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Livestock and Climate

WHY AND HOW TO SCALE UP LOW-EMISSIONS BEEF IN BRAZIL, AND THE ROLE OF CARBON MARKETS

Insights for beef production in Latin America

Photo: Wenderson Araújo

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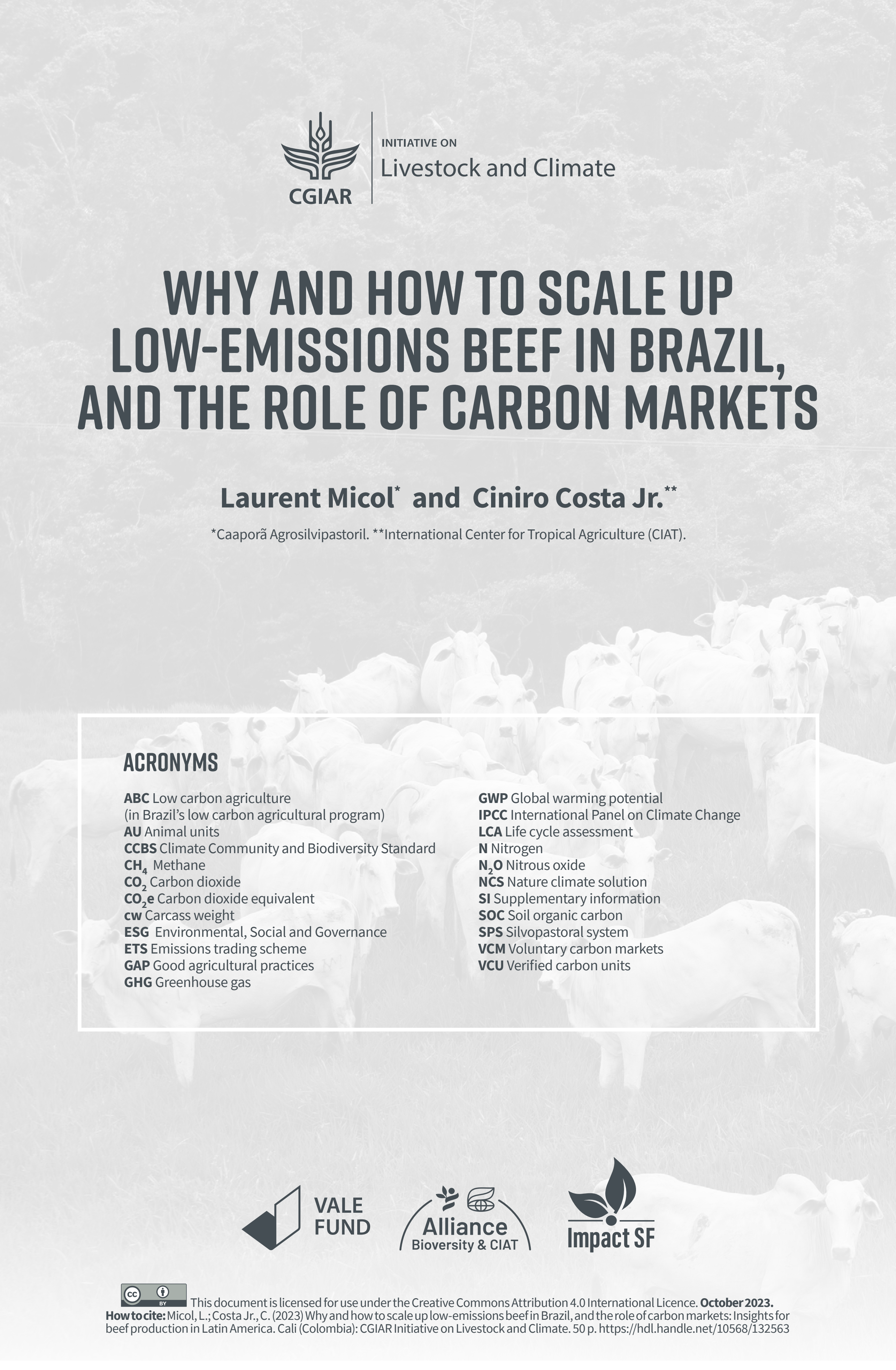

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WHY AND HOW TO SCALE UP LOW-EMISSIONS BEEF IN BRAZIL, AND THE ROLE OF CARBON MARKETS

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ACRONYMS

ABC	Low carbon agriculture (in Brazil's low carbon agricultural program)
AU	Animal units
CCBS	Climate Community and Biodiversity Standard
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
cw	Carcass weight
ESG	Environmental, Social and Governance
ETS	Emissions trading scheme
GAP	Good agricultural practices
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	International Panel on Climate Change
LCA	Life cycle assessment
N	Nitrogen
N_2O	Nitrous oxide
NCS	Nature climate solution
SI	Supplementary information
SOC	Soil organic carbon
SPS	Silvopastoral system
VCM	Voluntary carbon markets
VCU	Verified carbon units

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The CGIAR Research Initiative on Livestock and Climate is designed to address the challenges that climate change poses to livestock production, providing livestock-keeping communities with the support they need without accelerating greenhouse gas emissions or degrading land, water, and biodiversity. It forms part of CGIAR's new Research Portfolio, delivering science and innovation to transform food, land, and water systems in a climate crisis.

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EXECUTIVE SUMMARY

The beef value-chain is directly responsible for approximately 34% of global food systems' greenhouse gas emissions. Meanwhile, it also has the highest climate-change mitigation potential across food systems. In South America, a major beef-producing region, most of the mitigation potential lies in limiting land-use change (i.e., deforestation for agricultural land expansion) and in improving pasture management and animal feeding and breeding.

To realize this potential, a better understanding of how improved systems can contribute to reducing emissions is needed. Based on that, climate incentives must be put in place to overcome existing barriers and promote the dissemination of improved livestock projects. Since Brazil is pivotal in shaping the livestock sector's impact on climate, land, and livelihoods in the region, we used it as an example to investigate both a pathway for a transition to low-emissions beef production, and the role of voluntary carbon markets to support financing this transition.

Our analysis shows that adopting improved agricultural practices in beef cattle farms can deliver animal products with much lower emissions and land-use intensity. This generally involves sustainably intensifying production systems. In Brazil, improved (semi-intensive and intensive) livestock systems, compared to extensive systems, on average:

- **Increase herd productivity** (kg of carcass weight produced per animal unit) by **61-116%**;
- **Increase productivity per unit area** (kg of carcass weight produced per hectare of cattle-ranching system) by **220-640%**, and
- **Reduce emissions** intensity (kg of carbon dioxide equivalent (CO_2e) per kg of carcass weight produced) by **57-75%**.

Considering Brazil's current average emissions intensity of approximately 41 tCO_2e per ton of carcass produced, the scaling of improved systems could result in a 43% reduction in emissions intensity, reaching 55% when including changes in soil carbon stocks. Furthermore, since methane emissions are strongly reduced, the additional warming effect of such emissions over the next 20 years under a global warming potential star (GWP*) accounting system would be virtually zero with the adoption of an improved system. Furthermore, total emissions intensity under GWP* would drop by more than 80%, even with increases in emissions of other greenhouse gases such as nitrous oxide due to increased pasture fertilization. Notably, the realization of these results should be accompanied by reducing cattle herd size – a trend seen in regions with more intensive beef-cattle production.

These results illustrate the key importance of promoting large-scale implementation of pasture-based intensification with adequate production practices to create the conditions to reduce emissions while meeting growing global food demand.

A major barrier to the scaling of improved systems is, however, the size of the investment required, which can reach US$ 1,900 per ha in fixed assets (pasture improvements and ranch infrastructure), and up to US$ 4,000 per ha in working capital (cattle acquisition and production costs). Another related barrier is the risk-return relationship, as extensive cattle ranching is usually characterized as a low-risk, low return activity, while intensive systems are riskier due to higher input costs.

In this context, carbon-market incentives might be a game-changer for tackling those barriers. We applied a new methodology currently under development in the voluntary carbon market which uses output-based accounting to estimate the potential carbon revenues from a beef-cattle-intensification project in Brazil. We found that these carbon revenues in 10 years might represent from 42% (pessimistic scenario) to 126% (optimistic scenario) of the project's amount of investment in fixed assets – a very significant incentive to commit these investments. This indicates that voluntary carbon markets could be crucial for rapidly scaling cattle ranching intensification projects in Brazil.

BEEF & CLIMATE CHANGE: KEY POINTS

GLOBAL IMPACT

Beef value chain accounts for 34% of food systems emissions worldwide

MITIGATION POTENTIAL

Beef also has the highest mitigation potential across food value chains

SOUTH AMERICA FOCUS

Limiting deforestation, improving pasture and livestock management

IMPROVED PRACTICES

Boosting producticity shrinks land use and herd size and lowers emissions intensity

EMISSIONS REDUCTION SIZE

Improved production systems emit 55% less than Brazil's current average

POTENTIAL TO HALT WARMING

Reducing methane emissions might nullify the sector's warming effect

INVESTMENT CHALLENGE

High investment costs and risk-return issues are barriers to change

CARBON SUPPORT

Carbon revenues can significantly back beef cattle intensification projects

SUSTAINABLE PATH

Large-scale pasture changes meet global food needs while reducing emissions

INTRODUCTION

There is now a consensus that greenhouse gas (GHG) emissions from food systems and especially from beef-cattle production need to be tackled. It is also widely acknowledged that in regions where low-productivity systems are still prevalent, the improvement of production practices could achieve very significant emissions reductions along with other positive environmental (e.g., biodiversity) and economic outcomes (Roe et al., 2021; Gerber et al., 2021; Strassburg et al., 2014). This is the case in Brazil and other Latin-American countries, a region that produces more than a quarter of the global beef production (FAO, 2022). Many stakeholders believe that carbon markets (voluntary or compliance) could play a key role in accelerating this transition, as they remain the only global mechanism that attempts to valorize climate-change mitigation actions (ICC, 2021; Gerber et al., 2021).

Still, many questions remain as to how that can be achieved. This is due first to the complexity of the beef industry's emissions profile, which includes emissions from livestock, feed, fertilizer, fuel and energy inputs, as well as emissions and/or removals from soil carbon stock changes and deforestation/ reforestation. Moreover, some concerns have been raised regarding potential negative impacts of production intensification: Could intensification strategies lead to an increase in absolute emissions, despite the reduction in emissions intensity? Could the adoption of more profitable livestock systems create perverse incentives for the expansion of production and pasture areas instead of the intended reduction? Should we focus on reducing meat consumption (by promoting a plant-based diet), instead of trying to improve beef production?

In this context, the objective of this paper includes evaluating the importance of reducing emissions from pasture-based beef production through improved production practices in Brazil – a country recognized as one of the top five priority investment countries with potential to influence the livestock sector's impact on climate, land, and livelihoods across 132 low- and middle-income countries (Bonilla-Cedrez *et al.*, 2023). It also discusses the potential role of carbon markets, along with other potential climate-change management finance mechanisms, to stimulate the necessary changes in the beef sector. Since no compliance carbon market is yet established in Brazil, we focus on analyzing the voluntary carbon market. Furthermore, this analysis could provide important insights for similar large-scale, pasture-based production systems in other Latin American countries.

For that, we begin by reviewing existing literature on the role of sustainable livestock intensification in Brazil for global climate goals. Then, we examine GHG emissions quantification and assess the mitigation pontential of low-carbon cattle-grazing practices. Lastly, we explore a practical approach in the voluntary carbon market to support the shift towards low-emission, deforestation-free beef production in the region △

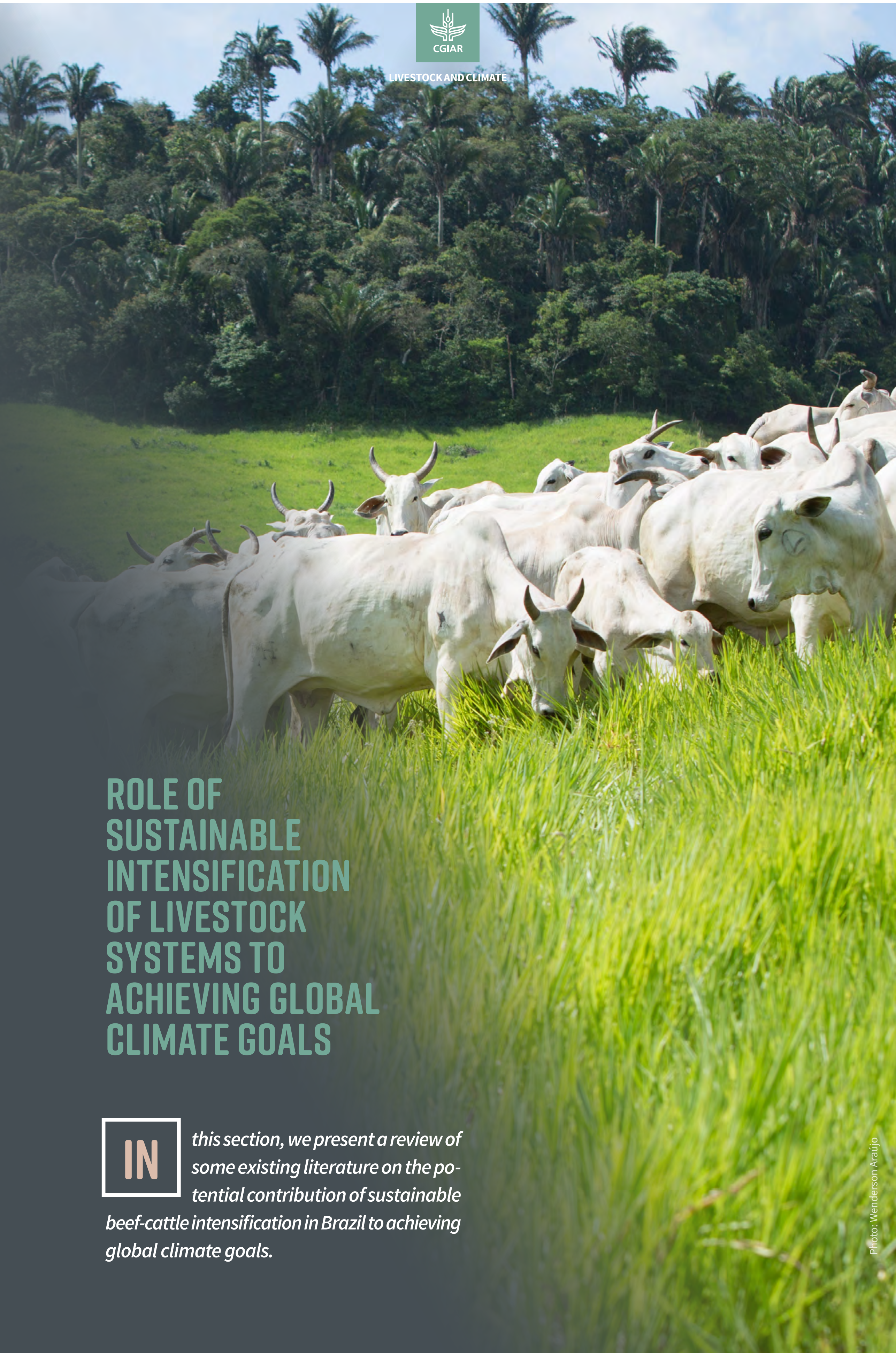


Photo: Wenderson Araújo

ROLE OF SUSTAINABLE INTENSIFICATION OF LIVESTOCK SYSTEMS TO ACHIEVING GLOBAL CLIMATE GOALS

IN this section, we present a review of some existing literature on the potential contribution of sustainable beef-cattle intensification in Brazil to achieving global climate goals.

IMPORTANCE OF IMPROVING CATTLE PRODUCTION PRACTICES IN BRAZIL

The Paris Agreement's goal of limiting the increase in global temperature to 1.5°C above pre-industrial levels can only be achieved with significant contributions from natural climate solutions – especially in food systems, including supply-side and demand-side measures, while strengthening food security and safety (IPCC, 2022; Roe *et al.*, 2021; Clark *et al.*, 2020, Conservation International, 2022).

LIVESTOCK AS A KEY PART OF THE PROBLEM – AND OF THE SOLUTION

Today, global food systems emit approximately 20.0 $GtCO_2e/y$ or one-third of global GHG emissions (Costa Jr *et al.*, 2022a; Tubielo *et al.*, 2022; Crippa *et al.*, 2021). Four food value-chains (beef, milk, rice, and maize) are responsible for nearly 65% of these emissions. The beef value-chain alone accounts for 34% of total food-system emissions (~7.0 $GtCO_2e$), being the most GHG emission-intensive across the food value-chain.

Beef production is projected to increase by about 40% by 2050 compared to today's levels (FAO, 2018; OECD-FAO, 2022). So, meeting the projected demand under current average production practices would increase emissions from the beef value-chain to about 11.0 $GtCO_2e/y$ (Costa Jr *et al.*, 2022a; FAO, 2022). This will also augment negative impacts on other environmental components (e.g., biodiversity and water) - a scenario that would put at risk global climate and environmental goals (IPCC, 2022; CBD, 2022).

On the other hand, although it is the most emission-intensive food value-chain, beef production also has the largest mitigation potential across food systems. Recent estimates show that by improving the efficiency of beef production with the adoption of existing technologies, emissions could be reduced by 70% compared to today's average values – from approximately 7.3 to 2.5 $GtCO_2e/y$ while meeting 2050 food demands (Costa Jr *et al.*, 2022).

HOW TO MITIGATE EMISSIONS AND INCREASE PRODUCTION IN THE LIVESTOCK SECTOR

Livestock management practices that promote mitigation of GHG emissions and enhance beef productivity include pasture management (i.e., recovery of degraded land and use of improved forage varieties, and rotational grazing), animal management (i.e., supplementary feeding and improved genetics and breeding techniques), and introduction of silvopastoral and agroforestry systems (Wang *et al.*, 2019; Kell, 2011; Rao *et al.*, 2001; Fisher *et al.*, 2007; Li *et al.*, 2022; Feliciano *et al.*, 2018).

These practices can enhance pasture net primary production and quality, and lead to greater soil carbon storage to the point it can exceed the level found in degraded pastures and even in native vegetation (Fisher *et al.*, 1996, 2007; Maia *et al.*, 2009; Carvalho *et al.*, 2009; Paulino *et al.*, 2016). These practices also tend to optimize feed quantity and quality, increasing feed conversion and system resilience. Furthermore, they have an especially marked effect on CH_4 emissions – the major GHG emitted by livestock systems, which is a short-lived climate pollutant – and thus could deliver a substantial short-term mitigation for beef-production climate impacts. A sustained ~0.35% annual decline in CH_4 emissions would be sufficient to avoid additional warming from the CH_4 emitted, which is analogous to an impact of net-zero CO_2 emissions (Costa Jr *et al.*, 2021).

POTENTIAL IMPACTS IN LATIN AMERICA AND BRAZIL

Thus, given the large impact on global emissions and the significant mitigation potential, beef-cattle emissions must be abated to reach global climate targets. This is especially true for Latin America (LATAM), the world's largest beef producing region, with 27% of global production (FAO, 2022). The region's production is still inefficient and strongly influenced by cattle herd growth and pasture area expansion, and beef productivity falls far short of its potential. One of the reasons is the large number of degraded areas across this region. According to the United Nation Convention to Combat Desertification (UNCCD) there are more than 2 billion hectares of degraded land in the world, of which 14% is in LATAM.

In this context, Brazil is a key actor. With the world's largest commercial cattle herd (~220 million heads) and approximately 160 Mha of pastures, the country produces approximately 10 Mt of beef annually, which represents 50% of LATAM's and 13% of the global beef production (USDA, 2022; LAPIG, 2021). The Brazilian beef-cattle value chain is also responsible for employing approximately 13 million people (IBGE, 2015) directly, and generated 7% of the country's GDP in 2021 (CEPEA/CNA 2022). But it also accounts for 25% of Brazil's direct GHG emissions, and for about 75% if land-use change due to converting forests to pastures is accounted for (SEEG, 2021). This relevance at global scale is reflected through the direct GHG emissions from Brazilian beef cattle (~400 $MtCO_2e/y$; SEEG, 2022), which represent almost 1% of global emissions.

As in most LATAM countries, beef production in Brazil is predominantly pasture-based. Although feedlot production has more than doubled in the last decade, it is predominantly used for finishing and accounts for less than 20% of Brazilian slaughters (Anualpec, 2022). From 1990–2020 the pasture area in Brazil increased by 17% (from 138 to 161 Mha, peaking at 174 Mha in 2007), the beef-cattle herd grew 62% (from ~130 to ~210 M heads), and beef production rose 99% (from 5.0 to 10.0 Mt carcass weight (cw)) (LAPIG, 2022; IBGE, 2022; USDA, 2022). Although productivity increased by 72% (from 36 to 62 kg of beef per ha per year) in the same period, it is still low, and the large area of degraded pastures, estimated at 90 Mha, is a key factor (IBGE, 2022; LAPIG, 2022). By adopting more efficient pasture- and animal-management practices in Brazil, beef productivity could exceed 200 kg of beef per ha per year, which is more than three times the current production rate (Cardoso *et al.*, 2016; Barbero *et al.*, 2021). With that, the industry could spare land for other uses – especially for Brazil's projected 9 Mha soybean expansion by 2030 (MAPA, 2021).

Therefore, making cattle ranching more productive is central to meeting future agricultural productivity demands and climate commitments, especially by focusing on expanding use of existing low-emission livestock practices and recovering degraded pastures (Garcia *et al.*, 2017; Strassburg *et al.*, 2014; Goldenberg *et al.*, 2014; BRASIL, 2015).

COMMON CONCERNS ABOUT LIVESTOCK INTENSIFICATION AND EMISSIONS REDUCTION

Adopting improved beef-production practices generally implies intensifying the production systems. Although there are substantial GHG emissions reductions attainable through this process (Roe *et al.*, 2021; Cusack *et al.*, 2021), it has been debatable whether:

- improving pasture conditions may rather increase the overall cattle herd and related GHG emissions instead of the intended reduction;
- higher economic returns from intensified systems could stimulate producers to expand land and eventually promote deforestation and even more emissions, thereby counteracting the mitigation benefits of improved production systems;
- the greater beef production needed to meet growing demand might outweigh the mitigation potential of improved production systems (Cusack *et al.*, 2021; Roe *et al.*, 2019; 2021; Clark *et al.*, 2020; Springmann *et al.*, 2018; Latawiec *et al.*, 2014; Tilman, *et al.*, 2014).

However, these arguments might not adequately consider the factors at play in the interactions between supply and demand, nor the criticality of the challenges related to beef production in the global food system.

First, the dependencies between supply and demand, and cost and price, need consideration. If pasture conditions and overall cattle ranching practices improve at scale, the projected demand for beef might be met using a much smaller area of land, and a significantly reduced cattle herd than current levels. However, if practices improve and the area and herd remain the same or even increase, total production would significantly exceed projected growth – but to meet what demand? The hypothesis that more production would imply more demand could only be true if prices were to fall – but for that to be possible, production costs or producers' profits would need to fall substantially. None of these two scenarios seems realistic, since improved production does not significantly affect production costs per unit of output, and historically livestock production is a low profit-margin activity. The US provides an example of increasing beef outputs while reducing total herd population: in the last four decades, beef production grew by 26%, from 10.2 to 12.2 Mt cw, while the total beef cattle herd reduced by 21%, from 104.5 to 82.5 M heads (USDA, 2022). The US produces more beef than Brazil with less than half the cattle herd.

Moreover, if cattle farmers could be properly rewarded for the environmental benefits derived from sustainable intensification, this may create a strong economic incentive to transition away from the extensive and environmentally costly traditional systems' that still predominate in the tropics – thus overcoming supposed perverse incentives for deforestation (Latawiec *et al.*, 2014). This would add to the fact that deforestation in the region is largely illegal, and more capital-intensive activities typically go along with higher aversion to legal risks and higher compliance with legal requirements, including in terms of conserving legal reserves and restoring degraded riparian forests, in addition to maintaining employees' health and safety and other rights.

Finally, livestock production is central to the critical, combined challenge of the global food system to substantially increase production while halting or slowing expansion of agricultural land, and strongly reducing GHG emissions.

This is due to its relatively high projected growth of 13% in the 2020s (USDA, 2022) and 40% by 2050 (FAO, 2018). No single solution will likely overcome this challenge – on the contrary, a combination of solutions addressing the different dimensions of the challenge is necessary (FAO, 2019; Searchinger *et al.*, 2018; Springmann *et al.*, 2018; Fischer, 2018).

For example, dietary changes aimed at reducing meat consumption in rich countries, and substituting animal-based proteins by plant- or lab-based proteins might contribute to addressing the challenge, but they would have to be extremely drastic to compensate or reverse the trend of increases in demand in low- and middle-income countries. On the other hand, if accompanied by implementing low emission practices, reducing consumption of livestock-based protein by 10%–25%, for example, could promote significant emission reductions of 0.5–2.5 $GtCO_2e/y$ by 2050 (Costa Jr *et al.*, 2022). In any case, no strategy could be a substitute for the short-term necessity of implementing significant changes in beef-cattle production, to be able to meet the growing beef demand with lower emissions and using less land.

The magnitude of these emissions depends on several factors, including climate, soil fertility and texture, in addition to the level of soil degradation and grazing management strategy, animal type, feed quality, and the use external inputs to sustain productivity (IPCC, 2006; Figueiredo *et al.*, 2016; Carvalho *et al.*, 2014; Cardoso *et al.*, 2016; Fisher *et al.*, 1996; Maia *et al.*, 2009; Cerri *et al.*, 2007). In this context, understanding GHG emissions in beef-cattle production systems, and how such emissions are quantified and can be reduced is fundamental to planning implementation of mitigation options in the sector △

ADOPTING IMPROVED BEEF-PRODUCTION PRACTICES GENERALLY IMPLIES INTENSIFYING THE PRODUCTION SYSTEMS.

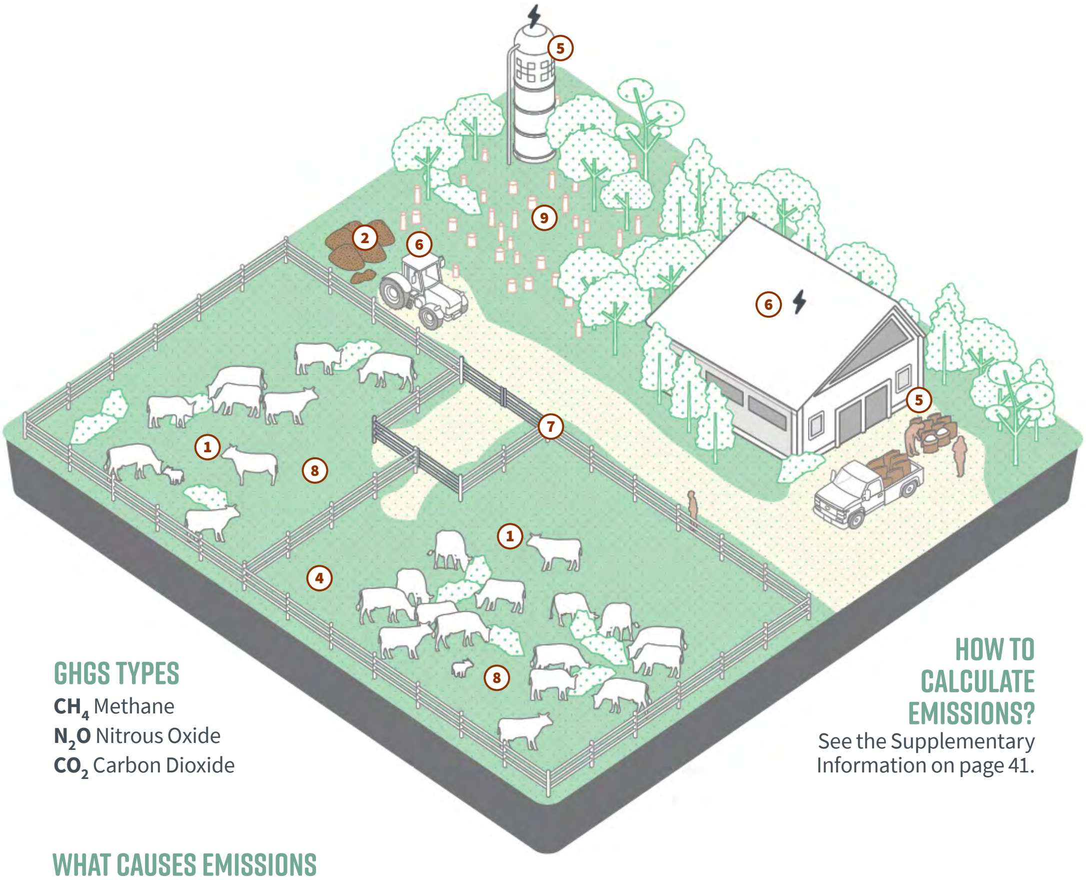
Photo: Tony Oliveira

MITIGATION POTENTIAL OF LOW-EMISSION CATTLE GRAZING PRACTICES

In this section, we describe the main gases, processes and drivers of beef-cattle GHG emissions. We then quantify these emissions per hectare and per kg of output in five beef-cattle production systems representing the main variations existing in Brazil. Finally, we estimate the mitigation potential of Brazilian low-carbon cattle-grazing practices. All the calculations are based on the applicable IPCC guidelines (IPCC, 2006 and IPCC, 2019).

UNDERSTANDING GHG EMISSIONS IN BEEF-CATTLE SYSTEMS: GASES, PROCESSES AND DRIVERS

GHG emissions from beef-cattle production arise from livestock, pasture management, feed inputs, fuel and energy consumption, farm infrastructure, and changes in soil carbon stocks. Additionally, cattle grazing can also be linked to emissions from land-use change connected to deforestation for land expansion, or to carbon sequestration from regenerating forests or reforestation. The main GHG emitted are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Here we examine the different GHG sources and sinks and associated drivers in pasture-based beef-cattle production systems.



GHGS TYPES

CH_4 Methane
N_2O Nitrous Oxide
CO_2 Carbon Dioxide

HOW TO CALCULATE EMISSIONS?

See the Supplementary Information on page 41.

WHAT CAUSES EMISSIONS FROM LIVESTOCK SYSTEMS?

LIVESTOCK

① **CH_4** from enteric fermentation

② **CH_4** and **N_2O** from manure management

PASTURE MANAGEMENT

③ **N_2O** from N-fertilizer application and pasture renewal, and **CO_2** from lime and urea production and application

④ **CH_4** and **N_2O** emissions from pasture burnings

FEED INPUTS

⑤ **CO_2** and **N_2O** (expressed in CO_2-equivalent) from feed production and transportation

FUEL AND ENERGY

⑥ **CO_2** from fossil fuel consumption and energy use

INFRASTRUCTURE

⑦ **CO_2** from materials used in fences, water pipes, constructions, vehicles and equipment

SOIL CARBON STOCKS

⑧ **CO_2** emissions from loss of soil carbon, or removals from increments of soil carbon

LAND-USE CHANGE

⑨ **CO_2** emissions from deforestation, or removals from reforestation or forest regeneration

LIVESTOCK EMISSIONS

Livestock emissions encompass CH_4 from enteric fermentation, and CH_4 and N_2O emissions from animal manure management. They account for most (~60–95+%) of the total emissions from beef-cattle production across systems.

CH_4 EMISSIONS FROM ENTERIC FERMENTATION

Enteric fermentation occurs when anaerobic microorganisms decompose and ferment carbohydrates, especially those in cellulose-based material, in the animal's digestive tract. It is a natural process that enables ruminants to eat plant materials that otherwise would not be digestible. The primary factors affecting enteric fermentation are the microbe population and the activity level in the rumen, which are largely affected by dietary composition. The higher the feed quality, the lower the CH_4 production from enteric fermentation per unit of dry matter intake. Estimations for CH_4 emissions from enteric fermentation are based on gross energy intake and a CH_4 conversion factor, and depend essentially on animal weight, which determines dry-matter intake, and diet digestibility.

CH_4 EMISSIONS FROM MANURE MANAGEMENT

Cattle dung and urine decomposition under anaerobic conditions produces CH_4. This process occurs most intensively when cattle are confined in feedlots, and where manure is disposed of in liquid form. CH_4 emissions from manure management are estimated based on volatile solid excretion and a CH_4 emission factor and depend essentially on animal weight, diet digestibility, and the manure management system.

N_2O EMISSIONS FROM MANURE MANAGEMENT

The soil deposition of manure nitrogen (N) in pasture-based systems, or the management of manure-N in feedlot operations, generates N_2O emissions. These emissions occur first directly, as a result of the combined nitrification and denitrification of manure-N, and indirectly as a result of the volatilization of ammonia and N oxides and subsequent redeposition to soils and waters, as well as of excreted-N leaching and runoff. Calculations for N_2O emissions from manure management are based on N-excretion and emissions factors for the direct and indirect N_2O emissions. N excretion is a function of animal weight, diet digestibility, diet protein content and animal weight gain. The direct and indirect N_2O emission factors as well as the fraction volatilized or leached/runoff depend on the manure management system, as well as on moisture and temperature.

PASTURE-MANAGEMENT EMISSIONS

Pasture-management emissions encompass i) N_2O emissions from N-fertilizer application; ii) CO_2 emissions from lime and urea production, transport, and application; iii) N_2O emissions from pasture-renewal crop residues, and iv) CH_4 and N_2O emissions from pasture burnings. These emissions are hardly relevant in extensive systems where no synthetic fertilizers or lime are used, but can become significant in intensified systems seeking to maximize cattle stocking per ha.

N_2O EMISSIONS FROM NITROGEN FERTILIZER APPLICATION

The application of N-fertilizers (synthetic or organic forms) to soils emits N_2O. These emissions, as for manure management, occur through the nitrification and denitrification of nitrogen contained in fertilizers, through direct and indirect processes. Calculations for direct and indirect N_2O emissions from N-fertilizer application are based on the amount of synthetic or organic N-fertilizer applied and emission factors for direct and indirect N_2O emissions. The emission factors and the fractions volatilized and leached depend on the type of N input (synthetic or organic) and on the climate (wet or dry).

CO_2E EMISSIONS FROM LIME AND SYNTHETIC FERTILIZERS MANUFACTURE AND TRANSPORT

The manufacture/ processing and transport of lime and of synthetic fertilizer inputs produce GHG emissions, included here as embedded emissions, which are calculated based on the amount of each product used and a country- or region-specific emission factor (typically, from a Life Cycle Assessment database).

CO_2 EMISSIONS FROM LIME AND UREA APPLICATION

As carbonate limes added to soil dissolve, bicarbonate is released and then evolves into CO_2 and water. Similarly, urea applied to soils is converted into ammonium, hydroxyl and bicarbonate ions, which evolve into CO_2 and water. Calculations for CO_2 emissions from lime and urea applications are based on the amount of limestone or dolomite or urea applied and an emission factor.

N_2O EMISSIONS FROM CROP RESIDUES

Crop residues from pasture renewal include above-ground residues, corresponding to the non-harvested portion of the pasture biomass, and below-ground residues, corresponding to the root system. They include nitrogen which is mineralized and produces N_2O emissions. Additionally, a fraction of those N inputs is subject to leaching and runoff, thus producing indirect N_2O emissions. Calculations for direct N_2O emissions from crop residues are based on an estimate of the amount of N in above- and below-ground crop residues, and a direct emission factor. Indirect emissions consider the fraction leached of these N inputs and an indirect emission factor. For pastures, direct and indirect emissions depend mostly on grass productivity, frequency of pasture renewal, and climate.

CH_4 AND N_2O EMISSIONS FROM PASTURE BURNING

Eventual pasture burning releases both CO_2 and non-CO_2 GHGs. CO_2 is not accounted for since it is considered that an equivalent amount will be removed as the grass regrows after the fire. As for non-CO_2 GHG, calculations for CH_4 and N_2O are based on the area burnt, the above-ground biomass available, a combustion factor and an emission factor for each gas. They depend essentially on the proportion of the area burned and on grass productivity.

EMISSIONS FROM CATTLE-FEED INPUTS AND FARM FACILITIES

CATTLE-FEED INPUTS EMISSIONS

Cattle-feed input emissions encompass primarily emissions related to crop production, which are similar to those of pasture management. Additionally, they also include emissions from transporting and processing feed ingredients. Typically, country- or region-specific emission factors (i.e., emissions per kg of feed ingredient consumed) are used in the calculation. As for pasture management emissions, feed input emissions are not relevant in extensive systems, where cattle are fed very small amounts of supplements. However, such emissions can become significant in intensified systems aimed at maximizing cattle weight gain.

FUEL AND ENERGY CONSUMPTION EMISSIONS

Cattle-ranching operations consume fossil fuels (manly diesel oil) for pasture management, and for animal feeding and manure management in more intensive systems. They also consume electricity for lighting facilities and employee housing, as well as powering agro-industrial operations, pumping water, among other uses. Fuel and energy consumption generate GHG emissions which are calculated based on the amount and type of fuel consumed and the amount and source of electricity consumed, considering country-specific emissions factors.

FARM INFRASTRUCTURE AND EQUIPMENT EMISSIONS

Creating farm infrastructure made of concrete or metal, such as fences, hangars, and feed and water troughs, or of plastics such as water pipes, as well as equipment, and vehicles such as tractors and implements, wagons, cars, among others, also produces GHG emissions. These embedded emissions are calculated considering a country-specific emission factor per square meter of such constructions and per item of equipment used, considering their typical lifetime. The emissions from fuel and energy and from farm infrastructure and equipment are typically not significant when compared to livestock or other sources or sinks.

CHANGES IN SOIL CARBON STOCKS

Carbon is the main element of soil organic matter (~55%), usually referred to as soil carbon or soil organic carbon (SOC), which is responsible for most soil functions, especially providing nutrients and structure for plant development. The SOC level is regulated by the deposition of plant biomass and dung, and its consumption by soil microorganisms. Thus, it can be affected by the type of land use and management adopted. Under degradation, this balance is usually disrupted, and carbon input to SOC is lower than its consumption, resulting in losses as CO_2 emissions.

By improving pasture systems, inputs of organic matter are newly balanced. This re-establishes and increases SOC levels through higher removal of CO_2 (carbon sequestration) from the atmosphere via plant photosynthesis and storage in the soil. Soil C is measured as a stock (SOC content per hectare in a given soil layer), and the related emissions or removals correspond to the variation of that stock.

CHANGES IN WOODY BIOMASS CARBON STOCKS

Changes in woody biomass stocks caused by deforestation or by forest regeneration or reforestation are not directly part of cattle-ranching operations but might be linked to cattle ranching when deforestation is followed by pasture planting, or when former pastures give way to new forests.

Carbon is the main element of above- and below-ground woody biomass (~50%) and the amount of CO_2 emitted by deforestation or sequestered by forest growth might be very significant when compared to cattle-ranching emissions. It is beyond the purpose of this paper t>o quantify such emissions or removals, but it is notable that improved beef-cattle production systems require far less land than extensive ones, and therefore such systems can contribute decisively to reducing deforestation pressure and/or to allowing conservation and reforestation, at both farm- and landscape-level.

EMISSIONS AND LAND USE PROFILES OF DIFFERENT PRODUCTION SYSTEMS IN BRAZIL

At this point we quantify how GHG emissions sources and sinks vary in different pasture-based beef-production systems. For that, we used a Life Cycle Assessment (LCA) approach to estimate livestock output and GHG emissions of five different beef-cattle production-systems representing the main variations existing in Brazil, from the most extensive to the most intensive system (Table 1). Our estimates encompassed all the sources and sinks presented in the previous section.

IMPROVED BEEF-CATTLE PRODUCTION SYSTEMS REQUIRE FAR LESS LAND THAN EXTENSIVE ONES.

The calculations were based on the equations and emissions parameters available in the 2019 Refinement of the 2006 IPCC Guidelines for National GHG Inventories, as well literature and expert knowledge for the production parameters, as detailed in the supplementary information (SI) section. This approach is similar to that used by Cardoso *et al.* (2016) – however, we updated and further developed the modeling of the beef-production systems, and parameters used in the calculations.

TABLE 1 - DESCRIPTION OF 5 TYPICAL BRAZILIAN BEEF-CATTLE PRODUCTION SYSTEMS

	1 - EXTENSIVE	2 - SEMI INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
PASTURE TYPE	*Brachiaria sp.*	*Brachiaria brizantha*	*Brachiaria brizantha*	*Panicum mombaça*	*Panicum mombaça*
CATTLE BREED	Nellore (mixed)	Nellore	Nellore	Nellore-Angus crosses	Nellore-Angus crosses
PASTURE MANAGEMENT	Continuous grazing w/o fertilization	Alternated grazing w/ minimum NPK fertilizatio	Alternated grazing w/ minimum NPK fertilizatio	Rotated grazing w/ high NPK fertilization	Rotated grazing w/ high NPK fertilization
ANIMAL STOCKING - CALVING & REARING (AU/HA)	**0.8**	**1.6**	**1.6**	**2.5**	**2.5**
ANIMAL STOCKING - FATTENING (AU/HA)	**0.8**	**2.2**	**NA**	**4.1**	**NA**
SUPPLEMENTARY NUTRITION - CALVING & REARING	Mineral supplement	Mineral supplement	Mineral supplement	Mineral & energetic supplement	Mineral & energetic supplement
SUPPLEMENTARY NUTRITION - FATTENING	Mineral supplement	Mineral & energetic supplement	Total mixed ration	Mixed ration + pastures	Total mixed ration
REPRODUCTION	Random animal breeding	Breeding season	Breeding season	Fixed-Time Artificial Insemination	Fixed-Time Artificial Insemination
SLAUGHTER WEIGHT - STEER (KG CW)	**268**	**311**	**304**	**330**	**327**
SLAUGHTER WEIGHT - HEIFER (KG CW)	**180**	**210**	**205**	**258**	**257**
SLAUGHTER AGE - STEER (M)	**43**	**27**	**25**	**21**	**20**
SLAUGHTER AGE - HEIFER (M)	**34**	**21**	**20**	**19**	**18**

OUTPUT, EMISSIONS PER HECTARE AND EMISSIONS INTENSITY OF EACH SYSTEM

In a traditional, extensive cattle-ranching system on degraded pastures in Brazil, annual output is very low – around 52 kg cw / ha. GHG emissions from Livestock, Pastures & silage, and Feed Inputs & Facilities amount to approximately 2.8 kg CO$_2$ e. This level of emissions per hectare is the lowest among the different systems, but in terms of emissions intensity it is the highest, at approximately 54 kg CO$_2$ e / kg cw of output (Table 2). With intensification, the annual output reaches 167–183 kg cw / ha of pastures in semi-intensive systems and 351–385 kg cw / ha of pastures in intensive systems. With that, the emissions intensity can be reduced to 30–32 kg CO$_2$ e / kg cw in a semi-intensive system and 24–26 kg CO$_2$ e / kg cw in an intensive system, where the share of livestock emissions decreases to 79–80%, and 66–67%, respectively (Table 2).

This reduction is essentially driven by cattle nutrition improvement, both in quantity (amount of forage and/or supplementary feed available) and quality (diet digestibility), leading to reductions in both slaughter age and daily emissions. Emissions from pasture management (from N-fertilization and liming) and feed inputs increase according to intensification level – but this increase is largely outweighed by the reduction in livestock emissions. These results are consistent with those in other studies, such as Cardoso *et al*. (2016), Figueiredo *et al*. (2016), and D'Aurea *et al*. (2021).

TABLE 2 - GHG EMISSIONS INTENSITY OF 5 TYPICAL BRAZILIAN BEEF-CATTLE PRODUCTION SYSTEMS

	1 - EXTENSIVE	2 - SEMI-INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
TOTAL **OUTPUT [KG CW/ HA]**	**52**	**166.6**	**183.5**	**351.5**	**384.7**
LIVESTOCK	2.8/98%	4.2/82%	4.3/81%	6.9/70%	6.2/71%
PASTURES & SILAGE	0.0/0.7%	0.5/0.9%	0.05/0.9%	1.4/17%	1.5/17%
FEED INPUTS & FACILITIES	0.0/0.2%	0.5/0.9%	0.6/10%	1.1/13%	1.1/13%
SUBTOTAL	2.8/100%	5.2/100%	5.4/100%	8.5/100%	8.7/100%
SOIL C	0.9/33%	0.0/0%	0.0/0%	-1.8/-20%	-1.8/-20%
TOTAL **GHG EMISSIONS [T CO$_2$E/ HA]**	**3.7**	**5.1**	**5.3**	**6.6**	**6.9**
SUBTOTAL **EMISSIONS INTENSITY [KG CO$_2$E / KG CW]**	54.3	30.6	28.8	24.1	22.7
TOTAL **EMISSIONS INTENSITY [KG CO$_2$E / KG CW]**	**71.9**	**30.6**	**28.8**	**18.9**	**17.9**

HERD PRODUCTIVITY

The reduction in livestock emissions intensity that accompanies the improvement of beef-cattle systems is strongly linked with the increase in herd productivity. Herd productivity is measured as the (carcass) weight of cattle produced, divided by the average number of animal units in the herd. The size of the cattle herd necessary to produce a determined output amount reduces as cattle-herd productivity increases. In an extensive system, herd productivity is 64 kg cw / animal unit (AU) /y and an average herd of 23 heads is necessary to produce 1 t cw per year. Herd productivity reaches 103–108 kg cw / AU / y in a semi-intensive system and 134–138 kg cw / AU / y in an intensive system, while the herd to produce 1 t cw / y reduces to 13–14 heads and 10 heads, respectively (Table 3). These figures demonstrate the herd reduction effect linked to cattle ranching intensification.

TABLE 3 - HERD PRODUCTIVITY OF 5 TYPICAL BRAZILIAN BEEF-CATTLE PRODUCTION SYSTEMS

	1 - EXTENSIVE	2 - SEMI INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
HERD PRODUCTIVITY [KG CW/ AU / Y]	63.6	102.6	107.6	133.7	137.8
HERD TO PRODUCE 1 T CW /Y [HEADS]*	23	14	13	10	10

* Total number of cattle in a complete cycle system, excluding lactating calves.

SOIL CARBON

Soil carbon stocks can be affected by the type of land use and management adopted. While pasture degradation tends to reduce SOC stocks over time, recovered and well-managed pastures can promote SOC accumulation (i.e., sequestration). Improved grazing management offers a high-carbon-gain option for nature-based climate solutions. If well managed, pastures can have SOC stocks higher than those in forests (FAO, 2007). Out of hundreds of studies evaluating SOC stock changes in introduced pasturelands globally, Conant *et al*. (2017) found that improved grazing management, fertilization, sowing legumes and improved grass species, irrigation, and conversion from cultivation all tend to lead to increased soil C, at rates ranging from 0.1 to more than 1.0 t C / ha / y.

In Brazil, Maia *et al*. (2009) observed in the Cerrado and Amazon regions that while degraded pastures lose 0.28 t C / ha / y, improved pastures accumulate 0.61–0.72 Mg t C / ha / y in the 0-20 cm layer. Braz *et al*. (2013) compared SOC stocks under native Cerrado vegetation, productive pasture, and degraded pastures in Brazil. They reported a rate of SOC accumulation by recovering and improving pasture management from 0.25 to 2.95 t C / ha / y in the 0–100 cm layer, over periods of up to 9 years. Damian *et al*. (2023) assessed how adopting more intensive and diversified pasture-management systems affect SOC stocks. They found that adopting integrated crop-livestock systems (under a subtropical and tropical humid climate) increased soil C by 0.15–2.00 t C / ha / y compared to conventional management. The same team modeled impacts of improving and diversifying pasture management on SOC in Brazil (i.e., integrated crop-livestock and forest-livestock systems). They estimated an increase in SOC stocks of 0.04–0.95 t C / ha / y (Damian *et al*., 2021). Discrepancies in the results may be attributed to differences in climate, soil texture, pasture management, forage-grass type, implementation time, soil-sampling design, and soil-C stock calculation and determination (Ayarza *et al*., 2022).

In this analysis, we consider i) a soil-C loss of 0.25 tC/ha/y in the extensive system on degraded pastures; ii) a constant soil-C stock in the semi-intensive systems, and iii) a conservative 0.5 tC/ha/y soil-C accumulation in the intensive systems, which we considered to be recovered from degraded pastures, in the 20 years following recovery. Based on these assumptions, in an extensive system, total emissions including soil-C losses, reach 72 kg CO_2 e/kg cw. On the other hand, the accumulation of soil C in an improved system with well-managed pastures can further reduce emissions intensity, leading to total emissions as low as 18-19 kg CO_2 e/kg cw in intensive systems. This represents a 73–75% reduction compared to the most extensive system (Table 2).

GHG EMISSIONS BY GAS

CH_4 emissions represent most of cattle ranching GHG emissions across all production systems. However, the share of CH_4 in the total emissions tends to decrease as production becomes more intensive. This is because CH_4 emissions intensity is much higher – more than 3x – in extensive systems compared with intensive systems (Table 4). Our analysis shows that the improved digestibility of diet in intensive systems allows for a reduction in daily CH_4 emissions of 15% in the calving phase, 18% in the rearing phase and 25% in the fattening phase – or up to 50% in feedlot finishing – and such emissions occur over a much shorter period.

N_2O emissions intensity does not vary substantially between the different systems analyzed (Table 4). That is because the increase in N_2O emissions from N-fertilization in more intensive systems is compensated for by the reduction in N_2O emissions from manure per kg of output, also due to the improved diet digestibility and shorter time to slaughter.

CO_2 emissions are almost insignificant in extensive systems but increase as production becomes more intensive (Table 4). These emissions represent essentially embedded CO_2 emissions in fertilizer, lime and feed inputs. Farm facilities (including direct energy use and fuel consumption) do not contribute significantly to beef-cattle ranching emissions, even in intensive systems.

TABLE 4 – GHG EMISSIONS INTENSITY AND BREAKDOWN PER GHG OF 5 TYPICAL BRAZILIAN BEEF-CATTLE PRODUCTION SYSTEMS [KG GHG / KG CW OUTPUT]

	1 - EXTENSIVE	2 - SEMI INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
CH_4 **KG CH_4 / KG CO_2E** **KG CW-1**	1.7/47.9 88%	0.8/22.4 73%	0.7/20.5 71%	0.5/14.9 62%	0.5/13.9 61%
N_2O **KG N_2O / KG CO_2E** **KG CW-1**	0.021/5.6 10%	0.018/4.9 16%	0.019/4.9 17%	0.020/5.3 22%	0.020/5.2 23%
CO_2 **KG CO_2E** **KG CW-1**	0.8 1%	3.3 11%	3.4 12%	3.8 16%	3.6 16%
SUBTOTAL	54.3 100%	30.6 100%	28.8 100%	24.1 100%	22.7 100%
SOIL C	17.6 32%	0.0 0%	0.0 0%	-5.2 -22%	-4.8 -21%
TOTAL	**71.9**	**30.6**	**28.8**	**18.9**	**17.9**

LAND-USE INTENSITY

The variation in land-use intensity between the different systems is even more drastic than in emissions intensity. The total agricultural land required to produce 1 t cw per year – including the area for cattle grazing as well as the areas for silage and crops production for cattle feed – is 19 ha for the extensive system but decreases to 5.8–6.3 ha for the semi–extensive systems and to 3.2–3.4 ha for the intensive systems, an 82–83% reduction (Table 5).

TABLE 5 - LAND USE INTENSITY OF 5 TYPICAL BEEF-CATTLE PRODUCTION SYSTEMS IN BRAZIL [HA / T CW OUTPUT]

	1 - EXTENSIVE	2 - SEMI INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
GRAZING AREA	19.2 100%	6.0 96%	5.4 94%	2.8 83%	2.6 82%
SILAGE AREA	0.0 0%	0.0 0%	0.0 1%	0.0 0%	0.0 1%
CROPPING AREA	0.0 0%	0.3 4%	0.3 5%	0.6 17%	0.5 17%
TOTAL	**19.2** **100%**	**6.3** **100%**	**5.8** **100%**	**3.4** **100%**	**3.2** **100%**

This very significant land-sparing effect also contributes indirectly to reducing emissions from deforestation – and/or increasing removals from reforestation – since it frees up land for agricultural expansion, forestry, conservation, and restoration without the need of further deforestation.

EMISSIONS AND LAND-USE INTENSITY PER PRODUCTION-CYCLE PHASE

Notably, the Calving phase has the highest emissions and land-use intensity compared to the Rearing and Fattening phases, due to a relatively lower annual output per animal unit. As a result, Calving represents more than 50% of total cattle ranching emissions across all systems (varying from 53 to 61%). Similarly, the Calving phase also has the highest land-use intensity among the different phases of the beef-cattle ranching cycle, and it occupies 57–72% of the total area used for cattle ranching (Table 6).

TABLE 6 - GHG EMISSIONS AND LAND-USE INTENSITY AND BREAKDOWN OF TOTAL EMISSIONS AND LAND OCCUPIED BETWEEN PHASES OF THE PRODUCTION CYCLE IN 5 TYPICAL BRAZILIAN BEEF-CATTLE PRODUCTION SYSTEMS

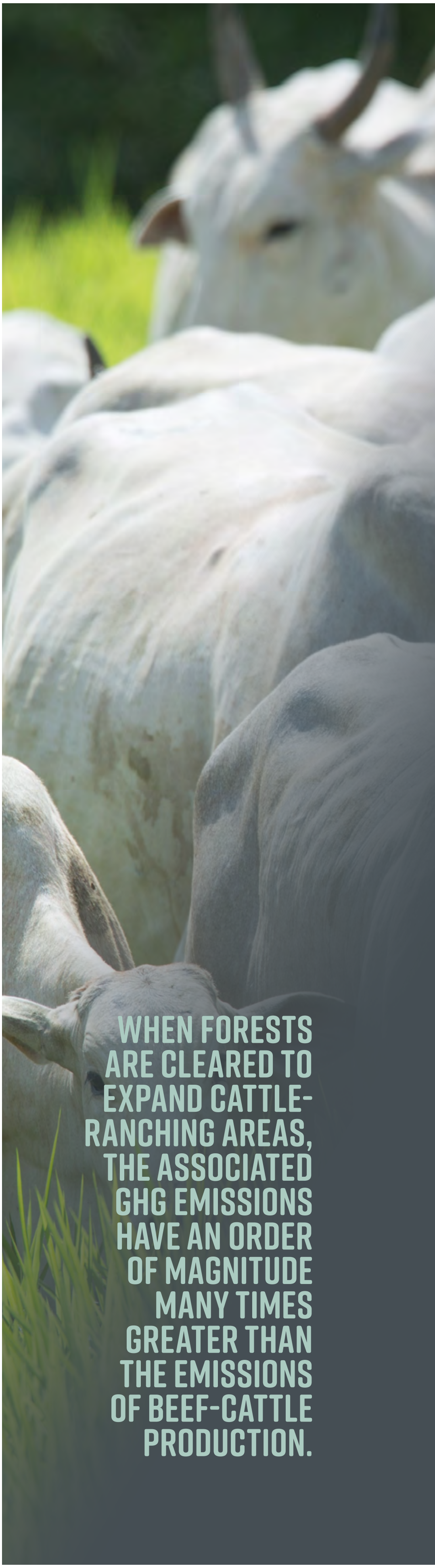
		1 - EXTENSIVE	2 - SEMI INTENSIVE	3 - SEMI INTENSIVE (FEEDLOT FINISHING)	4 - INTENSIVE, PASTURE BASED	5 - INTENSIVE (FEEDLOT FINISHING)
EMISSIONS INTENSITY [KG CO_2E / KG CW]	Calving	77.8	37.9	37.8	21.8	21.8
	Rearing	63.4	27.8	27.8	17.2	17.2
	Finishing	73.0	20.1	12.4	15.4	11.5
	Total	**71.9**	**30.6**	**28.8**	**18.4**	**17.9**
BREAKDOWN OF TOTAL EMISSIONS PER PHASE	Calving	53%	57%	61%	55%	59%
	Rearing	31%	26%	29%	23%	25%
	Finishing	15%	16%	10%	22%	17%
LAND-USE INTENSITY [HA / T CW OUTPUT]	Calving	22.3	8.9	8.9	4.5	4.5
	Rearing	14.9	4.3	4.3	2.5	2.5
	Finishing	19.7	3.7	1.5	2.4	1.4
	Total	**19.2**	**6.3**	**5.8**	**3.4**	**3.2**
BREAKDOWN OF TOTAL AREA PER PHASE	Calving	57%	66%	72%	62%	68%
	Rearing	28%	20%	22%	19%	21%
	Finishing	15%	14%	6%	19%	11%

EMISSIONS FROM DEFORESTATION AND REMOVALS FROM FOREST GROWTH AND RESTORATION/ REFORESTATION

When forests are cleared to expand cattle-ranching areas, the associated GHG emissions have an order of magnitude many times greater than the emissions of beef-cattle production. For example, the average emissions per hectare deforested and converted to pastures in the Amazon and Cerrado biomes amount to 342 tCO_2 / ha, according to Brazil's 4th National GHG Inventory (Brasil, 2020). That is equivalent to 92 years of emissions of an extensive beef cattle-ranching system (of 3.7 tCO_2e/ha/y), 65 years of a semi-intensive system (of 5.2 tCO_2e/ha/y), or 51 years of an intensive system (of 6.7 tCO_2e/ha/y) (Table 2).

Conversely, with forest growth or restoration in cattle farms, the associated GHG removals can also be very significant, though lower and much slower than the emissions from deforestation. These removals can contribute to compensating for cattle-ranching emissions. According to Brazil's 4th National GHG Inventory (Brasil, 2020), natural regeneration in areas previously occupied by pastures in the Amazon or Cerrado biomes typically remove 10.5–11.1 tCO_2 per hectare per year from the atmosphere. This can compensate for the emissions of 2.8 ha of an extensive beef cattle-ranching system, 2.0 ha of a semi-intensive system, or 1.6 ha of an intensive system.

For reforestation, growing homogeneous planted forests of eucalyptus typically remove 42 tCO_2 per hectare per year – though not all this stock is permanent (Brasil,2020). This growth can offset emissions from 11.3 ha of an extensive beef-cattle-ranching system, 8.1 ha of a semi-intensive system, or 6.3 ha of an intensive system.



WHEN FORESTS ARE CLEARED TO EXPAND CATTLE-RANCHING AREAS, THE ASSOCIATED GHG EMISSIONS HAVE AN ORDER OF MAGNITUDE MANY TIMES GREATER THAN THE EMISSIONS OF BEEF-CATTLE PRODUCTION.

PRACTICES DRIVING EMISSIONS REDUCTION IN LIVESTOCK SYSTEMS IN BRAZIL

This section considers the broader context of beef-cattle production and associated emissions, and the understanding and quantification of the different processes generating GHG emissions and removals in beef-cattle systems. Here, we indicate some key strategies to significantly reduce those emissions. These strategies are: i) controlling deforestation in the supply chain; ii) increasing productivity with a focus on improved pastures and animal weight gain; iii) implementing the use of CH_4 inhibitors; and iv) including trees in the production system.

CONTROLLING DEFORESTATION AND FOREST DEGRADATION IN THE BEEF SUPPLY-CHAIN: A BASIC REQUIREMENT

The order of magnitude of emissions from deforestation compared to emissions from cattle production itself implies that seeking to reduce emissions from production only makes sense (at the ranch level) if fully eliminating emissions from deforestation and forest degradation in the supply chain. The other reason why curbing deforestation and degradation should go along with reducing cattle-ranching emissions is that both require increasing cattle-ranching productivity (see below).

Cattle-ranching operations willing to eliminate deforestation and degradation from their supply chain must implement rigorous zero-deforestation strategies, using a sufficiently distant cut-off date (i.e., 10 years or more) and encompassing both their own activities and those of their suppliers – for cattle and feed ingredients:

- **For their own activities and areas,** ranching operations should actively promote conserving forest remnants, implementing strategies to prevent risks of degradation from fire as well as promoting recovery of degraded forests.
- **For cattle sourcing,** ranching operations should implement purchasing policies that: i) source cattle only from suppliers who have produced the animals themselves, and ii) check each supplier for recent deforestation prior to any purchase. They should keep records of this monitoring, which in large operations should be third-party verified.
- **For feed ingredients,** ranching operations can either: i) purchase directly from producing farms, which allows them to verify that they are free from recent deforestation, or ii) purchase from industries that have adopted environmentally-compliant policies, or that are subject to zero-deforestation requirements (e.g., the soy moratorium in Brazil).

Additionally, broader environmental compliance should accompany the control of deforestation in the supply chain, especially as regards restoring degraded riparian forests and legal reserves, as required by the Brazilian legislation.

INCREASING PRODUCTIVITY: THE KEY STRATEGY TO DRIVE EMISSION-INTENSITY REDUCTIONS FROM BEEF PRODUCTION

As demonstrated above, sustainably-intensified beef-cattle systems have a much lower GHG footprint than extensive ones. Thus, the adoption and/or diffusion of production practices that increase productivity should be the central strategy to decrease emissions in the industry. In Brazil, the national agricultural research agency (Embrapa) has developed a framework of Good Agricultural Practices (GAPs) for Beef-Cattle Ranching (Embrapa, 2022) which provides useful beef-production GAP guidelines. However, although intensification strategies tend to go together, as they require increased investments and improved management capabilities, not all of them have the same impacts on emissions. Here we identify key changes in production systems that can most substantially curb emissions intensity:

- **In the calving phase,** the major factor influencing emissions intensity is the weaning rate (ratio of calves weaned annually per mature cows in the herd). Improved breeding practices can substantially increase pregnancy rates and reduce calving interval, which is key to increase weaning rates. Such practices include adopting a breeding season and, subsequently, fixed-time artificial insemination, associated with monitoring cow pregnancies and enhancing cow-culling management. Improving pasture management and cow nutrition prior to the breeding season and during lactation also contributes to increasing pregnancy rates, and calf survival and weight. Subsequently, supplementary feeding for calves (creep-feeding) can further enhance the system's overall efficiency.

- **In the rearing phase,** emissions reductions depend mostly on adequate pasture management and supplementary nutrition. Thus, reforming degraded pastures and implementing rotated grazing-management is crucial, along with the necessary infrastructure and machinery for distributing supplements (feed troughs, hangar for feed storage, wagon for feed distribution) and water (central reservoir and network of water pipes and troughs).

- **In the fattening phase,** the requirements are similar to rearing, though with a stronger emphasis on nutrition. Ideally, after improving pasture management and overall infrastructure improvements, ranches should implement a mix of intensive pasture-based and feedlot fattening. Feedlot fattening with a total mixed ration composed of 65–80% of concentrate and 20–35% of silage fodder is the most efficient technique for finishing beef cattle in the dry season. This is well observed in the major producing regions of central and northern Brazil. In the rainy season, while muddy conditions are not conducive to feedlot finishing, intensive pasture-based systems where fresh pastures provide the fodder are an effective alternative.

- **Overall,** reducing emissions depends on increasing animal and herd productivity, not necessarily productivity per area. Improving pasture management can lead to both outcomes, but seeking to maximize cattle stocking per area will not directly reduce emissions and require more inputs – especially N-fertilizers. Thus, as already stressed by Batista *et al*. (2019), supplementary nutrition should be prioritized over super-intensification of pastures.

METHANE INHIBITORS: A PROMISING TECHNOLOGY TO FURTHER REDUCE EMISSIONS

Some feed additives can inhibit methanogens in the rumen, and subsequently reduce enteric CH_4 emissions. Among various classes of additives being studied for CH_4 mitigation efficacy in ruminants, two have routinely delivered over 20% reduction of enteric CH_4: 3-Nitrooxypropanol (3-NOP) and dried Asparagopsis (red algae). While red algae are not yet commercially available at viable cost for cattle feeding in Brazil, 3-NOP (under its commercial name Bovaer) has already been approved and is available for commercial use. The extent of impacts on beef-cattle enteric CH_4 is not yet fully established, but two recent meta-analyses indicate a mean reduction of 30% and 23%, respectively, though widely varying. In its current form, 3-NOP is suitable for use in intensive fattening operations only, but mechanisms for its application in pasture-based systems are expected soon. CH_4 inhibitors are a promising tool to be pursued to further reduce beef-cattle-ranching emissions (Almeida *et al*., 2021, Dijkstra *et al*., 2018). Other technologies can also contribute to reduce beef cattle emissions, whether well-established (such as biodigesters in feedlot operations), or still incipient (such as low CH_4 breeding—the genetic selection of animals, or grasses, with lower CH_4 emissions per kg of weight gain).

INTEGRATED LIVESTOCK SYSTEMS: POTENTIAL TO OFFSET REMAINING EMISSIONS, WITH IMPORTANT CO-BENEFITS

Integrating improved livestock systems with crops and/or forestry is a promising approach in terms of land-use dynamics in the context of the rapidly-evolving land use in Brazil. In this context, soybean and other crops and, in some cases, planted forests, have been substituting pasture areas at an accelerating rate. With integrated systems, it is possible to convert part of the pasture area to other uses, and intensify the remaining cattle-ranching areas, which reduces the expansion of cattle ranching to other potentially new areas. Besides that, integrated systems can compensate for part or all of the cattle-ranching emissions through the accumulation of C in soil and trees (Souza *et al*., 2019).

To calculate the potential of the forestry component of an integrated system to offset cattle-ranching emissions, we consider the sequestration potential of a typical eucalyptus forest of 42 tCO_2 /ha/y. The permanent portion of this C-sequestration includes: i) the average long-term stock of forest carbon, which represents half of the total carbon stored over a production cycle – considering here 10 years for eucalyptus for lumber; and ii) the portion of the harvested timber in each production cycle to be stored in long-lived wood products (or substitute fossil energy) – assuming here a lumber yield of 50% of the harvested timber, itself representing 90% of the above-ground biomass produced during each cycle.

Given these assumptions, we calculate that a forestry component occupying only 22% of the total area of a livestock-forestry system with semi-intensive cattle production would fully offset cattle-ranching emissions (Table 7). This could be, for example, a system with double-rows of eucalyptus with 3m spacing between trees, and 30m between rows. The share of the area occupied by the forestry component would need to reach 27% to fully offset cattle-ranching emissions in an intensive pasture-based system. These estimates consider the SOC sequestration of each cattle-ranching system, not including potential additional SOC benefits of crop-livestock-forest integration. Similar results can be expected from planting native species, in addition to the several other benefits such as biodiversity conservation, increased resilience, and potentially higher income (Soares *et al*., 2021). Further research on native species such as that carried out by the Brazilian Coalition on Climate, Forest, and Agriculture is fundamental to provide more confidence in adopting native species in integrated systems.

TABLE 7 - SHARE OF EUCALYPTUS IN TOTAL AREA OF LIVESTOCK-FOREST SYSTEM TO FULLY COMPENSATE FOR CATTLE RANCHING EMISSIONS

FOREST C-STOCK SEQUESTRATION **TCO_2 / HA / Y**	[A] Annual accumulation	**42.0**
	[D] Duration of forestry cycle (years)	**10**
	[P] Total period considered (years)	**50**
	[Sf] Sequestration = [A] x [D] x0.5 / [P]	**4.2**
WOOD PRODUCTS SEQUESTRATION **TCO_2 / HA / Y**	[B] AGB share of forest C stock	**74%**
	[H] Harvested timber	**90%**
	[L] Lumber yield	**50%**
	[Sw] Sequestration = [A] x [B] x [H] x [L]	**14.0**
TOTAL SEQUESTRATION **TCO_2 / HA / Y**	[S] Sequestration = [Sf] + [Sw]	**18.2**
CATTLE-RANCHING EMISSIONS **TCO_2 / HA / Y**	[C2] Semi-intensive system emissions	**5.1**
	[C4] Intensive system emissions	**6.6**
FORESTRY SHARE OF AREA TO COMPENSATE FOR CATTLE RANCHING EMISSIONS	[F2] Forest area in semi-intensive system = 1 - [S] / ([S] + [C2])	**22%**
	[F4] Forest area in intensive system = 1 - [S] / ([S] + [C4])	**27%**

EXAMPLES OF PROJECTS IMPLEMENTING LOW-CARBON BEEF-CATTLE PRODUCTION IN SOUTH AMERICA

In the **Orinoquia region in Colombia**, implementing a natural silvopastoral system in cow-calf systems, has produced calves with emissions of -17 kg CO2e / kg lwg*, a reduction of almost 200% compared to breeding farms in the region. This system includes regenerating woody species ("chaparro") along with livestock management that uses improved forages with deep rooting varieties, rotational grazing and breeding selection.

In the **Piedmont zone, Cumaral, Meta in Colombia**, silvopastoral systems (SPSs) composed of B. decumbens associated with Acacia mangium had a carbon footprint of -60 kgCO2e / kg lwg. Other SPSs also had large negative carbon footprint, with differences due to variations in carbon stored in biomass: –15.3, –21.8, –24.3, –20.4 kg CO2e / kg lwg in SPSs of B. decumbens + Gliricidia sepium, B. decumbens + Mangifera indica, B. decumbens + G. angustifolia and B. decumbens + citrus cinensis, respectively (Parra et al., 2022).

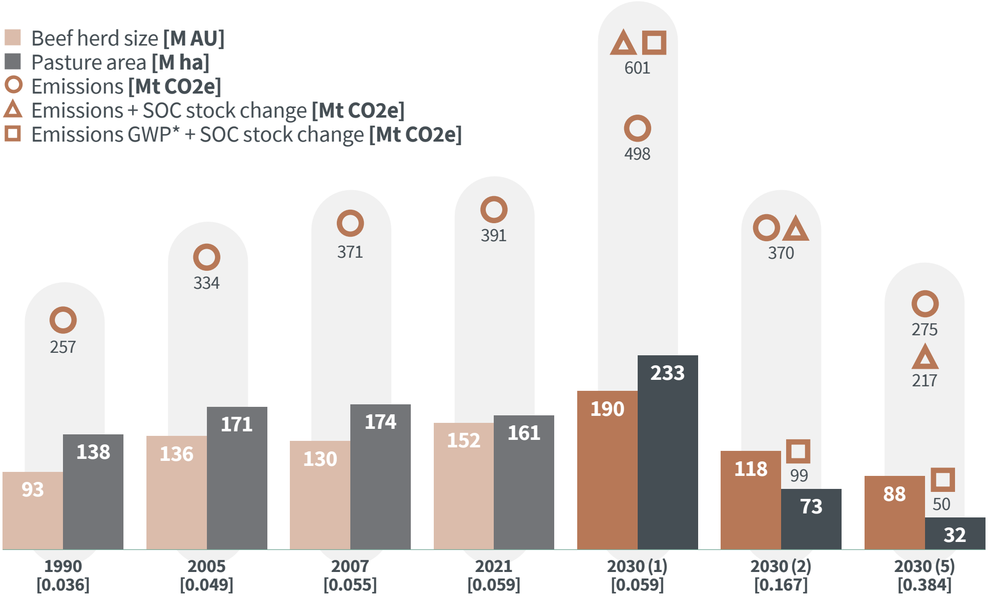
In **Uruguay**, the average GHG emissions of major production systems in the country is 20.8 kg CO2e / kg lwg (ranging from 11.4 to 32.2 kg CO2e / kg lwg). Improving grazing efficiency through optimizing the stocking rate and forage production has demonstrated increasing beef productivity by 22% and reducing GHG emissions per kg lwg by 28% compared to "low performance" management. Further improvements in reproductive efficiency can increase productivity by 41% and reduce GHG emissions per kg lwg by 23% (Becona et al., 2014).

Note: 1 kg of live weight gain (lwg) is equivalent to 0.5 kg cw gain.

COUNTRY-LEVEL IMPLICATIONS OF IMPROVING CATTLE PRODUCTION SYSTEMS: BRAZIL CASE.

As of 2021 beef-cattle production in Brazil emitted approximately 391 $MtCO_2e$, of which 87% was related to CH_4 emissions (SEEG, 2022). These emissions were the highest recorded in the country's history – along with the largest beef-cattle herd size. They were 50% higher than in 1990 (long-term historical data) (SEEG, 2022; IBGE, 2022), 17% higher than in 2005 (Brazil's NDC base year) (Brazil, 2022), and 5% higher than in 2007 (largest pasture area recorded) (LAPIG, 2022) (Figure 1). These figures are likely underestimated, as they only include emissions from enteric fermentation and manure management. However, considering the prevalence of extensive systems, we can assume it represents the bulk of the total on-farm emissions from beef production in the country. Beef-cattle production in Brazil is expected to continue increasing in the coming decades, to meet growing international demand. By 2030 it is projected to reach 12.1 Mt cw (USDA, 2022). The level of intensification achieved by then determines very different pathways in terms of beef-cattle herd size, area of pastures occupied, and total emissions. Meeting that demand with today's typical systems would imply further escalation in herd size, area and emissions, whereas accelerating the adoption of sustainably intensive systems could lead to very significant reductions compared to current and historical levels (graphic below).

BEEF-CATTLE EMISSIONS PATHWAYS BY 2030 UNDER DIFFERENT PRODUCTION SYSTEMS



Year (Production system) [average productivity in t cw / ha / y]. (1) Extensive; (2) Semi-intensive; (5) Intensive with feedlot finishing. **Note:** Considering (i) total emissions from beef cattle in 1990 (long-term historical data), 2005 (Brazil's NDC base year), 2007 (highest pasture area recorded) and 2021 (highest beef cattle emissions and herd size recorded) from SEEG (2022): 257.4, 333.7, 370.8, and 390.6 Mt CO_2e (GWP-100-AR5), respectively, of which ~85% was related to CH_4 emissions from enteric fermentation and manure; (ii) pasture area from LAPIG (2022); (iii) beef-cattle herd size from IBGE (2022), conversion from heads to animal units (AU) using the average of system 1-5 (Table 1) of 0.728 ; and (iv) beef production and projection from USDA (2022): 5.0, 8.3, 9.5, and 9.5 Mt of carcass in 1990, 2005, 2007, and 2021 - with a projection to increase 27.6% to meet domestic and international beef demands to 12.12 Mt of carcass by 2030; (v) 2030 scenarios emissions based on Table 2 .

In 2021, Brazil produced 9.5 Mt carcass (USDA, 2022), resulting in an emission intensity (not considering SOC variation) of 41.1 tCO$_2$e / t cw. Our estimates show that improved systems may have an emission intensity of 23.4 tCO$_2$e / t cw (considering the average of systems 4 and 5, Table 2), 43% lower than the country's current average. Where SOC sequestration is realized, this value may reach 18.4 tCO$_2$e / t cw, a 55% reduction (Table 8). Furthermore, considering that CH$_4$ emissions are reduced by more than 50%, the additional warming effect of CH$_4$ emissions over 20 years under a GWP* accounting system (Costa Jr *et al*., 2021) would be virtually zero. Thus, under GWP*, the total emissions intensity could drop by 90%, to 4.0 tCO$_2$/e per ton of carcass produced (Table 8).

Although Brazilian beef productivity has increased over the last three decades at an average rate of 1.8% per year, this pace of intensification, if maintained, will not be enough to curb emissions with the magnitude required to reach global climate goals by 2030. Scaling improved systems by that date could reduce total emissions from beef-cattle production by 27% to 87% compared to 2021 levels – while increasing beef production by 28% (Table 8).

Notably, not all the pasture areas are suitable for intensification – but on the other hand, intensification reduces dramatically the total area necessary, so that the availability of suitable areas should not be a limitation.

TABLE 8 - CURRENT AND FUTURE EMISSIONS FROM BRAZILIAN BEEF PRODUCTION, AND MITIGATION POTENTIAL BY SCALING IMPROVED SYSTEMS

	CURRENT	IMPROVED	IMPROVED + SOC SEQ.	IMPROVED GWP*	IMPROVED GWP* + SOC SEQ.
GHG EMISSIONS INTENSITY T CO$_2$E / T CW	41.1	23.4	18.4	9.0	4.0
TOTAL EMISSIONS IN 2030 MTCO$_2$E	498	284	223	109	49
MITIGATION POTENTIAL CO$_2$E		43%	55%	78%	90%
MITIGATION POTENTIAL COMPARED TO 2021 CO$_2$E		27%	43%	72%	87%

* **Note:** Considering that (i) total emissions from beef cattle in 2021 was 390.6 Mt CO$_2$e, of which 87% was related to CH$_4$ emissions from enteric fermentation and manure (339.9 MtCO$_2$e; GWP-100-AR5) (SEEG, 2022), and (ii) beef production was 8.6 Mt of carcass (IBGE, 2022).

Meanwhile, the total agricultural land and herd size necessary for beef-cattle ranching could be significantly reduced by disseminating improved systems, since they use only a fraction of the area of agricultural land required by more extensive systems (Table 5) and also have a much higher herd productivity (Table 3). We estimate Brazil's agricultural land area for beef production and cattle herd size could be retracted by more than 100 million ha and 70 million AU (~100 million heads), respectively, with the widespread adoption of improved systems, while meeting beef-production projections in 2030. These results show the importance of swiftly scaling the sustainable intensification of beef-production systems to create the conditions for reducing emissions while meeting food demands and sparing land for other uses

Photo: Wenderson Araújo

HOW VOLUNTARY CARBON MARKETS CAN ACCELERATE THE TRANSITION TO LOW-EMISSIONS BEEF PRODUCTION

In this section, we examine how carbon incentives - initially from the voluntary carbon markets - can help overcome existing barriers to the scaling of improved cattle ranching systems in Brazil. First, we describe the typical level of investment of a Brazilian beef-cattle-ranching intensification project. Based on that, we discuss why such projects can be deemed additional and what type of social and environmental safeguards they should include. Finally, we assess potential scenarios of repayment of project investments through generating carbon credits applying a new methodology for cattle ranching currently being developed under the Voluntary Carbon Standard.

Despite the substantial GHG emissions reductions attainable in livestock production systems, actions and investments to foster a meaningful transition to low-emissions beef in Brazil and other Latin-American countries are lacking. In the last decade, less than 1% of climate finance globally was directed to the livestock sector; and of the US$186 billion dedicated to climate-related development projects worldwide between 2012 and 2017, only 0.57% (US$1.0 billion) was related to the livestock sector (Gerber *et al*., 2021). In Brazil, the ABC (Low Carbon Agriculture) Program has provided subsidized rural credit for investments in low-carbon agriculture since 2010. It has contributed to the reform of approximately 3.3m ha of degraded pastures across the country between 2010 and 2018 (Manzatto, C. V. *et al*., 2020). In the 2021/22 agricultural year, it provided BRL 844m (equivalent to USD 160m) in financing (BNDES, 2023), though the information on how much of that amount was dedicated to cattle ranching intensification is not publicly available. Even though both the amount of financing and the area are significant, the ABC program still represents less than 5% of total investments of Brazil's subsidized rural credit. Although the development of climate-finance mechanisms in general could contribute to climate-change mitigation in the livestock sector, voluntary and compliance carbon markets may play a critical role, by providing targeted incentives to accelerate the transition to low-emission beef production (Rose *et al*., 2021).

CARBON MARKETS

Carbon markets refer to markets where carbon credits are generated and traded according to defined regulations and/or standards. Regulated markets represent roughly 95% of total value transacted today, and voluntary carbon markets the remaining 5% (Gerber *et al*., 2021).

- Regulated carbon markets, also known as Emissions Trading Schemes (ETS), are markets where governments determine intended levels (or caps) of emissions for targeted industries, and the players who emit below their cap can trade carbon credits with those who emit above their cap. In most existing ETS, the agriculture sector is not subject to caps, but in some cases, players in the sector might be allowed to sell carbon credits if they perform better than a determined level of reference for their activity – e.g. in Australia's Emissions Reduction Fund (Australia, 2023), as well as in Alberta, Canada (Alberta, 2023).
- In jurisdictions or activities not encompassed by an ETS, businesses can use Voluntary Carbon Markets (VCMs) to trade emissions. In VCMs, businesses (or governments) who voluntarily commit to reducing or neutralizing their GHG emissions can do so through purchasing credits from projects or programs that can demonstrate emissions reductions or removals that are additional (i.e., that are not compulsory and would not have occurred in the absence of the carbon project) and verified under a recognized standard.*

  * There are currently four major standards certifying credits in the Voluntary Carbon Market: Voluntary Carbon Standard (VCS), managed by Verra; Gold Standard; Climate Action Reserve; and American Carbon Registry.

Brazil currently does not have an ETS in place – although it has projects aiming to have one in the future (Brazil law project, 2022). When that happens, it will most probably not impose an emissions cap on the agricultural sector. In the short-term, therefore, the sector should consider possibilities in the VCM (ICC, 2021).

Further potential developments, such as the possibility of beef-cattle projects to provide offsets to other sectors in a future ETS, as is the case in the Australian ETS, or the possibility of specific gas-gas offsetting, are not addressed in this paper and should be explored in further research.

TYPICAL INVESTMENTS TO IMPLEMENT A LOW-CARBON BEEF-CATTLE PRODUCTION SYSTEM

As discussed above, several strategies might be used to reduce beef-cattle emissions. Here we focus on projects that reduce emissions through improved pasture management, supplementary nutrition and breeding techniques. We also consider the option of adding a forestry component to the system. We estimate the typical investment level for such projects to be approximately US$ 5,900 per hectare. This includes US$ 1,900 in fixed assets (pasture reform, infrastructure, and machinery) and US$ 4,000 in working capital (cattle herd adjustment and associated production costs for one production cycle) (Table 9). Adding a forestry component occupying part of the area would increase total costs by approximately US$ 150 and US$ 450 per hectare for 10% and 30% of the area covered, respectively. This estimate is based on parameters for a 1,000-hectare area provided by Caaporã Agrosilvipastoril, a Brazilian low-carbon protein company whose team has developed and implemented such projects in various regions in Brazil.

TABLE 9 - TYPICAL AMOUNT OF INVESTMENT FOR A LOW-CARBON BEEF PROJECT IN BRAZIL

	ITEM	DESCRIPTION	AMOUNT [US$ / HA]
FIXED ASSETS	**Pasture renovation**	Removal of existing pasture; Soil preparation; Liming and fertilization; Sowing of new pasture.	**900**
	Infrastructure	Rotated grazing modules and feedlot paddocks; Water catchment, reservoir, and pipe network; Corral (reform), Hangar for feed ingredients, Agrochemicals depository; Internal roads; Employee houses (reform), Internet communication; Work animals.	**650**
	Machinery and vehicles	Tractors; Feeding wagons; Wheel loader; Car, Motorbike.	**350**
SUBTOTAL FIXED ASSETS			**1,900**
WORKING CAPITAL (ADDITIONAL)	**Cattle herd**	Cows (or other cattle categories) to populate ranch.	**1,300**
	Production costs	Feed ingredients; fuel; energy and other inputs; breeding costs; vaccines; workforce; administrative & management expenses for 1 full production cycle.	**2,700**
SUBTOTAL WORKING CAPITAL			**4,000**
TOTAL INVESTMENTS			**5,900**

* **Note:** (i) Typical values per ha for the rehabilitation and intensification of a 1,000-ha degraded beef-cattle ranch . (ii) The cost of pasture renovation might be lower depending on the pasture degradation level. In some cases, part of the ranch pastures can be recovered. (iii) Economies of scale apply to the machinery and ranch infrastructure items. (iv) Working capital needs are additional investments compared to the previous situation and consider a complete cycle system. Backgrounding-fattening systems might be different. (v) Costs as of Nov 2022 considering 1 USD = 5.5 BRL.

ADDITIONALITY

In general, carbon projects in the voluntary market need to demonstrate additionality – which means they should demonstrate that the project scenario (i.e., reducing emissions and/or increasing carbon capture) would not occur in the absence of the incentive from the carbon credits. In this case, the question is whether cattle-ranching intensification would happen by itself anyway, or if carbon projects are needed to make it happen or to accelerate the process.

PRODUCTIVITY TRENDS

The first aspect to be considered here is current trends. On the one hand, the productivity of cattle ranching in Brazil has been clearly improving over time. For example, according to USDA (2022), Brazil's average beef-cattle-ranching productivity increased by 13% (from 53.0 to 59.8 kg cw / ha / yr) between 2011 and 2021. At the same time, average bull slaughter-weight has increased by 12% (from 264 to 295 kg cw) and the share of animals finished in feedlots has increased from 10% to 17%. On the other hand, average productivity level is still very low compared to the potential of intensive systems (300+ kg cw / ha / yr), and the adoption of intensive systems is still very limited. In most ranches, the business-as-usual scenario is of a continuity or very gradual improvement, while a swift change is needed.

ECONOMIC BARRIERS

The size of investment required compared to the producers' limited access to finance is a major barrier to accelerating production intensification. In our example, for a middle-size ranch of 1,000 ha, a total amount of US$ 5.9m is required. A typical ranch owner neither has the resources, nor access to third-party financing for this size of investment. As a result, investments are deferred or carried out partially, in a piecemeal fashion and over a long period. Another related barrier is the risk-return relationship. Extensive cattle ranching is usually characterized as a low-risk, low-return activity, where profits eventually occur through the long-term valuation of the assets, more than from the activity itself. When the level of investment increases, so does the risk, and the return remains largely dependent on commodity prices, which impacts the investment's attractiveness for risk-averse players. From this follows that a carbon incentive might be a game-changer for cattle-ranching intensification initiatives in Brazil.

NEED FOR A NEW CARBON METHODOLOGY BASED ON AN EMISSIONS-INTENSITY APPROACH FOR CATTLE RANCHING

A few methodologies related to grassland management and livestock production already exist in the VCM standards. However, most of these methodologies account for emission reductions through an area-based approach, which penalizes projects that increase productivity as they typically increase emissions on a per-area basis. Two methodologies account for emission reductions through an output-based approach, thus considering the benefits of efficiency improvements – however, they do not apply in the Brazilian context: one is applicable only to smallholder dairy production, whereas the other is applicable only to the finishing phase in Alberta, Canada. One methodology considers emissions reductions related to reduced enteric CH_4 emissions, but it focuses only on the effects of feed additives.

Recently, Microsoft, the giant tech company, engaged with a livestock farm in Australia to buy US$ 500.000 of carbon credits from SOC stocks increase, opening the door for this type of transaction in the livestock sector. However, identifying scalable livestock production systems and technologies in other producing locations to match with the increasing interest of investors and companies in carbon credits has been challenging. Unsurprisingly, up to this moment there are still no livestock carbon projects registered in the Latin-American VCM (VERRA, 2022), despite the increasing number of farms monitoring their GHG emissions using tools such as the GHG Protocol in Brazil (FGV, 2022).

Considering this gap, the development of a new methodology was proposed in 2021 by Imaflora, a Brazilian NGO, to incentivize emissions reductions from productivity improvements in pasture-based beef production, with land-sparing as a co-benefit. The methodology concept note was approved in mid-2022 and the full methodology is currently under development. Its pilot project is being implemented in the Amazon region of Brazil by Caaporã, through an investment from Vale Fund.

The new methodology will reward projects for the difference between their performance, calculated in terms of emissions intensity, and a crediting baseline to be based on a regional performance benchmark (i.e., the average of the project region's emissions intensity, informed by a regional survey).

SCENARIOS OF CAPITAL INVESTMENT REPAYMENT WITH CARBON CREDITS

To assess the potential impact of a carbon project using an output-based accounting on a low-carbon beef-cattle investment, we estimated potential carbon revenues over 10 years in different carbon-price scenarios. Considering Brazil's average as a baseline and the most intensive system in our modeling as the project, the project has a potential to generate approximately 80 Verified Carbon Units (VCU) per hectare (1 VCU corresponds to 1t CO_2e) over a 10-year period (Table 10). This figure includes the emissions reductions potential in the cattle-ranching system itself as well as the increase in soil-carbon stocks. If the project includes a forestry component, the corresponding removals could generate a significant amount of additional VCUs.

TABLE 10 - POTENTIAL GENERATION OF VCUS PER HA OF INTENSIFICATION PROJECT

	UNIT	VALUE
BASELINE EMISSIONS INTENSITY	kg CO_2e / kg cw	**41.1**
PROJECT EMISSIONS INTENSITY	kg CO_2e / kg cw	**17.9**
DIFFERENCE IN EMISSIONS INTENSITY	kg CO_2e / kg cw	**-23.2**
PROJECT OUTPUT	kg cw / ha pasture / y	**384**
POTENTIAL EMISSIONS REDUCTIONS	t CO_2e / ha / yr	**8.9**
DISCOUNT FOR UNCERTAINTY		**-20%**
POTENTIAL VCUS OVER 10 YEARS	tCO_2e/ ha	**80**

Note: considering a fully intensified complete cycle system, compared to Brazil's current average.

As for carbon prices in the voluntary market, they are currently around US$ 15 / t for a high-quality Nature Climate Solutions (NCS) project (OPIS, 2022). Future prices for this type of project will depend on overall carbon market trends – for which there are very positive prospects (TSVCM, 2021) as well as on the market's receptiveness for the new methodology and on the quality of each project. We simulated three price scenarios: US$ 10 (pessimistic), US$ 15 (conservative) and US$ 30 (optimistic). We compared the potential carbon revenues generated in each scenario with the amount of investment in pasture reform and ranch infrastructure, considering that the remaining investments (machinery, cattle and production costs) are more likely to be financed through existing financing sources.

In the pessimistic carbon price scenario, carbon revenues represent 42% of the total amount of investment in pasture reform and ranch infrastructure; in the conservative scenario, 84% and in the optimistic scenario, 126% (Table 11). In any case, the potential revenues represent a very significant incentive, and might indicate a novel financing solution for cattle-ranching intensification projects in Brazil.

TABLE 11 - PERCENTAGE OF PASTURE REFORM AND RANCH INFRASTRUCTURE INVESTMENTS POTENTIALLY COVERED BY CARBON REVENUES ACCORDING TO CARBON-PRICE SCENARIO

	US$ 10*	US$ 20*	US$ 30*
INVESTMENT IN PASTURE RENOVATION AND RANCH INFRASTRUCTURE [US$ / HA]	**1,900**	**1,900**	**1,900**
POTENTIAL CARBON REVENUES IN 10 YEARS [US$ / HA]	**800**	**1,600**	**2,400**
PERCENTAGE OF INVESTMENT COVERED	**42%**	**84%**	**126%**

Note: not including potential carbon revenues form reforestation or forest regeneration. * VCU price [US$ / t].

NECESSARY SAFEGUARDS FOR CATTLE INTENSIFICATION CARBON PROJECTS

Several key social and environmental safeguards should be in place to guarantee the positive outcomes expected from beef-cattle intensification projects. First, full control of deforestation and forest degradation of the project's supply chain should be required. This is necessary to guarantee that intensification projects cannot be linked directly or indirectly to land expansion, which would be totally contradictory. Various existing initiatives of supply chain control at the producer level have demonstrated that it is feasible at reasonable cost. Additionally, cattle intensification projects should be accompanied by a strong Environmental, Social and Governance (ESG) framework to monitor and mitigate potentially harmful social or environmental impacts, or promote potentially positive ones, focusing especially on:

- Manure management in confined systems;
- Animal welfare in all types of systems;
- Workers' health and safety, especially when dealing with toxic agrochemicals or risky situations;
- Compliance with the Brazilian Forest Law which requires fully protecting degraded riparian forests and other vulnerable ecosystems, and conserving native vegetation on a certain percentage of the total area of the property*;
- Inclusion of minorities and smallholders, whenever suitable.

* This percentage depends on the biome where the property is located, the area's specific history of occupation and the state zoning.

In general, carbon projects linked to production intensification should be considered as opportunities to raise the ESG profile of the industry, which should also translate into better market acceptance and higher prices for the carbon credits. These non-carbon benefits of a carbon project can be additionally certified, for example, via an "add-on" certification scheme under the Climate Community and Biodiversity Standard (CCBS). The CCBS requires the project to generate net-positive impacts for climate action, local communities and for biodiversity. The aim of this standard is to i) identify projects that simultaneously address climate change, support local communities and smallholders, and conserve biodiversity; ii) promote excellence and innovation in project design and implementation; and iii) mitigate risk for investors, offset buyers and increase funding opportunities for project developers (Verra, 2022). The CCBS can be applied to any land-management project, including projects that reduce GHG emissions.

CONCLUSION

Sustainably intensifying Brazilian beef-cattle systems is a promising pathway for mitigating their climate impacts, since it significantly reduces GHG emissions from production processes while minimizing their widely disproportionate land-use footprint, which has caused widespread deforestation.

Beef-cattle systems have improved over recent decades in Brazil and other countries in Latin America, but not at a pace compatible with today's climate emergency. To accelerate the transition to more efficient systems, new incentives are necessary. Voluntary carbon markets (through a new methodology currently being developed under VCM standards) represent a short-term game-changing opportunity to promote a swift transformation of the industry. Moreover, potential contributions from other climate-finance solutions might also be explored.

We expect that the findings from this work can encourage key players in the fields of conservation, beef-cattle production, finance, and carbon markets to engage and support initiatives to advance this emerging solution. One important necessary next step is to develop baselines of the emissions intensity of beef-cattle ranching in the main producing regions in Brazil, based on statistically representative surveys of production practices, which will be required for applying the new methodology. One such study has already been developed for the Northern Region of Tocantins state, where the pilot project is being implemented, and can serve as a reference.

Further research and developments in soil-carbon-stocks' dynamics in different livestock systems, as well as in the forestry component of integrated livestock-forest systems, among other important areas, will contribute to strengthening the case for improved cattle-ranching systems.

Although this white paper builds the case for Brazil, these results provide valuable information for other beef producing countries with similar pasture-based production systems, especially in Latin America, where the same approach might be applied △

VOLUNTARY CARBON MARKETS REPRESENT A SHORT-TERM GAME-CHANGING OPPORTUNITY TO PROMOTE A SWIFT TRANSFORMATION OF THE INDUSTRY.

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SUPPLEMENTARY INFORMATION

TABLE S1 - SUMMARY OF GHG SOURCES AND SINKS FROM BEEF LIVESTOCK PRODUCTION

LIVESTOCK

PROCESS	GHG	DESCRIPTION	EMISSIONS CALCULATION	DETERMINANTS OF EMISSIONS
ENTERIC FERMENTATION	CH_4	Digestion of carbohydrates through microbial fermentation, producing methane – especially in ruminants' digestion of cellulose fiber	**Gross Energy intake (GE) x CH_4 Emission Factor (Y_m)**	Animal weight and diet digestibility
MANURE MANAGEMENT	CH_4	Decomposition of cattle dung and urine under anaerobic conditions, producing methane – most intensively in feedlots	**Volatile Solid excretion (VS) x CH_4 Emission Factor (MCF)**	Animal weight, diet digestibility, manure management system
	N_2O – Direct	Combined nitrification and denitrification of nitrogen contained in manure in an anaerobic environment	**N excretion (N_{ex}) x N_2O direct Emission Factor (EF_3)**	Animal weight, diet digestibility, diet protein content, animal weight gain, manure management system, and moisture
	N_2O – Indirect	Volatilization and subsequent redeposition as well as leaching and runoff of excreted nitrogen, then emitted as N_2O	**N_{ex} x [Fraction volatilized ($Frac_{Gasm}$) x indirect Emission Factor (EF_4) + Fraction leached ($Frac_{Leach-(h)}$) x indirect Emission Factor (EF_5)]**	Same as direct emissions, and temperature

PASTURE MANAGEMENT

PROCESS	GHG	DESCRIPTION	EMISSIONS CALCULATION	DETERMINANTS OF EMISSIONS
N-FERTILIZERS APPLICATION	N_2O – Direct	Combined nitrification and denitrification of nitrogen contained in synthetic fertilizers	**N fertilizer x N_2O direct Emission Factor for synthetic fertilizers (EF_{1s})**	Amount and type of N fertilizer (synthetic x organic), and climate (wet or dry)
	N_2O – Indirect	Volatilization, leaching or runoff of nitrogen contained in synthetic fertilizers, subsequently emitted as N_2O	**N fertilizer x [$Frac_{Gasf}$ x EF_4 + $Frac_{Leach-(h)}$ x EF_5]**	Same as direct emissions
LIME AND UREA APPLICATION	CO_2	Dissolution of carbonate limes or urea releasing bicarbonate, which evolves into CO_2 and water	**Urea x EF_{Urea} + Limestone x $EF_{Limestone}$ or Dolomite x $EF_{Dolomite}$**	Amount of urea applied and amount and type of lime (calcic limestone or dolomite)
LIME AND FERTILIZERS MANUFACTURE & TRANSPORTATION	CO_2e	Energy use, CO_2 emissions and fuel consumption in in industrial processes and transportation of lime and synthetic fertilizers	**Amount of each input x Emission Factor (EFi) in CO_2e (typically, from a LCA database, including transportation)**	Amount and type of lime and fertilizers applied, and transportation distance
CROP RESIDUE	N_2O – Direct	Mineralization of N inputs from annual crop residues and periodic pasture renewal, then emitted as N_2O	**N input from crop residues and pasture renewal (F_{CR}) x N_2O direct Emission Factor for other N inputs (EF_{1o})**	Grass productivity, frequency of pasture renewal, and climate
	N_2O – Indirect	Same process with fraction of N inputs leached	**F_{CR} x $Frac_{Leach-(h)}$ x EF_5**	Same as direct emissions
PASTURE BURNING	CH_4 and N_2O	Emissions of non-CO_2 GHG from burning of available above-ground biomass	**Available biomass (M_B) x Combustion factor (C_f) x Gas Emission Factor (G_{ef})**	Proportion of area burned, grass productivity

SUPPLEMENTARY FEEDING

PROCESS	GHG	DESCRIPTION	EMISSIONS CALCULATION	DETERMINANTS OF EMISSIONS
N-FERTILIZERS, LIME AND UREA APPLICATION, AND CROP RESIDUE	**N_2O – Direct & Indirect, CO_2**	Same as emissions from pasture management	**Amount of each feed input x Emission Factor (EF_{feed}) in CO_2e (typically, from a LCA database, including transportation)**	Amount and composition of supplementary feeding

OTHER FARM EMISSIONS

PROCESS	GHG	DESCRIPTION	EMISSIONS CALCULATION	DETERMINANTS OF EMISSIONS
ENERGY AND FUEL CONSUMPTION	**CO_2e**	Fuel consumption for pasture management, animal feeding and manure management, and electricity consumption for lighting facilities and employee houses and powering operations	**Amount and type of fuel consumed x fuel Emission Factor (Ef_f) + Amount and source of electricity consumed x energy source Emission Factor (EF_{es})**	Amount and type of fuel consumed, and amount and source of electricity consumed
FARM INFRASTRUCTURE AND EQUIPMENT	**CO_2e**	Emissions embodied in the production of farm infrastructure made of concrete or metal (e.g. fences, hangars and feed and water troughs), plastics (e.g. pipes) and of equipment and vehicles (e.g. tractors and implements, wagons)	**Area of concrete or metal construction x construction Emission Factor (EF_c) / lifetime + Equipment used x equipment Emission Factor (EF_{eq}) / lifetime**	Area of concrete or metal construction and Number and size of equipment used

SOIL CARBON

PROCESS	GHG	DESCRIPTION	EMISSIONS CALCULATION	DETERMINANTS OF EMISSIONS
LOSS/ ACCUMULATION OF SOIL CARBON	**CO_2**	Soil-carbon stock changes due to the imbalance between the deposition of plant biomass and dung (inputs) and its consumption by soil microorganisms (outputs)	**Emission Factor per area of soil based on the soil management condition**	Soil quality and conservation status and pasture management practices. Degraded areas loose soil C, whereas improved areas accumulate soil C, especially during recovery

TABLE S2 - SUMMARY OF PARAMETERS FOR ACTIVITY

PASTURE

PHASE	PARAMETER	UNIT	1	2	3	4	5
CHARACTERISTICS	Pasture Harvest Yield	kg f.m/ha.yr	**9,300**	**18,600**	**18,600**	**27,900**	**27,900**
	Pasture Dry Matter content	%	**34**	**34**	**34**	**27**	**27**
	Pasture Digestible Energy	%	**52**	**56**	**56**	**60**	**60**
MANAGEMENT	Urea application	kg/ ha.yr	**0**	**50**	**50**	**200**	**200**
	P-fertilizer application	kg/ ha.yr	**0**	**25**	**25**	**50**	**50**
	K-fertilizer application	kg/ ha.yr	**0**	**25**	**25**	**50**	**50**
	Dolomitic lime application	kg/ ha.yr	**0**	**200**	**200**	**400**	**400**
	Pasture renewal	rate	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**
	Pasture burned	rate	**0.020**	**0.013**	**0.013**	**0.005**	**0.005**
SOIL C	Soil C emission (accumulation)	tC/ha.yr	**0.25**	**0.00**	**0.00**	**-0.50**	**-0.50**
STOCKING RATE	Calving & Rearing	UA/ha	**0.8**	**1.6**	**1.6**	**2.5**	**2.1**
	Fattening	UA/ha	**0.8**	**2.2**	**667**	**4.1**	**677**

Note: 1-Extensive; 2-Semi intensive; 3-Semi intensive with feedlot finishing; 4-Intensive pasture based; 5-Intensive with feedlot finishing.

HERD DYNAMICS

PHASE	PARAMETER	UNIT	1	2	3	4	5
CALVING	Cow body weight	kg	**390**	**420**	**420**	**450**	**450**
	Bull body weight	kg	**650**	**650**	**650**	**650**	**650**
	M Calf weight at weaning	kg	**180**	**195**	**195**	**230**	**230**
	F Calf weight at weaning	kg	**165**	**180**	**180**	**220**	**220**
	Weaning age	months	**8**	**8**	**8**	**8**	**8**
	Culled Cow slaughter weight	kg	**420**	**450**	**450**	**480**	**480**
REARING	M rearing duration	months	**25.2**	**13.0**	**13.0**	**8.3**	**8.3**
	F rearing duration	months	**19.7**	**9.5**	**9.5**	**7.2**	**7.2**
	M rearing Average Daily Gain	kg/ day	**0.313**	**0.569**	**0.569**	**0.813**	**0.813**
	F rearing Average Daily Gain	kg/ day	**0.250**	**0.469**	**0.469**	**0.713**	**0.713**
	M body weight at end of rearing	kg	**420**	**420**	**420**	**435**	**435**
	F body weight at end of rearing	kg	**315**	**315**	**315**	**375**	**375**
FATTENING	Steer finishing duration	months	**10**	**6**	**3.5**	**4.5**	**3.5**
	Heifer finishing duration	months	**6**	**4**	**2.5**	**4**	**3**
	Steer finishing Average Daily Gain	kg/ day	**0.313**	**0.888**	**1.250**	**1.200**	**1.400**
	Heifer finishing Average Daily Gain	kg/ day	**0.250**	**0.788**	**1.050**	**1.000**	**1.200**
	Steer body weight at slaughter	kg	**515**	**582**	**553**	**599**	**584**
	Heifer body weight at slaughter	kg	**361**	**411**	**395**	**497**	**485**
	Steer carcass weight at slaughter	kg	**268**	**311**	**304**	**330**	**327**
	Heifer carcass weight at slaughter	kg	**180**	**210**	**205**	**258**	**257**

Note: 1-Extensive; 2-Semi intensive; 3-Semi intensive with feedlot finishing; 4-Intensive pasture based; 5-Intensive with feedlot finishing.

ZOOTECHNICAL INDICATORS

PHASE	PARAMETER	UNIT	1	2	3	4	5
CALVING	Bulls per cow	%	3	4	4	2	2
	Calving interval	days	400	365	365	365	365
	Pregnancy rate	%	70	80	80	90	90
	Pre-birth loss rate	%	7	5	5	4	4
	Calving rate	%	65	76	76	86	86
	Calf mortality	%	5	4	4	3	3
	Weaning rate	%	62	73	73	84	84
	Cow mortality	%	1.1	1.0	1.0	1.0	1.0
	Bull mortality	%	1.1	1.0	1.0	1.0	1.0
	Replacement heifer mortality	%	1.5	1.25	1.25	1.0	1.0
	Cow culling rate	%	12	15	15	17	17
	Milk production per cow	kg / d	1.8	2.25	2.25	2.7	2.7
	Fat content in milk	%	4.3	4.25	4.25	4.2	4.2
	Protein content in milk	%	3.2	3.2	3.2	3.2	3.2
REARING	Unfinished steer mortality	%	2.0	1.0	1.0	1.0	1.0
	Unfinished heifer mortality	%	2.0	1.0	1.0	1.0	1.0
FATTENING	Finishing steer mortality	%	1.0	1.0	0.5	0.5	0.5
	Finishing heifer mortality	%	1.0	1.0	0.5	0.5	0.5
	Steer carcass yield	%	52	53.5	55	55	56
	Heifer carcass yield	%	50	51	52	52	53

Note: 1-Extensive; 2-Semi intensive; 3-Semi intensive with feedlot finishing; 4-Intensive pasture based; 5-Intensive with feedlot finishing.

SUPPLEMENTARY NUTRITION

PHASE	PARAMETER	UNIT	1	2	3	4	5
CALVING	Mother cow nutrition	kg/ day	0.06	0.10	0.10	0.15	0.15
	Calf nutrition	kg/ day				0.39	0.39
	Replacement Heifer nutrition	kg/ day	0.06	0.06	0.06	1.000	1.000
REARING	Steer nutrition	kg/ day	0.06	0.923	0.923	1.663	1.663
	Heifer nutrition	kg/ day	0.06	0.743	0.743	1.488	1.488
FATTENING	Finishing steer concentrate supplement	kg/ day	0.15	5.0	9.7	9.3	10.2
	Finishing heifer concentrate supplement	kg/ day	0.1	3.6	7.1	7.8	8.6
	Finishing steer forage supplement	kg dm/ day	—	—	2.4	—	2.5
	Finishing heifer forage supplement	kg dm/ day	—	—	1.8	—	2.1
DIGESTIBILITY	DE of supplement	%	—	80	80	80	80
	DE of silage	%	—	—	62	—	62

Note: 1-Extensive; 2-Semi intensive; 3-Semi intensive with feedlot finishing; 4-Intensive pasture based; 5-Intensive with feedlot finishing.

TABLE S3 - SUMMARY OF PARAMETERS FOR EMISSIONS FACTORS

LIVESTOCK

	PARAMETER	UNIT	VALUE	SOURCE
METHANE CONVERSION FACTOR [Ym]	Low productivity systems	%		ipcc 2019 Table 10.12, based on Table 10A.3 for Latin America
	Calves on milk		**0.0**	
	Other cattle		**7.0**	
	High productivity systems			
	Calves on milk		**0.0**	
	Growing heifers/ steers		**6.3**	
	Feedlot cattle		**4.0**	
	Other cattle		**7.0**	
MILK PRODUCTION PER COW	Low productivity systems	MJ d-1 kg-1	**1.8**	ipcc 2019 table 10A.3 for Latin America
	High productivity systems		**2.7**	
FAT CONTENT IN MILK	Low productivity systems	%	**4.3**	ipcc 2019 table 10A.3 for Latin America
	High productivity systems		**4.2**	
PROTEIN CONTENT IN MILK	Low productivity systems	%	**3.2**	ipcc 2019 table 10A.3 for Latin America
	High productivity systems		**3.2**	
COEFFICIENT FOR MAINTENANCE [Cf]	Bulls	MJ d-1 kg-1	**0.370**	ipcc 2019 Table 10.4
	Lactating cows		**0.386**	
	Other cattle		**0.322**	
COEFFICIENT FOR ACTIVITY [Ca]	Stall	MJ d-1 kg-1	**0**	ipcc 2019 Table 10.5
	Pasture		**0.17**	
	Grazing large areas		**0.36**	
COEFFICIENT FOR GROWTH [C]	Females	MJ d-1 kg-1	**0.8**	ipcc 2019 Equation 10.6, from NRC 1996
	Castrates		**1.0**	
	Bulls		**1.2**	
COEFFICIENT FOR PREGNANCY [Cp]	Cattle and buffalo	MJ d-1 kg-1	**0.1**	ipcc 2019 Table 10.17
URINARY ENERGY AS FRACTION OF GE [EU]	Most ruminants	—	**0.04**	ipcc 2019 Equation 10.24
	Ruminants fed with 85%+ grains		**0.02**	
ASH CONTENT OF MANURE	—	—	**0.179**	ipcc 2019 Section 10B.6
MAXIMUM METHANE PRODUCING CAPACITY [B0]	Pasture, Range & Paddock	m3 CH_4 kg VS-1	**0.19**	ipcc 2019 Table 10.16
	Low productivity - Non dairy cattle		**0.13**	ipcc 2019 Table 10.17 Note 2
	High productivity - Non dairy cattle		**0.18**	
METHANE CONVERSION FACTOR OF MM [MCF]	Lagoon	%	**80**	ipcc 2019 Table 10.17 for Warm, Tropical Moist climate
	Solid storage		**5**	
	Dry lot		**2**	
	Pasture/ range/ paddock		**0.47**	

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	PARAMETER	UNIT	VALUE	SOURCE
CRUDE PROTEIN IN DIET	Low productivity systems	%		ipcc 2019 Table 10.17 for Warm, Tropical Moist climate
	Mature females		**9.1**	
	Mature males		**9.6**	
	Growing heifers/ steers		**9.2**	
	Replacement / growing		**9.3**	
	Calves on milk		**9.5**	
	Calves on forage		**9.2**	
	High productivity systems			
	Mature females		**11.2**	
	Mature males		**11.2**	
	Growing heifers/ steers		**11.8**	
	Replacement / growing		**11.0**	
	Calves on milk		**9.5**	
	Calves on forage		**12.3**	
	Feedlot		**14.0**	
DIRECT N2O EF FROM EXCRETED N [EF3]	Lagoon	kg N_2O-N kg Nex-1	**0**	ipcc 2019 Tables 10.21 and 11.1 for wet climate
	Solid storage		**0.01**	
	Dry lot		**0.02**	
	Pasture/ range/ paddock		**0.006**	
FRACTION OF EXCRETED N VOLATILIZED [FRACGASM]	Lagoon		**0.35**	ipcc 2019 Tables 10.22 & 11.3
	Solid storage		**0.45**	
	Dry lot		**0.3**	
	Pasture/ range/ paddock		**0.21**	
INDIRECT N2O EF FROM VOLATILIZED EXCRETED N [EF4]	—	kg N_2O-N kg Nvol-1	**0.014**	ipcc 2019 Table 11.3 for wet climate
FRACTION OF EXCRETED N LEACHED OR RUN OFF [FRACLEACH]	Lagoon		**0.35**	ipcc 2019 Tables 11.3 & 10.22
	Solid storage		**0.02**	
	Dry lot		**0.035**	
	Pasture/ range/ paddock		**0.24**	
INDIRECT N2O EF FROM LEACHED OR RUNOFF EXCRETED N [EF5]	—	MJ d-1 kg-1	**—**	ipcc 2019 Table 11.3

PASTURE MANAGEMENT

	PARAMETER	UNIT	VALUE	SOURCE
UREA N CONTENT	—	%	**46**	chemical property
DIRECT N2O EF FROM N-FERT INPUTS [EF1S]	—	kg N_2O–N kg Ninput-1	**0.016**	ipcc 2019 Table 11.1 for synthetic fertilizer in wet climate
DIRECT N2O EF FROM OTHER N INPUTS [EF1O]	—	kg N_2O–N kg Ninput-1	**0.006**	ipcc 2019 Table 11.1 for other N inputs in wet climate
FRACTION OF APPLIED SYNTHETIC N-FERT VOLATILIZED [FRACGASF]	—		**0.15**	ipcc 2019 Table 11.3 for urea
INDIRECT N2O EF FROM VOLATILIZED N [EF4]	—	kg N_2O-N kg Nvol-1	**0.014**	ipcc 2019 Table 11.3 for wet climate
FRACTION OF APPLIED ORGANIC N VOLATILIZED [FRACGASM]	—		**0.21**	ipcc 2019 Table 11.3
FRACTION OF APPLIED N-FERT LEACHED OR RUN OFF [FRACLEACH-H]	—		**0.24**	ipcc 2019 Table 11.3 for wet climate
INDIRECT N2O EF FROM LEACHED OR RUNOFF N [EF5]	—	kg N_2O-N kg Nleached-1	**0.011**	ipcc 2019 Table 11.3
DOLOMITIC LIME APPLICATION EF	—	kg CO_2 kg L-1	**0.477**	ipcc 2006 topic 11.3.1 (note: EF multiplied by 44/12 for C-> CO2)
UREA FERTILIZER APPLICATION EF	—	kg CO_2 kg U-1	**0.733**	ipcc 2006 topic 11.3.1 (note: EF multiplied by 44/12 for C-> CO2)
LIME & FERTILIZER PRODUCTION & TRANSPORTATION EFS	Dolomitic lime	kg CO_2 kg fert-1	**0.0231**	GREET database
	Urea		**0.8736**	GREET database
	P-fertilizer		**0.3481**	GREET database for Brazil
	K-fertilizer		**1.0724**	GREET database for Brazil
RATIO RESIDUE : HARVESTED YIELD, PASTURES [R(AG) P]	—	—	**0.3**	ipcc 2019 Table 11.1A
RATIO BELOW-GROUND : ABOVE-GROUND BIOMASS, PASTURES [R:S P]	—	—	**0.8**	ipcc 2019 Table 11.1A
N CONTENT OF ABOVE-GROUND RESIDUES, PASTURES [N(AG) P]	—	kg N kg d.m.-1	**0.015**	ipcc 2019 Table 11.1A
COMBUSTION FACTOR, PASTURES [CF P]	—	—	**0.35**	ipcc 2019 Table 2.6 (Tropical pasture)
N CONTENT OF BELOW-GROUND RESIDUES, PASTURES [N(BG) P]	—	kg N kg d.m.-1	**0.012**	ipcc 2019 Table 11.1A
NON-CO2 GHG EF FROM BURNING OF GRASSLAND	Grassland burnt CH_4 EF	g CH4 kg d.m.-1	**2.3**	ipcc 2019 table 2.5
	Grassland burnt N_2O EF		**0.21**	ipcc 2019 table 2.5

CROP MANAGEMENT

	PARAMETER	UNIT	VALUE	SOURCE
RATIO RESIDUE : HARVESTED YIELD, CORN [R(AG) CORN]	—	—	**1**	ipcc 2019 Table 11.1A
RATIO BELOW-GROUND : ABOVE-GROUND BIOMASS, CORN [R:S CORN]	—	—	**0.22**	ipcc 2019 Table 11.1A
N CONTENT OF ABOVE-GROUND RESIDUES, CORN [N(AG) CORN]	—	kg N kg d.m.-1	**0.006**	ipcc 2019 Table 11.1A
COMBUSTION FACTOR, CORN [CF C]	—		**0.8**	ipcc 2019 Table 2.6
N CONTENT OF BELOW-GROUND RESIDUES, CORN [N(BG) CORN]	—	kg N kg d.m.-1	**0.007**	ipcc 2019 Table 11.1A
NON-CO2 GHG EF FROM BURNING OF GRASSLAND	Ag residue burnt CH_4 EF	g CH_4 kg d.m.-1	**2.7**	ipcc 2019 table 2.5
	Ag residue burnt N_2O EF		**0.07**	

FEED INPUTS

	PARAMETER	UNIT	VALUE	SOURCE
SILAGE PRODUCTION EF	—	kg CO_2e kg-1	**0.002**	
FEED INGREDIENTS PRODUCTION & TRANSPORTATION EFS	Corn meal	kg CO_2e kg-1	**0.476**	FEEDPRINT (BR)
	Soybean meal		**0.499**	FEEDPRINT (BR)
	Soybean grain		**0.530**	FEEDPRINT (BR)
	DDG		**0.299**	FEEDPRINT (US)
	WDG		**0.020**	FEEDPRINT (US)
	Cotton seed		**0.930**	
	Urea		**1.356**	FEEDPRINT
	Salt		**0.194**	FEEDPRINT
	Mineral compound		**1.188**	FEEDPRINT
	Mineral salt		**1.188**	FEEDPRINT

FACILITITES, EQUIPMENT, FUEL CONSUMPTION AND ENERGY USE

CATEGORY	UNIT	VALUE	SOURCE
EMBODIED EF FOR CIVIL CONSTRUCTIONS IN BRAZIL	kgCO_2e m^2-1	**365**	Based on S1 of Krynch et al (2021), considering 1st quartile
EMBODIED EF FOR FENCE STEEL PRODUCTION IN BRAZIL	kgCO_2e kg-1	**1.7**	Aço Brasil institute (2020)
EMBODIED EF FOR PVC PIPE PRODUCTION IN BRAZIL	kgCO_2e kg-1	**2**	GREET database
EMBODIED EF FOR SMALL TRACTOR PRODUCTION IN BRAZIL	tCO_2e unit-1	**34**	Li, J. et al.. 2019. Case Study in a Mono-Cropping System of Northeast
EMBODIED EF FOR MEDIUM TRACTOR PRODUCTION IN BRAZIL	tCO_2e unit-1	**97**	Idem
EMBODIED EF FOR LARGE TRACTOR PRODUCTION IN BRAZIL	tCO_2e unit-1	**123**	Idem
EF FOR DIESEL USE IN FARM EQUIPMENT	kg CO_2 kg-1	**3.188**	Revised 1996 IPCC Guidelines for National GHG Inventories (Table 1-47)
DIESEL OIL DENSITY	kgl-1	**0.832**	
ELECTRIC POWER USE EF IN BRAZIL	kg CO_2e MWh-1	**76.9**	MCTI emission factors webpage

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WHY AND HOW TO SCALE UP LOW-EMISSIONS BEEF IN BRAZIL, AND THE ROLE OF CARBON MARKETS

Photo: Wenderson Araújo

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