latawiec et al. (2014), the intensification of cattle farming in Brazil is described as “moderate,” mainly based on the exploitation of grazed resources. In this context, the intensification of systems comprises two sets of strategies: 1) the adoption of grazing practices designed to increase the production and quality of grazing (e.g., rotational grazing, fertilisation management); and 2) the use of feed and supplementation during the fattener phase. Adopting these practices can potentially contribute to greater weight gain, lower GHG emissions and lower energy consumption per kg of animal product. This also may contribute to increased animal stocking rates, decreased slaughter ages and better land use (de

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Abbreviations: ACCT, AgriClimate Change Tools; ELBF, Extensive-Large-Breeder-Fattener; ELF, Extensive-Large-Fattener; EMB, Extensive-Medium-Breeder; EMBF, Extensive-Medium-Breeder-Fattener; EMD, Extensive-Medium-Dairy; ES, Extensive farms; ESB, Extensive-Small-Breeder; ESD, Extensive-Small-Dairy; ESF, Extensive-Small-Fattener; ILBF, Intensive-Large-Breeder-Fattener; ILD, Intensive-Large-Dairy; ILF, Intensive-Large Fattener; IS, Intensive farms; ISD, Intensive-Small-Dairy; ISF, Intensive-Small-Fattener; MIS, Farms in moderate intensification; MLB, Moderate Intensification-Large-Breeder; MLB, Moderate Intensification-Small-Breeder; MLBF, Moderate Intensification-Large-Breeder-Fattener; MLF, Moderate Intensification-Small-Fattener; MMD, Moderate Intensification-Medium-Dairy; MMF, Moderate Intensification-Medium-Fattener.

Carvalho et al., 2023; Ruggieri et al., 2020; Rouquette Jr, 2016; Barbero et al., 2015; Gimenes et al., 2011).

In addition to traditional livestock systems, the adoption of integrated systems, such as silvopastoral systems (SPS), stand out as sustainable alternatives due to their potential to reconcile agricultural production and environmental conservation. These systems are capable of increasing livestock production, recovering the landscape and producing environmental/ecosystem services (Manzano et al., 2024; Mauricio et al., 2019). In the Amazon, the adoption of integrated systems, such as integrated crop-livestock systems (ICLS) and integrated crop-livestock-forest systems (ICLFS), has shown positive effects on the productivity, sustainability, and socioeconomic performance of livestock farms (Martorano et al., 2021).

To consider ways to maintain or increase agricultural production while simultaneously managing natural resources more effectively through the adoption of effective agricultural strategies, we decided to use the concept of eco-efficiency. Eco-efficiency can be defined as the efficiency with which a quantity of agricultural products is obtained from a set of natural resources (land, water, nutrients, energy, biological diversity) while minimising the production of negative environmental externalities, such as GHG emissions (Keating et al., 2013; Keating et al., 2010).

Livestock and deforestation: the colonization of land in the amazon

The Brazilian Amazon is a focal point in debates concerning livestock and the environment. It represents one of the largest biodiversity and forest biomasses in the world while also forming one of the largest reserves of land that is potentially convertible for agricultural use (Larrea-Alcázar et al., 2021; Lambin et al., 2013). The region is undergoing major transformations in its livestock system that are characterised by an agrarian transition where solutions are being developed in response to tensions between agricultural and ecological perspectives (Osis et al., 2019; Plassin, 2018).

The colonization of the Amazon rainforest beginning in the 1960s was closely linked to territorial occupation policies promoted by the government. These were based on opening roads and distributing land along pioneer fronts (Ianni, 1978). In addition to the public land settlement programs, a large-scale migration within the Amazon began (Vaz, 2013), causing a "struggle for land," where the opening of pastures was the main tool for land appropriation and valorisation (Schmink and Wood, 1992). This occupation led to the establishment of distinctive agrarian situations characterized by the predominance of extensive livestock management, significant deforestation, and minimal use of inputs and labour. Farm trajectories followed a main trend of deforestation for pasture expansion, causing progressive soil degradation. Since the beginning of the 21st century, mechanized agriculture, linked to soybean production, has been expanding on degraded pasture lands, with two main consequences: (i) livestock intensification thanks to soil fertilization, mechanization, and crop-livestock integration, and (ii) land valorisation, which has led to an increase in new deforestation and pasture expansion (Osis et al., 2019; Poccard-Chapuis et al., 2020; Richards et al., 2014).

The region of Paragominas is typical of this trajectory, with successive "boom and bust" cycles since the 1960s, involving timber extraction, livestock, charcoal and soybean (Piketty et al., 2015). Due to uncontrolled deforestation, the municipality was representative of the blacklist created in 2008 by the federal government. Three years later, thanks to an innovative jurisdictional policy known as "green municipality," Paragominas was removed from the blacklist and become a regional model for sustainable development (Viana et al., 2016).

Concurrent with the zero deforestation policies, an adaptation phase has been put in place, aimed at facilitating a transition to more sustainable systems and enhancing ecosystem services (Pinillos Cifuentes et al., 2020). Intensifying production in areas that were already open, starting with optimising grazing use and investing in practices such as rotational grazing, fertilisation, and agriculture-livestock integration, is expanding (Poccard-Chapuis et al., 2015; Cerri et al., 2016; Aubron et al., 2022). Nevertheless, the role of the forest remains inadequately recognized (Pinillos et al., 2021).

Diverse livestock systems are currently present in the Amazon, ranging from intensive confinement fattening systems to extensive pasture grazing systems. Consequently, there are different dynamics in the GHG and energy emission balance sheets, and thus very different frameworks and solutions for sustainable production. Agricultural practices in each production system impact GHG emissions and energy consumption. Adopting resilient practices is therefore one approach to facilitate the agroecological transition. To adapt these practices to the different livestock farming scenarios, it is first necessary to know these production systems.

Understanding emissions from livestock farming systems and their sources, and obtaining accurate national estimates, are crucial for informing a discussion on the scientific and policy priorities of the region (Moran and Wall, 2011). Similarly, to achieve energy efficient systems, it is necessary to first quantify and analyze the energy consumption and production of the different systems (Pérez Neira et al., 2014). However, there is little data on GHG intensity and energy balances in Brazil, especially in terms of data collected directly from producers, and data from the Amazon region are even rarer (Bogaerts et al., 2017; Clerc et al., 2012).

Among the tools used for the global assessment of the environmental impact related to livestock farming is life-cycle

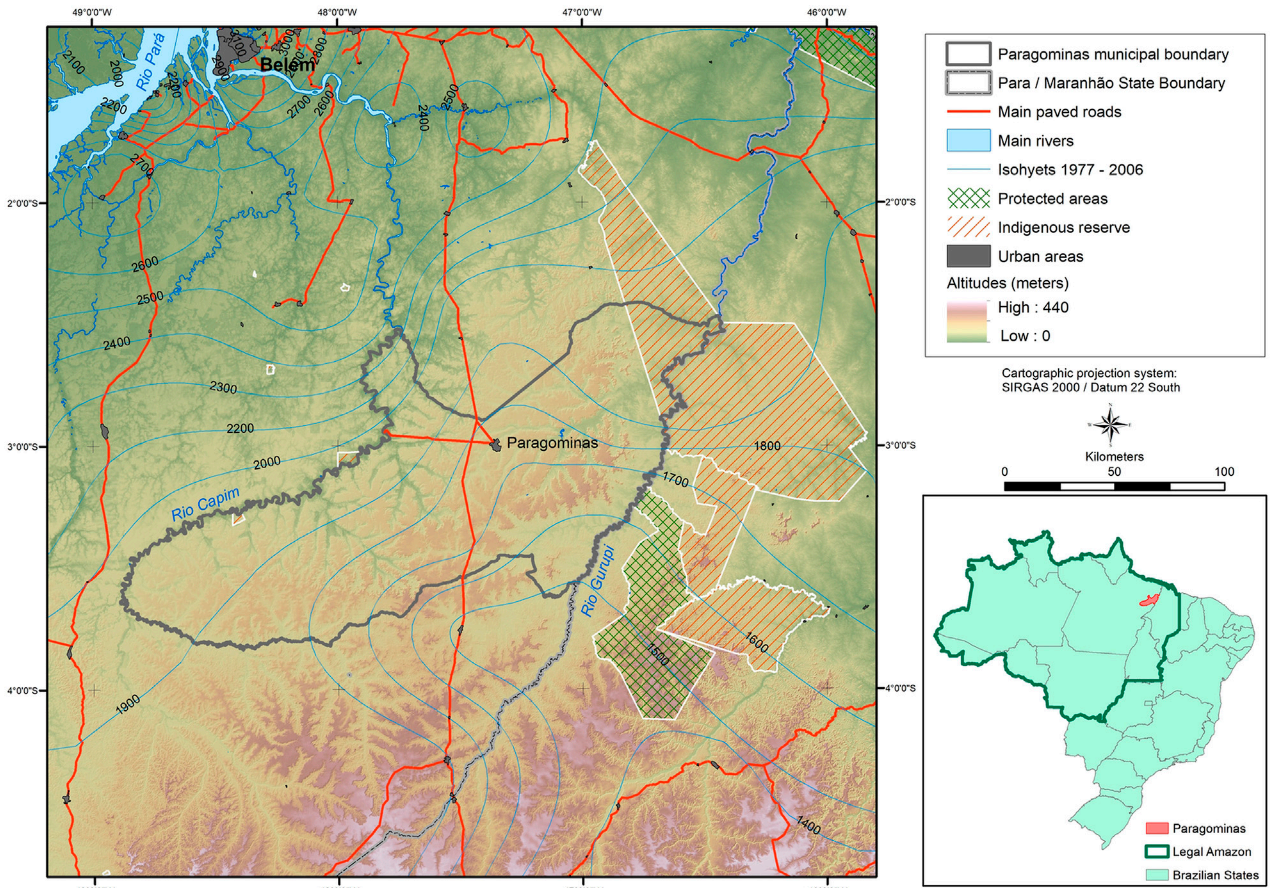

FIGURE 1
Location of the municipality of Paragominas in the Amazonian biome.

analysis - LCA (Scoones, 2023). This article conducted evaluations in accordance with the principles of LCA. It contributes to the production of information by profiling both the production and consumption of energy and GHG production in actual rural properties of the Amazon region, based on field data.

In this paper, we seek to understand how farm practices and the intensification of cattle farming systems impact the eco-efficiency of farms in terms of energy consumption and production and GHG emissions. This study aims to produce information on the GHG emissions and energy balance of 33 livestock farms with different intensification levels in the Amazon biome. The ultimate objective is to identify the most eco-efficient systems, in line with the practices adopted. Our work also aims to help enrich information regarding emissions and consumption associated with livestock activities under real conditions over an agricultural year, with a focus on farms in the Amazon biome where very few such studies have been conducted.

Materials and methods

Study area

The study was conducted in the municipality of Paragominas, located in the state of Pará in the northeastern region of the Brazilian Amazon (Figure 1). The climate in Paragominas is characterized as tropical, humid, and dry with a constant high temperature (26.6°C) and high humidity (on average 80%) (Pinto et al., 2009). Annual precipitation is high (2,000 mm per year between 2000 and 2014 in Paragominas) (Tropical Rainfall Measuring Mission - TRMM). This precipitation is unevenly distributed over the year, with a dry season between July and December during which only 14% of the annual precipitation is received.

The municipality has diverse agrarian situations, which correspond to pioneer fronts, slash-and-burn agriculture, extensive consolidated family farming on the periphery, specialised family farming, extensive livestock farming on the periphery, zero deforestation, and intensification corridor

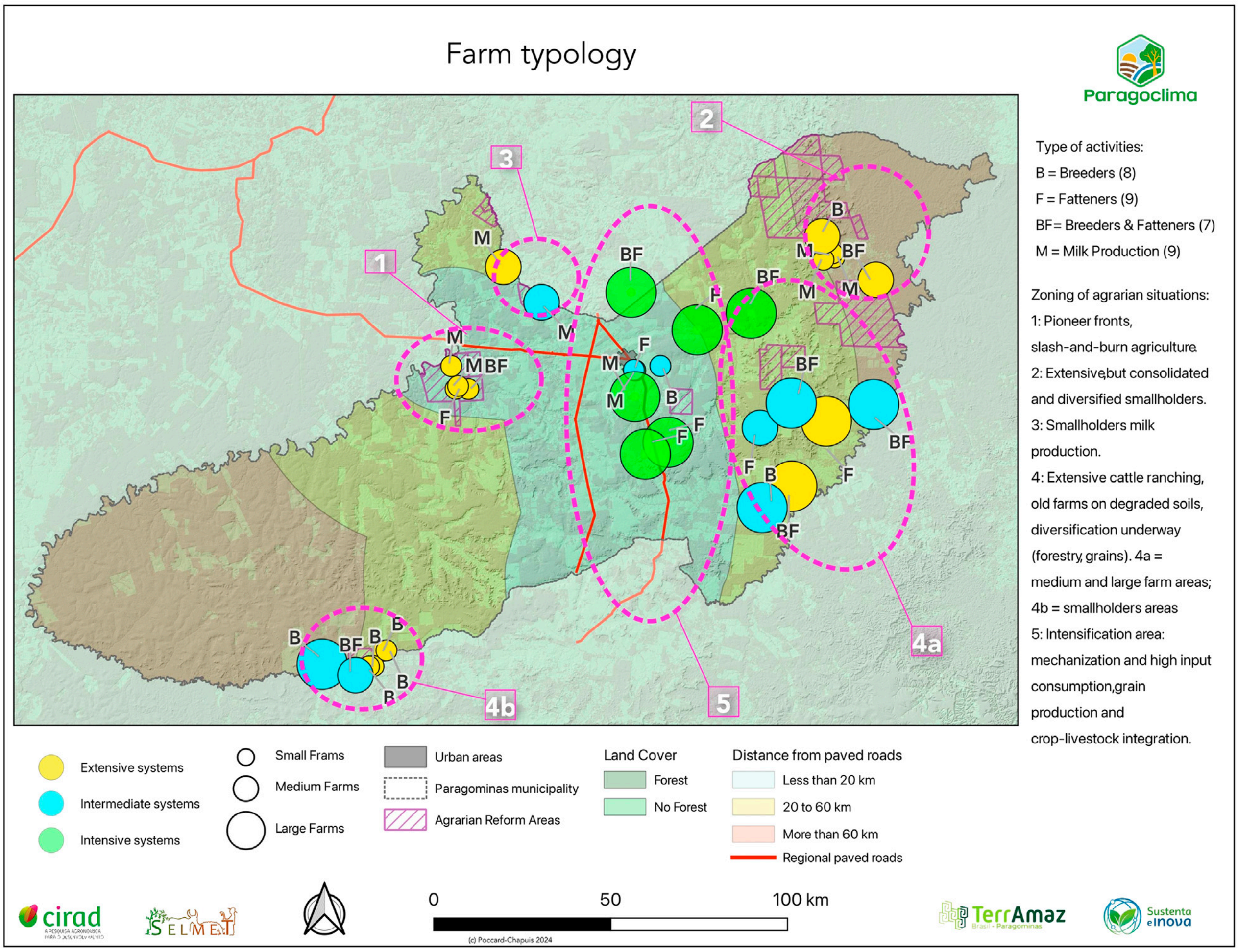

FIGURE 2
Different cattle farming systems studied in Paragominas, categorized according to their degree of intensification, production orientation and agrarian situation.

(Plassin, 2018). It also is developing livestock systems with different production orientations (milk, breeder, breeder-fattener, fattener) and intensification levels characteristic of the region (animal stocking rate, use of fertilisers and pesticides, pasture management, concentrate supplementation, etc.) (Figure 2).

On both large and small farms, the livestock systems in Paragominas can be characterized as livestock grazing ranches, with land properties delimited by fences and under individual private governance. Internally, these farms are divided into various plots of cultivated pastures, allowing the mobility of animals within the property. The ownership and management of herds are individual rather than collective. In some cases, mobility occurs between farms with different productive functions, such as units specialized in breeding, rearing or fattening. In rare cases, pasture management systems assume characteristics similar to pastoralism: low intensity of management over large areas can reflect pastoral practices, but in the context of private land and property.

In areas with extensive management, the use of fire for the renewal of pastures still persists; however, this technique has been progressively abandoned due to negative impacts on the soil, fire risks and reduced economic profitability, which has contributed to the decline of these systems in the region.

Assessment of the energy balance and greenhouse gas emissions at the cattle farm level

AgriClimate change tools - ACCT

AgriClimate Change Tools (ACCT), an on-farm tool based on the Planète (Solagro, 2002) and Dia'terre (Ademe, 2011) methods, which refer to international standards (AgriClimate

TABLE 1 Equations for energy yield and energy efficiency and GHG emissions.

Equation	Indicator	Equation
Equation 1	Energy Yield (GJ/GJ)	$\frac{\text{GJ of farm products}}{\text{GJ consumed for production}}$
Equation 2	Energy Efficiency (GJ/t produced)	$\frac{\text{GJ consumed for production}}{\text{ton of product (beef or milk)}}$
Equation 3	EL Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions (teqCO2)}}{\text{ton of product (beef or milk)}}$
Equation 4	ENL Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions+Storage de C (teqCO2)}}{\text{ton of product (beef or milk)}}$
Equation 5	ENT Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions+Storage de C+emissions from deforestation (teqCO2)}}{\text{ton of product (beef or milk)}}$

C storage = considered C storage of pastures over 20 years old, primary and secondary forests (aerial and underground), and practices that store C. Emissions from deforestation = from the last 20 years.

Change Project, 2013), was chosen from among the many tools used to calculate GHG emissions and energy balances. ACCT was in line with the needs of our study, in particular because of its global approach at the farm level and the distribution of energy and GHG consumption by agricultural activity. The main reason for our choice was that the tool, thanks to its design in Microsoft Excel, was modifiable and therefore adaptable (unlike a closed proprietary application), which was essential in a job like ours, determined by local conditions.

Indeed, the realisation of a balance sheet adapted to Amazonian farms relies in particular on an appropriate representation of the forest sector in the balance sheets (emissions due to deforestation and carbon storage in the aerial biomass). The tool also allowed the use of energy and GHG coefficients specific to the areas studied. Our work has thus led to a gradual improvement of ACCT for the Amazon region in certain areas of the territory.

Energy consumption

ACCT assesses the consumption of non-renewable energy, both direct (fuel, gas, electricity, etc.) and indirect (inputs, purchased feed, materials, buildings), across all farm activities during a crop year using the life-cycle analysis principle. Similarly, agricultural products (meat, milk, crops, etc…) are converted into energy. Material and energy inputs and outputs are inventoried and translated into energy flows by assigning coefficients from the literature that are considered robust. The energy results are expressed in primary energy (Gigajoule, GJ), thus making it possible to define all the energy flows of the holding (Agriadapt, 2013; ADEME, 2011). The tool provides two indicators at the year level: i) energy yield (Equation 1), which is defined as the ratio of GJs of farm products per GJ consumed for production, where high efficiencies are favourable; and energy efficiency (Equation 2), the ratio of GJs consumed for production per ton of product, where high efficiencies are unfavourable (Table 1).

GHG emissions and changes in carbon stocks (C)

The sources of gross GHG emissions considered in ACCT are related to the i) direct (fuel, gas…) and indirect use of energy (input manufacturing), ii) animal production (enteric fermentation and manure), and iii) soil.

ACCT provides an estimate of the annual change in on-farm carbon stocks induced by land use changes, including emissions from deforestation. The tool also takes into account favourable practices for C storage, including forest infrastructure using IPCC Tier 2, and emissions avoided by renewable energy production (Agriadapt, 2013; ADEME, 2011).

The result of the calculations provides the gross emissions per hectare indicator (teqCO_2/ha UAA/year), representing the ratio of gross emissions ($eqCO_2$) to hectares of utilised agricultural area (ha UAA). Efficiency values for GHG emissions (t $eqCO_2$/t produced/year) vary depending on the frame of reference used. Three efficiencies representing three scales of analysis were considered: (i) efficiency of livestock emissions - EL efficiency (Equation 3), (ii) efficiency of net livestock emissions - ENL efficiency (Equation 4), and (iii) efficiency of total net emissions - ENT efficiency (Equation 5) (Table 1).

Using the ACCT results of energy consumption and GHG emissions, it was possible to create farm groups based on their eco-efficiency performance, which in our work is measured by two indicators: energy efficiency and efficiency of livestock emissions.

Each efficiency is divided into low, medium, and high efficiency categories. This division was carried out using a graphical representation of the farms where it was possible to visually define the three categories.

Although the categorisation by sample mean is simple, we consider this method to be the most effective way to divide the categories. The reason is that there are no default efficiency values to make this classification, since performance is variable for each region and type of production, and depends on the intrinsic characteristics of the sampled universe.

To enhance the readability of the results, we refer to the farms by code, which represent respectively the degree of intensification (E - Extensive, M - Moderate Intensification, I - Intensive; categories defined at the beginning of the results), the size (S - small, M - medium, L - large) and the type of production

(D - dairy, B - breeder producer, BF – Breeder- Fattener producer, F - Fattener producer), and a figure which corresponds to the number of the farm.

Adapting to the Amazonian context

ACCT was developed in 2013 by the Solagro Association as part of the "Life+ AgriClimateChange" program for use in Europe, it was then adapted to overseas conditions in tropical zones (Martinique, Guadeloupe and Réunion) (Solagro, 2013).

In 2015, the adaptation focused on the specificities of French Guiana farms in an Amazonian context, including GHGs related to deforestation and soil C storage (Dallaporta et al., 2020; Dallaporta et al., 2016). The tool was then transposed into the context of the Brazilian Amazon (Lenoir, 2022; Moniot, 2021), using the Anerpaan tool (Clerc et al., 2012), which was already adapted to the Brazilian Amazon context.

The main changes concerned parameter values. They are detailed and substantiated in Supplementary Material S1.

Data collection

Sampling strategy

Thirty-three rural properties were selected in Paragominas - Pará - Brazil, for the years 2021 and 2022. The sample represented the diversity of agrarian situations in the municipality according to Plassin (2018), as well as the different production orientations and intensification levels.

Databases mobilised

Farm information was extracted from two databases. For primary and secondary forest cover and pasture and crop area, we used data from the Mapbiomas.org 4.1 collection (Mapbiomas, 2024), which is a platform that includes land use maps and informs land use changes. For deforestation, we used data from the Instituto Nacional de Pesquisas Espaciais - INPE (INPE, 2024), and the PRODES Project, which monitors satellite deforestation in the Legal Amazon; this allows us to compare the information obtained during interviews with that of official databases.

Where producers did not directly provide the necessary data or where the reported values were very divergent, we used standard values based on the literature and the available municipal database. The main elements reworked were the amount of salt, electricity consumption, fuel consumption for pasture reform and maintenance, the amount of seeds used for pasture, the amount of herbicides used on the holding and the areas in forest and pasture that were used from the official database of the Cadastro Ambiental Rural – CAR of farms, rather than declarative data (Supplementary Material S2).

Investigations

Data collection took place in three stages. The first was a semi-directional interview with the producer to learn about livestock systems and identify technical routes, inputs and farm products. In a second step, data from the Mapbiomas and INPE databases were inserted. Finally, in case of inconsistencies between the reported data and the official databases, a return to the producer made it possible to compare the two data sources, with the aim of understanding, modifying or explaining the observed variations.

Data analysis

After ensuring data consistency, we applied simple descriptive statistics. Eco-efficiency groups that take into account energy efficiency and gross GHG emissions were identified. Non-parametric statistics [Kruskal-Wallis, Mann-Whitney U test (or Dunn test)] were used to better identify the variables discriminating these groups.

Results

Farming systems evaluated

The farming systems observed differ in their degree of intensification, production (dairy and meat, dairy, breeder, breeder-fattener, fattener) and agrarian situation (1 - pioneer front, slash-and-burn agriculture; 2 - extensive but consolidated and diversified family farming; 3 - specialised family farming; 4 - extensive farming, old-growth farms on degraded land, diversification in progress; and 5 - intensification corridor).

Systems according to degree of intensification

Extensive farms (ES) are characterized by the exclusive use of grazing. They have monoculture grazing areas, with few plot divisions, do not engage in fertilising or liming, and do manual weed management (mowing or herbicides). In general, they have few inputs and reduced infrastructure and labour, and their production capacity is maintained through the exploitation of the abundant natural resources available.

Moderately intensified farms (MIS) have adopted relatively simple practices to improve the productivity of land and labour, increasing inputs, dividing grasslands into plots, regularly provide fertilisers and liming, and investing in mechanisation and animal supplementation.

Intensive farms (IS) are characterised by large infrastructure, high investment in inputs, mechanisation, and rotational grazing with annual fertilisation and liming, leading to a high animal stocking rate and the adoption of integrated agriculture-livestock systems or even feedlots.

TABLE 2 Characteristics of the extensive (ES), moderate intensification (MIS) and intensive (IS) cattle farming systems studied in Paragominas.

Features	Degree of intensification			
		ES (16)	MIS (9)	IS (8)
Total area (ha)	S	64 (11)	94 (2)	34 (2)
	M	363 (3)	857 (3)	-
	L	12,887 (2)	3,872 (4)	4,174 (6)
Utilised Agricultural Area UAA (ha)	S	55 (11)	93 (2)	34 (2)
	M	206 (3)	253 (3)	-
	L	5,005 (2)	1,668 (4)	1784 (6)
Herd (heads)	S	53 (11)	125 (2)	110 (2)
	M	278 (3)	289(3)	-
	L	3,194 (2)	1,432 (4)	5,912 (6)
Meat production (kg/ha UAA)	B	80 (5)	150 (3)	-
	BF	120 (2)	100 (2)	1,170(2)
	S	240 (3)	430 (2)	1,590 (4)
Meat production (kg/head)	B	59 (5)	111 (3)	-
	BF	117 (2)	129 (2)	175 (2)
	S	222 (3)	300 (2)	321 (4)
Milk production (L/cow/day)		5.7 (5)	6.0 (1)	9.0 (2)
Milk production (L/ha UAA)		492 (5)	327 (1)	2087 (2)
Meat Animal density (AU/ha)		0.8 (10)	0.9 (8)	3.4 (6)
Milk animal density (AU/ha)		1.0 (6)	0.5 (1)	1.5 (2)
Forest area (%)		2.5 (16)	41 (9)	32 (8)
Deforested area[a] (%)		38 (16)	7 (9)	7 (8)
Type of grazing	Alternate or rotational		Rotational	Rotational CLI
Fertilisers and liming	No		Little	Yearly
Weed control	Manual Mowing and herbicides		Manual Herbicides	Mechanised Mowing and herbicides
Supplementation	No		Finishing	Yes

[a] Surface deforested in the last 20 years. ES, extensive system; MIS, moderate intensification system; IS, intensive system; UAA = useful agricultural area; AU, animal unit (450 kg LW), S, small; M, medium; L, large; B, breeder; BF, breeder-fattener; F, fattener; CLI, crop-livestock integration. In brackets number of farms assessed.

Of the 33 farms, only two have crops (maize and sorghum) for animals. Farms are divided into small (S), medium (M) and large (L) areas or herds; and separated by type of production: dairy (D), breeder (B), breeder-fattener (BF) and fattener (F) for animal production (Table 2).

Two farms had been established for less than 2 years, and while they had invested in purchasing animals, they had not yet achieved significant sales. As a result, they were eliminated in the assessment of production and energy and GHG emissions balances and treated separately to illustrate early-stage operations.

On beef cattle farms, the production of meat in kilograms per hectare and kilograms per head varies according to the fattening method used. On dairy farms, the production per cow is similar in ES and MIS, and appears lower for MIS in litres per hectare, but this is based only on a single value. In IS, milk production per cow and per hectare is much higher than in the other two systems, linked to fertilisation of grassland and the provision of complementary feed.

TABLE 3 Energy consumption and greenhouse gas emissions from the extensive beef and dairy (ES), moderate intensification (MIS) and intensive (IS) cattle farming systems in Paragominas.

Energy consumption	**Beef farming systems**					**Dairy farming systems**				
	Degree of intensification			**SEM**	***p*-Value**	**Degree of intensification**			**SEM**	***p*-Value**
	ES *(10)*	**MIS *(7)***	**IS *(6)***			**ES *(5)***	**MIS *(1)***	**IS *(2)***		
Consumption range (GJ/t prod)	0.83–37.92	2.27–39.60	17.40–43.01			0.17–2.25	4.89	6.42–6.48		
Average consumption (GJ/t prod)	12.15	12.58	27.52	3.02	<0.10	0.82	4.89	6.45	0.98	<0.05
Average consumption (GJ/ha UAA)	2.52	3.3	35.2	3.82	<0.05	0.55	1.60	13.47	2.10	<0.05
Fuel (GJ/t lw)	1.03	0.96	1.26	0.20	NS	0.44	0.96	1.14	0.20	NS
Electricity (GJ/t lw)	0.04	0.20	0.65	0.14	NS	0.00	0.00	1.99	0.33	<0.05
Food (GJ/t lw)	0.00	0.93	1.74	0.31	<0.10	0.00	0.00	1.10	0.28	NS
Fertilisation (GJ/t lw)	0.14	1.11	5.57	0.61	<0.05	0.00	1.29	1.31	0.24	<0.05
Phytosanitary (GJ/t lw)	0.26	0.18	0.28	0.10	NS	0.06	1.46	0.05	0.18	<0.05
Purchase of animals (GJ/t lw)	9.72	8.59	17.59	2.78	NS	0.03	0.65	0.00	0.08	<0.05
Other (GJ/t lw)	0.71	0.61	0.43	0.02	<0.05	0.29	0.54	0.87	0.09	<0.05
GHG emission positions without lucf sector										
GHG emissions (tCO_2/year)	1,536	2070	14,250			251	322	930		
Emission range (tCO_2/t prod)	5.07–40.85	17.97–21.02	6.66–15.24			2.84–7.70	4.90	2.59–2.60		
GHG emissions (tCO_2/t prod)	23.18	15.17	10.32	2.33	<0.10	6.05	4.90	2.60	0.74	NS
GHG emissions (tCO_2/ha UAA)	2.08	2.52	14.94	1.77	<0.05	3.15	1.60	5.42	0.62	NS
% CO_2	1%	4%	9%		<0.05	1%	5%	25%		NS
% CH_4	89%	87%	76%		<0.05	75%	58%	64%		NS
% N_2W	10%	9%	15%		<0.05	24%	37%	11%		NS
GHG emission positions with lucf sector										
Emission range (tCO_2/t prod)	10.47–527.46	7.71–149.70	9.23–77.13			21.33–98.94	10.40	2.59–30.31		
GHG emissions (tCO_2/t prod)	160.95	51.26	35.13	27.23	<0.10	57.21	10.40	16.45	11.36	NS
GHG emissions (tCO_2/ha UAA)	14.09	5.55	39.71	5.17	<0.05	28.64	3.40	32.35	7.16	NS
% CO_2	0%	4%	5%		<0.05	0%	2%	21%		NS
% CH_4	31%	61%	36%		0.102	9%	27%	28%		NS
% N_2W	3%	6%	9%		<0.10	3%	18%	5%		<0.05
%Deforestation	66%	29%	51%		0.107	88%	53%	46%		NS

SEM, standard error of the mean; LUCF, land use change and forest; UAA = useful agricultural area, prod = product. In brackets number of farms assessed.

For dairy, the results only concern nine farms with just one MIS, which does not represent the reality of the municipality. The sample comprises six small farms (approximately 69 ha UAA and 19 dairy cows); two medium-sized farms (approximately 173 ha UAA and 40 dairy cows) and one large farm of 300 ha UAA and 177 dairy cows. These farms also have meat production (male calves and cull cows), the meat production is respectively 49, 122 and 128 kg ha of UAA for the small, medium and large farms.

As regards the degree of intensification, the average meat production of dairy farms is 49.2, 33.0 and 208.5 kg ha of UAA respectively for the extensive, moderate intensification (one farm) and intensive systems.

Systems according to production orientation

The economic activity of beef cattle farming can be breeder, breeder-fattener and fattener. In Paragominas, herds are composed mainly of the Zebus types of the Nelore and sometimes Sindi breed, and less frequently of the bullfighting types Angus, and Aberdeen. Eight, seven and nine breeder producers with ES, MIS and IS intensification levels were studied.

On breeder farms (B), the herd consists primarily of mothers for breeding (which will be sold as culled cows) and calves intended for sale. On breeder-fattener farms (BF), the herd consists of mothers and male calves for fattening. On fattener farms (F), grazer animals are purchased for finishing, mainly males, fattened with grass or in confinement or semi-confinement systems. On dairy production farms (D) that also produce meat, the main income comes from milk, which can be marketed *in natura* or processed into cheese. The herd is much smaller than in the B, BF and F, and consists mainly of cows and heifers crossed between the Zebu (Nelore and Gir) and Taurine (Dutch) breeds.

Systems according to agrarian situation

The five agrarian situations encountered are (Figure 1):

1) Pioneer front, slash-and-burn agriculture (Colônia Oriente) characterised by a recent colonisation (2000), with productive but fragile pastures and an intensification process with slash-and-burn and diversification (e.g., pepper), its land structure comes from an unregulated occupation;
2) Consolidated extensive family farming (assentamento Luiz Inácio e Colônia três lagoas) - recent colonisation (1999) with low-productive pasture and intensification process with slash-and-burn agriculture and diversification (dairy). The family farms are generally under 500 ha in size. Decisions are taken by the heads of holdings; salaried labour is in the minority and is not generally involved in decision-making;
(3) Family agriculture specialised in milk (assentamento Mandacaru) - recent colonisation (1999) with low-productive pasture (overgrazing, fire), subsistence, mechanisation and milk;
4) Extensive livestock farming on the periphery (zero deforestation) - colonisation between 1970–1980 with low-productive pasture (overgrazing, fire) and input-efficient intensification, diversification (forest plantations, grains). The land structure is a type of patronage agriculture (in this situation we also found an area of Assentamento, called Assentamento Águia, which we described as situation 4a). In this type of operation, the owners usually employ a manager and several farm workers. Strategic, tactical and operational decisions vary between the operations manager, manager and workshop managers depending on the size of the operation;
5) Intensification corridor - colonisation from 1960 onwards with productive pasture and intensification with high levels of inputs; the land structure is characterized by patronage agriculture (Figure 1).

Energy balance and greenhouse gas emissions

Energy consumption

Beef cattle farms

The energy consumption in gigajoule (GJ) per ton of live weight produced (t of LW) is not discriminating between degrees of intensification ($p = 0.081$), only an upward trend is observed in the intensive system. Energy consumption per hectare of UAA is similar in the extensive (ES) and moderate intensification (MIS) farm types (Table 3). However, meat production per hectare on MIS farms is 55% higher than ES farms (Table 1), showing that the MIS system produces more with the same amount of energy.

For ES and MIS farms, the main sources of energy consumption are the purchase of animals and fuel. For intensified systems (IS), these include buying animals and fertilisation. Fertilisation ($p < 0.05$) and feeding ($p < 0.10$) increase or tend to increase with intensification (adoption of practices such as grazing management and animal supplementation), while other purchases decrease with intensification ($p < 0.05$).

For IS farms, energy consumption per hectare is 14 and 11 times higher, respectively, than in ES and MIS farms (higher input use for production) (Table 3). Meat production per hectare is 9 and 6 times higher in IS (1.38 t) than in ES (0.15 t) and MIS (0.23 t) farms, respectively. This performance can be attributed to the prevalence of most of the fattening farms within the intensive system (Table 2).

Dairy farms with associated beef

Dairy farms are characterised by relatively small UAA areas averaging 83 ha for ES farms, 201 ha for MIS farms and 179 ha for IS farms, and produce 492, 327 and 2087 L of milk/ha UAA, respectively. The animals are exclusively grass-fed, and there are no self-consumption crops for the herd (Table 2).

Energy consumption (GJ) per 1,000 L of milk (1000 L) and per hectare of UAA (ha UAA) increases significantly ($p < 0.05$) as the system intensifies (Table 4), although the single MIS farm does not follow this trend. Production per cow remains similar between ES and MIS farms, with production two times lower than IS farms. This difference is even more pronounced if milk production per hectare is expressed; IS produces 4 and 6 times more milk than ES and MIS (Table 2). The main sources of ES

TABLE 4 Energy efficiency, energy yield, consumption and energy production in meat and milk farming systems with extensive associated beef (ES), moderate intensification (MIS) and intensive (IS) systems in Paragominas.

Degree of intensification	Farm	Energy (GJ/ha AAU)		Energy yield (GJ output/GJ input)	Energy efficiency (GJ/ton produced)
		Entrance	Exit		
	Beef				
ES	ESB1	0.1	0.3	2.69	4.98
	ESB2	0.2	1.2	7.70	1.74
	ESB3	0.3	1.4	5.48	2.44
	ESB4	0.1	0.3	4.07	3.29
	ESF1	10.3	6.6	0.64	37.92
MIS	ESF2	7.5	5.1	0.68	35.65
	EMB	0.1	1.5	16.23	0.83
	EMBF	0.4	1.5	3.51	3.95
	ELBF	1.1	2.0	1.85	8.73
	ELF	5.2	4.3	0.83	21.88
	MLB	1.1	2.4	2.17	6.07
	MLF	9.7	5.9	0.61	39.61
	MMF	17.6	13.1	0.75	28.23
	MLB1	0.2	1.0	5.89	2.27
IS	MLB2	0.8	2.7	3.27	4.1
	MLBF1	0.4	1.4	3.66	3.77
	MLBF2	0.3	1.2	3.31	4.04
	ISF	56.2	77.2	1.37	17.4
	ILBF1	7.3	5.9	0.80	20.35
	ILBF2	54.3	41.7	0.77	27.57
	ILF1	28.4	23.7	0.83	27.59
ES	ILF2	52.7	41.1	0.78	29.23
	ILF3	12.1	6.3	0.52	43.01
	Dairy with associated beef				
	ESD1	0.1	2.4	26.41	0.17
	ESD2	0.3	2.7	8.36	0.48
	ESD3	0.8	1.5	1.85	2.24
MIS	ESD4	0.9	3.9	4.30	0.82
	EMD	0.3	4.2	16.77	0.41
	MMD	1.6	1.7	1.06	4.89
IS	ISD	14.3	8.0	0.56	6.42
	ILD	12.6	8.0	0.64	6.48

Abbreviations: ESB: Extensive-Small-Breeder; ESF: Extensive-Small-Fattener; ESD, Extensive-Small-Dairy; EMB: Extensive-Medium-Breeder; EMBF: Extensive-Medium-Breeder-Fattener; EMD: Extensive-Medium-Dairy; ELBF: Extensive-Large-Breeder-Fattener; ELF: Extensive-Large-Fattener; MLB: Moderate Intensification-Small-Breeder; MLF: Moderate Intensification-Small-Fattener; MMF: Moderate Intensification-Medium-Fattener; MMD: Moderate Intensification-Medium-Dairy; MLB: Moderate Intensification-Large-Breeder; MLBF: Moderate Intensification-Large-Breeder-Fattener; ISF: Intensive-Small-Fattener; ISD: Intensive-Small-Dairy; ILBF: Intensive-Large-Breeder-Fattener; ILF: Intensive-Large Fattener; ILD: Intensive-Large-Dairy.

consumption are fuel, other purchases and plant health, related to farm maintenance and grazing (brush cutters and herbicides). On MIS farms, the same items have higher consumption than on ES farms, plus fertilizers.

IS farms have milking machines, milk tanks and supplementation for cows, which raises their energy consumption ($p < 0.05$ compared to ES and MIS), in addition to the fuel and fertilisation dedicated to pasture management.

Greenhouse gas emissions

Beef cattle farms

ES and MIS farms have similar GHG emissions per hectare of UAA, while IS farms emit 7.0 and 5.9 times more ($p < 0.05$) respectively. However, expressed in tons of meat, IS emissions are 55% and 32% lower than ES and MIS, respectively. In the three systems assessed, methane accounts for the bulk of emissions (per ha and excluding deforestation), representing over 75% of GHG emissions (Table 3).

N_2O emissions come mainly from fertilizers, liming, NH_3 production and leaching on agricultural soils. CO_2 emissions increase as the system intensifies due to fuel use and animal transport. Emissions from the land-use change sector vary between 29% and 66% of GHG emissions and are related to deforestation over the past 20 years with significant differences between systems ($p < 0.05$).

Dairy farms with associated beef

Emissions per hectare of UAA and per 1,000 L of milk produced are not significantly different ($p > 0.05$). However, a downward trend is observed in the intensive system (19% and 57%). In dairy farms, excluding deforestation, CH_4 emissions are also the largest contributors, accounting for 58% and 75% of total emissions. The N_2O comes second in the ES and MIS. The intensive system accounts for the largest share of CO_2 emissions (21%). Deforestation accounts for 46%–88% of emissions, far higher than on beef cattle farms. This is because the dairy farms studied were established recently, and have a higher percentage of deforestation (Table 3).

Energy and GHG efficiencies of cattle systems

Energy efficiency

Beef cattle farms

Table 4 presents the energy yield and energy efficiency, energy consumption and production per hectare of agricultural area used (GJ/ha UAA) of the 23 farms.

Energy efficiency is 16.29 GJ/t LW. The farms are ordered by degree of intensification, 12 farms have low efficiency, i.e., they have high livestock production relative to their input consumption. These are farms with extensive and moderately intensifying systems, where production is orientated around breeding and breeding-fattening. Eight farms with varying degrees of intensification but which are mostly based on animal fattening have high efficiency, with little production compared to inputs.

Efficiency groups are identified as follows: high efficiency farms are highlighted in red, medium efficiency in grey, low efficiency in green, and energy yield above 1, thus characterising farms that produce more than they consume.

Beef cattle farms with low energy efficiency have energy yield values above 1.85 GJ/GJ, while farms with average energy efficiency have an energy yield between 0.80 and 1.37 GJ/GJ. Finally, farms with high energy efficiency have energy yields ranging from 0.52 GJ/GJ to 0.83 GJ/GJ. Levels of energy consumption and production vary considerably by type of production, with larger fluxes on fattener intensive farms and smaller fluxes on breeder extensive farms (Table 4).

ES and MIS breeder operators consume on average 0.2 GJ/ha UAA, mainly fuel. On breeder-fattener farms, there are large variations in energy consumption depending on the animals in confinement (ILBF1 and ILBF2 with 7.3 and 30.8 GJ/ha UAA, respectively) leading to the purchase of animals, feed and fertilisers. On the other farms, the average consumption is 0.6 GJ/ha UAA. Consumption on ES and MIS farms is similar among fatteners (16.7 GJ/ha UAA on average), while on SI farms the average is 37.4 GJ/ha UAA through the purchase of animals, feed and fertilisers.

Dairy farms with associated beef

The average energy efficiency is 2.74 GJ/1000 L. Extensive farms tend to have low efficiency while intensive farms (MIS and IS) tend to have high efficiency (Table 3). Farms with an energy efficiency of more than 4.3 GJ/GJ are those in the low efficiency category, unlike MIS and IS farms with an energy yield of less than 1.1 GJ/GJ.

MIS and IS farms, with high energy efficiency, consume an average of 5.7 GJ to produce 1,000 L of milk, while ES farms with low energy efficiency consume 0.5 GJ of energy to produce the same amount of milk.

Efficiency of GHG emissions

Beef cattle farms

More than 75% of livestock emissions are from enteric CH_4 and manure on pasture (Table 3). The GHG emission efficiency values for the three scales of analysis are presented in Tables 5, 6.

Table 5 presents the efficiencies of beef cattle farms and the indicators that influence these efficiencies. Efficiency groups are identified as follows: high efficiency operations are highlighted in red, medium efficiency in grey, low efficiency in green and negative efficiency in dark green. The three efficiency groups are defined based on the average efficiency (EE) at the farm level, which is 17.40 t $eqCO_2$/t LW. This metric is commonly used in

TABLE 5 Efficiency of emissions from livestock (EL Efficiency), efficiency of net emissions from livestock (ENL Efficiency) and efficiency of total net emissions (ENT Efficiency) from cattle extensive meat (ES), moderate intensification (MIS) and intensive (IS) systems in Paragominas.

Degree of intensification	Farm	EL Efficiency	ENL Efficiency	ENT Efficiency	Production Indicators				Carbon indicators		
		t $eqCO_2$/ t LW	t $eqCO_2$/ t LW	t $eqCO_2$/ t LW	Heads	Kg LW/ ha UAA	Kg/ head	AU/ ha	tCO_2/ ha/ year	tCO_2/ ha/ year	Area
ES	ESB1	39.42	-169.58	82.1	22	24.1	63.6	0.3	6.07	5.04	4a
	ESB2	34.59	-12.87	-0.23	70	88.6	61.3	1.2	1.12	4.22	4a
	ESB3	40.85	-6.26	11.28	50	106.6	51.6	1.4	1.87	5.04	4a
	ESB4	38.84	-52.44	436.21	23	65.5	56.1	1.0	32.49	6.08	4a
	ESF1	8.44	-6.22	116.65	35	272.6	250.0	0.8	33.49	7.48	1
	ESF2	7.30	12.91	140.72	75	210.7	196.7	0.9	26.93	2.01	1
	EMB	21.73	-26.81	258.39	233	112.1	106.6	0.8	31.98	5.45	2
	EMBF	18.98	-86.23	-21.74	252	108.2	107.3	0.7	6.97	11.47	4
	ELBF	16.60	-104.39	-102.97	2000	126.4	127.0	0.8	0.18	15.62	4
	ELF	5.07	-66.41	-61.00	4387	235.8	430.0	0.5	1.27	18.62	4
	Average	23.18	-51.83	85.94	715	135.1	145.0	0.8	14.24	8.10	
MIS	MLB	18.0	-1.58	0.30	176	179.3	112.2	1.2	0.34	3.51	5
	MLF	8.26	8,00	9.60	74	244.7	250.0	0.7	0.39	3.20	5
	MMF	6.13	-23.82	-22.23	70	622.2	350.0	0.7	0.99	24.34	4
	MLB1	18.70	-47.62	183.39	860	75.9	111.1	0.5	17.54	5.06	4a
	MLB2	18.86	-139.28	-134.43	1450	199.5	110.0	2.0	0.97	31.57	4
	MLBF1	21.02	-164.32	-163.15	2008	99.1	104.3	0.8	0.12	18.43	4
	MLBF2	15.24	-143.50	-132.93	1409	86.2	152.9	0.4	0.91	13.70	4
	Average	15.17	-73.16	-37.06	954	215.3	170.1	0.9	3.04	14.26	
IS	ISF	10.07	12.98	12.98	114	3230.0	255.0	9.3	0.00	2.23	5
	ILBF1	13.99	-15.78	47.36	5800	359.6	194.8	1.3	22.70	11.83	5
	ILBF2	15.24	9.34	52.44	3990	1969.3	155.1	6.3	84.88	25.22	4
	ILF1	6.66	6.98	42.32	8,000	1030.9	350.0	1.1	35.33	9.11	5
	ILF2	7.04	2.13	4.33	16,000	1802.4	340.2	2.1	3.96	26.05	5
	ILF3	8.91	-10.74	-4.59	1000	281.0	340.0	0.3	1.73	8.42	5
	Average	10.32	0.82	25.80	5817	1445.5	272.5	3.4	24.77	13.81	

Abbreviations: ESB: Extensive-Small-Breeder; ESF: Extensive-Small-Fattener; EMB: Extensive-Medium-Breeder; EMBF: Extensive-Medium-Breeder-Fattener; ELBF: Extensive-Large-Breeder-Fattener; ELF: Extensive-Large-Fattener; MLB: Moderate Intensification-Small-Breeder; MLF: Moderate Intensification-Small-Fattener; MMF: Moderate Intensification-Medium-Fattener; MLB: Moderate Intensification-Large-Breeder; MLBF: Moderate Intensification-Large-Breeder-Fattener; ISF: Intensive-Small-Fattener; ILBF: Intensive-Large-Breeder-Fattener; ILF: Intensive-Large Fattener; LW: live weight; UAA: useful agricultural area; AU : animal unit (450kg LW). L/d: litre/day.

most studies to provide context for the results in relation to previous research.

In terms of livestock efficiency - EL (the emission/ production ratio and live weight), low or high values are highly dependent on meat production per head. Of the 23 farms, only four have high efficiency, intensive system farms have the lowest efficiencies.

By including the carbon stock of farms, all farms are very efficient in terms of ENL, mainly due to the conservation of forest areas, which is mandatory in the Amazon region under Brazilian

TABLE 6 Efficiency of emissions from livestock (Efficiency EL), efficiency of net emissions from livestock (Efficiency ENL) and efficiency of total net emissions (Efficiency ENT) from dairy farming systems with extensive associated meat (ES), moderately intensified (MIS) and intensive (IS) systems in Paragominas.

					Production Indicators				Carbon indicators		
		EL Efficiency	ENL Efficiency	ENT Efficiency					Emissions deforestation	Storage Total	
Degree of intensification	Farms	t $eqCO_2$/ 1000L	t $eqCO_2$/ 1000L	t $eqCO_2$/ 1000L	Heads	L/ha AAU	L/d/ cow	AU/ha	t CO_2/ha/year	t CO_2/ha/ year	Area
ES	ESD1	7.70	-4.9	36.2	47	543.1	4.9	1.5	22.32	6.95	1
	ESD2	6.54	5.1	45.2	126	658.5	5.6	1.2	26.41	1.40	2
	ESD3	6.76	0.9	92.9	50	365.8	5.0	0.8	33.67	2.20	2
	ESD4	2.84	-1.5	17.0	60	263.9	8.0	0.3	4.88	1.16	1
	EMD	6.44	-17.9	46.0	350	628.4	5.0	2.4	40.23	15.34	4
	Average	6.05	-3.66	47.48	127	491.9	5.7	1.2	25.50	3.02	
MIS	MMD	4.90	-7.22	-1.7	140	326.9	6.0	0.5	1.80	4.33	3
	Average	4.90	-7.22	-1.7	140	326.9	6.0	0.5	1.80	4.33	
IS	ISD	2.59	1.0	1.0	105	2230.9	9.0	1.3	0.00	3.75	5
	ILD	2.60	-6.9	20.8	680	1944.0	9.0	1.7	53.86	18.60	5
	Average	2.60	-2.95	10.9	393	2087.5	9.0	1.5	26.93	4.04	

Abbreviations: ESD: Extensive-Small-Dairy; EMD: Extensive-Medium-Dairy; MMD: Moderate Intensification-Medium-Dairy; ISD: Intensive-Small-Dairy; ILD: Intensive-Large-Dairy; LW: live weight; UAA: useful agricultural area; AU : animal unit (450kg LW). L/d: litre/day.

law. Large farms have the largest C stock, giving the lowest ENL values. By combining forest carbon storage (air and underground) and pasture carbon storage (soil carbon), farms have mostly negative emissions, they are carbon sinks, excluding deforestation.

In terms of ENT efficiency, 39% of farms have high efficiencies, owing to the massive emissions from deforestation over the last 20 years. In order to clarify the results of the different efficiencies presented, Figure 3 presents the values of emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from beef cattle farms. All farms that have had emissions from deforestation greater than gross emissions from livestock have high ENT efficiency. The exception is the EMBF farm, where the total storage exceeds emissions from the deforested area.

Gross CO_2 emissions per hectare of UAA in the extensive and intensifying system are similar, close to 2.0 t CO_2/ha UAA; in the intensive system, this average rises to 14.9 tCO_2/ha UAA/ year (Table 3).

For ENT efficiency, including deforestation, ES and MIS farms have high emission values, related to their agrarian situation (1, 2 and 4a - Assentamento areas), while large farms with high deforestation emissions belong to areas 4 and 5.

Dairy farms with associated beef

The efficiencies in Table 6 follow the same colour principle as in Table 5. The mean EL efficiency of livestock emissions is 5.05 t eqCO_2/1000 L. On intensive system farms, EL efficiencies are lower in relation to the level of milk production. However, there is an extensive farm (ESD4) with low efficiency due to a high unit production (8 L milk per cow). This farm has the smallest animal feed with 0.3 AU/ha and the lowest production per hectare, which refers to the discourse on land use, the same applies to the MMD farm. For ENL efficiency, we see the same trend for beef cattle farms, with rather negative emissions and only one farm with average efficiency.

Figure 4 presents the values of emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from dairy farms with associated beef. In terms of ENT efficiency, farms are performing well, even though emissions from livestock exceed total carbon storage, as is the case for the ISD3 and ISD farms. The ESD2 farm has an average ENL efficiency due to its higher gross emission from livestock compared to the total carbon storage of the farm.

By measuring ENT efficiency, most farms now have high efficiency, owing to large emissions from deforestation, with both low-ENT farms not having deforested in the last 20 years.

Energy consumption and GHG emissions from start-up farms

Two start-up farms were studied. The first is a medium size farm in a moderate intensification system (MIS) with breeder-fattener production - MMBF. The second is a small farm in an extensive system (ES) orientated around dairy production - ESD.

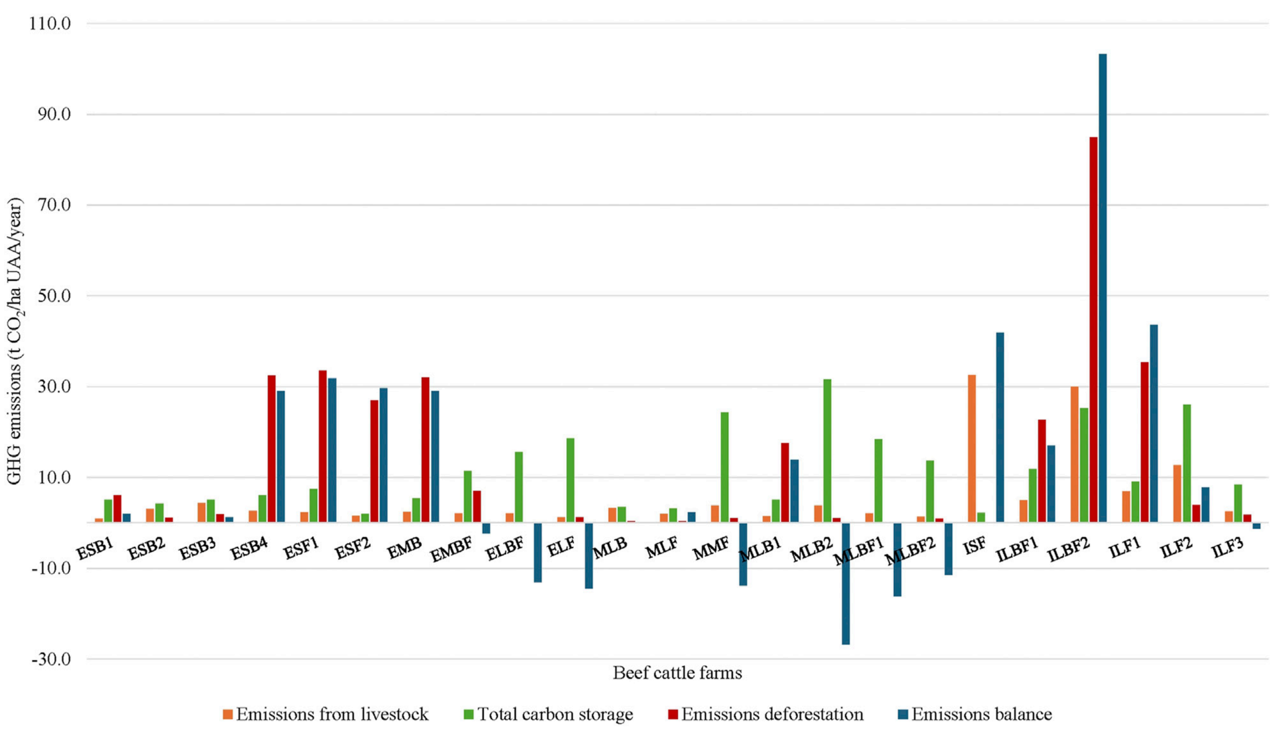

FIGURE 3
Emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from beef cattle farms.

Energy consumption

The MMBF farm has limited meat production of only 12 kg/ha UAA, which is low compared to the average of 227 kg/ha UAA seen in other moderate systems (Table 2). As a result, the energy consumption per ton produced reaches 84.82 GJ/t LW, which is well above the 12.58 GJ/t LW reported in Table 2 for the same system. Furthermore, the energy consumption per hectare is 1.0 GJ/ha UAA, compared to an average of 3.3 GJ/ha UAA for MIS meat farms. The main source of energy consumption of this farm was the use of plant protection products, agricultural fuel, fertilisers and limestone for the recovery of pastures, which were degraded when the producer arrived; investment in agricultural infrastructure and equipment also accounted for a large share of total consumption.

The ESD farm's initial investment in acquiring animals for herd formation yielded an energy input of 2.6 GJ/ha UAA, compared with an average of 0.55 GJ/ha UAA of the ES dairy farms. Low milk production of only 168 L/ha/year and 4 L/cow/day had an impact on consumption of 15.48 GJ/1000L, 19 times higher than the average for extensive farms (0.82 GJ/1000 L) (Table 3).

Greenhouse gas emissions

GHG emissions from the MMNE farm are 1.52 tCO_2/ha UAA and 127.89 tCO_2/t LW, which is extremely high compared to the average of 15.17 tCO_2/t LW of stable farms (Table 3). As with other farms, methane is the main gas accounting for 87% of emissions, and when land use, land-use change and forestry (LULUCF) emissions are considered, deforestation accounts for 89% of emissions.

Emissions from the ESD farm are 1.7 tCO_2/ha UAA and 6.99 tCO_2/t LW without taking into account the LULUCF sector; if the sector is taken into account, emissions related to deforestation now account for 96% of total emissions.

Eco-efficiency groups combining energy and GHG

Eco-efficiency groups based on the indicators of energy efficiency (GJ/t LW) and GHG emissions efficiency - Efficiency EL (t eq CO_2/t LW) were created, and were classified according to their performance. Two categories per indicator are proposed according to the average: beef cattle farms (16.29 GJ/t LW and 17.39 eqCO_2/t LW), and dairy farms with associated meat (2.74 GJ/1000L and 5.04 t eqCO_2/1000 L).

Four eco-efficiency zones were established: E-GHG+ group: low energy efficiency and high EL efficiency; E + GHG+ group: high energy efficiency and high EL efficiency; E-GHG-group: low energy efficiency and low EL efficiency; and E + GHG-group: high energy efficiency and low EL efficiency (Figures 5A,B).

The farms that belong to the E-GHG+ group are those that perform well in terms of energy. They operate with very few inputs

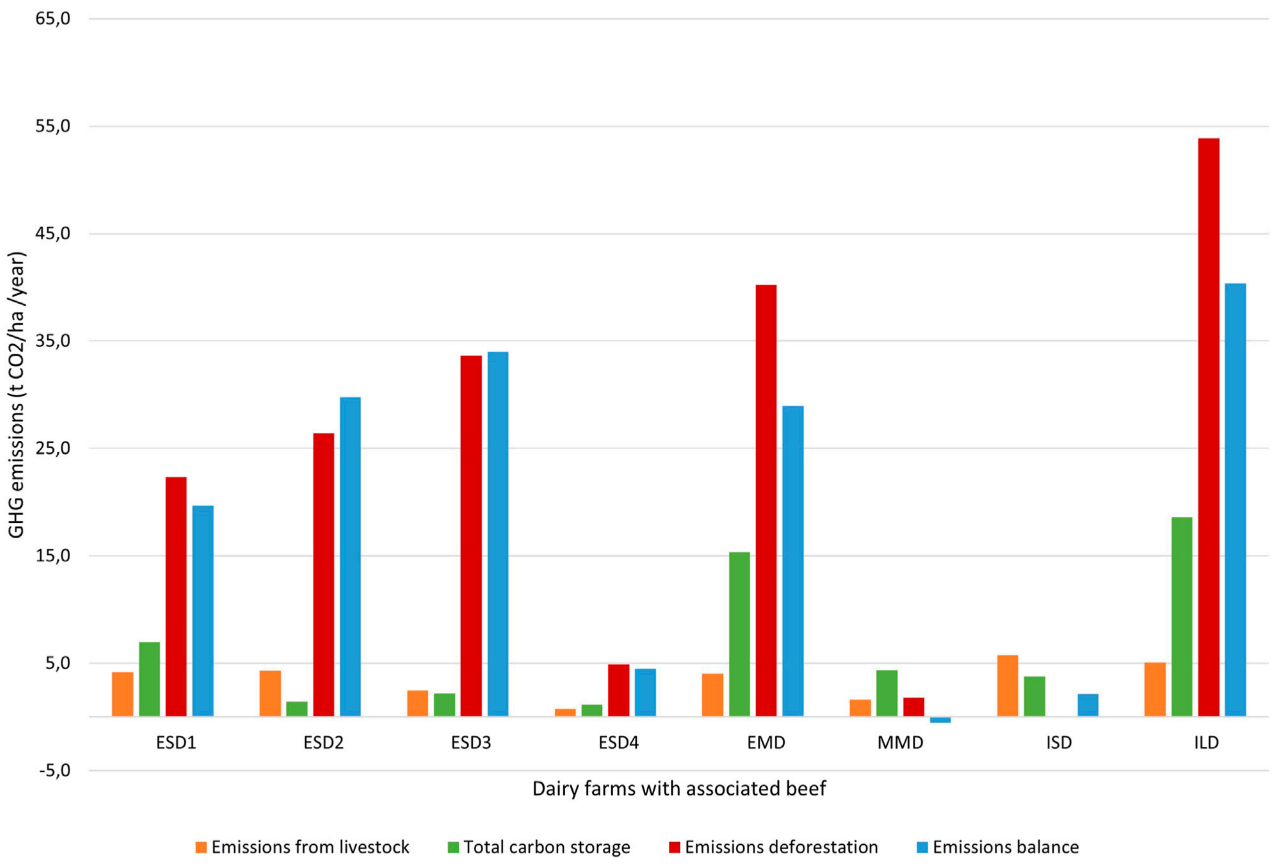

FIGURE 4
Emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from dairy farms with associated beef.

in an extensive system, producing meat or milk by taking advantage of the soil and climate resources that favour grass production, but which do not allow large production volumes, which increases the efficiency of livestock emissions. The farms more representative of the group are ESB1, ESB2, ESB3, ESB4, ESD1, ESD2 and EMD. None of the farms were representative of the E + GHG+ group.

In the E-GHG-group, which is ideally eco-efficient, there is only one ESD4 dairy farm, which is characterised by low input consumption and highly productive animals. The E + GHG-group includes intensive and moderately intensifying farms with high inputs not accompanied by an increase in production, are represented by the ILF1, ILF2, ILF3, MSF, MMF, ISD and ILD farms. In the meat system, the extensive farms ESF1 and ESF2 are also in this group.

Discussion

Energy balance

Energy consumption per hectare logically increases with the intensification of systems linked to a greater use of inputs. These intensive systems are based on the purchase of young animals and fattening them with purchased feed and/or fertilised pasture, all energy-consuming items. Sá et al. (2013) evaluated the energy balance of meat production in mixed or specialised agricultural systems for 20 years in the Cerrado, and obtained values of 20.38 GJ/ha in fertilised pastures and 62.59 GJ/ha in agriculture-livestock integration systems with direct seeding. Our meat intensive systems consume on average more (35.2 GJ/ha) than the specialised meat systems, while the ES and MIS systems consume much less (2.52 and 3.3 GJ/ha).

Analysing our 31.17 GJ/t LW fattener systems, they show similar energy efficiency as those of Vázquez (2020) in Mexico, who reported a value of 31.40 GJ/t LW in a study of three farms; and much lower than fattener farms in other tropical regions, such as Reunion (62 GJ/t LW) (Vayssières et al., 2011). For dairy farms, the same authors reported efficiency values of 7 GJ/1000 L compared to 2.74 GJ/1000 L in our study.

The IS farms tend to consume more energy per amount of output than MIS and ES farms. On dairy farms, fuel, fertilizers, and feed for cows are the main consumption items, and the low volume of milk production per cow makes for high efficiencies. In the dairy farms in our study, these are dual-ability mixed cows with low productivity, with an average production of 4.22 L/cow/

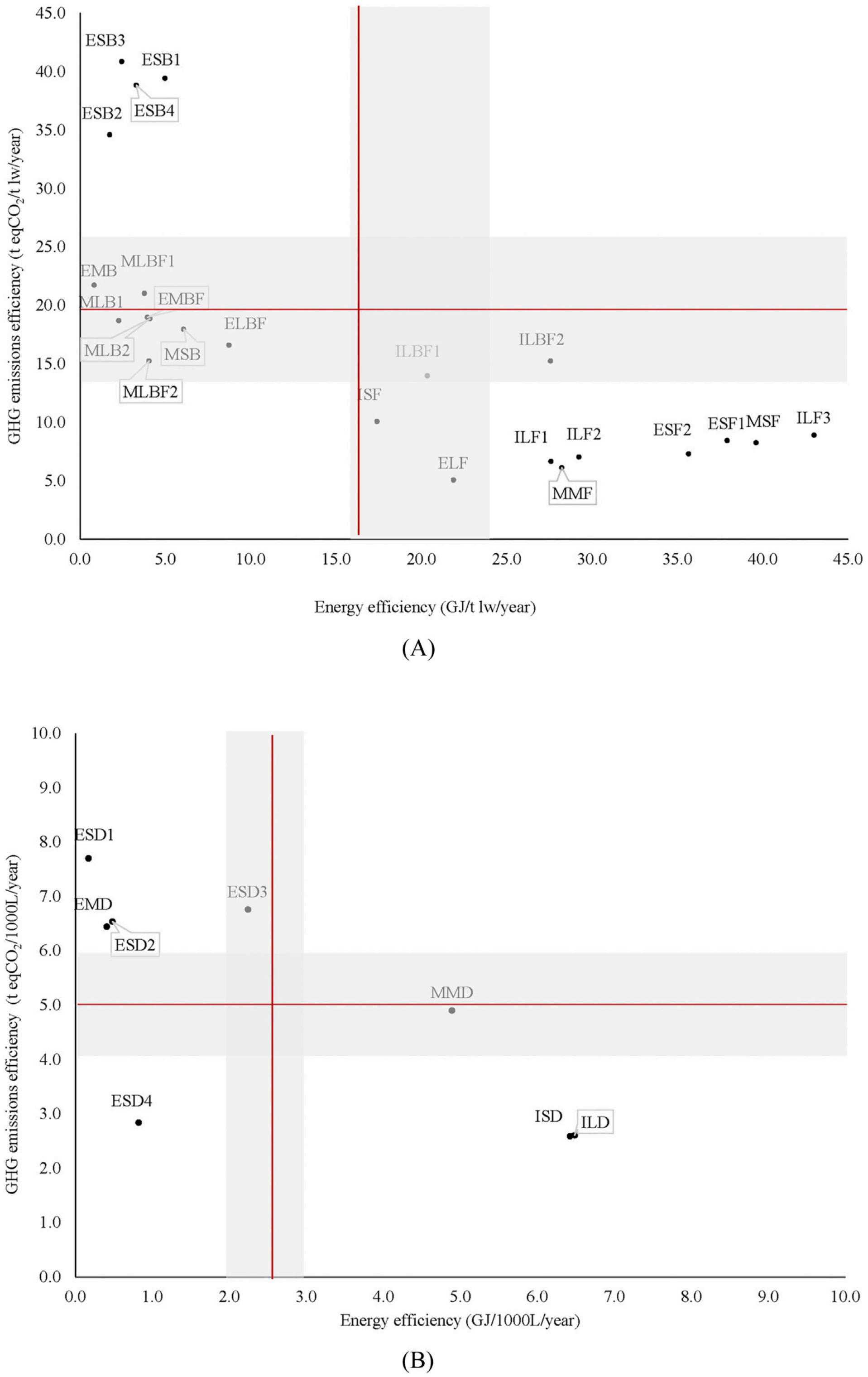

FIGURE 5
(A,B): Eco-efficiency groups based on indicators of energy efficiency (GJ/t LW or 1000 L) and GHG emissions efficiency (teq CO_2/t LW or 1000 L) from beef cattle and dairy farms with extensive (E), moderate intensification (M), and intensive (I) beef production systems in Paragominas. **(A)** Beef cattle farms. **(B)** Dairy farms with associated beef.

day. This is the reality in most properties in the municipality that do not have a well-consolidated milk production line (Rodrigues et al., 2020).

Extensive farms have the lowest efficiencies because they consume very few inputs, and even though they produce little, their outputs still exceed their inputs. These same farms have the highest energy yield values, i.e., they produce more energy than the total used, and can reach values above 16 GJ/GJ for animal meat and milk production systems (Table 4). Bonaudo et al. (2012), in a study carried out on six farms in Paragominas, report that the average energy yield of breeder, fattener and fattener-breeder farms was 3.48, 2.69 and 0.99 GJ/GJ. These yields were not related to the intensity of the system, but rather to the animal and plant production efficiencies. In our study, we found energy yield values of 5.94, 0.78 and 2.32 GJ/GJ for the same types of farming systems respectively, with higher values observed on ES farms.

In the search for more efficient livestock systems, the low energy efficiency observed in extensive systems represents a significant limitation. This low efficiency is associated with a reduced use of inputs, which, in turn, results in low levels of productivity in meat and milk production. Thus on one hand, extensive livestock farming preserves biodiversity but has low productivity. On the other hand, intensive livestock farming increases production at the cost of using chemical inputs that can harm ecosystems. In this context, moderate intensification has the potential to strike a balance between productivity and environmental conservation (Abramovay et al., 2025).

For MIS beef cattle farms, the energy yield and efficiency values are rather good and appear similar to those of the ES farms, but animal production per head is higher and can double, as for the breeder system. According to Manzano et al. (2024), it is essential to identify a balance between reducing dependence on fossil energy and maintaining adequate production levels to enable systems that are sustainable from both an environmental and economic point of view.

The moderate intensification of livestock farming is the main strategy for reconciling increased productivity with a reduction of socio-environmental impacts in Latin America (Poccard-Chapuis et al., 2015). This is a production model that is cost effective for all types of producers and does not require advanced technological skills to implement. In addition, it takes advantage of the region's favourable climatic conditions, such as high solar radiation and adequate rainfall, and is primarily based on renewable resources (Abramovay et al., 2025; Köberle et al., 2023; Pacheco et al., 2017).

On beef cattle farms, MIS appear to perform well in terms of energy: they increase production through investments on the farm without increasing energy efficiency. With an average efficiency of 12.58 GJ/t LW, these types of farms in the Brazilian Amazon are nearly three times more energy efficient compared to other regions such as Metropolitan France and French Guiana (30 and 36 GJ/t LW, respectively) (Bordet et al., 2010). Energy consumption per livestock production unit is higher than in cropping systems, due primarily to feed purchases (Pelletier et al., 2011). In our sampling, efficiencies are lower because these farms manage large areas of highly productive pasture with low input levels and little equipment and infrastructure.

Energy yield values in our study are more closely related to the type of production than to the intensification of the system. Fattener farms are disadvantaged by purchases of animals, while breeder and breeder farms are more energy efficient in ES or MIS. An MIS is more advantageous in that it has the potential to increase production from its investments, unlike an ES, which has low energy efficiency due to its mining and limited livestock farming.

A reasoned and limited use of energy is necessary for economic, ecological and social reasons. By quantifying the energy efficiency of livestock systems, it is possible to design a sustainable livestock system that produces both food and energy, as well as to make more informed policy decisions regarding livestock (Guevara et al., 2014; Perez-Neira et al., 2014; Funes-Monzote et al., 2009; Pervanchon et al., 2002).

This study analysed the energy consumption, use and production of different rural properties in the Amazon region. Its original approach makes it possible to propose productive practices. The moderate intensification system has demonstrated energy efficiency, whereas other studies indicate that the highest level of energy efficiency is achieved by eliminating synthetic fertilizers and herbicides, which also reduces fuel consumption (Bertilsson et al., 2008; Pimentel et al., 2005). However, this approach leads to limited animal production.

GHG emissions

Our results show that the averages of total GHG emissions increase with the intensification of the production system, with significant differences for meat-producing systems, and with the same non-significant trend for dairy farms. The main contributing gas is CH_4 from enteric fermentation of animals and faeces in the soil. Carbon dioxide (CO_2) emissions were the lowest, remaining below 15%, with the exception of the intensive system on dairy farms (25% due to feed purchases and fuel and electricity consumption).

In 2020, Brazil's agriculture and livestock sector contributed 28.5% of the country's total emissions, 62% of which came from enteric methane (MCTI, 2022). CH_4 emissions in livestock are intrinsic to ruminant physiology and soil biochemical processes, and a rise in the number of intensive systems leads to increased emissions per hectare. However, there are alternatives for reducing CH_4 emissions, including improved forage (low fibre content and greater digestibility) (Ruggieri et al., 2020; Barbero et al., 2015) obtained through practices such as rotational grazing (Rouquette Jr, 2016; Gimenes et al., 2011) and feed supplementation that alter ruminal fermentation (de Carvalho et al., 2023; Dias et al., 2023; Simioni et al., 2022; Neto et al., 2017; Fiorentini et al., 2013). These are practices adopted in particular on farms that intensify their production system.

Emissions per hectare are higher in the most intensive systems due to the animal stocking rate per hectare. Values of 2.08, 2.52 and 14.94 tCO_2/ha/year for ES, MIS and IS were observed. Thus, fertilisation increases emissions (Molossi et al., 2020), although fertilizers combined with good grazing management allows more productive grazing (Cunha et al., 2022; Berça et al., 2021; Corrêa et al., 2021; Oliveira et al., 2020; Delevatti et al., 2019), promoting carbon storage in soil (Azevedo et al., 2024; Figueiredo et al., 2017), and GHG mitigation.

Emissions per quantity of beef or milk produced (EL efficiency) tend to decrease in the most intensive farms compared to the extensive system, with a decrease of 57% (Table 3).

For beef cattle farms, the efficiency EL (17.40 t $eqCO_2$/t LW) is slightly higher than that observed in metropolitan France (14.20 $eqCO_2$/t LW) but much lower than that of neighbouring French Guiana (30.00 t $eqCO_2$/t LW). In dairy farms, the EL efficiency was 5.05 t $eqCO_2$/1000 L compared to 1.5 in metropolitan France (Planète, 2010) and 1.8 t $eqCO_2$/1000 L in La Réunion (Vayssières et al., 2011). In our study, EL efficiency was defined on a *per capita* basis, so on farms with breeder systems the efficiencies are not as good as on farms with the fattener systems. In our sample, intensive system farms have the highest efficiencies due to their higher output in kilograms per head and per hectare (Table 5).

Similar EL efficiency values were reported by Bonaudo et al. (2012), who obtained values of 18.9, 16.0 and 14.8 t $eqCO_2$/t LW for the breeder, fattener and breeder-fattener systems, respectively in Paragominas; and by Vayssières et al. (2011) in tropical conditions, with 18.5 and 10.4 t $eqCO_2$/t lw/year in the breeder and fattener systems.

The EL efficiency of dairy farms is much higher than the values reported in the literature, linked to low productivity per head. Improving it would require measures leading to better *per capita* productivity, including animal nutrition and genetics (Simioni et al., 2022; Oliveira et al., 2014; Freitas et al., 2011). With minimal investment, rotation grazing with a stocking rate adapted to the carrying capacity is a practical and viable alternative to a reduction in emissions per ton of product.

The low efficiency of emissions leads to low-carbon livestock production. However, these farms have very variable values for production per hectare and stocking rate, with only three intensive fattener-system farms having good animal production associated with a high animal stocking rate and good production per hectare.

Low-emission farms per product may not be effective in terms of land use. Most beef cattle farms produce between 24.1 and 200 kg/ha per hectare, below the national average for commercial farms of 258 kg/ha (Barbero et al., 2015). Approximately 50% of the farms in this study have an animal stocking rate of less than 0.9 AU/ha, while pastures in wetlands have a loading potential of between 1 and 3 AU/ha, which can rise to 2 to 8 AU/ha depending on fertilisation (Lira et al., 2017).

One of the main causes of deforestation in the Amazon biome is extensive livestock farming (Haddad et al., 2024; Poccard-Chapuis et al., 2020; Garcia et al., 2017). This is a historical dynamic that traces back to the territorial expansion in the Amazon, during which a simple technical model of livestock farming shaped deforested and homogeneous landscapes; and which is characteristic of the colonisation of Paragominas. Taking into account land and forest use change ("LUCF sector"), farms in the extensive system have a higher percentage of emissions from deforestation than those derived from livestock (Table 3). This response is linked to the agrarian situation of the farms. Eleven of the 15 farms in the extensive meat and milk system are located in a *colônia* or an *assentamento* (Tables 5, 6), characterized by a more recent installation, with a larger area deforested in the period considered.

"*Assentamento rural*" are rural settlements in Brazil established through a federal land regulation by the National Institute of Colonisation and Agrarian Reform (INCRA) allowing a policy of colonization or agrarian reform (Navegantes-Alves, 2011). "*Colônias*" are settlements that originate from the colonization process in the Amazon, and that can become *assentamentos*.

The different agrarian situations found in the municipality of Paragominas were studied in this work, and they show a deforestation specific to each system. MIS and IS farms are included in agrarian situation 4 - ES in perimeter "zero deforestation" and 5 - intensification corridor with a period of colonization between 1960 and 1980. The only MIS farm with significant deforestation is located in an *assentamento*, while the other MIS are in areas with significant carbon storage. On IS farms, most large farms have continued to open new areas over the past 20 years (Tables 5, 6).

In addition to the agrarian situation in the region, deforestation in the Amazon is driven by a combination of local production dynamics and external demands. The expansion of livestock and agriculture, particularly the cultivation of soybeans, corn, and sorghum, plays a major role in this process. Land dynamics and land competition between soybean farmers and ranchers intensify this process. While the domestic market is responsible for most of the deforestation, international demand has an even greater environmental impact, concentrating on high-value commodities. In this scenario, a systemic approach that integrates national and international actors is essential, strengthening environmental oversight and governance at multiple scales (Haddad et al., 2024; Moffette and Gibbs, 2021).

Looking at the efficiency of net livestock emissions, all farms have low or negative emissions per animal product. This comes from the characteristics of farms in the Amazon that have large forest areas and exploit pastures that are more than 20 years old and store carbon in the soil.

The moderate intensification system has the best emission indicators, although in terms of EL efficiency the values are average. Solutions for creating more sustainable systems include the ecological intensification of livestock farming through the adoption of practices that are accessible to all producers, such as rotational grazing, maintaining soil fertility, restoration, and forage management. More costly and technical practices, such as the integration of agriculture with livestock and agro-sylvo-pastoral systems, also are relevant options.

Practices for achieving eco-efficiency

The E-GHG+ group characterises traditional systems in the Amazon. They use abundant fodder, do not stock forage or use inputs, and have low production levels. The energy efficiency of this group is correct, but the GHG emissions per product are high. The lack of fertilisers to maintain soil fertility contributes to pasture degradation, leading to lower productivity and reduced sustainability of livestock farming (Dias-Filho, 2014), as well as lower livestock production per hectare (Oliveira et al., 2024).

One of the strategies to maintain low energy efficiency while reducing GHG emissions is moderate system intensification. This approach is particularly relevant for farms with energy efficiency below 7 GJ/t LW and average emission efficiency (below 25 t eqCO_2/t lw), which are close to qualifying for the E-GHG-group.

The ideal eco-efficiency of the E-GHG-group is achieved through low input consumption and highly productive animals linked, for example, to good grazing management. In meat production farms, medium and large MIS and ES farms are close to the E-GHG-group. They have a low input-to-output ratio relative to production, resulting in moderate emissions per hectare.

On beef cattle farms, high energy efficiency is due to the purchase of animals, which leads to a high energy cost. However, when inputs are more suitable for production and energy efficiency decreases, farms move closer to the E-GHG-group (e.g., ISF and ELF). These farms have completely different systems. An ISF farm has average energy efficiency through its high output per hectare with larger outputs related to grazing management and the provision of supplementation to animals. On an ELF farm, purchases of inputs are limited to the purchase of animals raised on a well-managed pasture with no other inputs for fattening. If inputs increase, with the purchase of feed, for example, without increased production, the efficiency of emissions increases, as for ILBF1 and ILBF2.

As an alternative to extensive livestock systems in the Amazon, integrated production systems such as SPS, ICLS and ICLFS also promote efficient land use, environmental recovery, and economic gains, configuring themselves as promising strategies for the sustainable intensification of livestock (Silveira et al., 2022). Systems integrating the forest component were not observed in our sample, however, they are beginning to be adopted in the municipality, impacting system improvement, mainly in relation to the stock of organic carbon in the soil compared to conventional systems (Sales et al., 2018).

Conclusion

The information in this study comes from interviews with farmers from different agrarian situations in the municipality of Paragominas, considered as a pole of agricultural development in the Amazon and presented as a model for sustainable livestock production. Our findings show that farms that adopt intensification techniques have lower GHG emissions per kilogram of product than extensive livestock under grazing, while energy consumption per kilogram and per hectare increases with system intensification, even though these farms are more energy efficient than those in other parts of the world. Differences in GHG emissions are also directly related to the agrarian status of properties in relation to land use change.

This work highlights some important limitations in the use of off-the-shelf calculators to assess livestock GHG emissions and energy balances, such as the use of regional energy and GHG cost coefficients for the transportation of poorly known inputs. The lack of accurate information from producers on entries and exits from the system, combined with information drawn from farmers' memories and registers, and not from measurements on the ground, lead to inaccurate reporting. Finally, the small sample size for dairy cattle limits the potential for causal inference.

However, despite this uncertainty, this study provides key insights for a coherent technical response focused on the production system. In addition to researching the absolute values of GHG emissions and energy consumption, this study used a tool to compare systems and identify practices aimed at optimizing the eco-efficiency of farms.

For future research, it appears necessary to continue the assessments based on methods of quantifying GHG emissions, such as the installation of a flow tower. The deforestation-related emission amortisation time and the envisaged carbon stock of old-growth pastures also has a major impact on the results and can be better understood and assessed in the light of developments in scientific studies in this field.

This study highlights the importance of using tools for calculating GHG and energy emissions that are tailored to regional conditions, which makes it possible to better identify the impacts of agricultural practices and thus adopt appropriate measures. This work also provided an opportunity to reflect on the impact of taking account of changes in land use and carbon stocks on emission balances, which are still not very well integrated in scientific studies. While we have solid data on the impact of agricultural practices on energy consumption and GHG emissions, broader analyses of environmental performance, such as water quality, air quality and biodiversity, are essential to complement information on the effects of different practices.

The results are important to promote the integration of virtuous practices into livestock systems that facilitate ecological intensification and reduce environmental impacts.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DC led the redaction of the paper and contributed to data analysis; RP-C administered the project, contributed as a co-supervisor and reviewed and edited the manuscript; VB contributed to the conceptual frame of the studies and the paper and interpreted the results; J-LB contributed to data processing and analysis at the farm level; PL served as the main supervisor, reviewed and edited the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The current work was supported by the TerrAmaz project funded by the Agence Française de Développement (Grant number: AFD CZZ264701G).

Acknowledgments

The authors thank Margot Moniot and Mathilde Lenoir for their contribution to data collection and the Brazilian Agricultural Research Corporation (EMBRAPA) for hosting the Paragominas campus. We also thank the local pastoral communities for their welcoming responses to the interviews.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2025.14461/full#supplementary-material

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