UNIVERSIDADE ESTADUAL PAULISTA
FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS
CÂMPUS JABOTICABAL

CARBON FOOTPRINT ANALYSIS OF INTEGRATED SYSTEMS WITH LIFE CYCLE ASSESSMENT FOR SUSTAINABLE BEEF CATTLE PRODUCTION

Pedro Henrique Francisco de Torres
Animal Scientist

2025

UNIVERSIDADE ESTADUAL PAULISTA
FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS
CÂMPUS JABOTICABAL

CARBON FOOTPRINT ANALYSIS OF INTEGRATED SYSTEMS WITH LIFE CYCLE ASSESSMENT FOR SUSTAINABLE BEEF CATTLE PRODUCTION

Student: Pedro Henrique Francisco de Torres
Advisor: Prof^a. Dr^a. Ana Cláudia Ruggieri
Coadvisor: Dr. André Mancebo Mazzeto
Coadvisor: Dr^a. Renata Helena Branco

Master’s thesis presented to the Graduate program in Animal Science at the Faculty of Agricultural and Veterinary Science – UNESP, Jaboticabal campus, as part of the requirements for obtaining the title of Master’s in Animal Science.

2025

T693c

Torres, Pedro Henrique Francisco de
Carbon footprint analysis of integrated systems with Life Cycle Assessment for sustainable beef cattle production/ Pedro Torres. -- Jaboticabal, 2025

64 p. : tabs., fotos

Dissertação (mestrado) - Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal
Orientadora: Ana Cláudia Ruggieri
Coorientador: André Mancebo Mazzetto

1. Agriculture systems. 2. Climate change. 3. Environmental performance. 4. Greenhouse gases mitigation. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Dados fornecidos pelo autor(a).

POTENTIAL IMPACT OF THIS RESEARCH

Livestock and agriculture are socially, economically, and environmentally crucial for Brazil. However, they are also major sources of greenhouse gas emissions in the country. Brazil plays an important role in global food security, being the largest exporter of beef and the largest producer of soybeans in the world. This research aimed to evaluate four cattle production systems, two of which are integrated approaches combining crops, livestock, and forestry, and are also included in Brazil's new NDC (Nationally Determined Contributions). These systems, analyzed alongside a system that intercropped nitrogen-fixing legumes with grasses, demonstrated great potential to reduce the environmental impact of cattle production as well as crude protein yield per hectare. This analysis was conducted using a Life Cycle Assessment (LCA), supported by ISO 14040 and 14044 standards. The present study can be directly linked to three of the United Nations Sustainable Development Goals (SDGs): Goal 2 (Zero Hunger), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). Indirectly, it also relates to several other SDGs. The findings highlight Brazil's ongoing efforts to maintain a leading role in sustainable agriculture in the era of climate change.

POTENCIAL IMPACTO DESTA PESQUISA

A pecuária e a agricultura são social, econômica e ambientalmente cruciais para o Brasil. No entanto, também são grandes fontes de emissões de gases de efeito estufa no país. O Brasil desempenha um papel importante na segurança alimentar global, sendo o maior exportador de carne bovina e o maior produtor de soja do mundo. Esta pesquisa teve como objetivo avaliar quatro sistemas de produção de bovinos de corte, dois dos quais são abordagens integradas que combinam agricultura, pecuária e silvicultura, e também estão incluídos na nova NDC (Contribuições Nacionalmente Determinadas) do Brasil. Esses sistemas analisados junto a um sistema que consorcia leguminosas fixadoras de nitrogênio com a gramínea demonstraram grande potencial para reduzir o impacto ambiental da produção de bovinos bem como de proteína bruta por hectare. Para Tal análise foi utilizada uma Análise de Ciclo de Vida (ACV), amparada pela ISO 14040 e 14044. O presente estudo pode ser diretamente vinculado a três dos Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas: Objetivo 2 (Fome Zero), Objetivo 12 (Consumo e Produção Responsáveis) e o Objetivo 13 (Ação Climática). Indiretamente, também se relaciona a vários outros ODS. Os resultados destacam os esforços contínuos do Brasil para manter um papel de liderança na agricultura sustentável na era das mudanças climáticas.

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Jaboticabal

CERTIFICADO DE APROVAÇÃO

TÍTULO DA DISSERTAÇÃO: CARBON FOOTPRINT ANALYSIS OF INTEGRATED SYSTEMS WITH LIFE CYCLE ASSESSMENT FOR SUSTAINABLE BEEF CATTLE PRODUCTION

AUTOR: PEDRO HENRIQUE FRANCISCO DE TORRES
ORIENTADORA: ANA CLÁUDIA RUGGIERI
COORIENTADORA: RENATA HELENA BRANCO
COORIENTADOR: ANDRÉ MANCEBO MAZZETTO

Aprovado como parte das exigências para obtenção do Título de Mestre em Ciência Animal, área: Nutrição Animal pela Comissão Examinadora:

gov.br Documento assinado digitalmente
ANA CLAUDIA RUGGIERI
Data: 28/07/2025 17:09:20-0300
Verifique em https://validar.iti.gov.br

Profa. Dra. ANA CLÁUDIA RUGGIERI (Participaçao Virtual)
Departamento de Zootecnia / FCAV UNESP Jaboticabal

gov.br Documento assinado digitalmente
ABMAEL DA SILVA CARDOSO
Data: 28/07/2025 12:50:18-0300
Verifique em https://validar.iti.gov.br

Pós-Doutorando ABMAEL DA SILVA CARDOSO (Participaçao Virtual)
Departamento Plant and Agroecosystem Sciences / University of Wisconsin - Madinson/Wisconsin/EUA

gov.br Documento assinado digitalmente
FLAVIA DE OLIVEIRA SCARPINO VAN CLEEF
Data: 28/07/2025 13:08:25-0300
Verifique em https://validar.iti.gov.br

Profa. Dra. FLAVIA DE OLIVEIRA SCARPINO VAN CLEEF (Participaçao Virtual)
Departamento de Ciência Animal / Universidade de Saskatchewan (USASK) - Saskatoon/Saskatchewan/Canadá

Jaboticabal, 28 de julho de 2025

AUTHOR DETAILS

Pedro Henrique Francisco de Torres, the son of Elisabete Francisco Maia and Ediomar Francisco Torres, was born on October 12, 1999, in Cavalcante, Goiás, where he lived until the age of 14. In 2018, he enrolled in the Animal Science undergraduate program at the Federal University of Santa Catarina (UFSC) in Florianópolis, from which he graduated in 2023. Throughout his undergraduate career, he completed numerous extracurricular internships and served as a teaching assistant for Basic Statistics and Diet Formulation for Monogastric Animals. In 2023, he was accepted with distinction into the graduate programs in Animal Science at both the Federal University of Lavras (UFLA) and São Paulo State University (UNESP), Jaboticabal campus. He chose to attend UNESP, working under the guidance of Prof. Dr. Ana Cláudia Ruggieri, with co-supervision by Dr. André Mazzetto and Dr. Renata Helena Branco. He received a CAPES scholarship and contributed to various research projects.

EPIGRAPH

"To learn is not to know; there are the learners and the learned. Memory makes the one, philosophy the other."

Alexandre Dumas

DEDICATION

Jesus Christ

ACKNOWLEDMGENTS

First and foremost, I thank God.

I extend my deepest gratitude to my advisor, Professor Dr. Ana Cláudia Ruggieri. I am truly thankful to God for the opportunity to have met her. Any success I have achieved in my brief academic career is due to her. Thank you so much, Professor Ana, from the bottom of my heart. I will be forever grateful, and you can always count on me.

I thank my family: my mother, Elisabete Francisco Maia; my sisters, Rosiene and Renata; and my father, Ediomar Francisco Torres. I am grateful for everything you have taught me.

To my life partner, Eduarda Santos, who has supported me for years. I love you very much.

To the friends I made in Jaboticabal and those I've left in other cities—you are all a part of this accomplishment as well.

I am grateful to UNESP and the PPGCA for providing the structure and support needed to carry out the many activities I undertook and learned from. My thanks go to all the staff members whose work makes this great institution run.

To the LabFor group, thank you for all the support, laughter, and shared knowledge. I hope to always be a part of this team.

To CAPES, without your financial support, it would have been nearly impossible for me to begin my master's degree. May you continue to open doors for others as you have for me.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001

SUMMARY

Abstract

The global livestock sector encounters increasing challenges to align growing food demands with the urgent need to mitigate greenhouse gas (GHG) emissions. While livestock systems are key to global food security, they are significant contributors to GHG emissions, particularly methane (CH_4) and nitrous oxide (N_2O). There is a pressing need for evidence-based strategies to improve productivity while reducing emissions, especially in tropical regions like Brazil, where diverse livestock systems operate simultaneously. This study addresses this gap by evaluating the environmental and productive performance of four livestock systems in Brazil over 10 years: a nominal system (low-input pasture), an integrated crop-livestock system (iCL), an integrated crop-livestock-forest system (iCLF), and a grass-legume consortium. A Life Cycle Assessment (LCA) approach was performed to estimate the carbon footprint of the different systems. Results with mass allocation indicated that the emissions intensity per kilogram of carcass was similar for the Consortium (10.73 kg CO_2-eq kg^{-1}) and iCLF (10.43 kg CO_2-eq kg^{-1}). The iCL exhibited a higher intensity (11.79 kg CO_2-eq kg^{-1}), whereas the Nominal presented the highest value (17.66 kg CO_2-eq kg^{-1}). Emissions intensity per kilogram of crude protein (CP) was lowest in the iCL (5.97 kg CO_2eq kg^{-1} CP) and highest in the nominal system (58.40 kg CO_2eq kg^{-1} CP). Total emissions per hectare were highest in the iCL (129.2 t CO_2-eq ha^{-1}) and lowest in the nominal system (18.4 t CO_2-eq ha^{-1}). This study provides a critical framework for balancing productivity and gases emissions, contributing to the development of climate-smart agricultural practices.

Keywords: Agriculture systems, Climate change, Environmental performance, Greenhouse gases mitigation

Resumo

A agropecuária enfrenta desafios crescentes para alinhar as demandas por alimentos em expansão com a necessidade urgente de mitigar as emissões de gases de efeito estufa (GEE). Embora os sistemas pecuários sejam fundamentais para a segurança alimentar global, eles contribuem significamente para as emissões de GEE, particularmente metano (CH4) e óxido nitroso (N2O). Há uma necessidade de estratégias validadas que busquem produtividade enquanto se reduz as emissões, especialmente em regiões tropicais como o Brasil, onde diversos sistemas pecuários operam simultaneamente. Este estudo aborda essa lacuna ao avaliar o desempenho ambiental e produtivo de quatro sistemas pecuários no Brasil ao longo de 10 anos: um sistema nominal, um sistema de integração lavoura-pecuária (ILP), um sistema de integração lavoura-pecuária-floresta (ILPF) e um consórcio de gramínea-leguminosa. Uma Análise de Ciclo de Vida (ACV) foi realizada para estimar a pegada de carbono dos diferentes sistemas. Os resultados com alocação por massa indicaram que a intensidade de emissões por quilograma de carcaça foi similar para o Consórcio (10,73 kg CO_2-eq kg^{-1}) e o ILPF (10,40 kg CO_2-eq kg^{-1}). O ILP exibiu uma intensidade de 11,68 kg CO_2-eq kg^{-1}, enquanto o Nominal apresentou o valor mais elevado (16,48 kg CO_2-eq kg^{-1}). A intensidade de emissões por quilograma de proteína bruta (CP) foi menor no ILP (5,97 kg CO_2-eq kg^{-1} CP) e maior no sistema nominal (58,40 kg CO_2-eq kg^{-1} CP). As emissões totais por hectare foram maiores no ILP (129.2 t CO_2-eq ha^{-1}) e menores no sistema nominal (18.4 t CO_2-eq ha^{-1}). Este estudo fornece um referencial crítico para o equilíbrio entre produtividade e emissões de gases, contribuindo para o desenvolvimento de práticas agrícolas climaticamente inteligentes.

Palavras-chave: Sistemas agrícolas, mudanças climáticas, desempenho ambiental, mitigação de gases de efeito estufa

ABBREVIATIONS

ADG – Average daily gain
CH_4 - Methane
CP – Crude protein
FAO – Food and Agriculture Organization
GHG – Greenhouse gases
GWP – Global warming potential
iCL – integrated crop-livestock
iCL – integrated crop-livestock-forest
IPCC – Intergovernmental Panel on Climate Change
LCA – Life Cycle Assessment
N_2O – Nitrous oxide

TABLES

FIGURES

1. INTRODUCTION

Brazil has 276.6 million hectares (ha) allocated to agricultural activities, of which 59.5% are pasture areas and 22% are used for the cultivation of crops, such as soybeans, which occupy approximately 39.8 million ha (MAPBIOMAS, 2024). Owing to its extensive territorial area and favorable tropical climate and topography, Brazil has established itself as a key player in the global food market. Nevertheless, alongside the continuous growth of the global population, the prevalence of undernourishment has also escalated. In 2023, an estimated 9.1% of the global population was affected by hunger (FAO, 2024). Due to the rising demand for animal and plant protein production driven by Brazil's remarkable productive potential, the country will play a fundamental role in addressing global food security challenges.

However, with the continued need for increased food production, the well-known concerns regarding climate change become more pressing, requiring more sustainable practices and innovative strategies to mitigate environmental impacts. GHG emissions totaled 54.5 gigatons of CO_2-eq ($GtCO_2$-eq) in 2024 (Crippa, 2024). Data from the SEEG estimate that Brazil emitted approximately 2.3 $GtCO_2$-eq in 2023. Agriculture, Land Use Changes, and Forestry account for 73.7% of total emissions (SEEG, 2025).

To address this challenge, Brazil has committed to reducing its emissions alongside other nations as a signatory of the Paris Agreement. During COP29, held in 2024 in Azerbaijan, Brazil presented its new emission reduction targets for 2035, pledging to cut emissions by 59% to 67% relative to 2005 levels. This corresponds to an absolute emission range of 1.05 to 0.85 $GtCO_2$-eq, based on the IPCC's AR5 GWP metric (Brazil, 2024). In the context of agricultural production, the country aims to invest in two main strategies: the conversion of degraded areas into iCLF and the enhancement of productivity gains through integrated systems, and the adoption of more intensive practices.

Significant progress has been observed in the adoption of strategies to mitigate GHG emissions. However, a gap still exists regarding the validation of the effectiveness of these strategies as part of governmental targets for reducing such gases. Through the use of LCA, it is possible to estimate the environmental impacts of products and systems, including the carbon footprint (kg CO_2-eq kg product^{-1}). As a standardized methodology, LCA provides a holistic assessment by quantifying inputs, outputs, and potential environmental impacts throughout a product's entire life cycle—from raw material extraction to end-of-life. This comprehensive approach is fundamental for validating environmental performance and supporting policy-making. LCA enables the simulation of productive intensification scenarios (Cardoso *et al.*, 2016; Mazzetto *et al.*, 2015), the evaluation of integrated systems (Figueiredo *et al.*, 2017; Monteiro *et al.*, 2024) and comparisons across different biomes (Dick *et al.*, 2021).

When it comes to integrated systems, the simultaneous production of multiple outputs within the same area presents significant challenges for the precise allocation of emissions among the various products. The complex biological and agronomic interactions between crops, forage species, and animals, as well as nutrient flows in the soil, make it difficult to quantify emissions for each product. In LCA, this partitioning procedure is known as allocation, where the total environmental burdens of the system are systematically divided among the products. When emission allocation is required, ISO 14044 recommends that allocation be conducted in a manner that reflects the physical relationships between the products. Studies evaluating integrated systems such as Integrated Crop-Livestock (iCL) and Integrated Crop-Livestock-Forest (iCLF) systems have not consistently reported whether allocation methods were applied (Costa *et al.*, 2018; Figueiredo *et al.*, 2017; Monteiro *et al.*, 2024). Allocation is important to avoid increasing the carbon footprint of products in a way that may not represent their true impact.

There is significant variation in the carbon footprint associated with beef production in different regions of the world. According to FAO estimates (2024), the average carbon footprint of beef produced in Europe is 15.8 kg CO_2-eq per kg of meat, whereas, in Africa, this value reaches 54.8 kg CO_2-eq per kg of meat. In Brazil, the highest value recorded was 58.3 kg CO_2-eq kg carcass^{-1}, associated with a low productivity scenario (Cardoso *et al.*, 2016). In contrast, the lowest value was 10.75 kg CO_2-eq kg carcass^{-1}, observed in a system based exclusively on cattle production on well-managed pastures (Monteiro *et al.*, 2024). Integrated systems apparently do not present significant advantages when analyzed in relation to kg carcass production. However, these systems stand out for their smaller carbon footprint associated with greater production of kg of CP per ha, thereby demonstrating superior environmental and social performance and representing a more effective management in the short term (Monteiro et al., 2024).

1.1 LITERATURE REVIEW

1.1.1 Overview of beef cattle production on pastures in Brazil

Brazil's cattle herd is predominantly distributed across 164.6 million hectares (ha) of pastures under varying environmental conditions (MAPBIOMAS, 2025). The Brazilian Institute of Geography and Statistics (IBGE, 2024) estimates that more than 50% of this herd is located in Central Brazil, where the Cerrado biome prevails. This macro-region is characterized by a climate with two well-defined seasons: a humid and warm summer, with greater light availability due to a more extended photoperiod, and a dry winter, marked by cold nights and a shorter photoperiod (Hofmann *et al.*, 2021). These climatic conditions directly influence forage growth dynamics and the productive performance of agricultural systems.

Brazil holds the world's largest commercial cattle herd, totaling 238.6 million animals (IBGE, 2024). In recent years, the country has established itself as the world's leading beef exporter. In 2024, for instance, exports reached 2.5 million tons, generating a revenue of 11.6 billion dollars (Brazil, 2025). Additionally, Brazil ranks as the second-largest beef producer, behind only the United States (USDA, 2024). As a result, pasture-based cattle production plays a strategic role in social, economic, and environmental aspects, reaffirming its significance in the global agribusiness sector.

Due to its vast territorial extension and the diversity of climatic and geographic conditions, Brazil has beef cattle production systems that vary considerably between regions, states, and even municipalities, reflecting local specificities (Telles *et al.*, 2024). In recent years, in response to the growing global and national demand for beef, as well as growing environmental concerns associated with the need for greater productivity, a transition from traditional extensive systems to intensive production systems has been observed (Cardoso *et al.*, 2020). These intensive systems are characterized by the use of practices such as the application of high doses of nitrogen fertilizers (Delevatti *et al.*, 2019; Lima *et al.*, 2023), integration of pastures with agricultural and tree crops (Lemaire *et al.*, 2014; Luz *et al.*, 2019; Macedo, 2009), intercropping with nitrogen-fixing legumes (Homem *et al.*, 2024; Pereira Neto *et al.*, 2024), inclusion of high levels of energy concentrates in the diets and, more recently, the adoption of feedlot finishing systems (Pinto and Millen, 2019).

1.2 Beef cattle production systems on pastures

1.2.1 Nominal pasture

The concept of nominal pastures, as defined by the IPCC (2006), refers to pasturelands that do not exhibit degradation and are managed using simple practices without the implementation of intensive improvement strategies, such as liming, organic fertilization, the application of high doses of fertilizers, irrigation, or intercropping with legumes. Despite the updates to the guidelines in 2019, the original definition of nominal pastures remained unchanged (IPCC, 2019). Mazzetto *et al.* (2015), in a life cycle assessment study, analyzed five productive scenarios, including one representing a nominal pasture. In this context, a stocking rate of one Animal Unit (AU) per hectare was adopted, without interventions such as liming or irrigation, utilizing basic management practices and the application of 50 kg of nitrogen per hectare per year. More recently, nominal pastures have been widely employed as a baseline in studies assessing soil carbon stocks under different management strategies (Oliveira et al., 2022; Maia et al., 2009a; Sousa et al., 2024).

1.2.2 Consortium of *Urochloa* spp. with *Arachis pintoi*

Grasslands composed of forage species from the *Urochloa* genus exhibit a rapid response to nitrogen fertilization, promoting enhanced growth and productivity in these forage systems (Delevatti *et al.*, 2019; Lima *et al.*, 2023; Nilsson *et al.*, 2023). Urea is the main nitrogen source used globally, accounting for approximately 73.4% of all nitrogen fertilizers applied in agriculture (Motasim *et al.*, 2024). However, its use is associated with several limitations, including high volatilization losses, low nitrogen use efficiency (Delevatti *et al.*, 2019; Motasim *et al.*, 2024) and a significant contribution to greenhouse gas (GHG) emissions (Cardoso *et al.*, 2019; Corrêa *et al.*, 2021). Specifically, urea is an important source of N_2O emissions, a gas with a global warming potential 273 times greater than that of CO_2 (IPCC, 2021). Given the increasing global interest in mitigating climate change and its environmental impacts, the integration of grasses with legumes emerges as a sustainable alternative to reduce dependence on synthetic fertilizers and minimize GHG emissions (Ledgard and Steele, 1992).

One of the main combinations of grasses and legumes for forage systems consists of the consortium between *Urochloa* spp. and *Arachis pintoi*, commonly known as forage peanut. Since 2006, Embrapa Acre has maintained a forage peanut germplasm bank, composed of approximately 110 genotypes, the majority of which belong to the species *Arachis pintoi* (Azevedo *et al.*, 2014). Under ideal climate and management conditions, this consortium has demonstrated productive performance equivalent to or superior to that of pastures formed exclusively by *Urochloa* spp., and fertilized with up to 120 kg of N ha^{-1} $year^{-1}$ (Pereira *et al.*, 2020). On the other hand, studies available in the literature present divergent results in relation to animal productivity in intercropped systems (Homem *et al.*, 2024, 2021a).

From an environmental perspective, although the study by Cardoso *et al.* (2016) did not specifically evaluate forage peanut, a life cycle assessment (LCA) of an intercropped grass-legume system demonstrated one of the lowest carbon footprints per kilogram of carcass. In addition, the non-use of nitrogen fertilizers significantly reduces direct and indirect N_2O emissions (Monteiro et al., 2024). While consortium systems may exhibit lower animal productivity, their carbon footprint tends to be lower, as CO_2 emissions associated with the manufacturing and transportation of nitrogen fertilizers represent a major contributor to the system's overall emissions (Homem *et al.*, 2024).

1.2.3 Integrated cattle production systems

The production of annual crops (agricultural component) in rotation, intercropping, or succession with cattle production is referred to as iCL, also known as an agropastoral system. A more complex approach, in which Brazil stands out in research, is iCLF, or the agrosilvopastoral system. This system differs from iCL by incorporating a tree component, with *Eucalyptus* being one of the most commonly used species (Balbino *et al.,* 2012; Bungenstab *et al.,* 2019).

Integrated systems can be structured in different arrangements (Magalhães *et al.*, 2019), allowing their adaptation to various regions worldwide through the use of local crops. Additionally, these systems play a fundamental role in promoting social, economic, and environmental sustainability (Sekaran *et al.*, 2021). Table 1 presents some of the main arrangements and crops adopted in different regions of Brazil, highlighting the diversity and adaptability of these systems to local conditions.

The benefits derived from integrated systems encompass all components of the soil-plant-animal system, aiming to optimize biological cycles and resource utilization (Macedo, 2009). Although the impacts of these systems on soil physical properties remain inconclusive (Oliveira *et al*., 2024), evidence suggests positive effects on biological attributes, such as increased enzymatic activity (Sarto *et al.*, 2020) and microbial biomass (Sousa *et al.*, 2020). Moreover, integrating forage species with annual crops enables the utilization of residual fertilization effects, reducing pasture establishment costs and maximizing nutrient use efficiency (Alves *et al.*, 2017). In integrated systems, the annual rate of soil carbon accumulation may be positively influenced (Oliveira *et al.*, 2024), and the bioavailability of certain nutrients, such as phosphorus, may be enhanced (Deiss *et al.*, 2016). Additionally, soil macrofauna exhibits greater diversity and activity in integrated systems compared to conventional agricultural monocultures or traditional pastures (Marchão *et al.*, 2009).

Table 1 - Different crops, animals, and trees used in experimental arrangements of iCL and iCLF systems, in different regions under different conditions in Brazil.

Climate zone, Institution, Local	System	Crops	Livestock	Trees	Reference
Aw, Embrapa, Mato Grosso, Brazil	iCLF	Soybean, Corn	Beef Cattle	Eucalyptus	Moreira *et al.*, 2018
	iCLF	Soybean, Corn, beans	Beef Cattle	Eucalyptus	Ferreira *et al.*, 2020
Aw, APTA, São Paulo, Brasil	iCL, iCLF	Soybean, Corn	Beef Cattle	Eucalyptus	Luz *et al.*, 2019
Aw, Minas Gerais, Brazil	iCLF	Sorghum	-	Eucalyptus, Acacia	Oliveira *et al.*, 2015
Cerrado, Brazil	iCL, iCLF	Corn	Cattle	Baru, Leucaena, Albizia, Cratylia	Gama *et al.*, 2014
Cfa, Rio Grande do Sul, Brazil	iCL	Soybean, Corn	Sheep	-	Schuster *et al.*, 2018
Bsh, Paraíba, Brazil	iCL	Coconut	Sheep	-	Lins *et al.*, 2021
Cfb, Paraná, Brazil	iCL	Corn	Sheep	-	Andreolla *et al.*, (2014)
Embrapa, Brasília, Brazil	iCLF	-	Dairy Cattle	Eucalyptus	Reis *et al.,* (2021)

Aw, Cfa, Cfb, and Bsh are classifications according to the Köppen classification; iCL – Crop-livestock integration; iCLF – Crop-livestock-forest integration (Source: Prepared by the author (2025).

Magalhães *et al.* (2019), evaluated different arrangements of integrated systems in comparison to various monocultures. The authors reported that the best animal performance, considering the ADG and productivity in kg per ha, was observed in an iCLF system. This outcome was directly attributed to the higher forage production, which enabled an increase in stocking rate, reaching 2.7 animal units (AU) per ha. Furthermore, in iCLF systems, the introduction of tree species plays a strategic role by providing thermal comfort and improving animal welfare, which positively impacts productivity (Romanello *et al.*, 2023).

The main agricultural crops used in integrated systems in Central Brazil include soybeans, which are cultivated as the first crop, followed by corn intercropped with a forage species. In general, the adoption of integrated systems has a neutral effect on grain productivity, indicating that it does not compromise production, although it does not lead to significant increases either. However, several studies report economic benefits, improvements in soil quality, and greater efficiency in water conservation (Peterson *et al.*, 2020).

1.3 Life Cycle Assessment (LCA)

With the growing interest in climate change and its negative impacts on life quality on Earth, the quantification of environmental impacts and the search for alternative products and systems have been widely studied in various regions worldwide (Finnveden *et al.*, 2009). Life Cycle Assessment (LCA) is one of the most commonly used tools to quantify the environmental impacts of products and systems, serving as a basis for decision-making in both private and governmental institutions.

The literature suggests that a study conducted by Coca-Cola in 1969 was likely the first documented model of LCA, although its records are not publicly available (Hunt *et al.*, 1996). However, during the 1970s and 1980s, LCA had not yet become a widely used tool in scientific research (Liu *et al.*, 2024). It was only in 1990 that the first formal concept of LCA was proposed, and in 1993, this methodology was incorporated into the ISO 14000 series of standards, which focus on environmental management (Liu *et al.*, 2024).

Currently, LCA is governed by ISO 14040 and ISO 14044 standards, which define it as the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). These standards establish standardized guidelines for conducting robust and comparable environmental assessments, ensuring methodological rigor and enabling consistent results for policy formulation and decision-making across various sectors.

A simple search conducted in the Web of Science and Scopus databases, using the keywords “(Life Cycle Assessment) AND (LCA)” and applying a country-based filter, identified 850 records in Web of Science and 1,072 in Scopus. The results from both databases reveal a growing academic interest in LCA, as evidenced by the increasing number of publications over time. However, Brazil's scientific output in this field remains comparatively low relative to developed nations. For example, the United States registered 3,229 publications in Web of Science and 4,628 in Scopus for the same search criteria, highlighting a substantially greater engagement with LCA research in countries with higher economic and technological development.

1.3.1 Allocation of GHG emissions

Recently, LCAs assessing the environmental impact of beef cattle production have been conducted across different strategies and regions of Brazil (Table 2). Most of these studies focus on systems based exclusively on pasture-based cattle production (Table 2). One of the advantages of integrated systems is the production of multiple outputs within the same area (Table 1). However, evaluating such systems presents significant challenges due to the complex interactions among system components and the need for an appropriate allocation of environmental impacts to each product generated (Goglio *et al.*, 2024). In this context, the concept of emissions allocation emerges.

Allocation is defined as the "partitioning of input or output flows of a process or product system between the studied product system and another product system" (ISO, 2006). ISO 14044 recommends avoiding allocation whenever possible through the subdivision of elementary processes or system expansion. In process subdivision, a process generating multiple products is divided into smaller processes, allowing the separate assessment of each product’s impact. Conversely, system expansion is recommended for the analysis of co-products (Weidema, 2000). In this approach, rather than applying direct subdivisions or allocations, it is assumed that the co-product can replace, in a more sustainable manner, other products available on the market. As a result, applying system expansion reduces the environmental impact attributed to the primary product due to the benefits provided by the co-product in other production contexts (Weidema, 2000).

However, in certain situations, system expansion or the subdivision of elementary processes may not be the most suitable approach, making allocation necessary. ISO 14044 recommends that whenever allocation cannot be avoided, it should be performed in a way that reflects the physical relationships between products. Additionally, if physical allocation cannot be established, the standard suggests that allocation should be based on other relevant relationships between inputs and/or outputs, such as the economic relationship between the products.

Table 2 - Carbon footprint of 1 kg of beef carcass (kg CO_2-eq kg carcass-1) estimated through life cycle analysis (LCA) of different production systems in different regions of Brazil.

Number of scenarios	Region	Evaluated integrated systems?	kg CO_2-eq kg carc^{-1}	Reference
5	Central	No	29.4 - 58.3	Cardoso *et al.*, 2016
7	South	No	40.0 - 85.2	Ruviaro *et al.*, 2015
7	Central	No	25.4 - 41.6	Guimarães (2022)
3	Central	Yes	18.8 - 37.0	Figueiredo *et al*2016
4	Central	No	34.58 - 62.42	Florindo *et al*2017
4	North	Yes	10.75 - 11.52	Monteiro et., 2023
2	South	No	18.32 - 45.05	Dick *et al.*, 2015
22	Central	No	9.56 - 16.4	Cerri *et al.*, 2016
4	Midwest, South, North,	No	24.2 - 42.37	Dick *et al.*, 2021
11	South	No	11.34 - 38.1	Dick *et al.*, 2015b
2	North East	No	15.5	Willers *et al.*, 2017
5	North	No	21.0 - 49.0	Mazzetto *et al.*, 2015

Source: Prepared by the author (2025).

Studies estimating the carbon footprint of beef through LCA in integrated systems are scarce in the literature. Among the available publications, the authors do not report whether emissions allocation, system expansion, or subprocess division was applied (Figueiredo *et al.*, 2017; Monteiro *et al.*, 2024). This highlights a clear gap in the LCA of integrated systems and the application of emission allocation strategies.

1.4 OBJECTIVES

1.4.1 General objectives

The main objective of this study was to assess the environmental impact (climate change) of integrated systems using a life cycle assessment (LCA).

1.4.2 Specific objectives

- To develop a complete inventory for a Nominal system, Consortium system, iCL system and iCLF system;
- To estimate the emissions of CO_2, CH_4, and N_2O of the four systems and compare them between them;
- To estimate the carbon footprint per kg of carcass and per crude protein of each system;
- To assess the use of emission allocation in integrated systems with the aim of reducing distortions.

1.5 REFERENCES

Alves, B.J.R., Madari, B.E., Boddey, R.M., 2017. Integrated crop–livestock–forestry systems: prospects for a sustainable agricultural intensification. Nutr Cycl Agroecosyst 108, 1–4. https://doi.org/10.1007/s10705-017-9851-0

Azevedo, J.M.A. de, Assis, G.M.L. de, Saggin Junior, O.J., Azevedo, H.S.F. da S., 2014. Richness and frequency of species of arbuscular mycorrhizal fungi in forage peanut genotypes in Acre, northern Brazil. Acta Amazon 44, 157–168. https://doi.org/10.1590/S0044-59672014000200001

Cardoso, A.S., Oliveira, S.C., Janusckiewicz, E.R., Brito, L.F., Morgado, E. da S., Reis, R.A., Ruggieri, A.C., 2019. Seasonal effects on ammonia, nitrous oxide, and methane emissions for beef cattle excreta and urea fertilizer applied to a tropical pasture. Soil Tillage Res 194. https://doi.org/10.1016/j.still.2019.104341

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I. das N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agric Syst 143, 86–96. https://doi.org/10.1016/j.agsy.2015.12.007

Cardoso, A.S., Barbero, R.P., Romanzini, E.P., Teobaldo, R.W., Ongaratto, F., da Rocha Fernandes, M.H.M., Ruggieri, A.C., Reis, R.A., 2020. Intensification: A key strategy to achieve great animal and environmental beef cattle production sustainability in Brachiaria grasslands. Sustainability (Switzerland). https://doi.org/10.3390/su12166656

Corrêa, D.C.C., Cardoso, A.S., Ferreira, M.R., Siniscalchi, D., Toniello, A.D., Lima, G.C. de, Reis, R.A., Ruggieri, A.C., 2021. Are CH4, CO2, and N2O Emissions from Soil Affected by the Sources and Doses of N in Warm-Season Pasture? Atmosphere (Basel) 12, 697. https://doi.org/10.3390/atmos12060697

Deiss, L., de Moraes, A., Dieckow, J., Franzluebbers, A.J., Gatiboni, L.C., Sassaki, G. lanzi, Carvalho, P.C.F., 2016. Soil phosphorus compounds in integrated crop-livestock systems of subtropical Brazil. Geoderma 274, 88–96. https://doi.org/10.1016/j.geoderma.2016.03.028

Delevatti, L.M., Cardoso, A.S., Barbero, R.P., Leite, R.G., Romanzini, E.P., Ruggieri, A.C., Reis, R.A., 2019. Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. Sci Rep 9. https://doi.org/10.1038/s41598-019-44138-x

Figueiredo, E.B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., La Scala, N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J Clean Prod 142, 420–431. https://doi.org/10.1016/j.jclepro.2016.03.132

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J Environ Manage 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Guimarães, Y. S. R. Impactos ambientais da suplementação de bovinos de corte na pegada de carbono e uso da terra. Dissertação de mestrado, 2022. UNESP, Jaboticabal, SP, Brazil.

Goglio, P., Smith, L.G., Saget, S., Folegatti Matsuura, M.I.S., 2024. Improved life cycle assessment (LCA) methods to account for crop-livestock interactions within agricultural systems. Agric Syst 220, 104084. https://doi.org/10.1016/j.agsy.2024.104084

Hofmann, G.S., Cardoso, M.F., Alves, R.J.V., Weber, E.J., Barbosa, A.A., de Toledo, P.M., Pontual, F.B., Salles, L. de O., Hasenack, H., Cordeiro, J.L.P., Aquino, F.E., de Oliveira, L.F.B., 2021. The Brazilian Cerrado is becoming hotter and drier. Glob Chang Biol 27, 4060–4073. https://doi.org/10.1111/gcb.15712

Homem, B.G.C., Borges, L.P.C., de Lima, I.B.G., Guimarães, B.C., Spasiani, P.P., Ferreira, I.M., Meo-Filho, P., Berndt, A., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Casagrande, D.R., 2024. Forage peanut legume as a strategy for improving beef production without increasing livestock greenhouse gas emissions. Animal 18. https://doi.org/10.1016/j.animal.2024.101158

Homem, B.G.C., de Lima, I.B.G., Spasiani, P.P., Borges, L.P.C., Boddey, R.M., Dubeux, J.C.B., Bernardes, T.F., Casagrande, D.R., 2021. Palisadegrass pastures with or without nitrogen or mixed with forage peanut grazed to a similar target canopy height. 2. Effects on animal performance, forage intake and digestion, and nitrogen metabolism. Grass and Forage Science 76, 413–426. https://doi.org/10.1111/gfs.12533

Hunt, Robert G., Franklin, W.E., Hunt, R. G., 1996. LCA — How it came about. Int J Life Cycle Assess 1, 4–7. https://doi.org/10.1007/BF02978624

IBGE. Instituto Brasileiro de Geografia e Estatística (IBGE). **Pesquisa da Pecuária Municipal (PPM)**: **efetivo de rebanhos, por tipo (cabeças)**, **2023**. Brasil, 2025. Disponível em: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9107-producao-da-pecuaria-municipal.html. Acesso em: 21 jan. 2025

Ledgard, S.F., Steele, K.W., 1992. Biological nitrogen fixation in mixed legume/grass pastures. Plant Soil 141, 137–153. https://doi.org/10.1007/BF00011314

Lemaire, G., Franzluebbers, A., Carvalho, P.C. de F., Dedieu, B., 2014. Integrated crop-livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric Ecosyst Environ 190, 4–8. https://doi.org/10.1016/j.agee.2013.08.009

Lima, L.D.O., Ongaratto, F., Dallantonia, E.E., Leite, R.G., Argentini, G.P., Fernandes, M.H.M.H.D.R., Reis, R.A., Vyas, D., Malheiros, E.B., 2023. N-fertilization of tropical pastures improves performance but not methane emission of Nellore growing bulls. J Anim Sci 101. https://doi.org/10.1093/jas/skac362

Liu, M., Zhu, G., Tian, Y., 2024. The historical evolution and research trends of life cycle assessment. Green Carbon 2, 425–437. https://doi.org/10.1016/j.greenca.2024.08.003

Luz, P.A.C., Andrighetto, C., Lupatini, G.C., Aranha, H.S., Trivelin, G.A., Mateus, G.P., Santos, C.T., Francisco, C. de L., Castilhos, A.M., Jorge, A.M., 2019. Effect of integrated crop-livestock systems in carcass and meat quality of Nellore cattle. Livest Sci 220, 83–92. https://doi.org/10.1016/j.livsci.2018.11.018

Macedo, M.C.M., 2009. Crop and livestock integration: the state of the art and the near future. Revista Brasileira de Zootecnia 38, 133–146. https://doi.org/10.1590/S1516-35982009001300015

Magalhães, C.A.S., Pedreira, B.C., Tonini, H., Farias Neto, A.L., 2019. Crop, livestock and forestry performance assessment under different production systems in the north of Mato Grosso, Brazil. Agroforestry Systems 93, 2085–2096. https://doi.org/10.1007/s10457-018-0311-x

Maia, S.M.F., Ogle, S.M., Cerri, C.E.P., Cerri, C.C., 2009. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. Geoderma 149, 84–91. https://doi.org/10.1016/j.geoderma.2008.11.023

Marchão, R.L., Lavelle, P., Celini, L., Balbino, L.C., Vilela, L., Becquer, T., 2009. Soil macrofauna under integrated crop-livestock systems in a Brazilian Cerrado Ferralsol. Pesqui Agropecu Bras 44, 1011–1020. https://doi.org/10.1590/S0100-204X2009000800033

Mazzetto, A.M., Feigl, B.J., Schils, R.L.M., Cerri, C.E.P., Cerri, C.C., 2015. Improved pasture and herd management to reduce greenhouse gas emissions from a Brazilian beef production system. Livest Sci 175, 101–112. https://doi.org/10.1016/j.livsci.2015.02.014

MDIC. Ministério do Desenvolvimento, Indústria, Comércio e Serviços. **Carne bovina fresca, refrigerada ou congelada**. Brasil, 2025. Disponível em: https://comexstat.mdic.gov.br/pt/comex-vis/4/011. Acesso em: 21 jan. 2025

Monteiro, A., Barreto-Mendes, L., Fanchone, A., Morgavi, D.P., Pedreira, B.C., Magalhães, C.A.S., Abdalla, A.L., Eugène, M., 2024. Crop-livestock-forestry systems as a strategy for mitigating greenhouse gas emissions and enhancing the sustainability of forage-based livestock systems in the Amazon biome. Science of the Total Environment 906. https://doi.org/10.1016/j.scitotenv.2023.167396

Monteiro, R.C., Santos, C.A. dos, Rezende, C. de P., Pereira, J.M., Macedo, R. de O., Alves, B.J.R., Homem, B.G.C., Urquiaga, S., Zaman, M., Boddey, R.M., 2024. Impact of a forage legume or nitrogen fertilizer application on ammonia volatilization and nitrous oxide emissions in Brachiaria pastures. Rev Bras Cienc Solo 48. https://doi.org/10.36783/18069657rbcs20240012

Motasim, A.M., Samsuri, Abd.W., Nabayi, A., Akter, A., Haque, M.A., Abdul Sukor, A.S., Adibah, A.Mohd., 2024. Urea application in soil: processes, losses, and alternatives—a review. Discover Agriculture 2, 42. https://doi.org/10.1007/s44279-024-00060-z

Nilsson, M.S., Fiorio, P.R., Takushi, M.R.H., Oliveira, A.K. da S., Garcia, A.C., 2023. EFFECT OF DIFFERENT NITROGEN FERTILIZATION RATES ON THE SPECTRAL RESPONSE OF Brachiaria brizantha cv. MARANDÚ LEAVES. Engenharia Agrícola 43. https://doi.org/10.1590/1809-4430-eng.agric.v43n3e20220008/2023

Oliveira, D.M.S., Santos, R.S., Chizzotti, F.H.M., Bretas, I.L., Franco, A.L.C., Lima, R.P., Freitas, D.A.F., Cherubin, M.R., Cerri, C.E.P., 2024. Crop, livestock, and forestry integration to reconcile soil health, food production, and climate change mitigation in the Brazilian Cerrado: A review. Geoderma Regional 37. https://doi.org/10.1016/j.geodrs.2024.e00796

Oliveira, P.P.A., Bernardi, A.C.C., Pezzopane, J.R.M., Bosi, C., Júnior, F.P., Tadini, A.M., Martin-Neto, L., Rodrigues, P.H.M., 2024. Potential of integrated trees-pasture-based systems for GHG emission mitigation and improving soil carbon dynamics in the Atlantic forest biome, Southeastern of Brazil. European Journal of Agronomy 158, 127219. https://doi.org/10.1016/j.eja.2024.127219

Oliveira, D.C., Maia, S.M.F., Freitas, R. de C.A., Cerri, C.E.P., 2022. Changes in soil carbon and soil carbon sequestration potential under different types of pasture management in Brazil. Reg Environ Change 22. https://doi.org/10.1007/s10113-022-01945-9

Pereira, J.M., Rezende, C. de P., Ferreira Borges, A.M., Homem, B.G.C., Casagrande, D.R., Macedo, T.M., Alves, B.J.R., Cabral de Sant'Anna, S.A., Urquiaga, S., Boddey, R.M., 2020. Production of beef cattle grazing on Brachiaria brizantha (Marandu grass)—Arachis pintoi (forage peanut cv. Belomonte) mixtures exceeded that on grass monocultures fertilized with 120 kg N/ha. Grass and Forage Science 75, 28–36. https://doi.org/10.1111/gfs.12463

Pereira Neto, J.D., Dubeux, J.C.B., Ferreira Dos Santos, M.V., Da Silva Santos, E.R., Bretas, I.L., Jaramillo, D.M., Ruiz-Moreno, M., Rodrigues Da Cruz, P.J., Dantas Queiroz, L.M., Tembe Oduor, K., Araujo Bernardini, M., 2024. Herbage responses and animal performance of nitrogen-fertilized grass and grass-legume grazing systems. Journal of Agricultural Science. https://doi.org/10.1017/S0021859624000182

Peterson, C.A., Deiss, L., Gaudin, A.C.M., 2020. Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: A meta-analysis. PLoS One 15, e0231840. https://doi.org/10.1371/journal.pone.0231840

Pinto, A.C.J., Millen, D.D., 2019. Nutritional recommendations and management practices adopted by feedlot cattle nutritionists: The 2016 Brazilian survey. Can J Anim Sci 99, 392–407. https://doi.org/10.1139/cjas-2018-0031

Romanello, N., Barreto, A. do N., Sousa, M.A.P. de, Balieiro, J.C. de C., Brandão, F.Z., Tonato, F., Bernardi, A.C. de C., Pezzopane, J.R.M., Portugal, J.A.B., Garcia, A.R., 2023. Thermal comfort of Nelore (Bos indicus) and Canchim (Bos taurus x Bos indicus) bulls kept in an integrated crop-livestock-forestry system in a tropical climate. Agric Syst 209. https://doi.org/10.1016/j.agsy.2023.103687

Sarto, M.V.M., Borges, W.L.B., Sarto, J.R.W., Pires, C.A.B., Rice, C.W., Rosolem, C.A., 2020. Soil microbial community and activity in a tropical integrated crop-livestock system. Applied Soil Ecology 145. https://doi.org/10.1016/j.apsoil.2019.08.012

Sekaran, U., Lai, L., Ussiri, D.A.N., Kumar, S., Clay, S., 2021. Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review. J Agric Food Res 5, 100190. https://doi.org/10.1016/j.jafr.2021.100190

Sousa, H.M., Correa, A.R., Silva, B.D.M., Oliveira, S.D.S., Campos, D.T.D.S., Wruck, F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the cerrado-amazonÔnia ecotone. Revista Caatinga 33, 9–20. https://doi.org/10.1590/1983-21252020v33n102rc

Souza de Sousa, C.E., Amaral Júnior, F.P., Cardoso, A. da S., Ruggieri, A.C., van Cleef, F. de O.S., de Pádua, F.T., Almeida, J.C. de C., 2024. Effects of integrating legumes or trees on soil C stock and organic matter dynamics in tropical grasslands. Applied Soil Ecology 202, 105560. https://doi.org/10.1016/j.apsoil.2024.105560

Telles, T.S., Bichel, A., Zanin, E., Pellini, T., Pontes, L. da S., 2024. Livestock Changes in Brazil and Sustainable Intensification Challenges. Agronomy 14. https://doi.org/10.3390/agronomy14102429

USDA. United States Department of Agriculture. **Livestock and Poultry: World Markets and Trade**. US, 2024. Disponível em: https://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf. Acesso em: 21 jan. 2025.

Weidema, B., 2000. Avoiding Co-Product Allocation in Life-Cycle Assessment. J Ind Ecol 4, 11–33. https://doi.org/10.1162/108819800300106366

CHAPTER 2 - CARBON FOOTPRINT ANALYSIS OF INTEGRATED SYSTEMS WITH LIFE CYCLE ASSESSMENT FOR SUSTAINABLE BEEF CATTLE PRODUCTION

2. INTRODUCTION

Brazil emitted approximately 2.29 GtCO$_2$-eq of greenhouse gases (GHGs) in 2023. Of this total, 27.49% originated from the agricultural sector (SEEG, 2025). Within this sector, enteric methane emissions accounted for 64.18%, a consequence of Brazil having the second-largest cattle herd in the world (USDA, 2025). Meanwhile, agricultural soil management was responsible for 29.75% of emissions, with emphasis on soybean and corn crops, which are of great economic and territorial importance in the country.

As a signatory to the Paris Agreement and having voluntarily committed to reducing its greenhouse gas emissions, Brazil, recently presented its Nationally Determined Contribution (NDC) during COP29. Among the main strategies announced to achieve this goal, the conversion of degraded areas into integrated systems, such as Integrated Crop-Livestock (iCL) and Integrated Crop-Livestock-Forest (iCLF) stands out. Currently, the country has around 164 million hectares designated for pasture activity, of which it is estimated that approximately 28 million are in a degraded state, but with agricultural potential for recovery and more efficient use (Bolfe *et al.*, 2024). Currently, Brazil has approximately 17 million hectares allocated to integrated systems. The national target is to expand this area by an additional 10 million hectares by the year 2030 (Reis *et al.*, 2025).

Integrated production systems in Brazil encompass a variety of arrangements and models tailored to regional conditions. Among the most established configurations are the soybean–corn–pasture–cattle system within iCL and the eucalyptus–soybean–corn–pasture–cattle system in iCLF (Balbino *et al.*, 2011; Magalhães *et al.*, 2019). These systems are characterized by the simultaneous or sequential production of multiple goods within the same area, which increases the complexity of GHG emission allocation, in other words, the process of determining the proportion of emissions attributable to each product, given their interdependent production dynamics. The soybean, corn, and beef produced in these systems are key sources of energy and protein for human nutrition. In this context, integrated systems have demonstrated higher efficiency in producing crude protein for human consumption per hectare when compared to monoculture systems (A. Monteiro *et al.*, 2024).

Nevertheless, there is a growing need to quantify emissions associated with each product generated within integrated systems. This demand stems primarily from how markets and certification mechanisms recognize and reward emission neutrality on a product-specific basis. In the case of beef, for instance, certification schemes already exist that require a precise understanding of the climate impact exclusively attributed to beef production (Lucchese-Cheung *et al.*, 2021). Life Cycle Assessment (LCA) emerges as a robust tool to address this challenge, particularly through the application of emission allocation strategies. Allocation is a methodologically complex process, often avoided due to the uncertainties and subjective choices it entails.

Agricultural practices, mainly fertilization, account for a significant impact on emissions in iCL and iCLF systems, contributing to the increased total emitted. In integrated systems, fertilizers are applied to high-demand crops, and pastures benefit from residual nutrients, enhancing productivity and animal performance (Bernardon *et al.*, 2021). This efficiency complicates emission accounting, as improper allocation may distort carbon footprint results by either overestimating cattle production impact or neglecting its role in overall emissions. However, allocation, in this case, is essential to more accurately reflect the reality of the distribution of impacts within integrated systems.

The LCA methodology was applied to evaluate the environmental sustainability of four distinct agricultural systems — Nominal, Grass-Legume Consortium, iCL, and iCLF — by estimating their carbon footprint. Three of these systems are strategic components of Brazil's governmental efforts to meet climate targets established under international agreements. The analysis was conducted in alignment with the guidelines of the IPCC.

3. MATERIAL AND METHODS

3.1 General Characterizations and Boundaries of the Systems

The life cycle analysis was performed in accordance with ISO 14040 and 14044 standards and guidelines, using the cradle-to-farm-gate approach (Figure 1). All four systems evaluated were based on the Central Brazil Tropical Climate macroregion (IBGE, 2002). The predominant climate classification, according to the Köppen classification, is Aw, characterized by dry winters and rainy summers. The predominant soils in the region are Ferralsols and Acrisols (FAO, 2004).

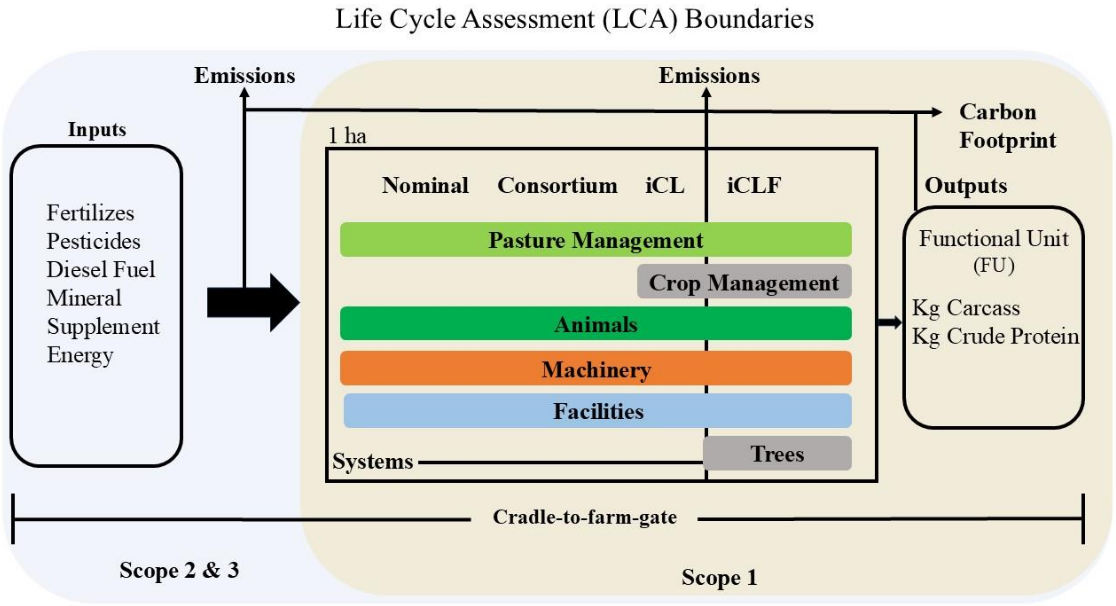

Figure 1 - Framework of system boundaries for the life cycle assessment. Diagram illustrating the framework of inputs, processes (pasture management, crops, animals, machines, facilities, and trees), emissions (Scopes 1, 2 and 3), and outputs (carcass and crude protein) across four systems, analyzed within the cradle-to-gate scope.

The four evaluated systems were Nominal, Grass-Legume Consortium, iCL, and iCLF. Common characteristics across all systems include the Nellore cattle breed and pastures of *Urochloa brizantha* cv. Marandu, Piatã, or Xaraes, a rearing-fattening system, entry age and weight, slaughter weight, mineral supplementation level, and carcass yield (CY). The time horizon considered for all systems was 10 years. The input parameters are detailed in Table 1. For the iCL and iCLF systems, the agricultural crops are commercially focused and intended for human consumption.

Enteric methane emissions, methane from manure, and nitrous oxide from dung and urine were estimated using the Tier 2 methodology (IPCC, 2019a). Emissions from the manufacturing processes of fertilizers and pesticides were estimated based on emission factors available in the literature. Emissions resulting from the application of nitrogen-based fertilizers were calculated using national emission factors. Fossil fuel combustion and electricity-related emissions were also accounted for. The IPCC recommends the use of national factors whenever possible to achieve a more accurate characterization of emissions (IPCC, 2019a).

The emissions were converted and presented as CO_2 equivalent (CO_2-eq). The conversion utilized the GWP factors over a 100-year horizon. The GWP values applied were 1 (CO_2), 27 (CH_4), and 273 (N_2O) (IPCC, 2023) Two functional units (FUs) were used: 1 kg of carcass and 1 kg of CP. The carbon footprint was expressed in kg CO_2-eq per kg of FU. All variables were expressed per hectare. Additionally, the land occupation footprint (m^2 kg FU^{-1}) was estimated (Table 1).

Table 3 - Components and annual average values for the four systems[1].

Variables	Unit	Nominal	Consortium	iCL	iCLF
Liming/fertilization					
Lime	kg/ha/year	0.0	500.0	720.0	720.0
Nitrogen	kg/ha/year	50.0	0.0	151.0	150.4
Phosphorus	kg/ha/year	0.0	42.0	112.0	58.0
Potassium	kg/ha/year	0.0	50.0	112.0	69.4
Herd/Performance					
Initial Body Weight*	kg	190	190	190	190
Final Body Weight	kg	510	510	510	510
Average daily gain	kg	0.35	0.636	0.733	0.522
AU[2]/ha	AU/ha	1	2.3	3.1	2.3
Slaughter time	months	30	17	15	20
Carcass Yield	%	52%	52%	52%	52%
Total Carcass	kg carcass/ha/year	104.42	569.25	874.76	327.05
Land Occupation	M^2 kg $Carc^{-1}$	124	27	19	31
Agriculture					
Soybean	bags/ha/harvest	0	0	72.4[3]	69[4]
Corn	bags/ha/harvest	0	0	62.3[3]	60[4]
Trees	trees/ha/10 years	0	0	0	332
Operational					
Diesel Fuel	Liters/ha/year	3.9	11.6	103.1	83.6
Electricity	Kwh/ha/year	0.0319	0.0319	0.0331	0.0331
Pesticides[5]	kg/ha/year	0.0	0.0	6.4	2.6

[1] Values calculated for a 10-year horizon; [2] AU – animal unit, 1 AU = 450 kg; [3] Spreadsheet S6 (Table 1 – corn, Table 2 – soybean); [4] Spreadsheet S6 (Table 3 – corn, Table 4 – soybean); [5] Spreadsheet S7; iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; *Weight at which the animals were acquired. Detailed information on references and calculations is available in Appendix 1 and 2 (Spreadsheet S1 – systems).

The values used were sourced from studies available in the literature. Detailed information is provided in the supplementary material appendix 1 (Spreadsheet S1 -

Systems) and 2. The data and calculations performed are also available in the supplementary material.

3.2 Description of systems

3.2.1 Nominal system

The nominal system used as a reference in this study refers to a production system formed exclusively by pasture. This system is characterized as a non-degraded pasture, without significant improvements such as high fertilizer doses, irrigation, or consortia. The management employed is considered simple, with little or no input from external resources. The grazing method and stocking rate are maintained according to the standards recommended for the species used. The expected animal performance in this system is sufficient to prevent weight loss and ensure animal health (Maia *et al.*, 2009b; Mazzetto *et al.*, 2015; Oliveira *et al.*, 2022). For this system, nitrogen fertilization of 50 kg of N per hectare per year in the form of urea was considered (Mazzetto *et al.*, 2015). The average daily weight gain of Nelore cattle produced in Central Brazil with similar fertilization levels is around 0.350 kg per day, and as a result, the animals in this system are expected to be slaughtered at 39 months of age (Braga *et al.*, 2020; Cardoso *et al.*, 2016; Mazzetto *et al.*, 2015).

3.2.2 Consortium system

The consortium of *Urochloa* spp. with legumes has been widely studied under the conditions of Central Brazil. Embrapa Acre has maintained a forage peanut germplasm bank since 2006, consisting of approximately 110 genotypes, primarily represented by *Arachis pintoi* (Azevedo *et al.*, 2014). For the system, a forage peanut (*Arachis pintoi*) was chosen, as it has shown good performance when intercropped with plants from the *Urochloa* genus (Homem *et al.*, 2021b, 2021a; Pereira *et al.*, 2020). Liming was performed with the application of 2,500 kg of dolomitic limestone every 5 years (Homem *et al.*, 2021b). During establishment, the following applications of phosphorus (P) and potassium (K) were considered: 60 kg P ha^{-1} $year^{-1}$ and 50 kg K ha^{-1} $year^{-1}$. In subsequent years, annual applications of 40 kg of P and 60 kg of K were considered (Longhini *et al.*, 2021). Nitrogen fertilization was not required, as forage peanuts, through biological nitrogen fixation, can fix amounts exceeding 100 kg N ha^{-1} (Carvalho *et al.*, 2019;

Miranda *et al.*, 2003). Pastures fertilized with doses above 90 kg N ha^{-1}, when well-managed, exhibit high production with quality (Delevatti *et al.*, 2019).

3.2.3 iCL system

For the evaluated system, soybean was sown in November and harvested in February, followed by the sowing of corn intercropped with forage in March, with the corn harvest occurring in June (Sekiya *et al.*, 2021). The application of herbicides and insecticides required for crop management, as well as those used for desiccation, was estimated based on data from the literature (Fritsch *et al.*, 2012; Luz *et al.*, 2019; Pariz *et al.*, 2017, 2011). Liming was performed triennially (2,400 kg ha^{-1} year^{-1}) throughout the 10-year evaluation period. The lime application rate was calculated to increase base saturation (BS) from 45% to 70%, adhering to the recommendations outlined in the Boletim 100 for soybean cultivation (Cantarella *et al.*, 2022). Detailed information on the fertilizer application rates for soybean and corn crops is provided in the supplementary material (Appendix 1 – Spreadsheet S1 Systems).

3.2.4 iCLF system

The iCLF system combines agricultural, livestock, and forestry components in either a consortium or succession arrangement. The eucalyptus hybrid selected for this system was *Eucalyptus urograndis* (*Eucalyptus grandis x Eucalyptus urophylla*). The trees configuration consisted of 166 trees/ha, with a spacing of 20 meters between rows and 2.5 meters between trees (Freitas *et al.*, 2023). To estimate the area occupied per eucalyptus tree, a width of 1 meter and the 2.5-meter spacing between trees were considered, resulting in an occupancy of 2.5 m^2 per tree. Overall, the trees occupied 4.1% of the total area. The harvested trees were utilized for furniture production, fencing, and livestock enclosures. Two cycles of five years were considered, aiming for optimal economic performance (Pacheco *et al.*, 2013). During the first 18 months, no animals were introduced into the integration areas, allowing for the establishment of soybean, corn, and *Urochloa spp.* to form ground cover. This initial animal-free phase was implemented to prevent damage to the trees. Livestock were introduced into the system at the end of corn harvesting in the second year, transitioning the area to a silvopastoral system until the tree harvest in the fifth year. The productivity of corn and soybean crops, as well as livestock performance, was based on averages reported in the literature and can be accessed in the supplementary material (Spreadsheet S1 Systems – Appendix 1). Between the first and fifth years, the areas received 150 kg N ha^{-1} annually. Over the 10-year evaluation period, the system received a cumulative total of 1,504 kg N ha^{-1}.

3.3 CH$_4$ emissions

3.3.1 Enteric fermentation

The calculation of enteric methane emissions followed the Tier 2 approach outlined in the IPCC guidelines (IPCC, 2019a). This method was selected due to the detailed herd characterization, the identification of enteric fermentation as a key category, and the significant contribution of cattle production to greenhouse gas emissions, making Tier 2 the most accurate approach, as recommended by the IPCC (IPCC, 2019a). The enteric methane emission factor was calculated using Equation 10.21 (1) from Chapter 10 of the IPCC (2019) guidelines. Equation (1) considers the gross energy (GE) requirements and is presented as follows:

$$EF_{CH4} = \frac{GE * \left(\frac{Ym}{100}\right) * 365}{55{,}65} \qquad (1)$$

Where:

EF_{CH4} = Methane emission factor (kg CH$_4$ head^{-1} year^{-1}),

GE = Gross energy intake (MJ head^{-1} day^{-1}); (GE was estimated with IPCC (2019) equation 10.16)

Y_m = Methane conversion factor (percentage of gross energy intake converted to methane),

55.65: Energy content of methane (MJ kg^{-1} CH$_4$),

365: Number of days in a year.

According to the IPCC, the estimation of GE requires the live weight of the animals, diet digestibility (DE), mature weight, and ADG. Thus, a Ym of 7% was used, as indicated by the IPCC for beef cattle fed with more than 72% forage and digestibility

≥ 62% (IPCC, 2019a). For the total enteric methane production over the 10 years, the value of animals produced during the period was multiplied by the emission factor.

3.3.2 Manure CH_4

Methane emissions from manure were calculated using the IPCC Tier 2 approach. To estimate the CH_4 emission factor from manure, it is necessary to calculate the total volatile solids (VS) produced. VS refers to the organic material excreted by animals, consisting of both biodegradable and non-biodegradable fractions (IPCC, 2019a). VS was calculated using equation 10.24 (2) (Chapter 10, IPCC, 2019). The calculation requires the DE, GEI, and mineral matter (MM) of the diet. The emission factor was determined using equation 10.23 (3) (Chapter 10, IPCC, 2019).

$$VS = \left[GE \cdot \left(1 - \frac{DE}{100}\right) + (UE \cdot GE)\right] \cdot \left[\frac{1 - ASH}{18.45}\right] \qquad (2)$$

$$EF_{(T)} = \left(VS_{(T)} \cdot 365\right)\left[B_{0(T)} \cdot 0.67 \cdot \sum_{S,k}\left(\frac{MCF_{(S,k)}}{100} \cdot AWMS_{(T,S,k)}\right)\right] \quad (3)$$

Where:

VS = volatile solid excretion per day on a dry-organic matter basis, kg VS day^{-1}

GE = gross energy intake, MJ day^{-1}

DE = digestibility of the feed in percent (e.g., 60%)

UE • GE = urinary energy expressed as fraction of GE (typically 0.04 GE for most ruminants; 0.02 GE for high-grain diets or swine)

ASH = ash content of feed, fraction of dry matter intake (e.g., 0.06 for sows; country-specific values preferred)

18.45 = conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}), constant across most forage and grain-based livestock feeds.

$EF_{(T)}$ = annual CH_4 emission factor for livestock category *T*, kg CH_4 $animal^{-1}$ yr^{-1}

$VS_{(T)}$ = daily volatile solid excreted for livestock category *T*, kg dry matter $animal^{-1}$ day^{-1}

365 = basis for calculating annual VS production, days yr^{-1}

$B0_{(T)}$ = maximum methane producing capacity for manure produced by livestock category T, m^3 CH_4 kg^{-1} of VS excreted

0.67 = conversion factor of m^3 CH_4 to kilograms CH_4

$MCF_{(S,k)}$ = methane conversion factors for each manure management system S by climate region k, percent

$AWMS_{(T,S,k)}$ = fraction of livestock category T's manure handled using animal waste management system S in climate region k, dimensionless

3.4 N_2O emissions

3.4.1 Manure N_2O

Direct and indirect N_2O emissions from manure were considered. Additionally, emissions were calculated using national emission factors, as recommended by the IPCC (2019a). Nitrogen intake rates were calculated using equation 10.32 (4) (Chapter 10, IPCC, 2019). Nitrogen excretion rates in urine and dung were calculated separately using equations 5 and 6, respectively (Laura Franco *et al.*, 2023), Subsequently, the sum of nitrogen excretions was used to determine nitrogen retention by the animal. Nitrogen retention was obtained as the difference between total nitrogen intake and total nitrogen excretion. The equations used to estimate nitrogen excretion through urine and dung are described below:

$$N_{intake(T)} = \frac{GE}{18.45} \cdot \left(\frac{\frac{CP\%}{100}}{6.25} \right) \qquad (4)$$

$$Nexc\ urine\ (g\ day^{-1}) = 3{,}26 + (3{,}68 * DMI) + (0{,}18 * NI) \qquad (5)$$

$$Nexc\ dung_{(g\ day^{-1})} = 2{,}55 + (0{,}048 * BW) - (3{,}47 * 4{,}40) + (0{,}30 * NI) \qquad (6)$$

Where:

$N_{intake(T)}$ = nitrogen intake rate for livestock category T (kg N $animal^{-1}$ day^{-1})

GE = gross energy intake, MJ day^{-1}

CP% = crude protein content of the feed as a percentage of dry matter
18.45 = conversion factor for dietary gross energy per kg of dry matter (MJ kg^{-1})
6.25 = conversion factor to estimate nitrogen from crude protein (since 1 g of N ≈ 6.25 g of CP).
DMI = Dry matter intake (kg $head^{-1}$ day^{-1}),
NI = Nitrogen intake (g $head^{-1}$ day^{-1}),
BW = Body weight (kg $head^{-1}$).

Direct N_2O emissions were calculated using the following emission factors for dung and urine, respectively: 0.725% and 0.405%. These values represent the average of two years of assessment (Cardoso *et al.*, 2019). The volatilization rates of nitrogen excreted as ammonia (NH_3) were 10.2% for urine and 6% for dung. These rates were calculated as the average between the rainy and dry seasons (Cardoso *et al.*, 2019). Additionally, 24% of the excreted nitrogen was considered leached (IPCC, 2019a). Indirect N_2O emissions included those derived from leaching and volatilization, with 1% of NH_3 being converted to N_2O and 1.1% of leached nitrogen emitted as N_2O (IPCC, 2019a). Direct and indirect emissions were calculated for both dung and urine. The total N_2O emissions from excreta were obtained by summing the direct and indirect emissions.

3.4.2 N_2O from nitrogen fertilization and crop residues

Emissions from urea application were calculated similarly to those from excreta. For direct N_2O emissions, an emission factor of 0.85% was used (Cardoso *et al.*, 2019). To estimate indirect emissions, 17% of the applied nitrogen was volatilized as NH_3 (Cardoso *et al.*, 2019) and 24% was leached (IPCC, 2019b). The N_2O emission factors for volatilized and leached nitrogen were the same as those used for excreta. N_2O emissions associated with nitrogen released into the soil through the processes of mineralization and biological nitrogen fixation were calculated for the residues of soybean, corn, forage peanut, and *Urochloa* spp., considering both aboveground and belowground residues. The amount of nitrogen that returned to the soil through residues and biological fixation was calculated using equation 11.6 (7) (IPCC, 2019b). One percent of the returned nitrogen was emitted as N_2O (IPCC, 2019b). It was assumed that all residues deposited in the soil were decomposed within one year (A. Monteiro *et al.*, 2024).

$$F_{CR} = \sum_T \left\{ \left[AGR_{(T)} \cdot N_{AG(T)} \cdot \left(1 - \mathrm{Frac}_{\mathrm{Remove}(T)} - \left(\mathrm{Frac}_{\mathrm{Burnt}(T)} \cdot C_f\right)\right)\right] + \left[BGR_{(T)} \cdot N_{BG(T)} \right] \right\}$$
$$AGR_{(T)} = AG_{DM(T)} \cdot \mathrm{Area}_{(T)}$$
$$BGR_{(T)} = \left(\mathrm{Crop}_{(T)} + AG_{DM(T)}\right) \cdot RS_{(T)} \cdot \mathrm{Area}_{(T)} \cdot \mathrm{Frac}_{\mathrm{Renew}(T)} \qquad (7)$$
$$AG_{DM(T)} = \mathrm{Crop}_{(T)} \cdot R_{AG(T)}$$

Where:

F_{CR} = annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually, kg N yr^{-1}

$AGR_{(T)}$ = annual total amount of above-ground crop residue for crop *T*, kg d.m. yr^{-1}

$N_{AG(T)}$ = N content of above-ground residues for crop *T*, kg N (kg d.m.)$^{-1}$

$\mathrm{Frac}_{\mathrm{Remove(T)}}$ = fraction of above-ground residues of crop *T* removed annually for purposes such as feed, bedding and construction, dimensionless.

$\mathrm{Frac}_{\mathrm{Burnt(T)}}$ = fraction of annual harvested area of crop *T* burnt, dimensionless

C_f = combustion factor (dimensionless)

$BGR_{(T)}$ = annual total amount of below-ground crop residue for crop *T*, kg d.m. yr^{-1}

$N_{BG(T)}$ = N content of below-ground residues for crop *T*, kg N (kg d.m.)$^{-1}$

$AG_{DM(T)}$ = Above-ground residue dry matter for crop *T*, kg d.m. ha^{-1}

$\mathrm{Crop}_{(T)}$ = harvested annual dry matter yield for crop *T*, kg d.m. ha^{-1}

$R_{AG(T)}$ = ratio of above-ground residue dry matter to harvested yield for crop *T*, kg d.m. ha^{-1} (kg d.m. ha^{-1})$^{-1}$

$\mathrm{Area}_{(T)}$ = total annual area harvested of crop *T*, ha yr^{-1}

$\mathrm{Frac}_{\mathrm{Renew(T)}}$ = fraction of total area under crop *T* that is renewed annually, dimensionless.

$RS_{(T)}$ = ratio of below-ground root biomass to above-ground shoot biomass for crop *T*, kg d.m. ha^{-1} (kg d.m. ha^{-1})$^{-1}$

T = crop or forage type

3.5 CO_2 emissions

The CO_2 emission sources considered were: the manufacturing of fertilizers and herbicides; limestone reaction; fossil fuel combustion (diesel); and electricity production and consumption. The emission factors (kg CO_2 kg product^{-1}) for the manufacturing of urea, triple superphosphate, and KCl were 0.97, 0.38, and 0.45, respectively (Ledgard and Falconer, 2019). The emission factor for limestone production was 0.45 kg CO_2 (IPCC, 2006). The emission factors for herbicides and pesticides were 26.63 kg CO_2 and 18.9 kg CO_2, respectively (Audsley *et al.*, 2009). The emission factor for diesel production and combustion was 3.2 kg CO_2 per liter (Carvalho, 2011), and 340 kg CO_2 per MWh for electricity production and consumption (BRASIL, 2024). Emissions resulting from the limestone reaction in the soil were calculated with an emission factor of 0.13 kg CO_2 per kg of limestone (IPCC, 2006). It was considered that 0.164 kg of CO_2 is emitted per kg of mineral supplement produced (Cardoso *et al.*, 2016).

3.6 Cumulative Production of Human-Edible Crude Protein

The production of beef carcasses and grains of soybean and corn was converted to human-edible CP (Table 2). For each system, the CP production was expressed in kg of CP per hectare (ha). For the calculations, the following average protein content values were considered for each product: 250 g per kg of carcass (Costa e Silva *et al.*, 2014), 119.6 g per kg of corn (Mittelmann *et al.*, 2011) and 400 g per kg of soybean (Silva *et al.*, 2006). Subsequently, the CP values were adjusted using the Digestible Indispensable Amino Acid Score (DIAAS), with values for beef, soybean, and corn being 121%, 98%, and 48%, respectively (Adhikari *et al.*, 2022).

Table 4 - Cumulative production of kilograms of animal, vegetable and total Crude Protein produced per ha in 10 years by the different evaluated systems.

Crude protein	Nominal	Consortium	iCL	%	iCLF	%
kg CP vegetal[1]	0	0	18990.1	87.8%	5697.04	85.2%
kg CP animal[2]	315.88	1721.99	2646.2	12.2%	989.33	14.8%
CP total/system	315.88	1721.99	21636.29		6686.37	

[1] Percentage of CP in Soybean= 40% (Silva *et al.,* 2006), Corn = 10,96% (Mittelmann *et al.,*2011); [2] Percentage of CP in Nellore beef carcass = 25% (Costa e Silva *et al.*, 2014); CP values were corrected using the Digestible Indispensable Amino Acid Score (DIABS) = Beef – 121%; Soybean – 98% and Corn – 48% (Adhikari *et al.,* 2022); iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed information of the calculations is available in Appendix 1 (Spreadsheet S6 – Table 8).

3.7 Emissions allocation

Mass allocation was used for the integrated crop-livestock (iCL) and integrated crop-livestock-forestry (iCLF) systems. The total mass output of the agricultural crops and the beef carcass was estimated. The fraction of the total mass output corresponding to the beef carcass was used as the emission allocation factor. This was done by dividing the amount of carcass mass produced by the total mass produced in the system, as described by (Michiels *et al.*, 2021). The emissions from the following agricultural processes were allocated to the beef carcass: fertilizer manufacturing, pesticide manufacturing, fertilization emissions, crop residue emissions, and diesel emissions. Formula (4) below exemplifies the calculation used:

$$Emc = Egrains * \left(\frac{kg\ beef}{kg\ total\ scb}\right) * 100 \quad (4)$$

where:

E_{mc} = Emissions from soybean and corn allocated to beef (kg CO_2-eq),

E_{grains} = Total emissions resulting from the production of soybean and corn crops (Emissions result from the manufacturing of fertilizers and pesticides, fertilization, crop residues, fuel combustion, and electricity consumption),

Kg_{beef} = Production (kg of carcass) produced per hectare,

kg $total_{scb}$ = Total mass production (soybean, corn and beef - scb).

4. RESULTS AND DISCUSSION

4.1.1 Productive performance of the systems

Among the evaluated systems, a considerable disparity was observed when considering the systems, which enhances the comparative discussion. The differences in animal performance were attributed to the specificities of each system, including management practices, system composition, and the integration strategies adopted. Consequently, productivity was directly influenced by these factors.

The system that produced the most kilograms of carcass during the 10 years was the iCL system, in contrast, the one that produced the least was the nominal system (Table 1). The differences regarding total carcass production are directly linked to the ADG and the stocking rate (AU ha^{-1}) of each system. In iCL systems, the integration of annual crops with different cultivars of *Urochloa brizantha* has shown a synergistic effect in several aspects (Dias *et al.*, 2022). Forage in the iCL system uses the residual effects of fertilization for more demanding crops. In addition, forage is planted annually and is desiccated to become cover for annual crops. Such processes promote greater vigor and quality of pastures, thus resulting in better animal performance (Dias *et al.*, 2022; Magalhães *et al.*, 2019). The lower productive values of the nominal system are directly linked to the lower stocking rate and lower ADG. Nominal pastures receive little or no fertilization, management is simple and there are no intense improvements.

The iCLF system was the second system with the lowest carcass production (Table 1). During the period of tree establishment, the animals did not enter the system, so they remained there for only seven years. In addition, a lower ADG reduced the number of production cycles within the system. The interrelationships among the different components of the iCLF system make it inherently complex. The presence of trees, for instance, increases the shaded area over the pastures. However, C4 forages, such as those of the *Urochloa* genus used in this study, require high levels of solar radiation; otherwise, biomass production is reduced, limiting forage availability, which results in a lower stocking rate and reduced ADG (Oliveira *et al.*, 2014). The winter in Central Brazil, where the systems are located, is characterized by dry conditions and a shorter photoperiod, which also poses challenges to forage and animal production, as observed by Magalhães *et al.*, (2019).

Unlike the other systems, the consortium system is the only one that did not receive nitrogen fertilizer application (Table 1). Alongside the nominal system, it is also one of the only systems with restricted cattle production. The consortium system produced 464.83 kg of carcass ha^{-1} more than the Nominal system and 305.51 kg of carcass ha^{-1} less than the iCL system, making it the second-highest system in terms of carcass yield per hectare. Although *Arachis pintoi* can fix considerable amounts of nitrogen, nitrogen fertilization with synthetic fertilizers remains the most common practice (Homem *et al.*, 2021b, 2021a). However, animals grazing on pastures fertilized with nitrogen fertilizers excrete higher amounts of nitrogen, leading to increased N_2O emissions (Homem *et al.*, 2021a), as discussed further below. Due to the practicality of using urea, large quantities can be applied per hectare, which intensifies N_2O emissions (Amaral *et al.*, 2016; Delevatti *et al.*, 2019).

There was a slight variation in grain productivity between the iCL and iCLF systems (Table 1). This difference is attributed to a 4.1% reduction in productivity due to the area occupied by trees, totaling 412 m^2. Over 10 years, the iCL system produced a higher quantity of grains per hectare, totaling 43,425 kg of soybean and 37,400 kg of corn, while the iCLF system produced, over 4 years, 16,675 kg of soybean and 14,361 kg of corn. In integrated systems with tree components, success depends on the proper management of trees, as they exert both positive and negative effects on other components (Sarto *et al.*, 2020). The shade generated by trees, along with competition for water and nutrients, can hinder the development of other crops and reduce productivity (Camargo *et al.*, 2023; Magalhães *et al.*, 2019; Pezzopane *et al.*, 2020). However, in the present study, it was unnecessary to account for a reduction in grain productivity in the iCLF system, as soybean and corn were grown during the first two years of each cycle when shading had not yet become a challenge for the plants. Franchini *et al.*, (2014), when evaluating the effects of eucalyptus trees on soybean productivity, observed a reduction only starting in the third year (-2.9%), reaching a 27% reduction in the fourth year. Similarly, Magalhães *et al.*, (2019) assessed the impact of different systems on soybean and corn productivity. They reported a decrease in soybean productivity in the iCLF system, which only started in the fourth year (18.2%). On the other hand, corn in the same system showed a 19% reduction in the third year, reaching a 37% reduction in the fourth year.

4.2 CH_4, N_2O and CO_2 emissions

4.2.1 CH_4 emissions

The CH_4 emissions from the four systems result from livestock production, specifically from enteric fermentation and emissions derived from dung (Table 3). The iCL system presented the highest cumulative CH_4 emissions, directly associated with its higher stocking rate. On the other hand, the iCL system also produced the highest amount of carcass weight over the 10 years evaluated. The iCLF system was the second-lowest in CH_4 emissions compared to the consortium and iCL systems. This lower emission volume is explained by the shorter grazing period of animals in the system (7 years) and the lower ADG. Another important factor is the emission factor per animal estimated using the Tier 2 method, where the lowest emission factor was observed in the iCLF system (83.9 kg CH_4 animal^{-1} year^{-1}). Monteiro *et al.*, (2024) evaluated different enteric methane prediction models and concluded that all models overestimate emissions, including the one used in this study. Overestimating emissions increases the perceived impact of cattle production in the context of climate change but ensures that actual emissions are accounted for without underestimation. Nevertheless, more data is needed to improve the precision and accuracy of these estimates. Additional information on enteric methane emissions from the systems is available in the supplementary material (Appendix 1 – Spreadsheet S3).

Table 5 - Cumulative CH_4 emissions (kg $^{-1}$ ha $^{-1}$) over 10 years

CH_4	Nominal	Consortium	iCL	iCLF
Enteric[1]	419.00	1974.76	3264.28	1035.26
Dung[2]	27.72	108.46	179.29	56.86
Total	446.72	2083.23	3443.57	1092.12

[1] Spreadsheet S3 – Estimated by equation 10.21 (Chapter 10 - IPCC, 2019a); Calculation of Gross Energy required to estimate enteric CH_4 emissions = Spreadsheet S2; [2] Spreadsheet S4 – Total solids excreted = equation 10.24 (Chapter 10 - IPCC, 2019a), CH4 Emission Factor from dung = equation 10.23 (Chapter 10 - IPCC, 2019a) (Table 1); iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed information on all factors and variables required for the respective estimates is detailed in the Spreadsheets mentioned above in Appendix 1.

LCA studies evaluating the environmental impact of beef production in Brazil have demonstrated that CH_4 is the gas that contributes the most to the carbon footprint within these systems (Cardoso *et al.*, 2016; Costa *et al.*, 2018; Figueiredo *et al.*, 2017; Mazzetto *et al.*, 2015; A. Monteiro *et al.*, 2024). In the present study, CH_4 accounted for more than 65% of total CO_2-eq emissions in the Nominal, Consortium, and iCL systems.

However, in the iCLF system, CH_4 contributed only 51.95% of total emissions (Table 4). Overall, there is a greater balance among the three gases evaluated, when converted to CO_2-eq, in the ICLF system. Unlike the iCL system, in the iCLF system, the temporal distribution of crops does not follow a continuous flow where all years are the same. In this arrangement, the first year and a half are dedicated exclusively to soybean and corn cultivation, as well as tree growth; therefore, there are no CH_4 emissions resulting from livestock production during this period. The contribution (%) of CH_4 to total emissions in the iCLF system contrasts with the results reported by Monteiro *et al.*, (2024), where 68.6% of the system's total emissions were attributed to CH_4. Part of this discrepancy can be explained by variations in productive variables and conversion factors for CH_4 and N_2O to CO_2-eq. In the study by Monteiro *et al.*, (2024), the iCLF system had the highest stocking rate among the four systems evaluated. Additionally, the ADG reported by the authors was 0.700 g, which is significantly higher than the value used in the present study. The conversion factors for CO_2-eq adopted here were CH_4 (27) and N_2O (273). On the other hand, Monteiro *et al.*, (2024) used 28 for CH_4 and 265 for N_2O.

Table 6 - CH4, N2O, and CO2 emissions expressed in tons (t) of CO2-eq per ha in 10 years for the four evaluated. The intensity scale (Low, Moderate, High, and Very high) is the weight of each gas emitted in relation to the different systems. The percentage shown is the ratio of each gas within each system.

System	CH_4 emission	N_2O emission	CO_2 emission	Observations
Nominal	**Low** (12t), the lowest among the systems (65.39% of the system's total emissions)	**Low** (4.5t) (26.23% of the total)	**Low** (1.5t) (8.38% of the total)	Maintains low emissions per hectare due to lower productive intensity.
Consortium	**High** (56.2t), approximately four times higher than Nominal (82.34% of the total))	**Low** with a slight reduction (5.8t) compared to Nominal (8.53% of the total)	**Moderate** (6.2t) (9.13% of the total)	Higher CH_4 and CO_2 emissions compared to Nominal while keeping N_2O lower than iCL and iCLF.
iCL	**Very high** (92.9t), the highest among all systems (71.92% of the total)	**High** (17.9t), almost five times higher than Nominal and Consortium (13.88% of the total)	**Very high** (18.3t) (14.20% of the total)	The greatest impact per hectare is due to the system's higher intensity.
iCLF	**Moderate** (29.4t), lower than Consortium and ICL (51.95% of the total)	**Moderate** (13.7t), reduced compared to ICL (24.27% of the total)	**High** (13.4t) (23.78% of the total)	Shows a better balance among the emissions of the three gases analyzed.

CH_4 emissions – Spreadsheets S3 e S4; N_2O emissions – Spreadsheet S5 (Table 2); Spreadsheet S8 (Tables 2 e 3); CO_2 emissions – Spreadsheet S8 (Table 2); Spreadsheet S9 (Tables 2 e 3); Spreadsheet S10 (Tables 1 e 2). iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed information on emission factors and references is available in the respective Spreadsheets mentioned above located in Appendix 1.

The annual enteric methane emissions per animal were as follows: Nominal (106.41 kg CH_4), Consortium (92.00 kg CH_4), iCL (98.96 kg CH_4), and iCLF (83.95 kg CH_4). The result for the ICLF system closely aligns with that reported by Monteiro *et al.*, (2024), at 80.9 kg CH_4. However, for the iCL system, a more pronounced discrepancy was observed, with Monteiro *et al.* (2024) reporting 81.4 kg CH_4. When evaluating different metrics for enteric methane emissions, it is essential to consider their inverse relationships (Beauchemin *et al.*, 2022). For instance, while the iCL system exhibits higher absolute emissions compared to the Consortium and iCLF systems, it demonstrates superior performance when analyzed using the emission intensity metric (kg CH_4 kg product^{-1}).

4.2.2 N_2O emissions

N_2O accounts for 69% of the net global anthropogenic GHG emissions from the Agriculture, Forestry, and Other Land Use (AFOLU) sector. Agricultural soils are identified as the primary contributors due to the use of nitrogen fertilizers, the application of manure to crops, and the deposition of excreta on pastures, which represent the main pathways (Nabuurs *et al.*, 2023). In livestock systems, N_2O emissions are associated with the processes of nitrification and denitrification, which are complexly influenced by biological and environmental variables (Barnard *et al.*, 2005).

Over the 10 years evaluated, the iCL system exhibited the highest N_2O emissions per hectare, followed by the iCLF system (Table 5). An average of 151.0 and 150.4 kg N ha^{-1} year^{-1} was assumed for the iCL and iCLF systems, respectively (Table 1). Consequently, nitrogen fertilization contributed 40.67% and 52.75% of the N_2O emissions in the iCL and iCLF systems, respectively. Data reported in the literature show variability regarding this metric of the relationship between nitrogen fertilization and N_2O emissions. For instance, in the iCLF system evaluated by de Figueiredo *et al.* (2017), N_2O emissions from nitrogen fertilization accounted for 44% of the total emissions of this gas. Conversely, Monteiro *et al.*, (2024), reported significantly lower values: 35% in the iCL system and 34% in the iCLF system. It is important to note that the systems evaluated exhibit distinct characteristics that contribute to data variability. However, in the Consortium system, emissions attributed to nitrogen fertilization were null since no urea was applied in this system. In contrast, in the Nominal system, due to the lower volume of excreta resulting from the reduced number of animals, the application of 50 kg urea ha^{-1} year^{-1} was sufficient to account for 67.01% of the total N_2O emissions.

Total N_2O emissions from excreta (dung + urine) accounted for 4.0%, 5.4%, 4.2%, and 3.2% of the total GHG emissions in the Nominal, Consortium, iCL, and iCLF systems, respectively. The lower values observed in the integrated systems may be associated with the greater diversity of emission sources and the proportional contribution of each. Similar findings were reported by Monteiro *et al.*, (2024), where excreta emissions represented 3.4% and 2.9% of the total GHG emissions in the respective systems. Conversely, excreta emissions in the iCLF system evaluated by de Figueiredo *et al.*, (2017), represented 7%, a higher value than those reported previously. This difference can be attributed to the use of a fixed value of 40 kg N excreted per animal per year. However, nitrogen excretion is highly complex and depends on numerous variables (Laura Franco *et al.*, 2023).

Table 7 - Cumulative N2O emissions (kg $^{-1}$ ha $^{-1}$) over 10 years.

N_2O	Nominal	Consortium	iCL	iCLF
Dung[1]	0.99	3.19	5.41	1.62
Urine[1]	1.71	8.98	14.25	4.96
Ureia[2]	8.85	0.0	26.72	26.62
Residues[3]	6.18	9.12	19.33	17.26
Total	17.73	21.36	65.71	50.46

[1] Spreadsheet S5 - N excreted in urine and dung (Table 1); Direct and indirect emissions from excreta (Table 2); Emission factors, ammonia volatilization and N leaching (Table 3); [2] Spreadsheet S8 – Emission factors of N2O resulting from urea application, ammonia volatilization, and leaching (Table 1); Emission calculations (Table 2); [3] Spreadsheet S8 – Annual quantity of crop residues returning to the soil (above and below ground) and annual quantity of N returning to the soil were calculated using equation 11.6 (Chapter 11 – IPCC, 2019b); iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed calculations are available in Table 4.

Figueiredo *et al.*, (2017) did not specify whether indirect emissions from NH_3 volatilization were included in their analysis, and they also did not account for nitrogen leaching. In the present study, a volatilization rate of 10.25% and 6% of the nitrogen applied via urine and dung, respectively, was assumed, with 1% of these amounts emitted as N_2O. According to IPCC (2019b), approximately 11% of the applied nitrogen is leached, of which 1.1% is emitted as N_2O. Detailed information on the N_2O calculation methods is available in the supplementary material (Appendix 1 – Spreadsheet S5). Finally, it is recommended to use distinct emission factors for dung and urine, as there are significant differences in both emission factors and the amount of nitrogen excreted, as demonstrated in the present study (Lessa *et al.*, 2014).

N_2O emissions from crop residues were calculated for corn, soybean, *Urochloa* spp., and forage peanut crops. Specific data were used to estimate the production of residue and N that returned to the soil from soybean and corn crops. The genus *Urochloa* spp. was considered a non-nitrogen-fixing species, while for forage peanuts, data from nitrogen-fixing forages were used (IPCC, 2019b). Information regarding the calculations and data is available in the supplementary material (Appendix 1 – Spreadsheet S8). In this context, N_2O emissions resulting from the decomposition of crop residues had a significant impact in all systems, especially in the integrated system systems, iCL and iCLF (Table 5). The productivity of each crop was used as a basis to estimate the amount of nitrogen returned to the soil via residues, which explains the greater differences observed in the integrated systems. Additionally, emissions associated with the residues of pastures in the animal-based production systems (Nominal and Consortium) were also estimated, unlike other studies that chose not to calculate these emissions or limited the analysis to crops (Beauchemin *et al.*, 2010; Cardoso *et al.*, 2016; Costa *et al.*, 2018; Figueiredo *et al.*, 2017; A. Monteiro *et al.*, 2024). While crop residues provide numerous benefits to the soil, such as maintaining fertility and structure, they also represent a significant source of N_2O emissions. Strategies to mitigate N_2O emissions from crop residues may have negative effects on other important soil attributes, such as reduced soil organic carbon (SOC), decreased productivity, and increased nutrient leaching, among others (Abalos *et al.*, 2022).

4.2.3 CO_2 emissions

Cattle production systems based exclusively on pastures exhibit lower CO_2 emissions. However, as these systems experience intensification processes, either through pasture improvement, increased supplementation levels, or integration with other crops, a higher CO_2 emission is observed (Beauchemin *et al.*, 2010; Cardoso *et al.*, 2016; Dick *et al.*, 2015; Figueiredo *et al.*, 2017; Mazzetto *et al.*, 2015; A. Monteiro *et al.*, 2024).

The iCL and iCLF systems emitted higher amounts of CO_2 per hectare, associated with the increased need for input usage (Table 6). Fertilizer manufacturing was the primary source of CO_2 emissions across all evaluated systems (Table 6).

Soils in the Central Brazil region are characterized as acidic and with low availability of nutrients such as nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) (Lopes and Guimarães Guilherme, 2016), which is why they require more frequent acidity correction and fertilization.

In the iCL and iCLF systems, fossil fuel combustion was the second-largest source of CO_2 emissions, contributing 17.98% and 19.82%, respectively. This is due to the higher number of machine hours required for fertilization, planting, pesticide application, harvesting, and tree cutting, which have a significant impact on both grain and tree production systems. Cerri *et al.* (2024) reported that CO_2 accounted for 99% of greenhouse gas (GHG) emissions in three farms producing soy and corn, while CH_4 and N_2O represented the smallest fraction of emissions. The authors identified that the main contributing sources were the use of synthetic fertilizers (26%) and fossil fuel combustion

(18%). Moreover, Scope 1, which includes emissions generated within the farm, was the largest source of GHG emissions, followed by Scope 3, which considers emissions from the manufacturing sector of inputs. According to Giusti *et al.*, (2023), the high demand for larger volumes of pesticides for corn and soybean crops can also represent a significant portion of CO_2 emissions. In the Nominal and Consortium systems, no pesticides were used; however, pesticide manufacturing in the iCL and iCLF systems accounted for 9.1% and 4.9% of CO_2 emissions, respectively (Table 6).

Table 8 - CO2 emissions (kg ha $^{-1}$ year $^{-1}$) resulting from the manufacture of fertilizers, pesticides, and mineral supplements; liming, fossil fuel combustion, and electricity consumption estimated for 10 years.

CO_2	Nominal	Consortium	iCL	iCLF
Fertilizers[1]	1077.78	3819.00	10359.42	8658.99
Pesticides[1]	0.0	0.0	1675.17	670.03
Suplement[2]	235.70	1284.89	1974.48	442.93
Limig[3]	0.0	650.00	936.00	936.00
Diesel Fuel[2]	123.68	371.04	3299.78	2675.01
Energy[2]	108.46	108.46	112.54	112.54
Total	1545.62	6233.39	18357.40	13495.49

[1] Spreadsheet S9 – Limestone, N, P, and K manufacturing (Table 2); Pesticides (Table 3);[2] Spreadsheet S10 – Mineral supplement manufacturing (Table 2); Emissions from diesel and electricity (Table 1); [3] Spreadsheet S8 - Emissions associated with limestone reaction after application (Table 2). iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed information about calculations and emission factors is in Appendix 1 in the respective Spreadsheets cited above.

The reduction of CO_2 emissions in the agricultural chain can be achieved through strategies such as optimizing the manufacturing processes of fertilizers and pesticides, using electric machinery and equipment, applying low concentrations of fertilizers, and proper management of agricultural residues. These measures can have a significant impact on the sustainability of different production systems (Cerri *et al.*, 2024; Northrup *et al.*, 2021; Scala Júnior *et al.*, 2012). Additionally, the adoption of integrated cropping, crop rotation, and system diversification (Northrup *et al.*, 2021) stand out as promising alternatives to mitigate the environmental impacts of these systems. Figure 2 summarizes the emissions from the four systems and the main emitting sources.

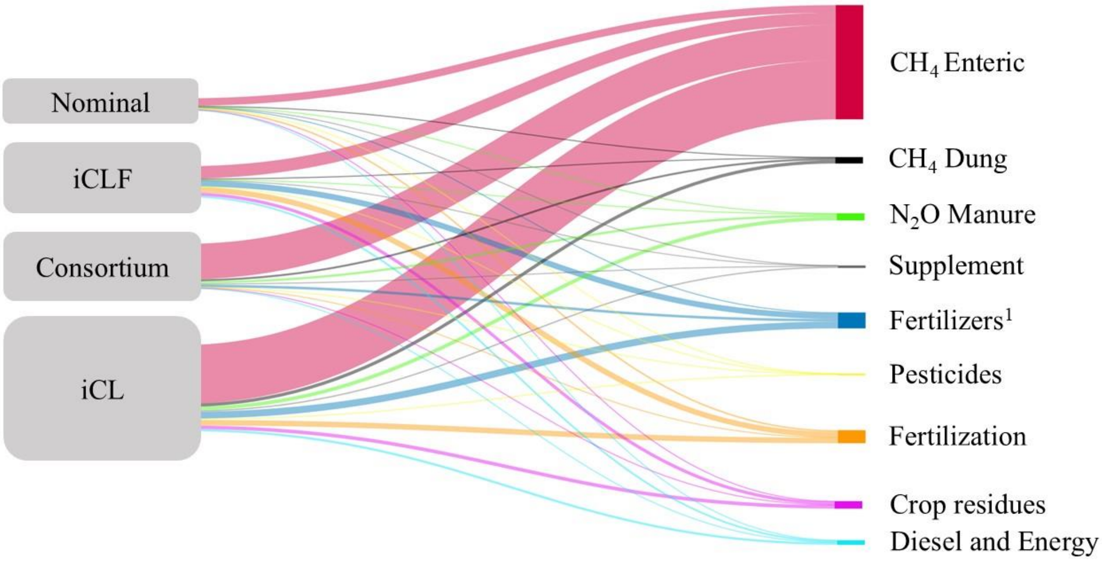

Figure 2 - Total Greenhouse Gases (GHG) emissions in kg of CO_2-eq. by the four systems evaluated over 10 years, as well as the flow of emissions by emitting sources.1 Manufacturing emissions. Abbreviations: iCL – integrated crop-livestock; iCLF – integrated crop-livestock; iCLF – integrated crop-livestock-forest.

4.3 Carbon Footprint of Beef Carcass and Crude Protein

The Consortium and iCLF systems exhibited the lowest carbon footprints per kg of carcass produced when allocation was used (Table 7). Both systems are approximately 40% more efficient when compared to the Nominal system. Without the use of allocation, the iCLF system becomes less efficient than the Nominal system. The difference between the values with and without allocation in the integrated systems, especially in the iCLF (10.43 vs. 17.35), indicates that the allocation of emissions among products plays a relevant role and must be carefully considered, particularly in analyses intended to inform public policies or management practices. For example, Monteiro *et al.* (2024) evaluated the carbon footprint of the bovine carcass in integrated systems (iCL and CLF), however, without using allocation. The results reported by these authors are similar to those found in the present study without the use of allocation. On the other hand, Figueiredo *et al.* (2017), when assessing the carcass carbon footprint in an iCLF system, reported a result well above that found in our study. These authors also did not allocate the emissions.

Table 9 - Carbon Footprint per kg of Beef Carcass, per kg of Plant and Animal Crude Protein, and Emissions per Hectare in four Cattle Production Systems.

System	Carcass		Crude Protein Footprint		Total emissions *(t CO_2-eq ha^{-1} 10 $years^{-1}$)*
	With*	Without*	Vegetal	Animal	
	kg CO_2-eq kg $carcass^{-1}$		*kg CO_2-eq kg CP^{-1}*		
Nominal	17.66	17.66	-	54.49	17.2
Consortium	10.73	10.73	-	34.37	59.1
iCL	11.79	14.78	1.34	39.25	129.2
iCLF	10.43	17.35	3.94	36.00	46.1

* With and without allocation; iCL – integrated crop-livestock; iCLF – integrated crop-livestock-forest; Detailed information on all factors and variables required for the respective estimates is detailed in the Spreadsheets mentioned above in Appendix 1. An allocation procedure was also employed to calculate the carbon footprint per kg of animal and plant crude protein. A detailed description of this methodology is provided in Appendix 2.

The carbon footprint values (CO2eq kg $carcass^{-1}$) estimated for different beef cattle production systems employing diverse strategies have shown substantial variability (Cardoso *et al.*, 2016; Dick *et al.*, 2015; Figueiredo *et al.*, 2017; Mazzetto *et al.*, 2015; A. Monteiro *et al.*, 2024). Generally, more intensive systems tend to exhibit lower carbon footprints (Cardoso *et al.*, 2016; Mazzetto *et al.*, 2015), as can be seen in Table 7, where the most intensive systems had a smaller carbon footprint. However, the carbon footprint of the Nominal scenario, considered the least intensive system, was lower than that of more productive scenarios reported by various authors (Cardoso *et al.*, 2016; Dick *et al.*, 2015; Figueiredo *et al.*, 2017; Mazzetto *et al.*, 2015). These discrepancies can be attributed to the use of older data reported by the IPCC, as well as differences in emission factors and global warming potential metrics employed in the analysis.

The Consortium System had the lowest carbon footprint per kg of animal protein, followed by the iCL and iCLF systems. These values are lower than those found by Monteiro *et al.* (2024) when evaluating the carbon footprint in bovine production systems. Regarding the carbon footprint per kg of plant protein produced by the iCL and iCLF systems, the values are significantly lower than those for animal protein. Overall, when assessing the intensity of total crude protein (plant + animal) production, the carbon footprint per kg of CP was 5.97 and 8.49 for iCL and iCLF, respectively. Despite the higher carbon footprint of protein produced in systems based exclusively on pastures, it is important to highlight the crucial role these systems play in non-arable areas. In these regions, they allow the conversion of forage with no direct nutritional value for humans into high-biological-value protein (Fernandes *et al.*, 2022).

Moreover, it is important to diversify protein production per hectare. The output of multiple products provides greater productive and economic security for the producer in the event of a pest outbreak or intense climatic variation. Along with that, Concerns about global food security have increased as the worldwide population elevates its demand for energy and protein. Simultaneously, discussions about the sustainability of plant- and animal-based protein production have gained prominence, especially considering the continuous changes in protein consumption patterns (Flachowsky *et al.*, 2017; Torres *et al.*, 2024). In this context, the FAO projects steady growth in plant- and animal-protein production by 2050 (FAO, 2018). Therefore, Brazil, with its diverse integrated systems, can contribute to ensuring global food security in an era of climate change.

5. CONCLUSIONS

LCA is a crucial tool in the pursuit of more sustainable systems and products. This study provided a detailed analysis considering three functional units (FU: kg of beef carcass, crude protein). Among the systems evaluated, the consortium system stood out with one of the lowest carbon footprints per FU of carcass produced, due to its lower N_2O emissions. The integrated systems (iCL and iCLF) showed the lowest carbon footprint based on the FU of crude protein produced. The use of national factors integrated with the IPCC guidelines for emission prediction and carbon footprint calculation underscores the relevance of the reported analyses. The study also highlights the importance of allocation methods in the analysis of more complex systems, as they may bias the data. Encouraging the adoption of sustainable systems is already part of Brazil's goals to reduce GHG emissions, although the complexity of managing such systems remains a challenge. However, further investigation into the interrelationships between various organisms—such as nutrient absorption, nitrogen fixation, and utilization, as well as symbiotic and allelopathic effects, is necessary. Such clarifications can be used as inputs for future LCAs, facilitating allocation calculations and carbon footprint estimations.

Acknowledgements

The author acknowledges the financial support provided by Coordination of Superior Level Staff Improvement- Brazil (CAPES).

6. REFERENCES

Abalos, D., Recous, S., Butterbach-Bahl, K., De Notaris, C., Rittl, T.F., Topp, C.F.E., Petersen, S.O., Hansen, S., Bleken, M.A., Rees, R.M., Olesen, J.E., 2022. A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues. Science of the Total Environment 828. https://doi.org/10.1016/j.scitotenv.2022.154388

Adhikari, S., Schop, M., de Boer, I.J.M., Huppertz, T., 2022. Protein Quality in Perspective: A Review of Protein Quality Metrics and Their Applications. Nutrients. https://doi.org/10.3390/nu14050947

Amaral, G.A., David, D.B., Gere, J.I., Savian, J. V., Kohmann, M.M., Nadin, L.B., Chopa, F.S., Bayer, C., Carvalho, P.C.F., 2016. Methane emissions from sheep grazing pearl millet (Penissetum americanum (L.) Leeke) swards fertilized with increasing nitrogen levels. Small Ruminant Research 141, 118–123. https://doi.org/10.1016/j.smallrumres.2016.07.011

Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Cranfield.

Azevedo, J.M.A., Assis, G.M.L., Saggin Junior, O.J., Azevedo, H.S.F. da S., 2014. Richness and frequency of species of arbuscular mycorrhizal fungi in forage peanut genotypes in Acre, northern Brazil. Acta Amazon 44, 157–168. https://doi.org/10.1590/S0044-59672014000200001

Balbino, L.C., Cordeiro, L.A.M., Porfírio-da-Silva, V., Moraes, A. de, Martínez, G.B., Alvarenga, R.C., Kichel, A.N., Fontaneli, R.S., Santos, H.P. dos, Franchini, J.C., Galerani, P.R., 2011. Evolução tecnológica e arranjos produtivos de sistemas de integração lavoura-pecuária-floresta no Brasil. Pesqui Agropecu Bras 46. https://doi.org/10.1590/S0100-204X2011001000001

Barnard, R., Leadley, P.W., Hungate, B.A., 2005. Global change, nitrification, and denitrification: A review. Global Biogeochem Cycles. https://doi.org/10.1029/2004GB002282

Beauchemin, K.A., Henry Janzen, H., Little, S.M., McAllister, T.A., McGinn, S.M., 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. Agric Syst 103, 371–379. https://doi.org/10.1016/j.agsy.2010.03.008

Beauchemin, K.A., Ungerfeld, E.M., Abdalla, A.L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C., Berndt, A., Mauricio, R.M., McAllister, T.A., Oyhantçabal, W., Salami, S.A., Shalloo, L., Sun, Y., Tricarico, J., Uwizeye, A., De Camillis, C., Bernoux, M., Robinson, T., Kebreab, E., 2022. Invited review: Current enteric methane mitigation options. J Dairy Sci 105, 9297–9326. https://doi.org/10.3168/jds.2022-22091

Bernardon, A., Simioni Assmann, T., Brugnara Soares, A., Franzluebbers, A., Maccari, M., de Bortolli, M.A., 2021. Carryover of N-fertilization from corn to pasture in an integrated crop-livestock system. Arch Agron Soil Sci 67, 687–702. https://doi.org/10.1080/03650340.2020.1749268

Bolfe, É.L., Victoria, D. de C., Sano, E.E., Bayma, G., Massruhá, S.M.F.S., de Oliveira, A.F., 2024. Potential for Agricultural Expansion in Degraded Pasture Lands in Brazil Based on Geospatial Databases. Land (Basel) 13. https://doi.org/10.3390/land13020200

Braga, G.J., Ramos, A.K.B., Carvalho, M.A., Fonseca, C.E.L., Fernandes, F.D., Fernandes, C.D., 2020. Liveweight gain of beef cattle in Brachiaria brizantha pastures and mixtures with *Stylosanthes guianensis* in the Brazilian savannah. Grass and Forage Science 75, 206–215. https://doi.org/10.1111/gfs.12473

Camargo, D., Fallgatter, J., Barreto, G.U., Behling, M., de Souza, A.L., Lange, A., 2023. Effect of thinning eucalyptus trees on soybean productivity in integrated crop-livestock-forestry systems. Ciencia Rural 53. https://doi.org/10.1590/0103-8478cr20220202

Cantarella, H., Quaggio, J.A., Mattos Jr, D., Boaretto, R.M., Raij, B. V., 2022. BOLETIM 100: RECOMENDAÇÕES DE ADUBAÇÃO E CALAGEM PARA O ESTADO DE SÃO PAULO. Campinas.

Cardoso, A. S., Oliveira, S.C., Janusckiewicz, E.R., Brito, L.F., Morgado, E. da S., Reis, R.A., Ruggieri, A.C., 2019. Seasonal effects on ammonia, nitrous oxide, and methane emissions for beef cattle excreta and urea fertilizer applied to a tropical pasture. Soil Tillage Res 194. https://doi.org/10.1016/j.still.2019.104341

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I. das N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agric Syst 143, 86–96. https://doi.org/10.1016/j.agsy.2015.12.007

Carvalho, C.H.R., 2011. Emissões relativas de poluentes do transporte motorizado de passageiros nos grandes centros urbanos brasileiros.

Carvalho, L.R., Pereira, L.E.T., Hungria, M., Camargo, P.B., Da Silva, S.C., 2019. Nodulation and biological nitrogen fixation (BNF) in forage peanut (Arachis pintoi) cv. Belmonte subjected to grazing regimes. Agric Ecosyst Environ 278, 96–106. https://doi.org/10.1016/j.agee.2019.02.016

Cerri, C.E.P., Damian, J.M., Alves, P.A., Cerri, D.G.P., Cherubin, M.R., 2024. On-farm greenhouse gas emissions and soil carbon stocks of a soybean–maize system. Nutr Cycl Agroecosyst 128, 309–324. https://doi.org/10.1007/s10705-024-10356-7

Costa e Silva, L.F., Valadares Filho, S.C., Chizzotti, M.L., Rotta, P.P., Zanetti, D., Valadares, R.D.F., Detmann, E., 2014. Models to predict muscle tissue and crude protein in beef cattle. Livest Sci 160, 186–193. https://doi.org/10.1016/j.livsci.2013.11.031

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Viñas, R.S., de Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J Clean Prod 171, 1460–1471. https://doi.org/10.1016/j.jclepro.2017.10.063

Delevatti, L.M., Cardoso, A.S., Barbero, R.P., Leite, R.G., Romanzini, E.P., Ruggieri, A.C., Reis, R.A., 2019. Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. Sci Rep 9. https://doi.org/10.1038/s41598-019-44138-x

Dias, M.B. de C., Costa, K.A. de P., Severiano, E. C., Bilego, U.O., Vilela, L., de Souza, W.F., de Oliveira, I.P., da Silva, A.C.G., 2022. Cattle performance with Brachiaria and Panicum maximum forages in an integrated crop-livestock system. Afr J Range Forage Sci 39, 230–243. https://doi.org/10.2989/10220119.2021.1901311

Dick, M., Da Silva, M.A., Dewes, H., 2015. Mitigation of environmental impacts of beef cattle production in southern Brazil - Evaluation using farm-based life cycle assessment. J Clean Prod 87, 58–67. https://doi.org/10.1016/j.jclepro.2014.10.087

FAO. 2004. Fertilizer use by crop in Brazil. Chapter 2 – Soils and Climate. Rome, 2024. Available in: https://www.fao.org/4/y5376e/y5376e06.htm. (Accessed: 10 out. 2024).

FAO. 2018. The future of food and agriculture – Alternative pathways to 2050. Rome, 2024. Available in: https://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/. (Accessed: 07 dez. 2024).

Fernandes, M.H.M.R., Cardoso, A.S., Lima, L.O., Berça, A.S., Reis, R.A., 2022. Human-edible protein contribution of tropical beef cattle production systems at different levels of intensification. Animal 16. https://doi.org/10.1016/j.animal.2022.100538

Figueiredo, E.B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., La Scala, N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J Clean Prod 142, 420–431. https://doi.org/10.1016/j.jclepro.2016.03.132

Flachowsky, G., Meyer, U., Südekum, K.H., 2017. Land use for edible protein of animal origin—A review. Animals. https://doi.org/10.3390/ani7030025

Franchini, J.C., Antonio Balbinot Junior, A., Sichieri, F.R., Debiasi, H., Conte, O., 2014. Yield of soybean, pasture and wood in integrated crop-livestock-forest system in Northwestern Paraná state, Brazil 1 Rendimento de soja, forragem e madeira em sistema integração lavoura-pecuária-floresta no Noroeste do Paraná 1006–1013.

Freitas, I.C., Ferreira, E.A., Alves, M.A., de Oliveira, J.C., Frazão, L.A., 2023. Growth, nodulation, production, and physiology of leguminous plants in integrated production systems. Agrosystems, Geosciences & Environment 6. https://doi.org/10.1002/agg2.20343

Fritsch, L.F. de A., Carvalho, M.A.C., Dallacort, R., Santos, C., 2012. Soil preparation and forage sowing time for crop-livestock integration in corn culture. Bragantia 71, 424–429. https://doi.org/10.1590/S0006-87052012005000039

Giusti, G., Galo, N.R., Tóffano Pereira, R.P., Lopes Silva, D.A., Filimonau, V., 2023. Assessing the impact of drought on carbon footprint of soybean production from the life cycle perspective. J Clean Prod 425. https://doi.org/10.1016/j.jclepro.2023.138843

Homem, B.G.C., de Lima, I.B.G., Spasiani, P.P., Borges, L.P.C., Boddey, R.M., Dubeux, J.C.B., Bernardes, T.F., Casagrande, D.R., 2021a. Palisadegrass pastures with or without nitrogen or mixed with forage peanut grazed to a similar target canopy height. 2. Effects on animal performance, forage intake and digestion, and nitrogen metabolism. Grass and Forage Science 76, 413–426. https://doi.org/10.1111/gfs.12533

Homem, B.G.C., de Lima, I.B.G., Spasiani, P.P., Ferreira, I.M., Boddey, R.M., Bernardes, T.F., Dubeux, J.C.B., Casagrande, D.R., 2021b. Palisadegrass pastures with or without nitrogen or mixed with forage peanut grazed to a similar target canopy height. 1. Effects on herbage mass, canopy structure and forage nutritive value. Grass and Forage Science 76, 400–412. https://doi.org/10.1111/gfs.12532

IPCC, 2023. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity, in: Climate Change 2021 – The Physical Science Basis. Cambridge University Press, pp. 923–1054. https://doi.org/10.1017/9781009157896.009

IPCC, 2019a. Chapter 10: Emissions from livestock and manure management. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2019b. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2006. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application.

Laura Franco, P., Fernanda Helena Martins, C., Abmael da Silva, C., Ana Claudia, R., Mario Luiz, C., Igor Lima, B., Breno de Castro, S., Polyana Pizzi, R., Luiz Fernando Costa e, S., Sebastião de Campos, V.F., 2023. Prediction of nitrogen and phosphorus excretion for beef cattle, in: Nutrient Requirements of Zebu and Crossbred Cattle - BR-CORTE. Editora Scienza, pp. 321–338. https://doi.org/10.26626/978-85-8179-194-4.2023.c013.p.321-338

Ledgard, S., Falconer, S., 2019. Update of the carbon footprint of fertilisers used in New Zealand.

Lessa, A.C.R., Madari, B.E., Paredes, D.S., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Alves, B.J.R., 2014. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. Agric Ecosyst Environ 190, 104–111. https://doi.org/10.1016/j.agee.2014.01.010

Longhini, V.Z., Cardoso, A.S., Berça, A.S., Boddey, R.M., Reis, R.A., Dubeux, J.C.B., Ruggieri, A.C., 2021. Could forage peanut in low proportion replace N fertilizer in livestock systems? PLoS One 16. https://doi.org/10.1371/journal.pone.0247931

Lopes, A.S., Guimarães Guilherme, L.R., 2016. A career perspective on soil management in the Cerrado region of Brazil, in: Advances in Agronomy. Academic Press Inc., pp. 1–72. https://doi.org/10.1016/bs.agron.2015.12.004

Lucchese-Cheung, T., de Aguiar, L.K., Lima, L.C., Spers, E.E., Quevedo-Silva, F., Alves, F.V., Giolo de Almeida, R., 2021. Brazilian Carbon Neutral Beef as an Innovative Product: Consumption Perspectives Based on Intentions' Framework. Journal of Food Products Marketing 27, 384–398. https://doi.org/10.1080/10454446.2022.2033663

Luz, P.A.C., Andrighetto, C., Lupatini, G.C., Aranha, H.S., Trivelin, G.A., Mateus, G.P., Santos, C.T., Francisco, C. de L., Castilhos, A.M., Jorge, A.M., 2019. Effect of integrated crop-livestock systems in carcass and meat quality of Nellore cattle. Livest Sci 220, 83–92. https://doi.org/10.1016/j.livsci.2018.11.018

Magalhães, C.A.S., Pedreira, B.C., Tonini, H., Farias Neto, A.L., 2019. Crop, livestock and forestry performance assessment under different production systems in the north of Mato Grosso, Brazil. Agroforestry Systems 93, 2085–2096. https://doi.org/10.1007/s10457-018-0311-x

Maia, S.M.F., Ogle, S.M., Cerri, C.E.P., Cerri, C.C., 2009. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. Geoderma 149, 84–91. https://doi.org/10.1016/j.geoderma.2008.11.023

Mazzetto, A.M., Feigl, B.J., Schils, R.L.M., Cerri, C.E.P., Cerri, C.C., 2015. Improved pasture and herd management to reduce greenhouse gas emissions from a Brazilian beef production system. Livest Sci 175, 101–112. https://doi.org/10.1016/j.livsci.2015.02.014

Michiels, F., Hubo, L., Geeraerd, A., 2021. Why mass allocation with representative allocation factor is preferential in LCA when using residual livestock products as organic fertilizers. J Environ Manage 297. https://doi.org/10.1016/j.jenvman.2021.113337

Miranda, C.H.B., Vieira, A., Cadisch, G., 2003. Determination of biological nitrogen fixation by the forage groundnut (Arachis spp.) using the 15N natural abundance technique. Revista Brasileira de Zootecnia 32, 1859–1865. https://doi.org/10.1590/S1516-35982003000800008

Mittelmann, A., Miranda Filho, J.B. de, Nass, L.L., Lima, G.J.M.M. de, Hara-Klein, C., Silva, R.M. da, 2011. Quantitative variation for grain quality in Brazilian maize populations. Sci Agric 68, 50–56. https://doi.org/10.1590/S0103-90162011000100008

Monteiro, A., Barreto-Mendes, L., Fanchone, A., Morgavi, D.P., Pedreira, B.C., Magalhães, C.A.S., Abdalla, A.L., Eugène, M., 2024. Crop-livestock-forestry systems as a strategy for mitigating greenhouse gas emissions and enhancing the sustainability of forage-based livestock systems in the Amazon biome. Science of the Total Environment 906. https://doi.org/10.1016/j.scitotenv.2023.167396

Nabuurs, G.-J., R., Mrabet, A., Abu Hatab, M., Bustamante, H., Clark, P., Havlík, J., House, C., Mbow, K.N., Ninan, A., Popp, S., Roe, B., Sohngen, S., Towprayoon, 2023. Agriculture, Forestry and Other Land Uses (AFOLU), in: Climate Change 2022 - Mitigation of Climate Change. Cambridge University Press, Cambridge, pp. 747–860. https://doi.org/10.1017/9781009157926.009

Northrup, D.L., Basso, B., Wang, M.Q., Morgan, C.L.S., Benfey, P.N., 2021. Novel technologies for emission reduction complement conservation agriculture to achieve negative emissions from row-crop production. Proceedings of the National Academy of Sciences 118. https://doi.org/10.1073/pnas.2022666118

Oliveira, C.C., Villela, S.D.J., de Almeida, R.G., Alves, F.V., Behling-Neto, A., Martins, P.G.M. de A., 2014. Performance of Nellore heifers, forage mass, and structural and nutritional characteristics of Brachiaria brizantha grass in integrated production systems. Trop Anim Health Prod 46, 167–172. https://doi.org/10.1007/s11250-013-0469-1

Oliveira, D.C., Maia, S.M.F., Freitas, R. de C.A., Cerri, C.E.P., 2022. Changes in soil carbon and soil carbon sequestration potential under different types of pasture management in Brazil. Reg Environ Change 22. https://doi.org/10.1007/s10113-022-01945-9

Pacheco, A., De Queiroz Chaves, R., Maia, C., Nicoli, L., 2013. 4 Integration of Crops, Livestock, and Forestry: A System of Production for the Brazilian Cerrados.

Pariz, C.M., Andreotti, M., Azenha, M.V., Bergamaschine, A.F., Mello, L.M.M. de, Lima, R.C., 2011. Produtividade de grãos de milho e massa seca de braquiárias em consórcio no sistema de integração lavoura-pecuária. Ciência Rural 41, 875–882. https://doi.org/10.1590/S0103-84782011000500023

Pariz, C.M., Costa, C., Crusciol, C.A.C., Meirelles, P.R.L., Castilhos, A.M., Andreotti, M., Costa, N.R., Martello, J.M., Souza, D.M., Protes, V.M., Longhini, V.Z., Franzluebbers, A.J., 2017. Production, nutrient cycling and soil compaction to grazing of grass companion cropping with corn and soybean. Nutr Cycl Agroecosyst 108, 35–54. https://doi.org/10.1007/s10705-016-9821-y

Pereira, J.M., Rezende, C. de P., Ferreira Borges, A.M., Homem, B.G.C., Casagrande, D.R., Macedo, T.M., Alves, B.J.R., Cabral de Sant'Anna, S.A., Urquiaga, S., Boddey, R.M., 2020. Production of beef cattle grazing on Brachiaria brizantha (Marandu grass)—Arachis pintoi (forage peanut cv. Belomonte) mixtures exceeded that on grass monocultures fertilized with 120 kg N/ha. Grass and Forage Science 75, 28–36. https://doi.org/10.1111/gfs.12463

Pezzopane, J.R.M.E., Bonani, W.L., Bosi, C., Fernandes Da Rocha, E.L., De Campos Bernardi, A.C., Oliveira, P.P.A., De Faria Pedroso, A., 2020. Reducing competition in a crop-livestock-forest integrated system by thinning eucalyptus trees. Exp Agric 56, 574–586. https://doi.org/10.1017/S0014479720000162

Reis, J., Valentim, J., Wruck, F., Pereira, M., Coutinho, G., Rocha, L., 2025. Synthesis of economic results of integrated crop-livestock-forest-systems in Brazilian Amazon and Cerrado biomes.

Sarto, M.V.M., Borges, W.L.B., Sarto, J.R.W., Pires, C.A.B., Rice, C.W., Rosolem, C.A., 2020. Soil microbial community and activity in a tropical integrated crop-livestock system. Applied Soil Ecology 145. https://doi.org/10.1016/j.apsoil.2019.08.012

Scala Júnior, L., Figueiredo, D., Panosso, A.R., 2012. A review on soil carbon accumulation due to the management change of major Brazilian agricultural activities, Braz. J. Biol.

Sekiya, B.M.S., Lupatini, G.C., Andrighetto, C., De Oliveira Neves, F., Marangoni, G.A.O., Mulero, J., Lopes, R.M., 2021. Forage characteristics and beef cattle production in perennial pastures of BRS Paiaguás and BRS Piatã in integrated crop livestock system. Semina:Ciencias Agrarias 42, 2979–2992. https://doi.org/10.5433/1679-0359.2021v42n5p2979

Silva, M.S., Naves, M.M. V., Oliveira, R.B. de, Leite, O. de S.M., 2006. Composição química e valor protéico do resíduo de soja em relação ao grão de soja. Ciência e Tecnologia de Alimentos 26, 571–576. https://doi.org/10.1590/S0101-20612006000300014

Torres, P., Santos, E., Carvalho, S., Pereira, M., 2024. IMPACTS OF COVID-19 ON BRAZILIAN MEAT CONSUMPTION. Revista Baru - Revista Brasileira de Assuntos Regionais e Urbanos 10, e13191. https://doi.org/10.18224/baru.v10i1.13191