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RESEARCH ARTICLE

Low-carbon agricultural technologies improve forage and feed production in the Caatinga biome, Brazil: Characteristics, comparison, effects of climate change, resilience, local development, and food security

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Abstract

Adjustments in Brazilian livestock are necessary to minimize greenhouse gas (GHG) emissions, since the largest source of methane comes from ruminants' enteric fermentation, and of carbon from deforestation. Low-carbon agriculture technologies (LCAT) contribute to mitigating these emissions and this study evaluates the role of these technologies on ruminant forage production in Caatinga. A Strength, Weakness, Opportunity, and Threats analysis was used to elucidate the main features, followed by an Analytic Hierarchical Process, ranking the LCAT, and a risk analysis. Integrated Crop-Livestock-Forest System (ICLFS) is the most recommended technology, followed by Sustainable Forest Management (SFM) and Recovery of Degraded Areas with Pastures (RDA-P). The results can aid in the choice of the LCAT to be implemented by the smallholder in Caatinga, demonstrating the need to strengthen rural technical assistance, so that there is a real benefit to the producer and the environment.

Keywords: GHG Emission; Semiarid; ICLS; Ruminants; SWOT; AHP; Production Factors.

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1. Introduction

Concerns with the increase of greenhouse gas (GHG) emissions have encouraged public policies and international agreements creation, promoting mitigation actions and adaptation to climate change, with Low-Carbon Agriculture Technologies (LCAT) (Rathmann et al., 2017). Among the mitigation actions are native forest preservation, degraded areas recovery, deforestation reduction, and sustainable agriculture.

LCAT are based on economic, social, and environmental sustainability and related to low-energy consumption, circular and organic farming, (Xiong et al., 2016, Su et al., 2017). They can reduce natural resource damage, recover ecosystem quality and services, enable sustainable farming by minimizing climate change effects (droughts, loss of fertility, reduced water access), and enhance resilience, local economy, and food security (Alvalá et al., 2019; Anuga et al., 2020; Shajedul, 2021). These are important issues for Caatinga farming to be productive and resilient to climate change (Rangel et al., 2020).

The employment of LCAT in Asia has enhanced agricultural economic growth and individual farmers' welfare (Xiong et al., 2016; Chi et al., 2024). In China, one of the most widely used LCAT is NTS, which covers the soil with crushed straw (Hui et al., 2023; Zhou et al., 2023), further detailed below.

Agriculture, especially livestock farming, is the sector with the main methane (CH_4) and nitrous oxide (N_2O) emissions, as observed in China (Su et al., 2017; Shajedul, 2021). LCAT can help different countries reduce emissions in this sector, selecting the appropriate technology for each region regarding economic, social, and ecological features (Shajedul, 2021; Chi et al., 2024). Indeed, Anuga et al. (2020) highlighted agroforestry, rotational farming, improved livestock breeding, and intensification of ruminants' diets as strategic practices to be adopted in Africa to contribute to GHG emission mitigation.

Even so, animal production is the main economic activity in the Caatinga biome, especially small ruminants like goats and sheep because they present greater drought resistance than rainfed agriculture, ensuring food security for producers and income (Araújo Filho, 2014, Signor et al., 2022). Traditionally, ruminant grazing in Caatinga is carried out extensively, which raises animals' metabolism and, considering the diet type, can increase enteric fermentation and methane (CH_4) emission (Barbosa, et al., 2017). This is because fermentation depends on the feed quality.

Indeed, according to some authors, (Eugène et al., 2021, Fouts et al., 2022) enteric digestion can be reduced with feed adjustments. Low-nutritional fiber has low digestibility and takes longer to digest and ferment; so, it can produce more methane than the intake of high-nutritional quality, which spends little time in the rumen (Barbosa et al., 2017). On the other hand, despite the high fiber and low digestibility, Caatinga plants can contribute to decreased methane emission, due to the high amount of tannin, which inhibits bacteria action in the rumen (Eugène et al., 2021). Besides that, the small ruminants, more abundant in the biome, emit less methane than cattle.

LCAT were selected from the ABC-Plan (Brasil, 2012) and Newton et al. (2016): Integrated-Crop-Livestock-Forest-System (ICLFS), up to three different productive systems in the same area, in sustainable production, with crop rotation and consortium (Vinholis et al., 2021). It increases productivity, product diversity, and income, without deforestation (Gontijo Neto et al., 2018, Rangel et al., 2020). It is indicated to recover degraded areas, including pastures, because it enhances soil quality, pests' natural control, and reduction of fertilizers (Almeida et al., 2013, Florida Rofner et al., 2022). Integrations seek to reduce overgrazing and thermal comfort for animals (Rangel et al., 2020); and increase forage availability, cultivating crops and pruning Caatinga native vegetation (Miccolis et al., 2019). Sustainable Forest Management (SFM), enables carbon conservation (plants and soil), improves biodiversity, and rivers protection, encourages smallholders to keep the native vegetation; involves extensive livestock breeding (Araújo Filho, 2014). In Caatinga, SFM by vegetation pruning, thinning, and enrichment, increases forage up to 80%, providing sustainable livestock (Cavalcante et al., 2013). Recovery of Degraded Areas with Pastures (RDA-P) aims to reestablish natural flows of a pasture to become productive again with improvements in soil structure and fertility, and increases in carrying capacity, productivity, biomass, and carbon in the soil (Feltran-Barbieri & Féres, 2021). Usually, RDA-P is made only with forage grass but, at the Caatinga it should be done also with rangeland legumes and shrubs or small trees of natives or adapted species used as forage (Pinheiro & Nair, 2018). Biological Nitrogen Fixation (BNF) in the Caatinga is usually made by intercropping or rotating legumes with other crops, called Green Manure, it is an efficient strategy for the recovery of degraded areas, as it provides nitrogen to plants without the use of additives, generating savings and mitigating GHG emissions, especially nitrous oxide, N_2O (Fouts, 2022, Fernández-Ortega et al., 2023). Green manure can also be used as pasture, supplying a forage of high nutritional quality, to increase livestock productivity (Cavalcante et al., 2013). No-till System (NTS) aims not to revolve the soil over, thus avoiding carbon and nitrogen losses, thus increasing crop productivity (Malhi et al., 2021). Its main techniques are permanent soil covering (with straw from previous crop), crop rotation, intercropping, and direct seeding (Fernández-Ortega et al., 2023; Hui et al., 2023). According to Abdalla et al. (2016), NTS is an effective measure for mitigating carbon dioxide (CO_2) losses in dry soils. Even if BFN and NTS can provide forage, this is not their main goal; moreover, they are usually included in the previous LCAT, so they were not considered in the analysis.

This study aimed to understand how LCAT contribute to ruminants' forage production in the Caatinga, comparing them regarding the increase in productivity while decreasing GHG emissions.2.

Methodology

Caatinga is the only exclusively Brazilian biome (Figure 1), with a semiarid climate, with low precipitation and irregular, sporadic periods of prolonged drought; high temperatures; high aridity index, and water deficit (Alvalá et al., 2019). It hosts several endemic species of animals and plants, considered the highest-biodiversity dry forest in the world, characterized by cacti and shrubs with whitish branches and deciduous leaves, adaptations to withstand drought (Tabarelli et al., 2017). However, part of its native vegetation and resources have been deteriorating due to its intensive use in agriculture, monoculture crops, and extensive livestock (Tabarelli et al., 2017, Menezes & Silvas, 2024).

To avoid these devastating productive systems, the LCAT play an important role in ruminants' forage production in the Caatinga. This study, as previously explained, will only evaluate ICLFS, SFM, and RDA-P.

To better comprehend the relationship of ruminant's forage-production with GHG mitigation emission, a literature review was conducted, further a Strength, Weakness, Opportunity, and Threat (SWOT) analysis was built, followed by an Analytic Hierarchical Process (AHP) combined with a risk analysis. Topics on GHG emission by agriculture and livestock, the vulnerability of these productions related to climate change, and Low-carbon agriculture in Caatinga were raised. A survey with 31 stakeholders that work at Caatinga, was held and consisted of technical, economic, financial, social, and cultural themes on smallholders' production and the previous topics mentioned above (Figure 2). These topics and the survey served as inputs for the analyses made in MS Excel files.

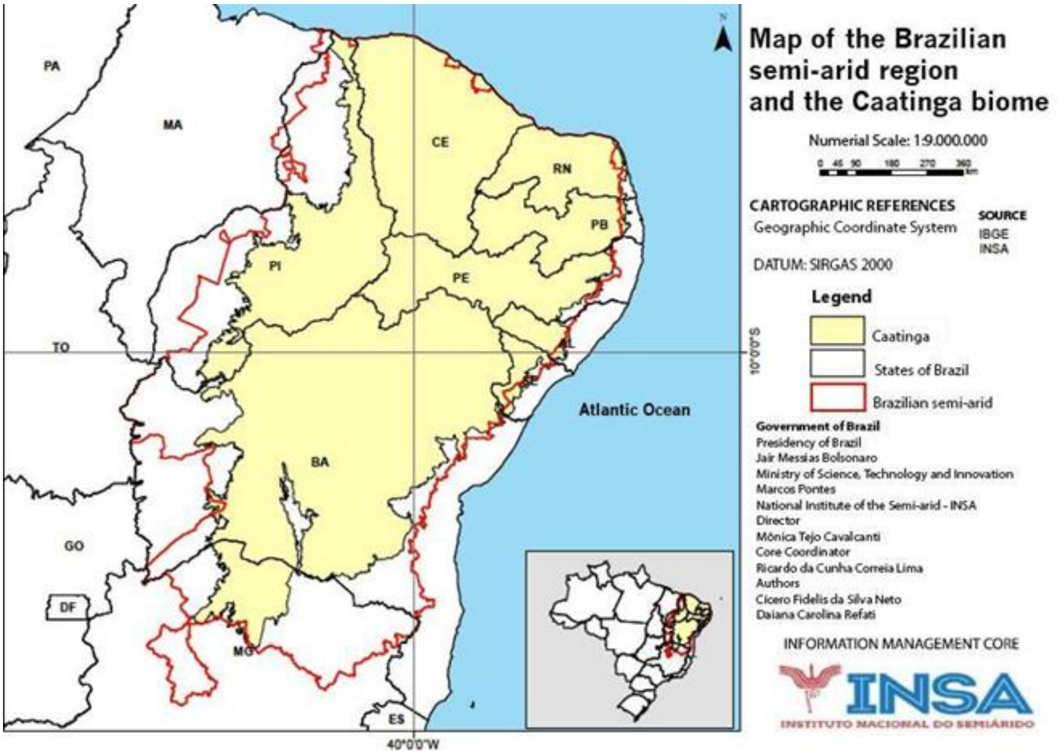

Figure 1. Delimitation of Caatinga biome. Sourced from: IBGE/INSA, 2000.

Stakeholder	No
Research and Development Centers	7
Universities	3
Governmental institutions	7
Non-governmental institutions	10
Private organizations	4

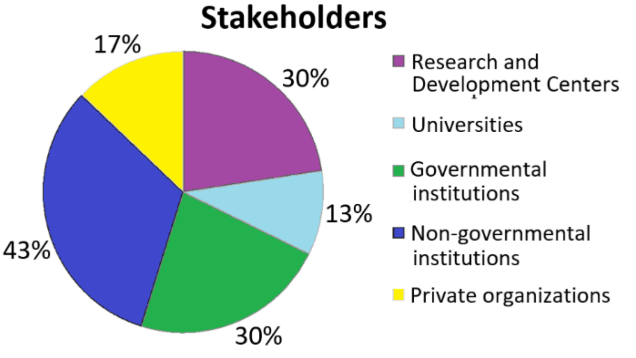

Figure 2. Survey participants and stakeholders' breakdown.

The SWOT analysis highlighted the strengths and weaknesses of LCAT, and the opportunities and threats related to forage production in the Caatinga (Schäler et al., 2019). From the AHP it was possible to measure how much one LCAT was preferred over the others, according to their importance on forage production for ruminants with the lowest GHG emission. For this purpose, a hierarchic structure and a parity comparison between criteria and sub-criteria were made, analysis steps in Figure 3 (Sahani, 2021). The pairwise comparison weights were based on Saaty's Fundamental Scale (Saaty, 2005) and chosen considering SWOT results, stakeholders' survey, and the authors' judgment. If the Consistency Ratio (CR) was higher than 10% (CR ≤ 0.10), "False", the pairwise comparison had to be repeated, to be consistent with reality (Saaty, 2005), Figure 3.

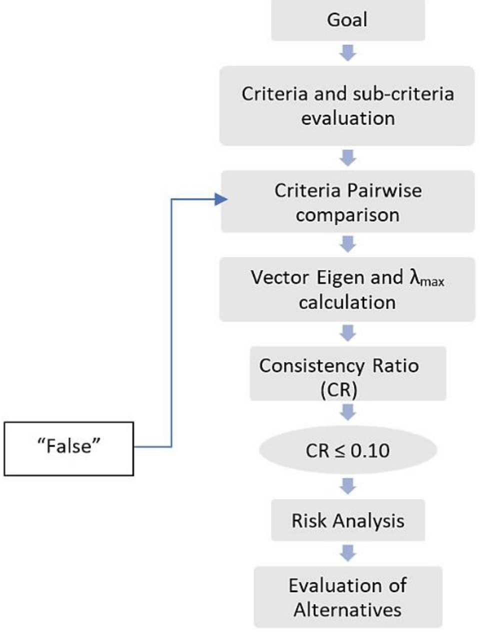

Figure 3. AHP flowchart of the analysis.

Finally, the AHP was combined with a risk analysis, where sub-criteria were valued regarding their impact, probability, and control (Tolmasquim et al., 2020). These variables' influence was determined according to a scale of values judged by the authors based on data inputs and previous analysis outputs. Thus, the following were evaluated: the effect of the sub-criterion on forage production for ruminants with GHG mitigation (Impact); the possibility of this impact actually occurring (probability), and, finally, how much control the smallholder has over this impact; at the end, a ranking of LCAT was obtained.

3. Results and discussion

LCATs' characteristics assessed and their employability, according to the Caatinga features, were represented in the SWOT matrices (Table 1). Besides LCAT strength, to mitigate GHG emission, productive gain and increase in smallholder's income, ICLFS and SFM also have a short payback time on forage production.

The relationship of the criteria definition with the items' Strengths and Weaknesses from the SWOT analysis and their influence on the five criteria stipulated for the AHP is shown in Table 2.

From the data inputs and SWOT outputs, besides the five criteria, nine sub-criteria were defined for the AHP, detailed in Table 3 to analyze LCAT.

From the five criteria, ten parity comparisons were made based on their importance about the study objective, presented in the judgment matrix (Table 4).

Forage Supply represented 45% of the total weight among the criteria, followed by Natural Capital (27%), Human Capital (17%), Physical Capital (7%), and GHG mitigation (4%). Natural Capital is the main production factor since forage production is directly related to natural resource availability. Regarding Human and Physical Capital, the former is more important, due to familiar agriculture, and the need for technical assistance for LCAT to be successful. Physical Capital can support operational labor increasing production, but some inputs can be purchased through cooperatives. Finally, the GHG mitigation criterion, refers to a refinement of which LAT would be the most efficient mitigating these emissions.

With the risk analysis, it was possible to establish the contribution of each sub-criteria regarding Impact, Probability, and Control (Figure 4).

The three LCAT evaluated were ranked by comparing them in relation to each sub-criterion, Figure 4. The criterion Forage Supply was divided into two sub-criteria: forage variety with a slightly higher importance than forage quantity, Figure 4. In both, ICLFS offered the highest forage supply for ruminants in the Caatinga (Table 5). With this LAT, different plants are grown, enabling a selected forage, with nutritional and digestibility issues combined to obtain better food and concentrate, as suggested by Barbosa et al. (2017). This greater diversity is due to the presence of crops and forests, with cacti, woody legumes, crop residues, maize, and grasses, in nature or silage and hay, as mentioned by Vinholis et al. (2021).

Table 1
SWOT matrix of the LCAT (ICLFS, SFM, and RDA-P)

Strengths of ICLFS	Weaknesses of ICLFS
- Integrates two or three productive components in the same area, providing increasingly diversified forage. - Increases forage productivity per unit. - Forest component provides thermal comfort and forage for the ruminants.	- Needs extra workforce and technical support for its implementation. - If implemented without the forest component, it lacks important nutritional forage and environmental benefits. - It can be from medium to high cost, depending on the arrangement.
Opportunities of ICLFS	Threats of ICLFS
- Presence of agroforestry on the property and raising livestock in a non-integrated manner. - Temporary crop production: fodder corn and palm and other forage species. - Expressive creation of sheep and goats and presence of dairy cattle breeding. - Beekeeping.	- High conventional cultivation in the properties. - Land use patterns and property ownership conditions - Low production of temporary tillage, as it would make it difficult to insert herbaceous forage.
Strengths of SFM	Weaknesses of SFM
- Maintains native vegetation, preserves ecosystem services, increases forage for ruminants. - Generates less expenses with inputs for forage-production.	- Bureaucracy: management plan, authorization, regularization and monitoring. - Excessive labor to manage the vegetation with expensive machinery to increase forage supply.
Opportunities of SFM:	Threats of SFM:
- Presence of Caatinga vegetation within the property and its use as a natural pasture. - Raising mainly sheep and goats. - Extractivism of native fruit. - Beekeeping.	- Deforestation for rural production and firewood and charcoal extraction. - Presence of large, degraded pasture areas.
Strengths of RDA-P	Weaknesses of RDA-P
- Restores areas that were already pastures, recovering physical, chemical and biological features, such as soil structure and fertility, ecosystem's services, enhancing biomass. - Enhance the productivity of the degraded pastures, increasing forage-producing diversity and quality. - Avoids native forest deforestation, for cropping or new rangeland.	- The area management must be continuous, tracking seedlings' growth, avoiding pests and diseases and controlling animals grazing (fallow and grazing rotation). - Long payback time for feed production. - High cost of implementation.
Opportunities of RDA-P	Threats of RDA-P
- The presence of more pastures than food cropping in the property. - Degraded pastures that can be recovered on the properties. - Possibility to avoid desertification of degraded pastures, recovering them also with shrubs and small trees.	- Smallholders raising ruminants, mainly bovine herds, on grass monocultural pasture and are not used to traditional tree and shrubs Caatinga rangeland. - Smallholders not used to rangeland management, leaving pasture to reestablish itself. - The need to plant the seedlings during the rainy season to be better established. - Smallholders' low financial availability.

Table 2
SWOT outputs and the AHP criteria related to them

SWOT outputs	Criteria
- Increasing diversified forage for ruminants. - Increasing forage quantity by enhancing productivity. - The forest component provides ruminants' forage.	Forage Supply
- The maintenance of the native vegetation and ecosystem services and soil structure recovery. - Reduction of native forest deforestation, to create new cropping or pasture areas. - Recovery of degraded forest and pastures restore ecosystem services and soil structure.	Natural Capital
- Extra manpower and technical support needed for its implementation. - Bureaucracy for LCAT implementation: management plan, authorization, regularization, maintenance, and monitoring. - Excessive labor to manage the vegetation.	Human Capital
- The implementation of the LCAT can be from medium to high cost, depending on the arrangement and the area conditions. - Generates less expenses with inputs for the production. - Use of expensive machinery needed. - Long payback time for forage-production. - High cost of implementation.	Physical Capital
- The maintenance of the native vegetation and forest recovery. - The enhancement of soil carbon sequestration. -The enhancement of the productivity of degraded rangeland. - The reduction of native forest deforestation to create new cropping or pasture areas.	GHG Emission reduction

Table 3
Description of Criteria and Sub-criteria of Analytic Hierarchical Process (AHP) and its relationship with risk analysis

AHP analysis Criteria	Risk analysis Sub-criteria
Forage Supply High quality plant-based forage from LCAT, plants quality and availability, minimizing the need of food supplements.	Variety of Forage: nutritious Caatinga vegetation: legumes, cacti, tillage straw, shrubs and grass. Quantity of Forage: natural or hay/silage, that is supplied by LCAT most of the year.
Natural Capital Renewable and non-renewable natural resources available that influence forage-production.	Geophysical and Geochemical Factors: abiotic resources (area, soil, water). Biological Factors: preservation of biodiversity and ecosystem services and its living beings, as edaphic fauna, pests and weeds controlled by plants and insects.
Human Capital Personnel related to the implementation and maintenance of LCAT, such as: property management, documentation, knowledge, technical assistance and operational personnel.	Property Management: planning, implementation and monitoring of LCAT, diagnosis of the area (soil, land use, productive arrangements), infrastructure, equipment and logistics assessment, consultancy and technical assistance. Operational Labor: operational manpower demand, familiar or specialized (usually for LCAT implementation and harvesting).
Physical Capital Equipment and products essential for LCAT. Monetary value between the inputs is quite different and therefore only a relation among the items foreseen was made, without considering the monetary discrepancies.	Permanent Assets: machinery, equipment, property improvement needed. Investment is rewarded in the long term and can be collectively, by cooperatives. Consumable Materials: necessity to purchase inputs for the LCAT, biological and chemical, not produced on the property (fertilizers, correctives, pesticides, seedlings, grains, seeds, others).
GHG Mitigation LCA-Technology's estimated potential to mitigate GHG emission directly involved in ruminant forage production.	Reduction of carbon and methane emissions: related to methane emissions, due to displacement of animals and to the possibility of waste management. It also refers to avoiding deforestation and to the accumulation of carbon in biomass.

Table 4
Criteria judgment matrix

Criteria	Forage Supply	Natural Capital	Human Capital	Physical Capital	GHG Mitigation
Forage Supply	1.00	2.00	3.00	7.00	9.00
Natural Capital	0.50	1.00	2.00	5.00	6.00
Human Capital	0.33	0.50	1.00	4.00	4.00
Physical Capital	0.14	0.20	0.25	1.00	3.00
GHG Mitigation	0.11	0.17	0.25	0.33	1.00

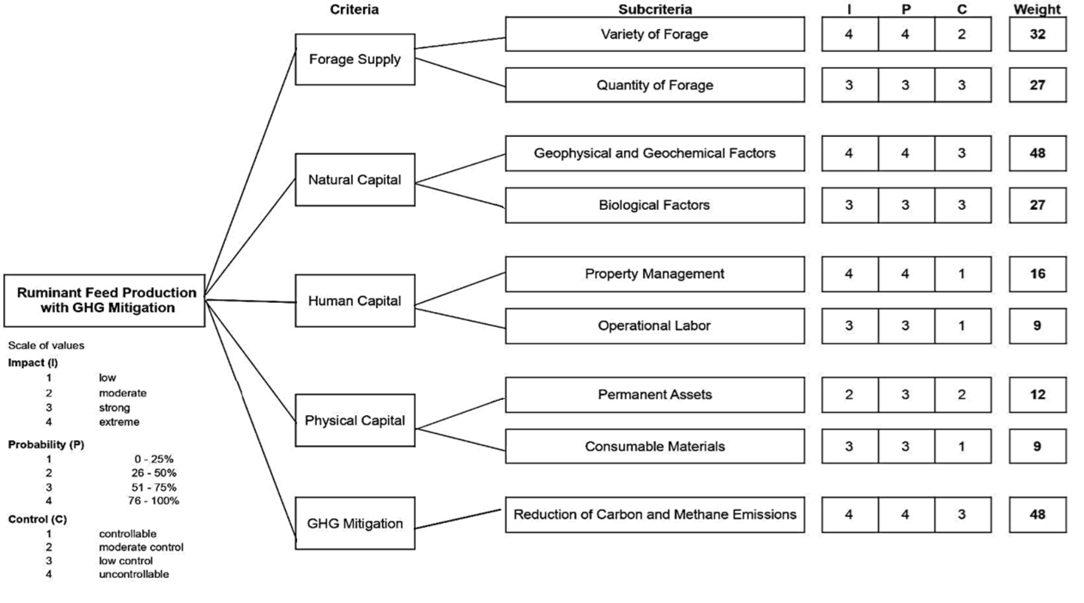

Figure 4. Risk analysis decision map, based on Tolmasquim et al. (2020).

The integration of these plants, destined to feed animals, is called fodder banks. This is an important hay resource for animals during the dry season, avoiding overgrazing. The pioneering model was the Caatinga, Buffel Grass, and Legumes (CBL) integration, developed by Embrapa, in experimental areas (Rangel et al., 2020). Another usual Caatingas fodder bank is cacti, because it is drought resistant and provides water to animals, it has great importance in goats' nutrition (Pinheiro & Nair, 2018, Socolowski et al., 2021, Lima et al., 2023). It can also be integrated into annual crops and substitutes corn in concentrate to be offered with forage, according to Barbosa et al. (2017).

Table 5
Criteria and Sub-criteria relevance regarding each LCAT.

	Low-carbon Agriculture Technologies (LCAT)		
	ICLFS	SFM	RDA-P
Criteria and Subcriteria			
Forage Supply	63%	27%	10%
Variety of Feed	67%	23%	10%
Quantity of Feed	57%	33%	10%
Natural Capital	50%	41%	9%
Geophysical and Geochemical Factors	63%	28%	9%
Biological Factors	27%	64%	9%
Human Capital	23%	65%	12%
Property Management	23%	67%	10%
Operational Labor	25%	59%	16%
Physical Capital	24%	64%	12%
Permanent Assets	25%	59%	16%
Consumable Materials	24%	70%	6%
GHG Mitigation Emission	68%	20%	12%
Overall Ranking	49%	41%	10%

SFM has the second largest Forage Supply because it is made in a structured forest area, with a diversity and quantity of plants that can be directly exploited. With the SFM there is more quantity of forage than variety (Table 5), and this one can increased with the enrichment technique, planting grass (buffel, elephant grass, ...) and arboreal species, as Caatinga native legumes: *Mimosa caesalpiniifolia* (*"sabiá"*), *Bauhinia cheilantha ("mororó")*, *Croton conduplicatus ("quebra-faca")*, or exotic (*Leucaena* sp. and *Gliricidia sepium*).

Caatinga is a source of forage in the three vegetation strata, especially to feed goats and sheep and to resist the regional climate conditions. Its management is widely used in livestock to increase forage supply by changing the structure and floristic composition, with the techniques of pruning, thinning, and planting ruminant forage, allowing a sustainable production in semiarid, avoiding deforestation, as also previously related (Araújo Filho, 2014). These techniques make it possible to give hay and silage to the herd when it is in the paddock, as well as in the dry season, and sell the surplus (Cavalcante et al., 2013).

RDA-P at Caatinga biome should be recovered with a variety of plants in the three strata and not just grass, as mentioned above, to then produce a variety of forage over time, because the area can be designated to fodder bank and annual crops during the fallow. However, a longer time is required for the soil and vegetation in the RDA-P to be established, that's why it had a lower weight. Thus, RDA-P can have in the beginning a lower forage supply, because it would take more time to be established. Another important consideration regarding RDA-P's low weight, compared to SFM and ICLFS, is that even considering these two technologies also from the implementation until their establishment, from 3 to 5 years (Araújo Filho, 2014, Gontijo Neto et al., 2018), the environment they are located was already productive, and was just adjusted for the technology, unlike RDA-P, where soil enhancement necessarily needs to be done. At the beginning of RDA-P, the fodder bank system can be prioritized without animal entry so the soil can be decompressed, and its structure and nutrients recovered and allow the seeds bank to grow and help the recovery of the pasture.

In addition, ICLFS and SFM can increase smallholders' income due to the diversity of extra agricultural and forest products they can offer (Brasil, 2012). Vinholis et al. (2021) identified the integration crop-livestock (ICL) to ensure economic viability and to improve smallholders' quality of life quality in SFM, the Caatinga enrichment technique can be alternated with planting food crops (maize, beans, cassava) to partially cover costs and strengthen family food security (Araújo Filho, 2014).

Natural Capital was divided into geophysical and geochemical factors and biological factors, the former sub-criteria being more representative, Figure 4. In this criterion, ICLFS presented greater relevance regarding abiotic factors, because as it is done in a cultivated area, the soil is already structured and nourished (Iwata et al., 2021, Signor et al., 2022). ICLFS can also be implemented in association with Social Technologies such as water harvesting and storage technologies and rainfed, as in SFM. Regarding soil conservation, fodder banks, and animal grazing rotation in the managed forest are alternatives to avoid Caatinga degradation. In both ICLFS and SFM, paddocks are necessary for a herd rotation in the pastures or in the Caatinga vegetation, with natural fertilization of their waste, allowing the plants to regenerate, by avoiding overgrazing, which has modified the floristic composition and increased soil compaction (Cavalcante et al., 2013, Rathmann et al., 2017). Another important strategy to improve soil fertility is planting legumes, herbaceous or arboreals, as green manure.

Regarding biological factors, SFM has the greatest weight, as it is a native forest that, even anthropized, has better established ecological flows and ecosystem services than ICLFS (Table 5). It is important to highlight that the tree component in ICLFS helps to reduce soil and water loss and it is relevant for ecological complexity because trees enhance organic matter and the biome recovery (Torres et al., 2020). Thus, the presence of trees promotes sustainable production and biodiversity, leading to a natural increase in productivity (Gontijo Neto et al., 2018).

Finally, RDA-P showed considerably lower weight in respect to Natural Capital, because it is an area poor in natural resources and, consequently, with low biodiversity, aspects that will not yet be re-established to the point of being higher than in the other two LCAT environments, during the period considered (Table 5).

Human Capital, divided into the sub-criteria of property management labor and operational labor, showed that technical and planning issues have greater representativeness (Figure 4). A new productive technology should be implemented in an organized approach with technical assistance following up (Suela et al., 2023). Operational Labor is important and is considered the main contributor to changes in carbon emissions in China by Su et al. (2017), but it can be adapted or substituted by hiring extra workers at specific seasons or using machinery and equipment. In this criterion, the lower the need for labor, which involves time and financial resources, the greater the weight one LAT had over the other in the pairwise analysis.

Therefore, SFM was the best-performing technology, regarding both management and operational labor (Table 5), although it requires qualified labor for the specific machinery. On the other hand, ICLFS and RDA-P had lower percentages, because both need a lot of planning and technical assistance, as well as more operational labor for soil care, crop, seedlings, and harvesting. However, RDA-P had a lower weight than ICLFS due to the greater care taken in land preparation, soil restructuring, planting, and monitoring the development of the seedlings.

Regarding Physical Capital, the sub-criterion permanent assets had a higher weight than consumable materials (Figure 4) and, as they are related to expenses, followed the same of Human Capital: the lower the need, the higher LCAT weight. SFM presented the best performance because, although it needs to fence the area and use specific machinery, the costs of materials and goods for land preparation and planting in ICLFS and RDA-P are higher.

Regarding consumables, SFM performed even better than the other LCAT, because it needs less inputs, only required for the enrichment technique, using seedlings, seeds, and phosphate fertilization, if necessary. ICLFS appears in second place, as it has a lower demand than RDA-P, which requires more inputs to recover soil and vegetation, while ICLFS generates its inputs due to the integration (Table 5). It should be noted that, although ICLFS and RDA-P require additional staff and technical support for their implementation, the use of external labor, machinery, and inputs decreases over time, according to Vinholis et al. (2021).

The Physical Capital was estimated in 1 hectare of Caatinga for each LAT, and the values varied considerably within the same technology, due to the diverse possible arrangements, especially in ICLFS, that was analyzed with an intermediate estimated value. And, although Physical Capital was less important than the other factors in the ranking, its importance is due to the financial limitations of smallholders and the bureaucracy of credit access.

Finally, related to mitigating GHG Emissions, the ICLFS showed a significantly higher estimated mitigation potential due to cattle in confinement, which reduces the enteric methane emitted (Rathmann et al., 2017). These authors also recommended reducing the size of the herd and anticipating slaughter, for a shorter-lived herd and thus lower enteric methane emissions. With SFM and RDA-P semi-extensive breeding could also be possible, but it is not traditionally common and would be more difficult to implement.

Furthermore, the diversity of the forage offered, aiming to provide more nutrients, greater digestibility, and lower methane emission, can be obtained in the semi-extensive breeding, that takes advantage of the natural pasture of the biome, with the animals in confinement part of the time (Signor et al., 2022), favoring also waste management, which can be done in a ICLFS.

SFM presented a slightly higher potential for mitigating GHG emission than the RDA-P (Table 5), both reduce deforestation, but SFM is applied in a native vegetation that minimizes the emission of enteric methane from food supplied with this technology. This is because tannin, present in Caatinga vegetation, inhibits methanogenesis and woody legumes have high digestibility for the ruminant; therefore, their ingestion generates less rumen methane and improves animal productivity (Eugène et al., 2021). This is also valid for ICLFS which has plants rich in tannin as SFM and moreover, it has other species that contribute to a balanced diet for the ruminant animals.

In fact, according to experts, SFM has reduced deforestation and burning, contributing to carbon maintenance in the ecosystem. However, in some regions of the semi-arid, there are still many smallholders who suppress native trees to plant crops or grass. Others still use fire to clear the land, which disrupts the soil, reduces the amount of organic matter, increases CO_2 emissions, and decreases the rate of vegetation regeneration (Iwata et al., 2021). In those localities where these degrading practices are still rooted, it becomes more difficult to convince the smallholders to implement a LCAT or to produce sustainably (Silva et al., 2020). On the other hand, where goat farming predominates, deforestation does not happen at the same rate, because it is believed that the animals are used to grazing in the Caatinga and are more resistant to drought (Milhorance et al., 2022). But goat livestock needs to be management in environmentally sustainable way, as keeping 400 to 800 trees/ha, recommended in an SFM, such as legumes: *Caesalpinia bracteosa ("catingueira")*, *Aspidosperma pyrifolium ("pereiro")* and *Mimosa tenuiflora ("jurema-preta")*, which have high protein content, serve as shadow and provide nitrogen to the soil (Araújo Filho, 2014, Milhorance et al., 2022).

Among the Brazilian NDC targets are a 40% deforestation reduction in the country, the recovery of native vegetation by 2030, and the increase of carbon stock in the soil through the expansion of integrated systems and the recovery of degraded pastures (Rathmann et al., 2017). Although, according to Signor et al. (2022), the Caatinga emits less GHG than other biomes; it is, by its characteristics, a key biome in the goals of reducing deforestation and desertification, requiring investments to implement projects with regenerative and conservative agriculture.

In this study, the LCAT mitigation GHG emissions potential ($MtCO_2e$) was estimated based on the Intergovernmental Panel on Climate Change (IPCC, 2014) in the report "Mitigation Trajectories and Public Policy Instruments for Achieving Brazilian Targets in the Paris Agreement" (Rathmann et al., 2017). The information used is related to the mitigation potential of the agricultural and land use change (AFOLU) sectors, whose topics were correlated with the LCAT used here.

By the above, the ICLFS appears as the best alternative to produce forage for ruminants in the Caatinga and, at the same time, mitigate GHG emissions (Table 5), and it is also an umbrella technology because it incorporates other LCAT, like BNF and NTS. SFM comes second, due to the forage an established forest provides, and the RDA-P comes third, because of the investment and inputs needed to re-establish the area and the uncertainties of the payback time and success in its recovery.

With RDA-P, by making a misused area productive, the smallholder will have, in addition to the economic return, ecological benefits: restoration of water flows and carbon sequestration in vegetation, avoiding deforestation (Malhi et al., 2021), mainly when it is made with arboreal and shrubs species. One difficulty in implementing this technology is to convince cattle smallholders to plant trees and shrubs, as they traditionally raise their livestock with grass pastures, even if grass alone is not resilient to a semiarid climate. An incentive would be to point out that forest restoration would not be a burden but a bonus for them (Miccolis et al., 2019). Therefore, technical assistance is needed to demonstrate that intercropping provides biodiverse pastures more resilient to climatic and soil adversities (Socolowski et al., 2021). And that the best way to recover a degraded area for pasture or forage banking in the Caatinga is with ICLFS.

Finally, it is important to emphasize that the lack of technical assistance, credit lines, and public policies tends to stimulate empirical knowledge diffusion, where the smallholder can change his production mode within his financial limitations (Nasuti et al., 2013). One strategy is to diversify income with new products, and benefits of ICLFS. Nevertheless, investing in qualified technical assistance for LCAT implementation is necessary and urgent.

But before that, it is necessary to offer training to qualify technicians and smallholders for a successful implementation of the technology, its development, and consolidation, as realized by PRS Caatinga (Ciancio et al., 2024). An important way to stimulate LAT adoption and its consolidation is its inclusion in the local and national markets by integrating it into the local productive arrangements.

4. Conclusions

This study elucidates how LCAT can interact with forage production in the Caatinga. ICLFS was identified as the LAT most recommended to increase the forage supply, followed by SFM and RDA-P. SFM has an important representativeness because Caatinga's vegetation is a natural source of forage, but it needs to be adjusted with vegetation and animal management, to increase forage production and conserve the biome. Although RDA-P is more difficult to implement, it is a fundamental technology for pasture recovery and conservation of the biome, when it is done with arboreal and shrub species as in an ICLFS.

GHG emission mitigation measurement for each LAT is complex due to the scarcity of data for the Caatinga. The AFOLU sector mitigation options mention the LCAT assessed here, but some items had to be shared across more than one technology and to be interpreted for an estimation. This research area should be better studied, with local GHG emission measurements.

Finally, a fragile climate-stressed biome as Caatinga is an important example of necessary adaptations and it is expected that new public policies and credit lines, associated with technical assistance, will be expanded to the biome, to subsidize more studies and implementation of LCAT in the region.

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The authors declare that they have no conflict of interest.

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