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Future perspectives of Brazilian beef production: what is the role of Silvopastoral systems?

Katrin Agethen · Rogerio Martins Mauricio · Claus Deblitz · Maria Dolores Izquierdo · Ernesto Reyes · Julian Chará

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Abstract Against the backdrop of changing production conditions and market requirements, it seems time has come to rethink Brazil's beef production systems. We analyse the economic and environmental performance of three beef production systems: classic beef production system (CB), and two types of silvopastoral systems: the integrated crop-livestock-forestry system (ICLFS) and the natural regeneration system (NR) in a comparative case study analysis. We find that, though costs of production are the lowest for CB, only the ICLFS and NR case studies are generating long-term profits. While greenhouse gas emissions per kg live weight added are lowest in ICLFS, followed by NR and CB, per hectare (ha) emissions are highest in NR, followed by ICLFS and CB. Considering the system's carbon removal, NR and potentially ICLFS are sequestering more than releasing. Additionally, the land required to produce beef is lowest in NR, followed by ICLFS and CB. Considering the additional outputs produced by ICLFS and NR, they showcase the potential of multifunctional production systems for future scenarios, where land scarcity puts land-demanding production systems, such as beef, under pressure. The three production systems perform differently depending on the indicators analysed. How they will reply to future challenges depends on the location and the specific environment. Yet, from the analysed systems, CB is the least sustainable, economically and environmentally.

Keywords Production system analysis · GHG emissions · Carbon sequestration · Sustainable beef production

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K. Agethen (✉) · C. Deblitz
Institute of Farm Economics, Thünen Institute, Bundesallee 63, 38116 Braunschweig, Germany
e-mail: katrin.agethen@thuenen.de

K. Agethen
Faculty of Life Sciences, Humboldt-Universität zu Berlin, Invalidenstr. 42, 10115 Berlin, Germany

R. M. Mauricio
Universidade Federal de São João del-Rei, São João del-Rei, Brazil

M. D. Izquierdo
Agralys, Potsdam, Germany

E. Reyes
agri benchmark, Pollensa, Spain

J. Chará
Centre for Research on Sustainable Agriculture Production Systems CIPAV, Calí, Colombia

Introduction

Agriculture and especially livestock producers are facing a triple challenge regarding sustainable development in a changing climate: they need to adapt themselves to the rising climatic risks (Kummu et al. 2021), and at the same time, reduce their contribution to

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climate change through mitigation of greenhouse gas (GHG) emissions (Gerber et al. 2013; Rojas-Downing et al. 2017) while continuing generating income and providing livelihoods to producers and employees, and contributing to sustainable development (Schneider and Tarawali 2021). Grassland-based livestock systems are at the centre of this debate. Compared to other beef production systems, they show higher emission intensity and land used per kilogram of beef produced (Blaustein-Rejto et al. 2023). Depending on their location, they are especially vulnerable to projected changes in weather and climate (Mbow et al. 2019). Yet, as low-investment production systems, they play a crucial role in offering income opportunities (agri benchmark 2017). Pastures and grasslands also offer huge opportunities for climate protection and soil health as potentially they can sequester 148 to 699 megatons of CO_2 equivalents per year through improved grazing management (Bai and Cotrufo 2022). In South America, pastures store from 49 to 56 tonnes C per hectare and can capture up to 0.9 tonnes C per year with good management (Dondini et al. 2023). Additionally, cattle's capability to transform non-edible feedstuff into highly nutritious food for human consumption underlines their importance for future food security (Mottet et al. 2017; Smith et al. 2013).

Brazil's beef production, the world's second-largest (FAOStat 2023), relies greatly on its vast grasslands. Only a share of 16% of its herd is finished in grain-fed production systems at the end of the fattening cycle or in semi-confinements where supplement feeding is offered on pastures (USDA/GAIN 2021). 80–90% of these grasslands consist of *Brachiaria ssp.* grass (Caldas 2018). The state of these grasslands however is under debate: recent research classified 63.5% of the Brazilian grasslands as in some state of degradation (MapBiomas Project). The status of grazed pasturelands is expected to experience further stress with ongoing climate change and strong seasonality in rainfall. Besides, beef production on pasture is in the focus of the discussion about land use succession in deforested areas (França et al. 2021).

Compliance with environmental laws (the so-called forest code) (Planalto/Presidência da República 2015) gets more important as private agreements (Lui 2021), public announcements for trade requirements (European Commission 2022), and technological innovations in traceability are advancing (Ferguson et al. 2020). The forest code defines how much of the property's land needs to be declared as native habitat (so-called Legal Reserve) depending on the biome and region the property is located (Fig. 1). In the region Legal Amazon, the following applies: If the farm is located in the Amazon biome, 80% of the property needs to be conserved as native habitat. Exceptions exist e.g. for small properties, in case indigenous areas or natural state reserves cover more than 50% of the municipality's area, as well as for producers that applied to the previous laws (until August 1996) and did not deforest beyond a maximum of 50% of their property. Those are not required to restore up to the 80% required by the current regulations. If the farm is located in the Cerrado biome, 35% of the property needs to be set aside as a natural reserve. If it is located in neither biome or outside the Legal Amazon region, a share of 20% applies (Machado 2016; Planalto/Presidência da República 2015).

Recently Brazil's traditional beef production areas are facing pressure from the expansion of croplands: land prices are rising, especially in regions at the cropping frontier (Cohn et al. 2016; McManus et al. 2016). Future climate change perspectives might even increase the re-location pressure of pasture lands and livestock production (Zilli et al. 2020). While this opens new income opportunities for land owners, it also challenges beef production with typically lower returns per hectare compared to cropping activities. A similar effect is caused by the enforcement of the Brazilian forest code. As a consequence of both, the opportunity costs for land use increase, which impacts the long-term whole-farm profitability and economic sustainability of beef production.

At the same time, domestic demand for beef remains high, and global demand is expected to further increase (OECD/FAO 2023). Despite increasing awareness of environmental concerns of beef production, consumers' preference for affordable meat (Hötzel and Vandresen 2022) is not encouraging producers to invest in production systems with higher production costs.

The above-mentioned perspectives challenge the "business as usual" (BAU) pasture-based beef production system as a future scenario of Brazilian beef production. There is the need to produce more efficiently on the available land resources, in a way that multiple benefits are realised, and the provision of non-commercial goods, such as biodiversity or water storage, is integrated.

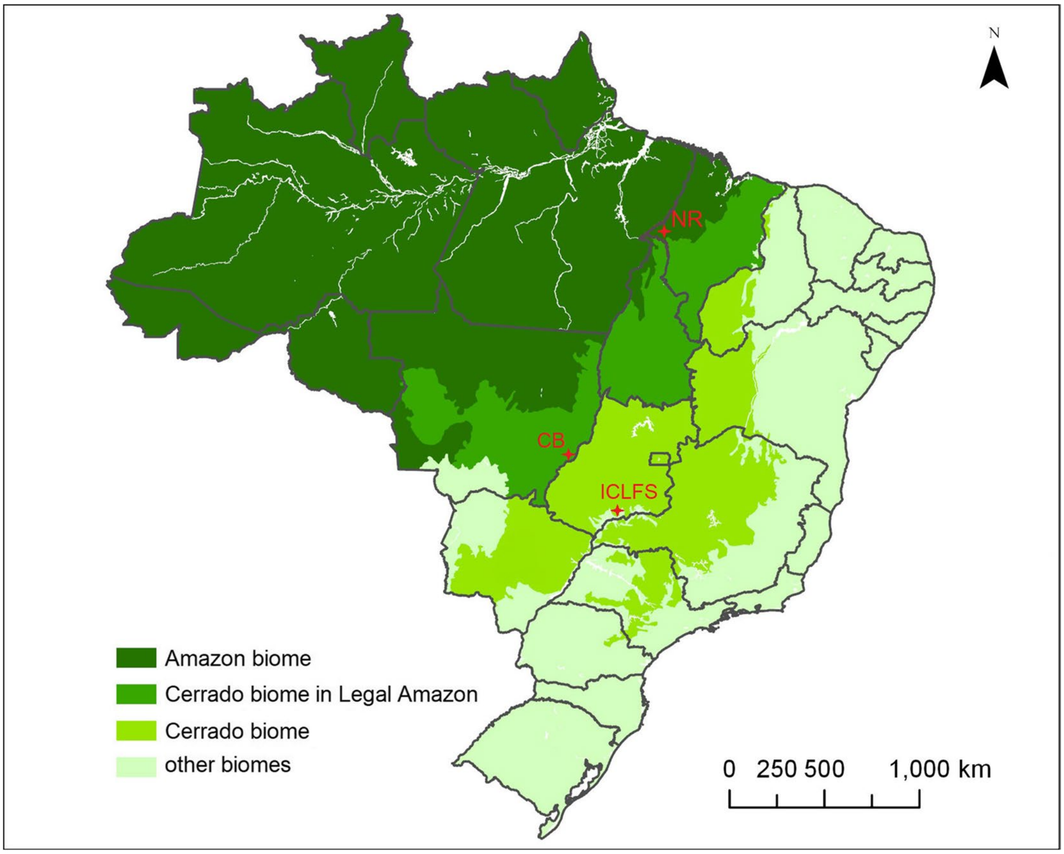

Fig. 1 Map of Brazil biomes, the region Legal Amazon, and the location of analysed beef finishing systems. CB: Classical beef production system; NR: Natural regeneration; ICLFS: integrated crop-livestock-forestry system

Silvopastoral systems (SPS) are multifunctional land-use systems that combine forage plants with perennial shrubs and trees for livestock feeding and complementary uses (Murgueitio et al. 2011). Tropical SPS offer alternatives to conventional grazing systems with vast opportunities for environmental and productive challenges, e.g. ecosystem services, climate change, sustainable productivity, and landscape restoration. Various forms of SPS have been adopted in Latin America over the past years (Chará et al. 2019). In Brazil, two relevant SPS concepts are Integrated Crop Livestock Forestry systems (ICLFS) and natural regeneration (NR) of native trees.

ICLFS, as a specific form of SPS, augmented in popularity and importance with the ABC plan, introduced in 2010, and its successor ABC+ (MAPA 2021). This policy framework underlines the relevance of ICLFS as a technology restoring degraded pasture lands, developing multifunctional land use systems, increasing land use efficiency, and mitigating GHG emissions. The system has been developed with extensive research by EMBRAPA (Bungenstab et al. 2019) and surpassed adoption expectations reaching more than 10 million hectares in 2020 (MAPA 2023). Various combinations of ICLFS exist, adapted to local conditions (Almeida et al. 2013; Moraes et al. 2019). Most commonly the integrated crop-livestock-forestry system is established by introducing *Eucalyptus* trees on open pasture, planted in rows with alleys of crops, typically soy or corn, which are cultivated for one or two seasons and then followed by pasture for cattle finishing.

Besides, Brazil has been identified as a potential key area for assisted Natural Regeneration (Alves et al. 2022). Especially tropical rainforest landscapes show high restoration opportunities (Brancalion et al. 2019). Originally a concept for the restoration of forests, it is also applied for the establishment of SPS.

This process can be described as a selective mechanical cutting of regrowing native trees and bushes in productive pasture lands and makes use of remaining seed banks in the soils as well as seed dispersal from neighbouring (remaining) native vegetation (Mauricio et al. 2019). The additional introduction of leguminous shrubs further benefits the productivity of the livestock and forage systems and thus the economic performance. This system of managed regeneration of secondary native vegetation could be especially implemented in degraded pastures in the Amazon region (estimated to 30 million hectares or 50% of the managed pastures) (Dias-Filho 2015).

The introduction of these alternative beef production concepts comes along with economic, managerial, and environmental consequences. Although a growing literature body of case study assessments of SPS, ICLFS, or conventional pasture-based beef production exists (e.g. Cardoso et al. 2016; Dick et al. 2015; Figueiredo et al. 2017; Mazzetto et al. 2015; Ruviaro et al. 2015), comparative assessments of systems that simultaneously analyse economic and environmental indicators are scarce (Siqueira and Duru 2016). This limits the comparability of results, as especially economic and environmental assessments strongly depend on the defined system boundaries, referenced methodology, and price assumptions. Additionally, the scope of analysis differs among studies, e.g. does not include GHG emissions and sinks in SPS (Leite et al. 2023).

For our case study analysis of three different beef production systems, we use a framework based on the economic assessment developed by the *agri benchmark* Beef network (agri benchmark 2013; Chibanda et al. 2020) as well as a partial Life Cycle Assessment (LCA), a common framework for environmental performance evaluation (Cederberg et al. 2013). To our knowledge, our contribution is the first one to comparatively analyse the above-mentioned three concepts regarding their performance, farm-level economics, and environmental performance, including GHG emissions and sinks. Beyond, we expand our discussion to further sustainability indicators to conclude on the systems' potential to address the above-mentioned premises of future development pathways.

With our case study analysis, we aim to contribute to a better understanding of beef production systems with relevant development potential and enhance the discussion on potential future development pathways and bottlenecks.

Materials and methods

Data collection and farm case studies

The goal of this study is to compare the economic and environmental performance of three beef production systems in Brazil representing three major managerial concepts. These three different beef production systems selected for our analysis (Fig. 1), are classic beef finishing production system (CB), integrated crop-livestock-forestry system (ICLFS), and natural regeneration system (NR). We selected three farm case studies representing those concepts. The case studies have in common, that they rely on established farm systems, which means the system was implemented more than 10 years ago and the production systems provide accurate data. All farms already provided data for research, including publications, and farm managers contributed to completing the comprehensive questionnaire on the economic and production characteristics of the farms.

The farm data set for the CB system originates from the network of typical beef production systems in Brazil, managed by CEPEA (Center for Advanced Studies on Applied Economics located in the Luiz de Queiroz College of Agriculture at the University of São Paulo in Piracicaba, Brazil). As such, it has been established and specified by a focus group including local producers and technical staff from local farmers' unions applying the standard operating procedure of the *agri benchmark* Beef network (Deblitz 2018). The so-called typical farm data gathers detailed information on economic and technological characteristics being considered representative for beef production in this region (Chibanda et al. 2020; Siqueira and Duru 2016). The data for the CB system was collected in the municipality of Barra do Garças, Mato Grosso, in 2016, reflecting the production technology and prices of the calendar year 2015.

The farm data set compiled for the ICLFS represents an individual farm in the municipality of Inaciolándia, Goiás. As such, it relies on producer information, cross-checked and consolidated with farm documents, expert knowledge, and publications (Da Silva et al. 2020). The farm data has been collected by the authors in 2022, reflecting the production technology and economic features of the calendar year 2021.

The farm data set for the NR system represents an individual farm in the municipality of São Francisco do Brejão, Maranhão. Data was collected by the authors during fieldwork in 2018 and 2019, reflecting the technological and economic features of the calendar year 2018 (Agethen et al. 2022). It has been cross-checked and consolidated with farm documents, expert knowledge, and publications (Campagnani et al. 2017; Cangussu et al. 2020).

The three systems are described below. The main characteristics of the three described production systems are summarised in Table 1.

The CB system stands for the BAU of a vast majority of Brazil's beef production, which is based on improved pastures of *Brachiaria brizantha* or *Megathyrsus maximus*. In our analysis this typical production system is located in Mato Grosso state, in the municipality of Barra do Garças, which belongs to the Legal Amazon and the Cerrado biome. The state of Mato Grosso is the most important beef-producing state in Brazil, representing 14% of the national herd (IBGE 2021). From 2017 to 2021, the cattle herd increased by 9%. 60% of its farming area is covered by pastures. Although the area under agriculture increased by 35% over the last decade, the pasture acreage was relatively stable (MapBiomas Project). The net increase in the farming area occurred at the expense of natural vegetation, such as forests and

Table 1 Production system characteristics of the three selected cases: classic beef (CB), integrated crop-livestock-forestry (ICLFS) and natural regeneration (NR)

Production system	CB	ICLFS	NR
Farm description			
Land coverage	945 ha open pasture 525 ha Legal Reserve	177 ha ICLFS 110 ha arable land 68 ha Legal Reserve	500 ha pasture with NR, of which 430 ha for cow-calf, incl. 25 ha of maize as double-crop 70 ha for finishing 500 ha Legal Reserve
Additional farm activities	-	arable farming timber (Eucalyptus)	cow-calf production
Beef finishing system			
Finishing duration	24 months	9–12 months	15 months
Average daily weight gain	493 g/day	1037 g/day	713 g/day
Feeding strategies	24 months grazing with mineral supplementation, including six months with additional concentrate supplementation	Strategy A: 12 months grazing in ICLFS with mineral and protein supplementation Strategy B: 6 months grazing with mineral and protein supplementation +3 months confined finishing on grain	12 months grazing on mixed SPS pasture with mineral supplementation +3 months confined finishing on corn and protein supplements
Grazing management & stocking density	Continuous grazing of larger areas; 0.84 LU/ha	Continuous grazing of plots of 28 ha; 2 LU/ha	Rotational grazing of plots of 4 ha, 3.6 LSU/ha
Pasture management	Pasture renewal every 20 years; incl. Partial re-seeding and minimal fertilizer application	Pasture renewal through ICLFS (re)-establishment every 7 years	Renewal every 10 years, incl. partial re-seeding, application of natural phosphate fertilizer and limestone
Pasture composition	*Brachiaria brizantha* or *Megathyrsus maximus*	*Megathyrsus maximus* cv. Tamani	50% *Brachiaria brizantha* cv. Marandu + 25% *M. maximus* cv. Mombaça + 25% *M. maximus* cv. Massai; additionally, as double-crops: *Mucuna pruriens* on 20% of area, *Tithonia diversifolia* and *Glyricidia sepium* on 5% of area

Sources: Farm data sets, based on structured interviews, farm documents and published literature savannahs. The state belongs to the Legal Amazon. The total area of the CB farm is 1470 ha, of which 36% are declared as legal natural reserve (LR). The farm finishes 500 steers per year. Feeding consists of grazing improved pastures and mineral supplementation. Additionally, concentrate is fed during the last six months of finishing. Pastures are partly renewed in an interval of 20 years. The stocking density is at 0,84 livestock units (LSU) per ha. Continuous long-term land use and management led to a steady state of carbon fluxes. Land prices are lower compared to the neighbouring state of Goiás. The focus of producers is to produce beef at low costs, balancing pasture production potential and forage intake needs of the stock, especially in the dry season.

The ICLFS farm case in our analysis is located in the municipality of Inaciolándia, in the state of Goiás, Cerrado Biome. The state of Goiás is the second most important beef producer in Brazil with 11% of the national herd. The cattle population grew by 6% between 2017 and 2021, although in the past decade, pasture areas declined by 11% due to the expansion of cash crops (MapBiomas Project; IBGE 2021).

The displacement of beef production has occurred as a consequence of the higher profitability of cash crops due to advances in cropping systems, changing environmental conditions, and the establishment of infrastructure and related processing facilities (Ferreira Balieiro 2021; McManus et al. 2016). The majority of the state of Goiás is not part of the Legal Amazon (only areas north of latitude 13° S) and belongs to the Cerrado biome. The total ICLFS farm size is 338 ha, including 177 hectares of ICLFS. 500 steers are finished annually. The finishing strategy includes seasonal confinement with supplementary feeding of concentrate. The stocking rate is 2 LSU/ha. New pasture establishment and fertilisation increased its productivity and carbon capture compared to previous management. Besides its ICLFS area, the farm owns 110 ha of arable land which is rented out for cropping activities (soy or maize). The rents bring additional income and access to financial resources for the establishment of the ICLFS. On six different plots, eucalypt plantations (ICLFS) have been established, which are renewed every seven years. The increase of land prices as well as the construction of a sugarcane plant nearby motivated the producer to identify strategies that could significantly increase output and return from the available lands to continue beef production.

The NR farm case is located in the state of Maranhão, in the municipality of São Francisco do Brejão, in the Legal Amazon and the Amazon biome. In the state of Maranhão, beef production has expanded continuously in acreage and number: the cattle population grew by 11% in the past five years (IBGE 2021). Around 80% of the state's farming lands are covered by pasture that replaced native forest. Recently, agricultural use as well as forest plantations, too, were increasing in acreage (MapBiomas Project). The western part of Maranhão belongs to the Legal Amazon (west of longitude 44°W) and therefore producers have to comply with the conditionalities on legal reserves. The NR covers a farm area of 1000 hectares, of which 50% is legal reserve. In total, 320 animals are finished per year, grown from a cow-calf herd with 600 productive cows. Cattle graze on improved grasslands mixed with introduced leguminous shrubs. Through rotational grazing on subdivided pasture areas, a stocking density of 3.6 LSU/ha is attained. Improved management increased its productivity and carbon capture compared to previous management. The corn fed during the final feeding period in the confined system is grown within the farm, as intercrop on a part of the periodically renewed pasture area. Currently, all pasture lands have scattered native trees as part of the SPS (approx. 250 trees/ha). Those were introduced by a natural regeneration process that was initiated after the purchase of the farm by the current owner in 2015, taking advantage of the seed bank remaining in the soil and neighbouring native areas. The location as well as the specific conditions, led the producer to search for a way of increasing the productivity of the land sustainably while reducing the dependence on off-farm inputs.

Economic assessment methodology

The analysis is done with the TIPI-Cal tool. TIPI-Cal is a deterministic, recursive, and dynamic simulation model to analyse the performance, productivity, and economics of agricultural production systems (Deblitz 2023). It is widely applied for benchmarking and practice change analysis in the *agri benchmark* network (Chibanda et al. 2020, 2023; Kress and Verhaagh 2019).

Due to the fact, that the data collection took place in different years, the economic data of the three case studies were aligned by projecting the prices via price indices to price levels of the calendar year 2021. To align with the functional unit chosen for the GHG emission analysis, costs are expressed in USD per 100 kg live weight (LW) added.

In the economic analysis, a total cost approach is applied with a focus on the beef enterprise only. In that approach, besides beef enterprise-specific costs, whole farm and overhead costs, such as buildings, machinery, labour costs, and further activity costs attributional to beef production are considered. These costs are assigned to the beef enterprise by the extent of their direct use in the enterprise (e.g., for example, hours worked, land area used, building, machines, and fences employed for the beef enterprise). Where this is not possible (e.g., overhead costs like taxes, insurance, and accounting costs), assignment is done by economic allocation reflecting the share of the beef enterprise in total returns. The costs of beef production include cash costs and depreciation, specifically animal purchases, feed costs (incl. feed purchase and forage production inputs such as seed and fertilizer), machinery costs (incl. maintenance costs, as well as depreciation for specific and allocated machinery), fuel and energy costs, costs for buildings and equipment (such as fences, incl. their maintenance and repairs, as well as depreciation), veterinary costs, and other beef specific insurances and further other inputs. The expenses for other farm enterprises, such as crop and timber production in ICLFS and pasture management for the cow-calf enterprise in NR, are not considered in the cost analysis.

Besides the costs of production, different levels of profitability are analysed to allow conclusions for the economic sustainability of the production systems. In the ICLFS and the NR case studies, beef production is only one yet an integral part of the whole farm. To reflect this, we calculated medium-term and long-term profits at the whole-farm level. For this, we differentiate the total costs of production into cash costs, depreciation, and opportunity costs. The depreciation is calculated as linear depreciation on machinery and buildings over their economic utilization period, based on replacement values. We reflect opportunity costs, specifying the alternative uses of own factors, including own labour (by alternative wages for own labour), own land (by alternative rents for own land), and own capital (by interest for equity). Three levels of profitability are calculated by deducting different cost levels from total returns: (a) short-term profit: total returns minus cash costs, (b) medium-term profit: short-term profit minus depreciation, and (c) long-term profit: medium-term profit minus opportunity costs.

Greenhouse gas emission methodology

The GHG emissions of beef production are calculated by applying a partial LCA approach (ISO 2006, 2006). As required by the methodology, in the following, goal and scope, inventory analysis, and selected impact assessment indicator are briefly defined.

The goal is to compare the GHG emissions and sinks of the specified beef finishing systems (CB, ICLFS and NR) in a farm-gate to farm-gate scope, focusing on the finishing stage only. The functional unit (FU) is one kilogram (kg) live weight added in beef finishing and one hectare (ha) of agricultural land used. Although the FU of one kg carcass weight (CW) is a common unit to assess the environmental impact of beef production systems, this is difficult to apply to our analysed specialised beef finishing systems. The cow-calf stage represents a significant additional share of the total beef emissions (Rotz et al. 2019). It is not covered in our analysis, thus the calculation per CW is not suitable for our analysis.

The system boundaries include the relevant components to add one kg of live weight within the finishing stage. As depicted in Fig. 2, this includes the most relevant forage production inputs (mineral fertilizer and lime) and the off-farm produced feedstuffs (mineral supplements, concentrates, and grains). Impacts associated with further inputs or infrastructure are excluded, including machinery and installations, fuel and energy consumed, seeds and pesticides applied, incoming animals, and transport.

Inputs entering and live weight produced in the beef finishing systems are defined in the farm data sets by the specification of finishing productivity, feed rations, and forage production. On-farm emissions of beef production include all on-farm emissions related to the finishing animal, manure, and pasture management according to IPCC methodology and coefficients, where possible of the IPCC 2019 refinements (IPCC 2006, 2019). Feed nutritive values are calculated by feeding periods considering

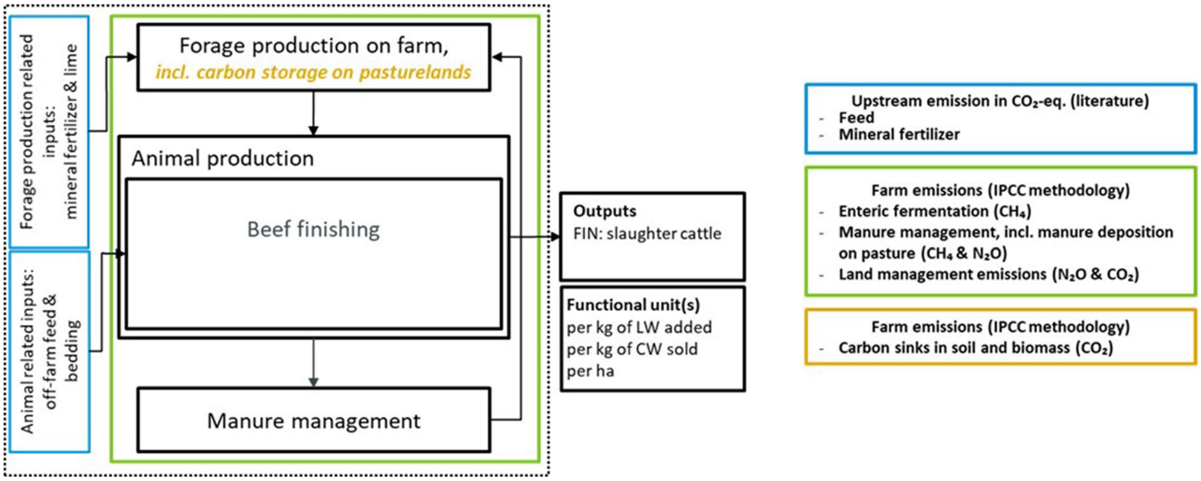

Fig. 2 Applied GHG emission framework to compare three beef finishing production systems in Brazil

available feed characteristics analysis (CQBAL (Valadares Filho et al. 2018) and Feedipedia (INRAE et al. 2012) and following Freer (2007). Database and literature values are considered to reflect the off-farm emissions related to purchased feed inputs and fertilizers. A detailed description of the beef production parameters, as well as secondary emission factors for upstream emissions, are available as supplementary material.

Global warming potential (GWP) in CO_2-equivalents is assessed by applying GWP^{100} conversion factors of 28 for methane and 265 for nitrous oxide (IPCC 2013).

In addition to the GHG emissions from beef production, we assess the carbon sinks from pasture land management. Carbon fluxes can be classified by permanence within the system. Short-term sinks consist of edible above-ground biomass, or seasonally greening bushes and trees. This carbon pool is constantly built up and released, e.g., through ingestion of the animals, and therefore not reflected as a sink in our assessment. Even though more productive pastures in ICLFS and NR capture more carbon in above-ground biomass, it underlies the same patterns. Below-ground biomass production is related to above-ground productivity. This pool is not undergoing constant renewal but is subject to decomposition with the renewal of the plants and pastures. We therefore classify it as a medium-term sink. Following the IPCC guideline (IPCC 2006), practices can reach a maturity level, the so-called steady-state, where no additional accumulation is accounted for. For growing biomass, the maturation age needs to be considered, where no further accumulation is observed and growth equals decomposition. Woody biomass in the ICLFS is considered as growing forests and carbon capture is therefore classified as a medium-term sink, not considering its potential end use.

As long-term sinks, we classify soil sequestration following a permanent improvement in the production systems as well as perennial woody biomass, e.g. in native trees, that are prohibited from cutting and can therefore be considered permanent. Again, one needs to consider, that GHG accounting suggests a maturity level for such storages (e.g. for soils by default after 20 years) where no further sequestration takes place (IPCC 2006). Woody biomass from ICLFS used for construction or furniture could also be considered as a long-term sink. These long-term sinks can be seen as compensatory to GHG emissions from other activities. In contrast to carbon sinks from additional carbon fluxes, we do not consider already existing soil carbon storage or biomass storage in legal reserves in our assessment.

Results

Economic analysis

The comparative analysis shows different levels of costs of production (Fig. 3). The costs for beef production are lowest for the CB system with 3,31 USD per kg LW added, followed by NR with 3,87 per kg LW added and ICLFS with 4,82 USD per kg LW added. Animal purchases account for the largest contributor in all systems (73% in CB, 72% in NR, and 59% in ICLFS), followed by feed costs. Here the increasing intensification is visible: while in CB its share is 18%, in NR 23% and in ICLFS 38% of the costs of production are allocated to forage production and feed purchase. Especially, the level of feed costs makes the ICLFS and NR system more expensive.

The comparison of the total costs of beef production in relation to the yielded returns from animal sales shows that all systems are profitable in the medium term. This means, that the farm can cover the cash expenses and the depreciation costs and is thus able to stay in the business. Being mid-term profitable means, that depreciation from machinery, equipment, and buildings is covered, thus the farm is able to re-invest in the production. However, the opportunity costs for own land, labour, and capital, are not fully covered by the returns of the beef enterprise only (Fig. 3). In all three case studies, the opportunity cost for land is an important cost component. It represents 86% of the opportunity costs in CB, 96% in ICLFS, and 88% in NR. It is highest in the ICLFS and lowest in the CB system and reflects the price of the land and the beef productivity of the land. At the enterprise level, these production systems are not profitable in the long-term, meaning not able to pay their own production factors, including land, labour, and capital, and thus not able to generate additional equity to stay in the business in the long-term.

As described before, this is one reason for the diversification of business activities in the ICLFS and NR systems, where beef finishing is an integral part of further farm activities. The additional income from cropping and forestry activities secures long-term profitability at the whole-farm level of the ICLFS. For the NR system, this is reached through the combination with the Cow-calf enterprise. Both farming systems are able to cover all costs occurring with the additional enterprises with their combination of agricultural returns and are profitable in the long term (Fig. 4).

Greenhouse gas emission analysis

Considering the GHG emissions related to animal and manure management, forage production on-farm as well as feed production off-farm and land management, the GHG emissions per kg live weight (LW) added are assessed. They range from 12.5 kg CO_2 equivalents per kg LW for CB, 9.0 kg CO_2-eq/kg LW for ICLFS to 10.9 kg CO_2-eq/kg LW for NR (Fig. 5).

The emissions related to enteric fermentation make the biggest difference in the comparison of the systems. This is mainly related to the improved

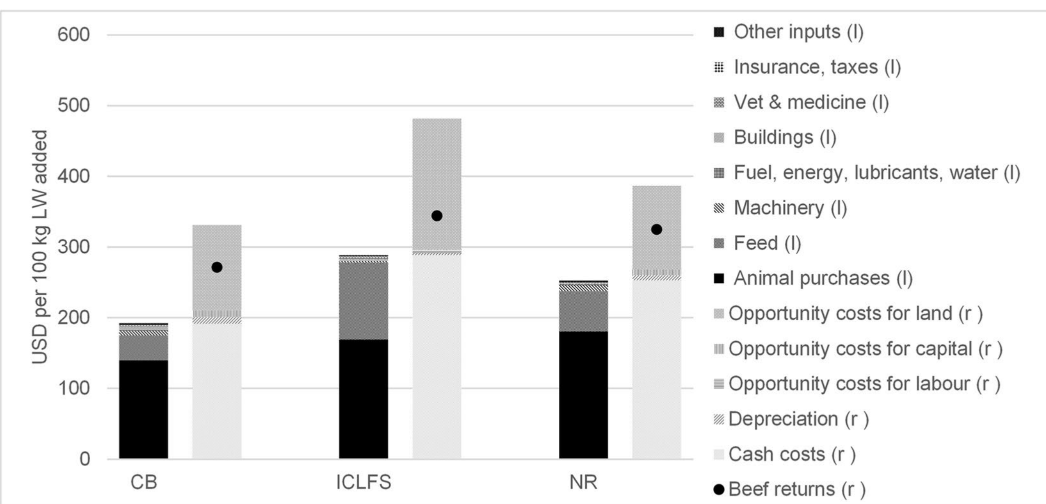

Fig. 3 Cash costs and depreciation (left column (l)), total costs (right column (r)) and returns of the beef enterprise in USD per 100 kg live weight (LW) added

Fig. 4 Whole farm medium and long-term profit in USD per hectare

performance of the finishing system, but also to the improved feed digestibility, especially in the confinement periods. Partly this improvement is outbalanced by additional emissions from feed production or by the increase in land-related emissions due to higher renewal frequency or fertilizer inputs in the ICLFS and NR system.

The GHG emissions per hectare cultivated are mainly influenced by the stocking density, but also the land management and pasture renewal interval. The range is from 2.233 Mg CO_2-eq/ha (CB) to 6.526 Mg CO_2-eq/ha (ICLFS) and 12.938 Mg CO_2-eq/ha (NR).

As two of the three systems include the cultivation or restoration of woody biomass, the emission analysis is extended to the created carbon sinks (Table 2). Not considering the short-term and medium-term sinks, our assessment suggests that NR can compensate for its GHG emissions from beef finishing with the sinks created in the same area during the carbon accumulation phase of woody biomass and soil. Also, the ICLFS potentially compensates for GHG emissions from beef production, however, this would require at least parts of the produced woody biomass to be used in long-lasting products such as furniture.

Land use analysis

Per hectare of pastureland, 187 kg (CB), 944 kg (ICLFS), and 1492 kg (NR) of beef LW are produced. However, the impacts reach beyond the farm gate: To

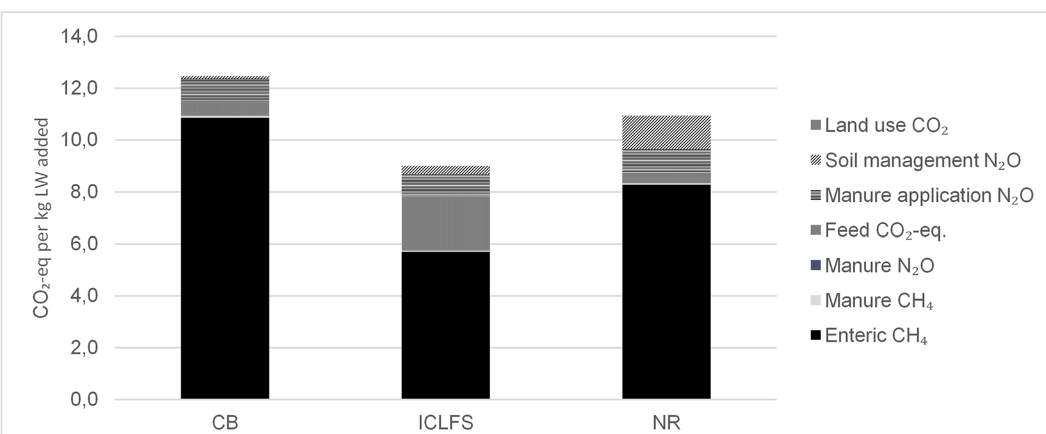

Fig. 5 GHG emissions of the beef finishing enterprise in kg CO_2 equivalents per kg LW beef added

Table 2 GHG emissions and storages in Mg CO_2 equivalents per year and per hectare of cultivated area

Production system	CB	ICLFS	NR
Emissions per ha cultivated area	2.233	6.526	12.938
Long term sinks			
Soil sequestration	-	-1.881	-1.465
Woody biomass in trees	-		-12.031
Medium-term storage			
Forestry plantations (*Eucalyptus*)		-74.629	
Pasture biomass below-ground	-12.546	-29.931	-26.254
Short term storage			
Pasture biomass above-ground	-15.682	-37.414	-37.814

produce the necessary feed, especially for the semi-confined feeding regime in ICLFS and NR, additional arable lands are required. Considering only the corn supplemented to the feeding regime, this would require 53 ha of corn (at average Brazilian yield 2020/21 (CONAB 2023)) in ICLFS and 48 ha of corn in the NR. Still, the area of impact per 100 kg of beef LW added is lower in the SPS than in CB (0.53 ha per 100 kg LW beef added in CB, 0.14 ha/100 kg beef LW added in ICLFS and 0.11 ha/100 kg beef LW added in NR). The ICLFS also produces crops (in the first year of establishment) as well as renewable biomass in the same area. Beyond the farm gate, this has important implications. Through increasing land productivity, already cleared lands can support the growing need for land-based resources for food and as a base for the bio-economic transition, reducing the pressure on converting native vegetation into agricultural lands.

Environmental services analysis

Beyond costs of beef production, GHG emissions, and carbon sinks as well as land use, the analysed beef production systems provide further environmental co-benefits to different degrees at the farm level and beyond (Table 3). In these categories, the SPS as multifunctional land use offer broader services compared to CB. Beyond preserving grasslands, these systems can have positive impacts on environmental services such as water storage capacity, animal welfare, and biodiversity (Chará et al. 2019). Through the shade provided by trees, SPS contribute to the thermal

Table 3 Summary of results of the integrated analysis comparing the systems

Production system	CB	ICLFS	NR
Cost of beef production	Low	Medium to high	Low to medium
Profitability	Medium-term - not covering opportunity costs of land	Long-term, incl. crop and eucalypt return	Long-term - covering cash costs, depreciation, and land opportunity costs
Climate change impact	High GHG emissions per kg beef produced, no compensatory sinks	Reduced emission intensity per kg beef produced, temporary carbon storage in trees	Reduced emission intensity per kg beef produced, long-term storage, and net carbon sink
Output	Beef	Beef, Soy/maize and Eucalyptus	Beef
Area impact beyond farm scope	Requires only minimal crop cultivation for feed supplement	Less area needed through high stocking rate, maize/soy, and timber production	Less area needed through high stocking rate
Climate change adaptation	Possible adaptation via supplementary feeding	Reduced heat for animals and wind erosion, reduced variability in pasture yield & quality	Reduced heat for animals and wind erosion, reduced variability in forage yield & quality
Added environmental services	Maintenance of grasslands	Soil improvement, improved microclimate, and animal welfare	Soil and vegetation regeneration, high biodiversity, water storage, animal welfare

comfort of the animals (Romanello et al. 2023), an important element also concerning the growing need to adapt to climate change and rising temperatures. Beyond benefits to animal welfare, recent research also suggests positive impacts on human health through the potential cooling effects of large-scale SPS implementation in tree-poor landscapes, such as vast pasture lands (Zeppetello et al. 2022).

Discussion

Evaluation of calculated results

The economic assessment (Fig. 3) of the three systems is influenced by the selected data from the year 2021. Due to the geopolitical and economic circumstances, this year showed a strong year-to-year increase in energy prices as well as further key prices including land, feed, and animals (Supplementary Material, SF1). However, cost structures are comparable to data published by Siqueira and Duru (2016). To assess the sensitivity of costs of production and profitability to changes in prices, we varied three key prices: livestock price, feed price, and beef price (Supplementary Material ST4). The result shows that the variation in the beef prices has the biggest impact. Under ceteris paribus conditions, only the variation of the beef price could impact the profitability in such a way, that beef production in ICLFS and NR was not profitable enough to cover cash costs. However, one needs to consider, that beef prices and key input prices, such as weaner and feed prices developed accordingly in the past years, meaning in years with low beef prices, also lower input prices were observed (Supplementary Material SF1). In general, the pasture-based beef production system is rather slow in adjusting, related to the long production period of more than one year. In the ICLFS and also NR, adaption mechanisms exist, such that in both cases the cost of the intensive grain finishing phase could be skipped through earlier selling of cattle. This means, that theoretically, the producer has more options to quickly react to unfavourable prices (animals or feed).

GHG emission results available in the literature can differ quite substantially in chosen system boundaries, selected functional unit, as well as methodological base, e.g. different IPCC methodologies and tiers, as well as selected GWP. Our results per kg LW added during the finishing stage range from 9 to 12.5 kg CO_2 equivalents (Fig. 5). Considering the selected system boundaries of beef finishing only, our GHG emission analysis compares to the study of Figueiredo et al. (2017), which finds comparable results. The emissions per hectare are strongly influenced by the stocking rate, and their comparability to other studies is also impacted by the above-mentioned differences in methodological choices. Monteiro et al. (2024) analysed different forms of production systems. They find higher emissions per hectare, but also assume a higher stocking density, as well as applying direct methane measurement.

Response of analysed systems to future perspectives

We show that there are economically viable beef production alternatives for areas where producers face challenges related to land competition and climate change. In global comparison, Brazilian pasture-based beef production, typically CB, is among the most competitive globally (Deblitz 2021). In our case study analysis, total costs per kg CW sold range from 4,24 USD in CB over 4,54 USD in NR to 5,30 USD in ICLFS. Even with the increase in production costs, as analysed for the NR and ICLFS, it would still be competitive compared to other major global producers. We also show that the beef finishing enterprise in all production systems was not able to cover the total costs including opportunity costs. While this poses the question, of why CB is still the most common beef production system in Brazil, we find agreement with this finding in the literature. Siqueira and Duru (2016) already pointed out the lack of long-term profitability of beef production and discussed this in the context of low-input-low-output beef production. This system does only rely on external feed inputs to a very limited extent, which however comes at the expense of future generations, especially when stocking rate and land productivity are not carefully balanced, considering the state of degradation in many pasturelands in Brazil.

Recent market trends showed an increase in confinement and semi-confinement, however with the latest turbulences of grain markets, this development was discontinued (USDA/GAIN 2021). For ICLFS and NR, both applying semi-confined feeding regimes to different extents, this risk needs to be considered. Yet, both systems integrate risk mitigation strategies as in their described production system specifics: ICLFS produces different outputs diversifying risk (Nicoli et al. 2017), and in NR the producer can adapt to high prices by earlier selling of animals. Concerning the whole farm profitability of the systems, the medium and long-term perspective of CB especially depends on the land market development and the expansion of alternative and competitive uses for (former) pasturelands. In the future, this type of production might additionally require high investments to restore lands affected by degraded soils. Yet, financial investments could also be substantial for implementing SPS. Chará et al. (2019) described the potential negative cash flow during the initial transition period due to investments made to pasture management (fences, watering), SPS implementation (forage diversification, planting), and additional animal purchases to make use of additional forage availability. The analysed case studies of ICLFS and NR suggest beneficial conditions: In the case of ICLFS, the farm made use of contractors engaged in cropping activities (of the same farm) to establish the maize crop at the beginning of the ICLFS cycle. The proximity to market infrastructure and processing facilities also favoured the establishment of Eucalyptus row plantations consecutively in smaller land areas of 28 ha on average. Proximity is seen as a major descriptor of changes in land use (Cohn et al. 2016; Melo Celidonio et al. 2019). In the case of NR, restoration of native vegetation from remaining seed banks and dispersal from adjacent forests allowed to establish tree cover at low costs. The introduction of leguminous shrubs additionally offers a low-cost solution for soil fertilisation and protein supplementation to the animals. The nature-based restoration of degraded pasturelands is identified as a key to addressing Brazil's policy goals on various targets (Feltran-Barbieri and Féres 2021). However, the long establishment period might hinder adoption (Dias-Filho 2015).

Growing (international) market demands might challenge marketing beef originating from the BAU systems in the future for its generally high environmental impact. Yet, it remains unclear how the provision of additional environmental services might be renumerated, or at which rate BAU-produced beef might be sanctioned. While ICLFS offers a ready-to-market solution through diversifying farming business and opening new income through woody biomass and crop production, the additional goods provided through NR, namely biodiversity and long-term carbon sequestration are only at the doorstep of market entry.

Recently, four criteria have been defined (European Commission 2022) after which carbon sequestration can be considered as carbon removal or sink: they need to be quantifiable, additional, long-lasting/persistent, and cannot be linked to leakage. Applying these criteria, the additional carbon sequestered in soils in ICLFS and NR following the improved pasture management, as well as the additional woody biomass in shrubs and trees could be potentially considered as sinks. However, especially the criterion of persistence needs to be addressed by the ICLFS. While woody biomass accumulated through natural regeneration in the NR system cannot be cut by law and therefore accumulated stocks are long-lasting, the potential net sink of ICLFS strongly depends on the end use of the produced woody biomass. ICLFS has the potential to mitigate GHG emissions through higher animal productivity. Whether it offsets GHG emissions from agricultural production is under debate (Monteiro et al. 2024; Morales et al. 2023). Yet, the emergence of carbon markets, be it through temporary credits for ICLFS or permanent credits for NR, could further support the establishment of SPS with additional income provision to producers. Also, new market opportunities for natural, sustainable beef might increase generated value.

Beyond farm economics, restoring forests, and diversifying agricultural production, proactively adapting beef production systems to changing weather and climate risks is crucial to make producers more resilient to current and potential future developments. Considering the time horizon of investments in beef production systems, it seems reasonable to more carefully consider future scarcities, especially water availability and management (Lathuillière et al. 2019). Through this lens, SPS that help restore coverage and shade and reduce surface temperature are beneficial to the water balance. However, the effect of Eucalyptus plantations on the net water balance needs further investigation concerning the specific location (Reichert et al. 2021). In light of recent research on the relationship between deforestation and rainfall in the southern Amazon (Leite-Filho et al. 2021), the positive impact of SPS on the water balance is also supported by its increased land productivity, as it reduces the pressure on expanding agricultural lands into natural forests.

With the analysis of three case studies reflecting three major beef production concepts, we aim to enrich the discussion on sustainable development pathways for Brazil's beef production. Beef production is an activity, that takes place in all regions and biomes of Brazil. Their diversity and their inherent heterogeneous production conditions for the establishment of SPS can hardly be assessed by one study. Yet, research pointed out, that the potential for the establishment of SPS exists in every region, if those systems are adapted to local conditions (Almeida et al. 2013). Besides the natural preconditions, managerial capacities on farm level are crucial to be reflected. Our case study analysis covered rather big farms. How the results could be transferred to smaller business entities could be part of further investigation. Yet, the observed consecutive transition of the ICLFS and NR system suggests the applicability also to smaller farms. This consecutive investment observed in the establishment of the ICLFS and the NR system reduces the financial burden of the transition on the annual cash flow and reduces the risks for the producers. It also enables them to react to changes in the cash flow, as well as in land and herd management. Beyond these economic considerations, access to knowledge and the acquisition of new skills are key for producers as well as for employees as the relevant agents of change towards more sustainable practices.

Conclusions

In our analysis, we investigate how three analysed farm case studies representing different concepts of beef production systems respond to current and future production conditions identified as decisive by producers and research. They perform differently depending on the indicators analysed. In the current conditions, these farms are able to manage the challenges they face. How they will reply to future challenges depends on the location and the specific environment. While additional costs related to the more intense management of pastures and animals are potentially covered by higher productivity, land price developments will particularly impact the long-term profitability of beef finishing. Diversification of farm activities, where beef finishing can be integrated as a production element offers interesting economic and environmental opportunities. The challenges of transformation lay within the establishment of these diversified SPS, as they require a reliable policy framework, additional specific knowledge, financial investments, and market access. Reflecting on potential future development pathways and challenges ahead this is on the one hand reassuring. On the other hand, it stresses the importance of investing in producers' capabilities to adjust - be it through the provision of good access to financial resources, be it through knowledge generation and transfer, or be it through the development of new technologies or systems and market opportunities.

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Data availability Beyond the data published in this article and its supplementary information files, all data generated or analysed for this study as well as the corresponding versions of the tools used for the calculation of economic indicators and greenhouse gas emission estimation are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare they have no financial interests. Julian Chará is a member of the editorial board as guest editor of the Special Issue "Current Trends in Silvopastoral Systems".

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