FINAL REPORT

Carbon footprint and mitigation scenarios for Hacienda San Jose:

Identifying opportunities and challenges using a consolidated modelling framework

Prepared by: Jacobo Arango[1], Mike Bastidas[1], Ciniro Costa Jr.[1], Ricardo González[1], Alejandra Marin[1], Natalia Matiz[1,2], Alejandro Ruden[1] & Daniel Villegas[1].

[1]International Center for Tropical Agriculture (CIAT), Cali, Colombia.
[2]University of Stuttgart, Germany.
February 2022

Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture
Km 17 Recta Cali–Palmira CP 763537
Apartado Aéreo 6713
Cali, Colombia
Phone: +57 2 4450000
Website: www.ciat.cgiar.org
February 2022

Arango J; Bastidas M; Costa Jr C; González R; Marin A; Matiz N; Ruden A; Villegas D. 2022. Carbon footprint and mitigation scenarios for Hacienda San Jose: Identifying opportunities and challenges using a consolidated modelling framework. Final Report. International Center for Tropical Agriculture (CIAT). Cali, Colombia.

Acknowledgements

The team is grateful to partners and colleagues of the World Bank Group (WBG), Hacienda San Jose (HSJ) and Impacto Capital (IC) for their contributions to this study. The report is strengthened by several rounds of consultations as well as technical inputs invaluable to the conceptualization, design and modelling for the identification of mitigation scenarios in HSJ. The team acknowledges the International Finance Corporation (IFC), who commissioned the first technical analyses of HSJ in 2020, which served as the basis for this study.

The team would like to especially express its gratitude to the following contributors for their advice, support and inputs provided throughout the development of this study: Juan Pablo Albornoz (IC), Tobias Baedeker (WB), Rafael Barreneche (HSJ), Lee Cando (WB), Juan Felipe Cortes (IC), David Jaramillo (HSJ), Gabriel Jaramillo (HSJ), Manuel Marquez (HSJ), Paulo Moreira (IC), Luciano Ospina (HSJ), Lorena Ramirez (IFC), Mariangela Ramirez (WB), Felix Teillard (WB), and Guillermo Terol (IFC).

This study is co-financed by the World Bank Group:

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

World Bank Project, 'Livestock sector readiness to access climate finance', which aims to increase the readiness of public and private entities within the livestock sector to access climate finance towards low-carbon transformation.

World Bank BioCF project under the Initiative for Sustainable Forest Landscapes (ISFL), 'Developing Climate-Smart Agriculture Supply Chains: Opportunities, Challenges and Emerging Lessons', aims to support generation, validation, and sharing of knowledge about effective approaches for promoting the emergence of climate-smart agricultural supply chains in the Orinoquia region.

IFC BioCF project under the Initiative for Sustainable Forest Landscapes (ISFL), MAS Advisory Services in Colombia, working with clients to develop sustainable production systems in beef, cocoa, and other sectors, to support the development of climate-smart land use and green supply chains to secure sustainable livelihoods and reduce land-use GHG emissions.

OneCGIAR Initiative, Livestock Climate and System Resilience (LCSR).

University of Stuttgart's Institute of Energy Economics and Rational Energy Use, from the research network BioGeCo 'Bioeconomy in Germany and Colombia'.

Layout and design by José Luis Urrea (CIAT). Ver 220425

Abbreviations

3-NOP	3-nitroxypropanol (scenario)
AFOLU	Agriculture, forestry and other land use
BD	Bulk density
BL	Baseline
CIAT	International Center for Tropical Agriculture
CCAFS	Climate Change, Agriculture and Fodd Security
CP	Crude protein
DE	Feed digestibility
DM	Dry matter
DMI	Dry matter intake
DNDC	DeNitrification-DeComposition model
ED	Energy density
EF	Emission factors
FAO	Food and Agriculture Organization
GBIF	Global Biodiversity Information Facility
GE	Gross energy
GHG	Greenhouse gas
GWP	Global warming potential
HSJ	Hacienda San Jose
IC	Impacto Capital
IFC	International Finance Corporation
IP	Improved pastures
IPCC	Intergovernmental Panel on Climate Change
ISFL	Initiative for Sustainable Forest Landscapes
LEG	Legumes scenario
LF	Life fences scenario
LW	Live weight
MACC	Marginal abatement cost curve
NAMA	National appropriate mitigation actions
NE	Net energy
NIR	National inventory report
NS	Native savannah
REF	Reference scenario
SAFA	Sustainability Assessment of Food and Agriculture
SELF	Self-sufficiency scenario
SOC	Soil organic carbon
SRM	Specified risk materials
WB	World Bank
WBG	World Bank Group
WFPS	Water-filled pore space

Contents

List of figures

List of tables

Part 1: Executive summary

This report summarizes findings of the work carried out by CIAT under the World Bank project, 'Livestock sector readiness to access climate finance', whose objective is to increase the readiness of public and private entities within the livestock sector to access climate finance.

The Colombian beef sector is growing rapidly as a response to increased demand in the domestic as well as foreign markets. There is a growing body of evidence showing that growth in the beef sector is driving deforestation, as expansion of pastures results from encroachment on forest cover. Thus, negatively impacting the environment. Consumers may be more attracted to buying sustainably-produced beef, thereby avoiding deforestation and using low-carbon methods of production, at a competitive price. However, consumers are often far removed from production zones such as the Orinoquia and may not recognize negative or positive environmental impacts of production systems. The World Bank project is thus testing the investment potential of a value chain finance approach. If transparent and reliable traceability systems can be put in place to earn consumers' confidence that the beef they see in the supermarket has been produced in a climate-friendly manner, this can add value to the product and ultimately compensate actors along the value chain for what may be perceived as higher costs, and at the same time reduce the sector's climate impact.

Hacienda San Jose (HSJ) is a flagship enterprise for cattle production in the Orinoquia region, under the department of Vichada in Colombia. Hacienda San Jose owns a combination of high-quality cattle genetics and improved pastures which increases efficiency in cattle ranching whilst reducing the climate impact of its operations.

The International Center for Tropical Agriculture (CIAT) was commissioned by the World Bank to develop a life cycle-based model of HSJ to calculate the annual and cumulative climate impact of its operations for the period 2017 to 2023.

The scope of the life cycle-based model comprises of HSJ's high-quality genetic resources (breeding stock, weaned heifers, embryos, and semen units) and cow-calves within the boundary "cradle to farm-gate", including upstream activities such as infrastructure and production of feed supplements. Relevant greenhouse gas GHG emissions and removals were quantified to calculate the carbon footprint at the farm and product level (CFP). The estimation of climate impact was completed through calculation of carbon (C) offsets (occurring in the forest outside the product system but still within the boundaries of HSJ), and through quantification of avoided emissions from improved management practices, i.e. no burning of savannah and using electricity from photovoltaic panels.

Some of the key findings indicate that HSJ reduced GHG emission intensity by -46% compared to other cow-calf farms in Meta, a department near Vichada (González-Quintero et al. 2021); 8.4 vs. 15.5 kg CO_2eq kg^{-1} live weight (LW). However, savannah burning is a phenomenon rarely documented in Meta (González-Quintero et al. 2021). Thus, a reference farm in Vichada was simulated in this study and resulted to an even higher GHG emissions intensity of 23.0 kg CO_2eq kg-1 LW, brought about by savannah burning.

The improved productive and reproductive performance of the specific cattle breed-short-cycle Nelore, resulted to 8.6 kg CO_2eq kg^{-1} LW for a cow and two calves. In comparison, the Brahman female, the most commonly used breed in the region, would produce in the same simulated time only one offspring, resulting to 10.4 kg CO_2eq kg^{-1} LW, an increase of 21%.

These results suggested a very attractive potential substitution of meat from inefficient production systems currently operating in the region at a rate of 17.5 kg CO_2eq kg^{-1} LW (fattening farms in Meta, González-Quintero et al. 2021).

Soil measurements at HSJ revealed two important aspects related to soil organic carbon (SOC) stocks for clay soils in the Colombia's Orinoquia. First, SOC measurements helped refine the value of the SOC stock reference for this region. The SOC stock estimated in the native savannah was almost 40% higher (79.9 t C ha^{-1} for the 0-30 cm soil depth) than the reference default value for this climate zone and soil type provided by the IPCC (52±6% t C ha^{-1}; IPCC, 2019). Improvements are encouraged by the IPCC and contribute to refining estimates of global SOC stocks and potential sequestration. Running the life cycle-based model with the corrected value for SOC stock reference and the relative stock change factors of IPCC (2019) for improved grassland management like HSJ's leads to a potential annual CO_2 removal of 2.5 t CO_2 ha^{-1} yr^{-1} during 20 years.

Second, the clay soil in the Orinoquia showed a large potential for SOC accumulation. Soil measurements indicated a SOC stock (0-100 cm) 15% higher in the improved pasture compared to the native savannah. However, statistical differences were only found in the upper layers which suggested an accumulation of approximately 2.0 t C ha^{-1} y^{-1} (0-20 cm) after ~6.5 years of the implementation of improved practices. This corresponds to 7.2 t CO_2 ha^{-1} yr^{-1}. The higher plant biomass productivity of the tropical pasture *Urochloa humidicola* (CIAT/679), together with the introduction of a rotational grazing strategy with animals depositing urine and dung have likely increased the deposition of organic residues, especially on the soil surface, with subsequent percolation into the soil profile. Significant changes in SOC stocks occurring in deeper soil layers in the coming years can be expected if the current management continues or improves. However, the accumulation rate in the upper layers should be reduced overtime once SOC stocks approach a new steady-state. Thus, the conservative assumption of 2.5 t CO_2 ha^{-1} yr^{-1} was kept in HSJ's life cycle-based model.

Besides the C removal in soil, minor contributions came from the biomass of the pastures' roots and in the woody species on grasslands. The CFP of HSJ during the period from 2017 to 2023 was calculated as negative with -17 kg CO_2eq kg^{-1} LW – meaning, total GHG removals are higher than GHG emissions. Additional 367 t CO_2 were removed from the atmosphere per year by the riparian forest on the farm. The avoided emissions of methane (CH_4) and nitrous oxide (N_2O) due to no savannah burning accounted for 0.4 t CO_2eq ha^{-1}. This shows an important mitigation potential for the whole Orinoquia region, where savannah burning is a common practice which happens at least once a year.

Carbon removals can help offset GHG emissions and is an important strategy to align with the 1.5°C global climate target. However, it only provides a net mitigation effect for a finite period, (e.g., until SOC reaches a new equilibrium). After which, annual livestock emissions will outweigh the current CFP of HSJ unless additional sinks and/or mitigation practices are realized. Monitoring future GHG emissions and SOC stocks are therefore critical to validate findings and better understand net mitigation benefits of improved livestock systems in the region.

Other opportunities to further reduce GHG emission and increase GHG removals were identified at HSJ with a scenario analysis at different points in the product system. These mitigation actions have a clear potential for implementation in HSJ: using feed additives to reduce enteric CH_4 emissions, silvopastoral systems as live fences to increase C sequestration in biomass, legumes to enhance SOC accumulation, and intercropping of improved pastures with maize to reduce soil-born N_2O emissions.

An initial assessment of an expanded boundary “cradle to slaughterhouse-gate” was made for the first time in Colombia. The study utilized HSJ data on fattening farms which will be used to commence operations in 2028 and made some assumptions for the transport and slaughterhouse activities based on common practices, expert judgement and literature. GHG emissions intensity accounted for 25.4 kg CO_2eq kg^{-1} beef. Gathering of actual data is needed to validate the assumptions of the activities taking place outside the farms. For example, the result is sensitive to variations on the assumed animal weight loss during transportation and probably to outcomes of slaughterhouse activities’ co-products.

The study presents robust evidence that HSJ’s production system leads to climate benefits compared farms with traditional management practices. These results will undergo a critical review prior to public dissemination, whilst a suitable communications strategy should be developed to reach beef consumers. The life-cycle model will be crucial in calculating the carbon footprint of HSJ's expansion plan along the value chain covering 150,000 ha and 150,000 head of cattle until 2035 in cow-calf and fattening farms.

Below are suggested **recommendations for future work,** building on the results of this study.

Results by field measurements

- Further field experiments are needed to refine the rate of SOC accumulation and differentiate the impact of improved pastures and grazing strategy.
- In-situ measurements of enteric CH_4 emissions are recommended given its huge contribution in HSJ's overall CFP.
- Improved pastures play a critical role in the production efficiency of HSJ due to the relatively high forage production during the dry season compared to native savannah. The evaluation of the variability of the feed characteristics during the year, such as digestibility, energy and crude protein may give more insights on the benefits of the use of the improved pastures.
- Setting a Measurement, Reporting and Verification (MRV) system is critical for validating results over time and engaging with sources of climate finance (e.g., carbon markets), as it is important to keep in mind that "the reality of soil carbon is that it is highly variable, hard to measure, hard to shift and easy to lose" (Burke, 2021).

Methodology and model

- The system boundary of the life cycle-based model of HSJ should be expanded to include activities up to the retail value of 1 kg beef to cover the complete value chain and for transparency in providing accurate information to the customer.
- A functional unit regarding the nutritional value of the beef would highlight potential benefits of the production system and contribute to the discussion of food security/sovereignty and healthy diets within planetary boundaries.
- Consideration of the short-life span of CH_4 in the atmosphere is important considering new metrics such as Global Warming Potential Star (GWP*), compared to the classical GWP metric used in this study (i.e., constant herd size could lead to a cooling effect in the atmosphere after ~12 years). This may play a major role when analysing soil carbon dynamics within a longer time horizon and estimating the GHG emissions needed to be offset by then.
- The time horizon across all farm units, i.e., HSJ, satellite cow-calf and fattening farms should be harmonized to get an accurate picture of the whole production system's climate impact.
- This study needs to be peer reviewed prior to public dissemination and communication.

Supporting HSJ's operations and expansion plan

- Adapt HSJ's life cycle-based model to its expansion plan, aiming at covering 180,000 hectares with 150,000 cattle in the region.
- Develop an MRV system on GHG fluxes considering the following:
  - Specific emission factors (including in-situ measurements) generation for enteric CH_4 emissions and consolidated SOC and N_2O emissions data.
  - A higher SOC sample size to achieve 10% uncertainty at 90% confidence.
  - Development of a digital tool to collect key activity data at HSJ which can extend to its expansion plan.
  - Development of regional datasets of feed supplements' production to decrease the uncertainty of the model.

After a test phase, the MRV system can also be replicated for use by other companies and farms in Colombia.

- Generate a scoping report and preliminary calculations for HSJ operations to access carbon markets.
- Apply the Sustainability Assessment of Food and Agriculture systems (SAFA) from FAO including four pillars: environment, governance, social and economy at HSJ and its expansion plan to go beyond climate impact evaluation.
- It should be clearly stated that the estimated carbon footprint "is one of many environmental indicators and it does not reflect overall environmental preferability" (ISO 14026:2017). The model can be complemented with additional inputs and processes to assess other environmental aspects such as water footprint and impacts on biodiversity.
- Engage with HSJ to test proposed explorative scenarios on i) supplementing 3-nitroxypropanol (3-NOP) to cattle to reduce enteric CH_4 emissions, ii) expanding live fences with already implemented or new woody species, e.g. Melina (*Gmelina arborea*) to increase C uptake in the above-ground biomass, iii) introducing *Arachis pintoi* to the *Urochloa humidicola* (Humidicola) pastures to increase C uptake in below-ground biomass and SOC, and decrease enteric CH_4 emissions, and iv) intercropping of Humidicola with maize crop.
- Test new developments at CIAT through remote sensing technologies for precision cattle management in HSJ, land use planning, grazing management, forest and water protection.

Upscaling and mid-term horizon

- A roadmap for achieving the national/regional climate goals, similar to the recent Methane Pledge of 30% reduction in beef cattle production systems in Colombia/Latin America.
- Evaluate the contribution of improved beef cattle production systems to net-zero food systems and food companies' net-zero pledges.

Finally, lessons learned from the study included the following:

- Moving to higher tiers brings less uncertainty and has an important effect in the results of the climate impact of the farm. However, this is associated with higher effort, time and costs in the producer's data documentation and the modeller's data gathering.
- Physical visits to the farm are important. The CIAT team got valuable insights about the production system that helped strengthen the model in a more accurate manner. Furthermore, physical visits could ease data gathering through identification of critical processes such as those with a potential higher climate impact along the life cycle, which could lead to the identification of more relevant and precise questions resulting to a more efficient workflow.
- The identification of the key staff in HSJ and their respective roles are fundamental as knowledge and management of different aspects of the farm was dependent on different people, e.g. cattle diet and soil management. *Impacto Capital* (the commercial branch of HSJ) was an interface to the farm but direct contact to the farm staff is crucial.
- "Translate" the findings to an accessible language to ensure that critical messages are disseminated to target stakeholders for uptake.

Selection No. 1275602
Internal report
Part 2

Part 2: Scenario analysis for mitigation of the climate impact of Hacienda San Jose

Background and rationale

The main objective of this study is to advance the readiness of Hacienda San Jose (HSJ) to climate finance investments. HSJ is a cattle farm located in the department of Vichada in Colombia's Orinoquia region in the plains of the Meta River (IGAC 2012) (Figure 2.1). The global ecological zone is tropical moist forest (FAO 2012) and the climate zone tropical, wet (IPCC 2019). The soil is categorized as low activity clay (Neira et al. 2017). HSJ started operations in 2014 with two productive orientations: high-quality genetics and cow-calf production. The core of their strategy relied on the introduction of animals and pastures with high-quality genetics aiming for sustainable intensification of conventional production systems of the region. Its expansion plan regarding herd consolidation and implementation of grazing area is expected to be fulfilled by 2023 with approximately 10,000 cattle heads of the breed short-cycle Nelore grazing in around 7,500 ha of *Urochloa* pastures.

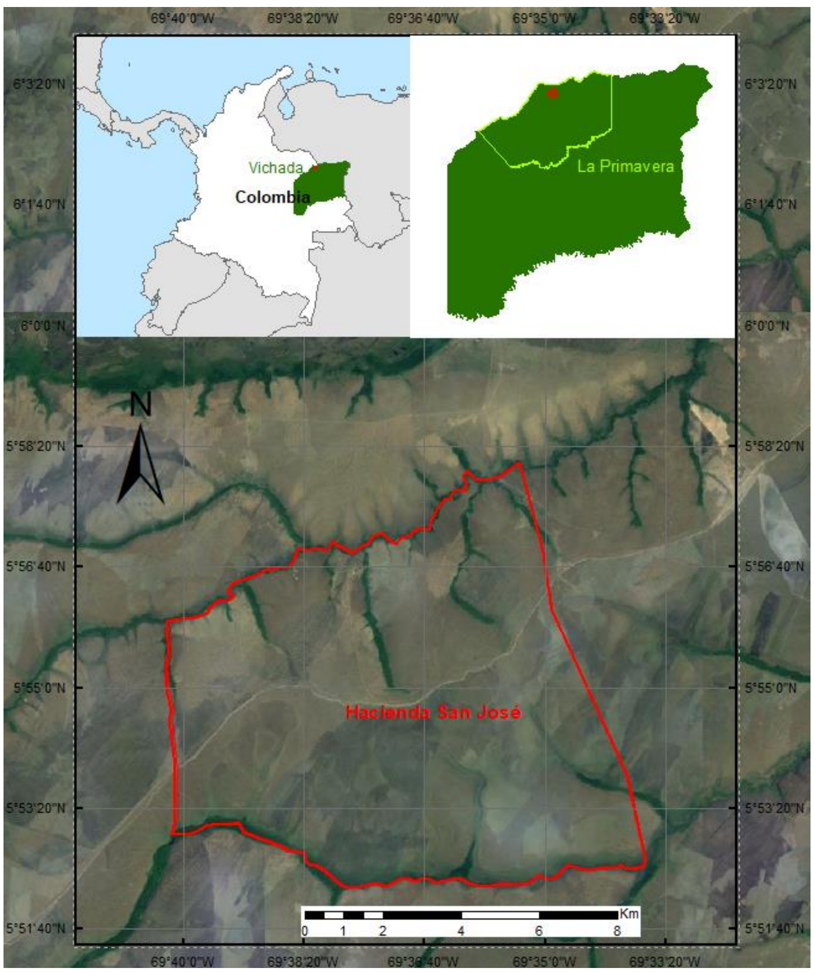


Figure 2.1. Location of Hacienda San Jose (HSJ) and aerial view of the farm taken from HSJ's YouTube channel.

This study is built on the recently developed life cycle-based model of HSJ commissioned to the International Center for Tropical Agriculture (CIAT) by the International Finance Corporation (IFC) in 2020 on the farm's carbon footprint. This study aims to decrease the uncertainty of the model by means of i) on-site measurements of carbon (C) in soil and nitrous oxide (N_2O) soil born emissions, and ii) gathering more detailed data on HSJ operations during the period 2017 to 2023, corresponding to the expansion plan of the farm.

The improved and consolidated version of the life cycle-based model constitutes the **baseline (BL)** for a scenario analysis. It was first compared with a hypothetical **reference (REF)** farm operating with conventional practices in the region, to quantify the climate impact of HSJ's management practices. Four **explorative scenarios** with further mitigation options were designed and compared with the BL scenario: i) supplementation of the feed additive 3-nitroxypropanol **(3-NOP)**, ii) expansion of live fences **(LF)**, iii) introduction of legumes **(LEG)**, and iv) own maize production **(SELF)**. All scenarios were assessed on a cost-effectiveness basis.

Methods and data

ISO standards: Carbon footprint of products and life cycle assessment

HSJ's carbon footprint was assessed following the standard ISO 14067:2018 "Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification". The carbon footprint of a product (CFP) is defined as the "sum of greenhouse gas (GHG) emissions and GHG removals of a product system expressed as CO_2 equivalents (CO_2eq) and based on a life cycle assessment (LCA) using the single impact category of climate change" (ISO 14067:2018). The LCA method is standardized in the ISO 14040:2006 "Environmental management – Life cycle assessment – Principles and framework", and ISO 14044:2006 "- Requirements and guidelines" (ISO 14044:2006).

For the climate impact assessment, the study used the baseline model of 100 years of the IPCC (2013) implemented in the Software SimaPro with the underlying characterization factors from Muñoz and Schmidt (2016) (Table 2.1):

Table 2.1. Global warming potential (GWP) of greenhouse gases (Muñoz and Schmidt 2016)

Greenhouse gas	GWP, kg CO_2eq kg^{-1} GHG
Carbon dioxide, CO_2	1
Methane, CH_4	30,5
Nitrous oxide, N_2O	265

The global warming potential (GWP) of 30,5 kg CO_2eq kg^{-1} CH_4 consistently addresses the methane oxidation to CO_2 by adding the pulse emission of 28 (IPCC 2013) with 2,5 kg CO_2eq kg^{-1} CH_4 for methane decay in 100 years (Muñoz and Schmidt 2016).

Four types of GHG fluxes were estimated in the study as shown in Figure 2.2. GHG emissions (highlighted in blue) and removals (highlighted in violet) were considered for the calculation of HSJ's CFP following this equation:

$$\text{CFP, CO}_2\text{eq} = \text{GHG emissions} - \text{GHG removals}$$

Greenhouse gas removals taking place outside the product system was not included in the CFP computation. This is the case for the CO_2 uptake in the HSJ forest (highlighted in green). Since animals do not have access to it, it is not considered as part of the product system. Yet, it contributes to the C offsetting of HSJ operations (ISO 14067:2018) and may be reported separately (ISO 14021:2016, ISO 14026:2017). The final component of the HSJ's climate impact relates to avoided emissions (highlighted in grey) due to the implementation of mitigation practices. These GHG fluxes don't change the CFP of the farm. However, they are important for the calculation of the mitigation costs.

System boundary, functional unit and footprint communication

In an LCA, the product system constitutes the life cycle model of a product collecting the processes performing one or more functions (ISO 14040:2006). The life cycle of a product starts with the raw material acquisition and ends with the final disposal, including further processes, e.g., energy supply, production, transport, use, and recycling. The functional unit represents the quantified performance of a product system and is used to compare it with other systems.

For the scenario analysis, the system boundary was "cradle to farm-gate" (Figure 2.2). It includes inputs required for HSJ operation and the production of the co-products female (f) and male (m) breeding stock, weaned heifers, embryos, and semen units, which are sold in the market for genetic resources to other cow-calf farms. The co-products cull animal (f, m) and weaned calves are sold to fattening farms. The functional unit of the product system was defined as the annual operation of HSJ represented by the reference unit 1 kg of exported[1] animal live weight (LW) during the period 2017 to 2023. Consequently, no climate impacts were allocated to the embryos and semen units. Furthermore, no differentiation was made among the LW of the different sold animals and therefore no allocation rule was applied.

The required processes to produce the final product for the consumers' "beef", e.g., fattening operations, slaughterhouse and retail activities are outside the scope of this scenario analysis. Thus, only the *partial* CFP (14067:2018) of the beef was calculated. As a consequence, the results of this study shall only be used for business-to-business communication in accordance with the guidance of ISO 14026:2017 "Principles, requirements and guidelines for communication of footprint information". Due to the comparative assertions made for HSJ vs. a reference farm and some explorative scenarios, a critical review is needed prior to communication to third parties (ISO 14040:2006). Moreover, it should be clearly stated that the estimated carbon footprint "is one of many environmental indicators and that it does not reflect overall environmental preferability" (ISO 14026:2017). Following results gathered by CIAT authors, this study has been submitted for peer review through submission to a scientific journal.

[1] Exported LW means animals that cross the farm-gate. They are not exported to another country.

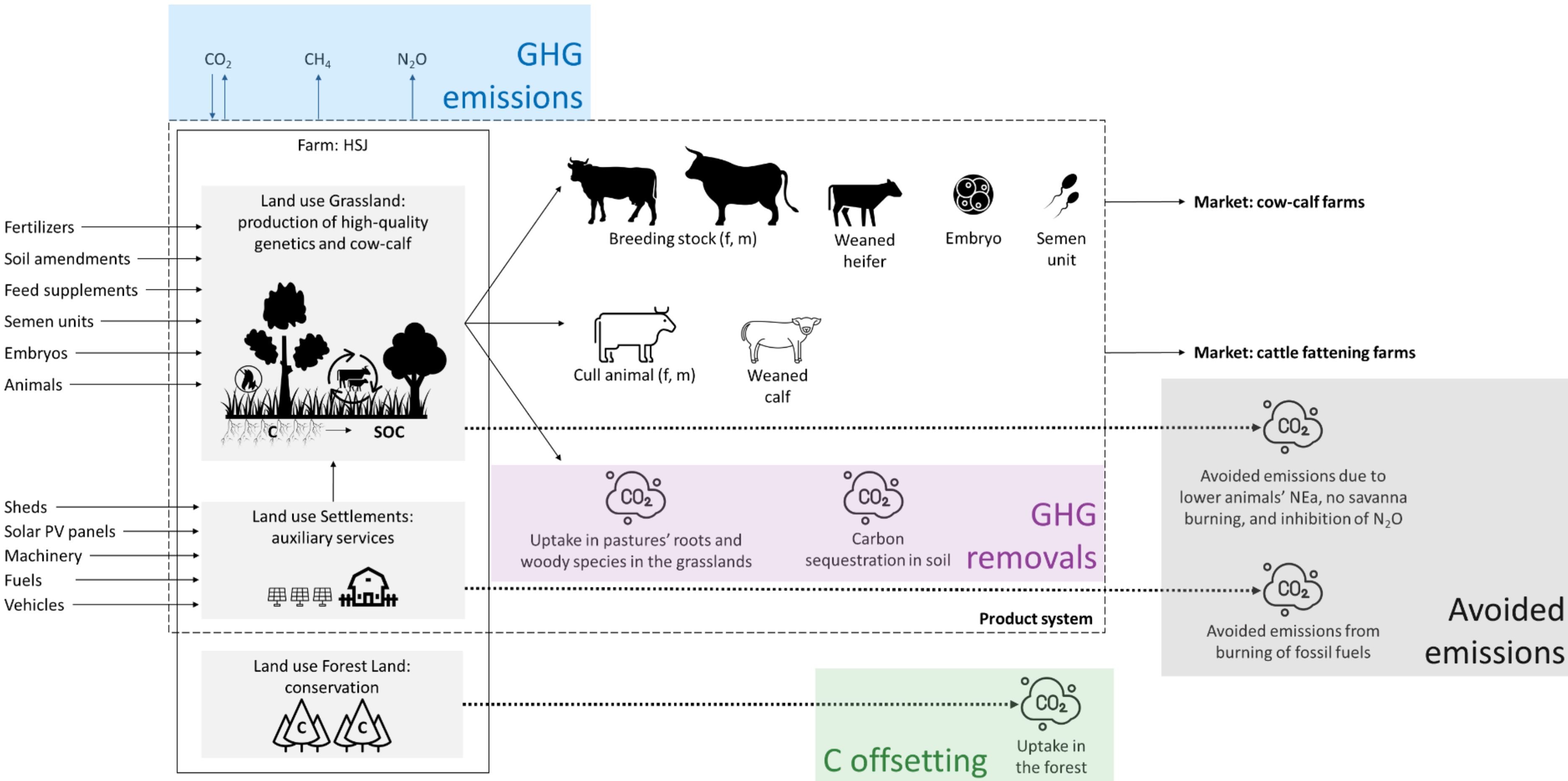


Figure 2.2. Product system of Hacienda San Jose (HSJ) from "cradle to farm-gate" and estimated greenhouse gas (GHG) fluxes. f: female, m: male, SOC: soil organic carbon, PV: photovoltaic. Icons from the Noun Project (thenounproject.com).

IPCC Guidelines for National Greenhouse Gas Inventories

The GHG emissions and removals of HSJ were estimated according to the Volume 4 on Agriculture, Forestry and Other Land use (AFOLU) of the IPCC Guidelines for National GHG Inventories (2006 and Refinement 2019). Land use present in HSJ include Grassland, Settlements and Forest Land (Figure 2.2).

The Grassland is economically used through cattle ranching. GHG fluxes result from the equations presented in the chapters “Emissions from livestock and manure management” and “N_2O emissions from managed soils, and CO_2 emissions from lime and urea application”. The estimation of the gross energy (GE) demand of animals needed for the estimation of the emissions from livestock was undertaken using actual dry matter intake (DMI, data available from HSJ) as a basis and per suggestion by Kristensen et al. (2011) (see Box 2.1). Emission factors for the livestock emissions were further calculated with the IPCC (2019) equations. The feed digestibility (DE), energy density (ED), crude protein (CP), and ash content of the improved pastures were available from bromatological studies commissioned by Corpoica (2018).

The chapter “Grassland” was used for CO_2 uptake through biomass increase in the pastures’ roots and the woody species, while the “Generic Methodologies applicable to multiple land-use categories” was used for the assessment of changes in soil organic carbon (SOC) due to roots turnover. The chapter “Forest land” was used as the source for CO_2 uptake in the forest.

The three hierarchical tiers of methods considered were dependent on data availability. A tier describes “a level of methodological complexity” (IPCC 2006a). A combination of tiers among the GHG sources and sinks was used as follows:

- Tier 1 stands for the use of IPCC default parameter values,
- Tier 2 for the adoption of country- or region-specific data retrieved from the last National Inventory Report (NIR) in Colombia (IDEAM et al. 2018), and
- Tier 3 for the process-based modelling tailored to HSJ operations.

The list of the GHG emissions and removals by sources and sinks, IPCC equations, Tiers, and coefficients used in the BL scenario are shown in Table 3.7. The variations made in the other scenarios are described directly in the “Results and discussion” section.

Box 2.1. Estimating gross energy (GE) intake for animals

The calculation of emission factors (EF) for GHG emissions from enteric fermentation under a Tier 2 approach relies on the GE intake of the animals (IPCC 2019). This is dependent on animal performance, diet composition and quality. If this information is not well documented, which is the usual case in Colombia (González-Quintero et al. 2020), IPCC (2019) guidelines present default values to estimate the net energy (NE) requirement by the animals for maintenance, activity, lactation, work, pregnancy, growth and wool. The NE combined with the feed digestibility was used to obtain the GE. CIAT has undertaken this exercise for HSJ in the first phase of the project in 2020. However, with this current study, CIAT gathered more accurate diet information at an animal subcategory level (Table 3.14) and was able to move towards a Tier 3 approach for the calculation of the enteric CH_4 emissions.

Using an undifferentiated diet for all the herd and the Tier 2 IPCC default coefficients, the enteric CH_4 emissions were considerably higher in comparison to the actual DMI (Tier 3). For the breed short-cycle Nelore, the differences range from 19% for the subcategory bull_550 to 429% for the heifer_200 (Table 3.17). The reason was an overestimation of the GE, which suggested that the Tier 2 IPCC default coefficients were not suitable for a cattle system like HSJ's, due to a breed with high daily LW gains despite a diet with a relatively low ED. For example, according to the last Colombian NIR, the calves pre-weaning in the Eastern plains gain 0.37 kg LW d^{-1} (IDEAM et al. 2018) compared to 1.02 kg LW d^{-1} in HSJ. On the feed side, IPCC (2019) suggests a default value of 18.45 MJ kg^{-1} DM for the ED, which, depending on the diet of each animal subcategory in HSJ ranges between 16.54 and 17.17 MJ kg^{-1} DM. Such discrepancies would imply daily DMI in HSJ between 3 and 12% depending on the animal subcategory: i) physiologically not feasible and ii) far from the actual DMI of the animals HSJ around 2.3%. Therefore, the authors concluded that using the Tier 3 approach, GHG emissions could be calculated more accurately than using the Tier 2 IPCC default coefficients.

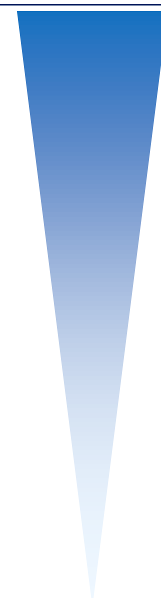
Activity data

The basic equation to quantify the emissions and removals of a country presented by IPCC (2006a) was applied to the product system of HSJ:

$$\text{GHG emissions/removals} = \text{Activity data} \times \text{Emission/removal factor}$$

Activity data represents "the magnitude of a human activity resulting in emissions or removals taking place during a given period of time" (IPCC 2019). The activity data collected on the HSJ operations for the period 2017 to 2023 is listed in Table 2.2. All data was available at HSJ and was considered as primary data. For the SOC, field sampling was undertaken. On the right side of the table an inverted triangle shows the impact of the activity data on the results of the model and the required frequency for data collection: the darker the point on the chromatic scale, the higher the impact and the frequency.

Table 2.2. Activity data for the inventory of HSJ

Activity data	Position in the report	Data collecting frequency and impact in the results
Herd composition and annual animal inventory	Table 3.8	
Productive parameters by animal sub-category	Table 3.8	
Reproductive parameters by breed	Table 2.4	
Diet composition and intake by animal sub-category	Table 3.14 to Table 3.16	
Area by land use category	Table 3.11	
Grazing strategy	Table 2.3	
Soil carbon (reference) stock	Part 3, Workstream 1	
Bromatological studies of the pastures	Table 3.7	
Soil management practices	Table 3.12	
Tree species	Section “Woody species”	
Energy demand	Table 3.13	
Infrastructure and machinery	Table 3.13	

For activities without field data, ecoinvent datasets version 3.6 from the system model “Allocation, cut-off by classification” were used (ecoinvent 2019). Most activities are from the region “rest of the world” (RoW) as a proxy for Colombia.

Baseline scenario (BL)

The design of scenarios started by characterizing the production system of HSJ to build the baseline of the study. It was defined as the current expansion plan of HSJ for the period 2017 to 2023. The focus was on five interconnected management practices aimed at reducing the climate impact of the farm, classified in three types of strategies, i.e. production efficiency, land-based carbon removal (Cusack et al. 2021) and energy management (Table 2.3).

Table 2.3. Characterization of the production system of HSJ by three strategies to reduce the climate impact

Strategy	Management practice in HSJ	Expected climate impact
Production efficiency	Introduction of the breed short-cycle Nelore	Lower GHG emission intensity due to earlier precocity and faster growth
	Introduction of improved pastures	Higher CO_2 uptake from the atmosphere due to higher biomass productivity
		Reduction of N_2O soil born emissions
Land-based carbon removal	Implementation of intensive rotational grazing	Lower CH_4 emissions from enteric fermentation due to lower animals' NEa
		No emissions from biomass burning
		Carbon sequestration in soil
	Introduction of woody species in the grasslands	CO_2 uptake from the atmosphere
	Forest conservation	CO_2 uptake from the atmosphere
Energy management	Installation of polycrystalline silicon solar panels	Avoided emissions from burning of fossil fuels

HSJ: Hacienda San Jose, GHG: greenhouse gas, NEa: net energy for activity

Herd characterization

Prior to HSJ, the farm used to be a cow-calf production system with a herd consisting completely of the regional breed Brahman. Per the genetic improvement program, it is envisaged that the herd will consist 100% short-cycle Nelore by 2023. The breed short-cycle Nelore has shown to be economically sustainable due to earlier precocity, shorter reproductive cycles (Table 2.4) and higher daily LW gains (Table 3.8).

Table 2.4. Reproductive parameters of the cattle herd in HSJ.

Parameter	Short-cycle Nelore	Brahman
Female precocity, months	16	28
First calving, months	25	37
Calving interval, months	12	14

The crossbreed "F1" (Brahman X Angus), of which the heifers were used to implant the short-cycle Nelore embryos have the same productive parameters, i.e. approximately 11% lower daily LW gain than the short-cycle Nelore. For practical reasons, the sum of their figures are reported here under the breed Brahman.

For the characterization of the herd composition and subsequent estimation of emissions, three categories defined by IPCC (2019) were adopted: "cows used to produce offspring for meat" (here referred as "cows"), "bulls used principally for breeding purposes" (here "bulls"), and "calves pre-weaning" (here "calves"). They were classified by the mature LW in each life cycle stage, and by lactation and pregnancy resulting in 15 sub-categories (Table 3.8). Figure 2.3 shows the annual animal inventory from 2017 to 2023 in HSJ (Costa et al. 2022).

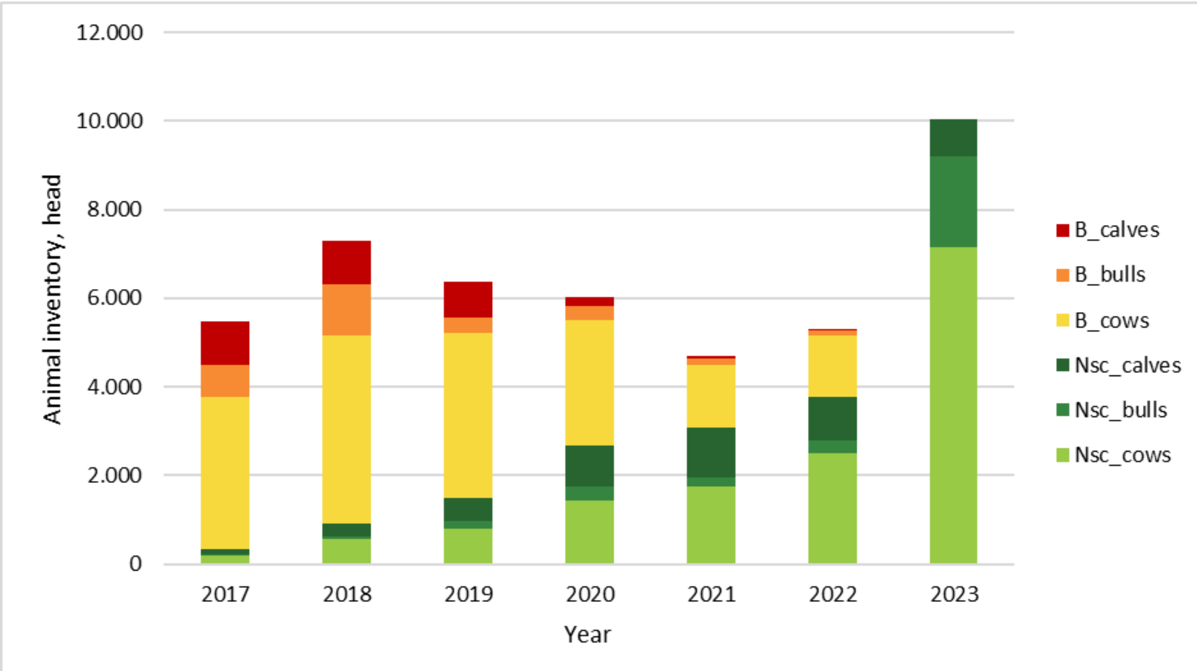


Figure 2.3. Annual animal inventory in HSJ during the period of the expansion plan at the farm level. B: Brahman, Nsc: short-cycle Nelore.

Exported co-products

The economic activity of HSJ delivers co-products for two markets, namely breeding stock (f, m) weaned heifers, embryos and semen units for cow-calf farms, and cull animals and weaned calves for cattle fattening farms (Figure 2.2). The characteristics and prices of the co-products are shown in Table 3.9 and Table 3.10. Figure 2.4 shows the annual exported LW from 2017 to 2023 of HSJ.

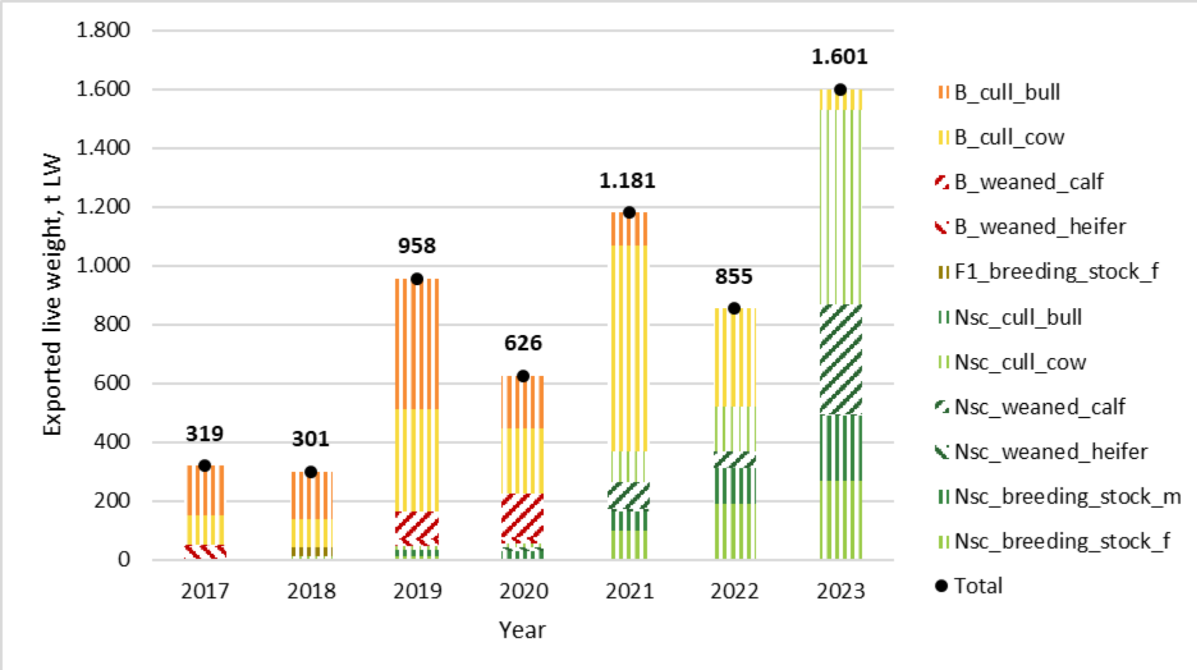


Figure 2.4. Annual exported live weight (LW) of HSJ during the period of the expansion plan at the farm level. B: Brahman, Nsc: short-cycle Nelore, F1: crossbreed Brahman X Angus, f: female, m: male.

In 2017 the exported LW began at 319 t LW. With herd expansion and consolidation, the expected exported LW in 2023 will be five times higher.

Land use

The land use in HSJ was characterized following IPCC classification (IPCC 2019) and guidelines of the Colombian Federation of Cattle Ranchers (Ayala Prieto et al. 2017). The total area of the farm is 8,670 ha. By 2023 approximately 86.5% would correspond to improved pastures, 7.8% to native savannah, 5% to riparian forest, 0.5% to woody species on grasslands, and 0.2% to infrastructure (Figure 2.5). Time series of land use development is shown in Table 3.11.

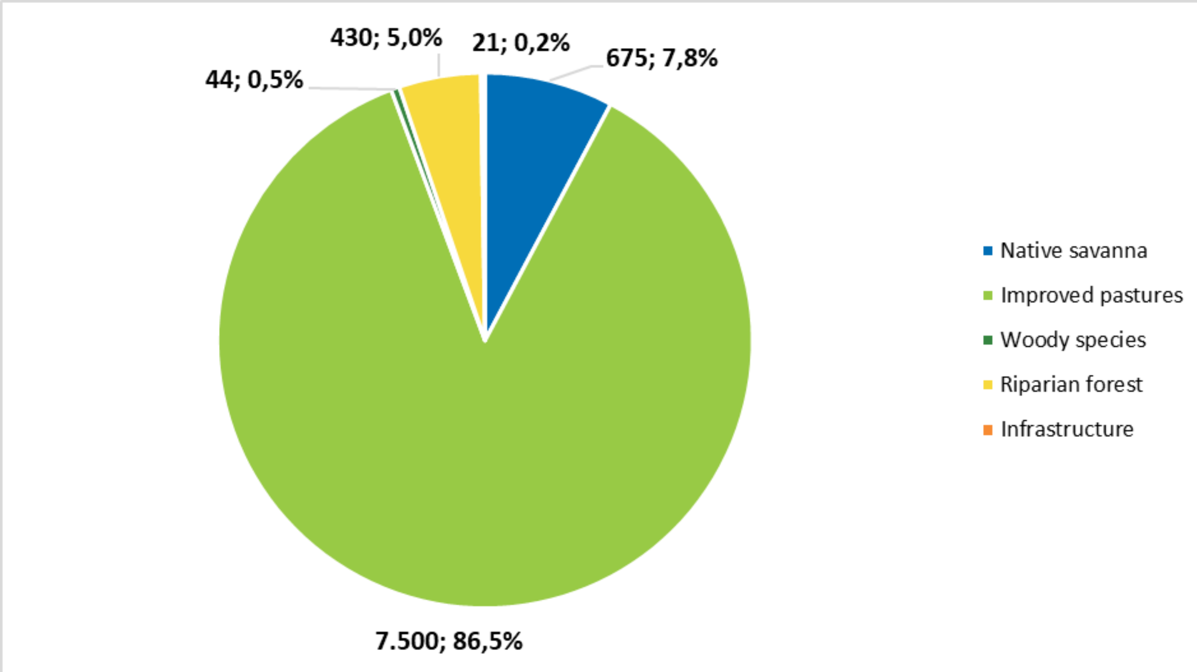


Figure 2.5. Area (ha) and share by land use type in HSJ in 2023.

Improved pastures

Pasture improvement was mostly achieved through the introduction of five forage grass cultivars, i.e. *Urochloa humidicola* CIAT 679 cv. Tully (Humidicola), *U. brizantha* CIAT 6780 cv. Marandú, *U. humidicola* CIAT6133 cv. Llanero, *U.* hybrid CIAT BR02/1752 cv. Cayman, and *Megathyrsus maximus* CIAT 6962 cv. Mombasa. The area of improved pastures expanded from 0 (zero) ha in 2014 to approximately 7,200 in 2021 covering more than 80% of the total 8,670 ha of the farm. Dolomitic lime, phosphate rock and gypsum were applied in 2017 to amend soil acidity of 5,027 ha of land. Only the cultivar Mombasa (32 ha) is fertilized with urea, diammonium phosphate (DAP) and potassium chloride. The grazing area in HSJ corresponds to improved pastures, excluding the area planted with Mombasa, which is used as silage.

Improved pastures are more resistant to floods and are well adapted to acid soils in the region, leading to higher biomass productivity than the native pastures, e.g., Guaratara - *Axonopus purpusii*, which is found in the farm. Today, around 50% of the 7,206 ha of grazing area is covered by Humidicola. HSJ team observed this to be most suitable to regional conditions among cultivated species on-site. This is shown by the above-ground biomass production (forage) during the year and during dry season as shown in Figure 2.6. Biomass productivity of Humidicola vs. Guaratara is 14% higher compared to annual figures. During the dry season, productivity of Humidicola is almost 8 times higher.

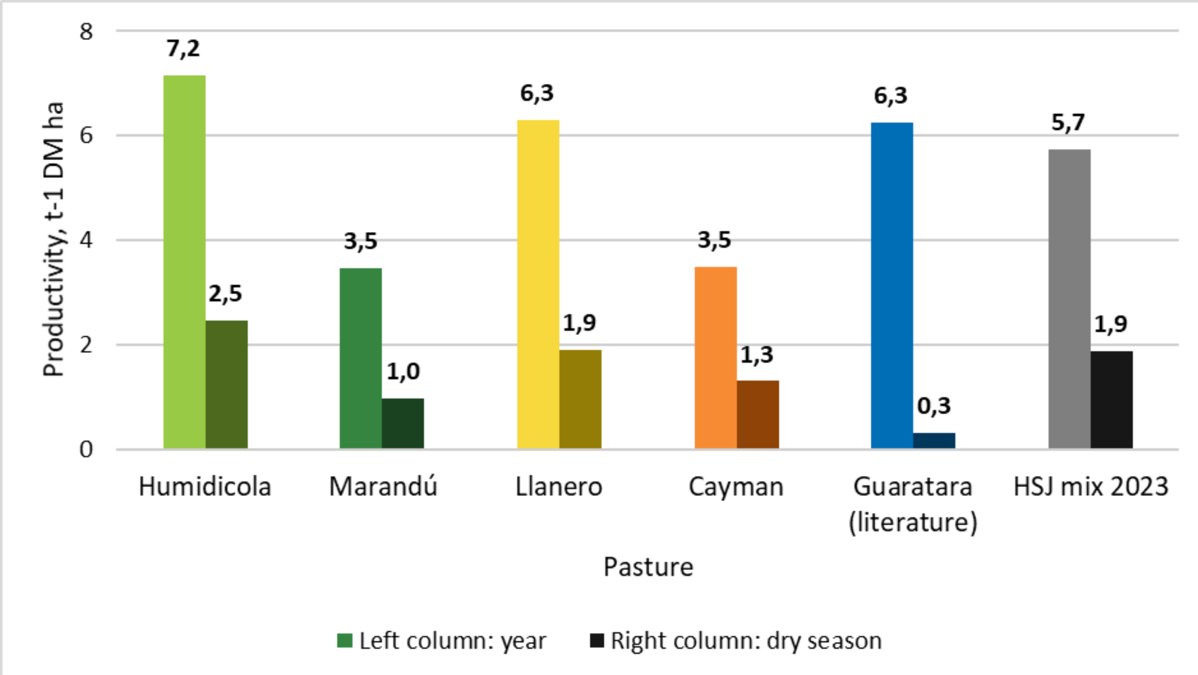


Figure 2.6. Productivity of the improved pastures vs. a native pasture in HSJ. The HSJ mix considers the composition of the grazing area in HSJ in 2023.

The forage of pastures is assumed to remain in an approximate steady-state because its growth is balanced by the animals grazing (IPCC 2006a). However, the below-ground biomass (roots) contributes to the C pool "biomass". This was accounted for as a one-time event for the whole 2017-2023 series, occurring the year of pasture introduction. The amount of C in roots is assumed by considering forage productivity (potential growth in one year) and the ratio between above- and below-ground biomass. This C in roots remains constant if the pasture continues to be grazed. The coefficients for these calculations are listed in Table 3.7.

Grazing system

The grazing area is divided through a radial distribution system of the paddocks. It converges in the centre, equipped with drinking troughs and cattle salting for the welfare of the animals. The grazing strategy is a rotational system, where the entrance and exit of animals from pastures are determined by the height of the pasture. The Brazilian company Boviplan supports HSJ in this system.

Soil organic carbon

Decreasing the amount of atmospheric C and storing it in the terrestrial biosphere has been proposed as one of the options for offsetting GHG emissions (Albrecht & Kandji, 2003), pastures such as Humidicola have been found to sequester significant amounts of organic C deep in the soil (Fisher et al., 1994). The accumulation of SOC occurs over a period based on soil absorption rates specific to agro-ecological conditions and management practices (Godde et al. 2020) until the soil potential to store C is reached (Smith 2014).

The hypothesis of the study is that the conversion of native savannahs to improved pastures and combined with the rotational grazing system can improve SOC stocks, thus mitigating their loss to the environment. The SOC reference stock in the native savannah of HSJ and that contained in a paddock with Humidicola after 6 years of grazing were measured as described in Part 3 of the document, Workstream 1. The stock change factor and the accumulation period used for this estimation are the default values of IPCC (2019) listed in Table 3.7. More details are also given in the Info Note "Soil carbon stocks in tropical pasture systems in Colombia's Orinoquia region: supporting readiness for climate finance" (Villegas et al. 2021), published online in the CGIAR website.

Woody species

There is a wide variety of woody species in HSJ covering 11 ha. An additional 22 ha will be planted in 2023. In 2020, 11 ha of *Eucalyptus pellita* was planted. This afforestation results to increasing animal wealth through the tree's shadows. The CO_2 uptake from the mango tree, (used as a proxy for native trees) and *Eucalyptus pellita* can be found in Table 3.7.

Infrastructure

HSJ's infrastructure includes houses, offices, storage and sheds As the farm is not connected to the electricity grid (Figure 2.7), photovoltaic panels were installed. The activity data and emission factors of this land use and utilities for electricity, heat and fuel are listed in Table 3.12.

Figure 2.7. Electricity grid in Colombia (UPME 2019). The red star indicates the location of HSJ.

Animal diet

The diet of the animals at HSJ consists mainly of pastures. The DMI of each improved pasture was provided by the company Boviplan and is provided in Table 3.7. They manage the pastures with a score that includes the stocking rate, the height of the pastures, and the grazing and regeneration periods. All adult animals receive mineral salt enhanced with protein. Additionally, lactating females receive mineral salt. The adult males get a concentrate and Mombasa silage during the final 90 days before reaching its mature LW.

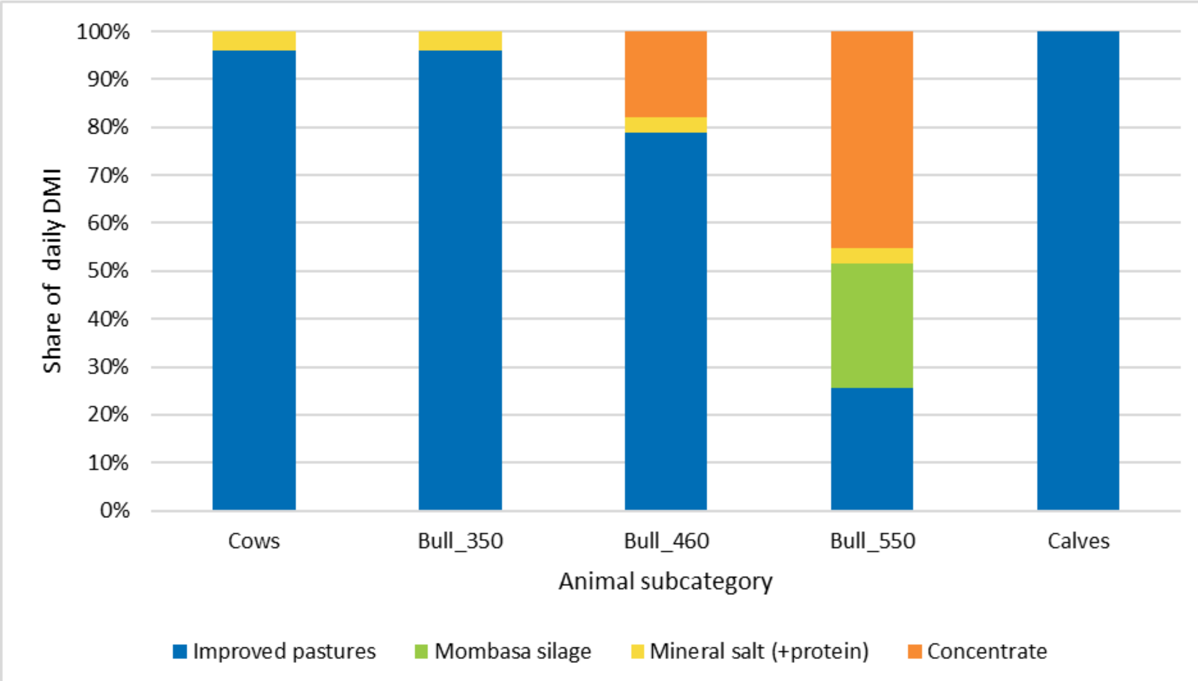


Figure 2.8. Share of daily dry matter intake (DMI) of the feed supplements by animal sub-category in HSJ.

The intake of feed supplements by animal sub-category is presented in Table 3.13. Figure 2.8 presents the share of the daily DMI by animal subcategory. The mineral salt is not shown because it has no nutritional value. Hence, it is not computed in the calculation of the DM, which is then used to calculate GE demand of the animals. The feed composition and datasets, including feed characterization used in the inventory are shown in Table 3.14 and Table 3.15, respectively.

Scenario matrix

A scenario matrix was designed based on the characteristics of HSJ, the already implemented management practices and the screening of potential mitigation practices. Table 2.5. presents ten descriptors and the corresponding information for the BL scenario. The variations made in the other scenarios are described directly in the "Results and discussion" section.

Table 2.5. Scenario matrix and characterization of the Base Line (BL) scenario

Descriptor	BL
Cattle breed	Short-cycle Nelore
Species of pastures	Improved pastures: *Urochloa humidicola* cv. Humidicola *Urochloa brizantha* cv. Marandú *Urochloa humidicola* cv. Llanero *Urochloa* hybrid cv. Cayman *Megathyrsus maximus* cv. Mombasa
Diet	Specific mix by animal sub-category of improved pastures, mineral salt, mineral salt (+protein) and concentrate
Grazing strategy	Rotational system
Savannah burning	No
Level of grassland management	Improved grassland
Woody species in grasslands	Variety of native trees and introduction of *Eucalyptus pellita*
Forest	Conservation
Electricity supply	Solar photovoltaic panels
Raw materials for feed supplements	Outsourced

Assessing cost-effectiveness of mitigation practices of explorative scenarios

In the scenario assessment, the relative costs of the establishment and maintenance of mitigation measures, and the quantities of GHG emissions that would be reduced after implementing these measures were calculated to build a marginal abatement cost curve (MACC). A MACC shows the cost per unit of CO_2, of emission abatement for varying amounts of emission reduction. The MACC contrasts the marginal abatement cost on the y-axis and the emission abatement level on the x-axis (Kesicki & Strachan, 2011). The GHG emissions reductions were estimated as the difference between the total GHG emissions of the BL scenario for the year 2023 and those under each scenario. The cost-effectiveness of the mitigation measures was estimated by dividing the costs of implementation and maintenance by the GHG emissions reductions.

Results and discussion

In this section, results of the BL scenario is presented first, followed by explorative scenarios.

Baseline scenario (BL)

Annual results

The results of the annual GHG emissions and removals, and the resulting CFP of the BL scenario are presented in Table 2.6 and Figure 2.9. Figure 2.9 shows additionally the GHG and CFP intensities by exported kg LW of HSJ.

Table 2.6. Annual greenhouse gas emissions and removals (t CO_2eq) in the BL scenario of HSJ.

Source/sink	2017	2018	2019	2020	2021	2022	2023
Enteric CH_4	4,349	5,789	5,196	4,668	3,425	4,130	7,479
Manure CH_4	58	79	70	63	47	56	102
Manure N_2O direct	107	144	129	117	70	89	160
Manure N_2O indirect	53	71	63	57	34	44	78
Feed supplements	680	834	821	503	319	442	712
Semen	0.5	0.5	0.2	0.2	0.3	0.4	0.5
Embryos	5	6	9	8	8	7	9
Animals imported	1,698	950	0	0	0	0	0
Soil management	1,366	48	48	48	48	48	48
Auxiliary services	2,002	144	144	335	389	389	389
Improved pastures (roots)	-20,683	0	0	-4,092	-16,443	-2,004	0
Soil organic carbon (SOC)	-11,338	-11,338	-11,338	-12,670	-18,024	-18,677	-18,677
Woody species in grasslands	-54	-54	-54	-701	-701	-701	-812
Total GHG emissions	10,319	8,065	6,481	5,799	4,340	5,205	8,977
Total GHG removals	-32,075	-11,392	-11,392	-17,463	-35,168	-21,381	-19,489
Total CFP	-21,757	-3,327	-4,911	-11,664	-30,828	-16,176	-10,512

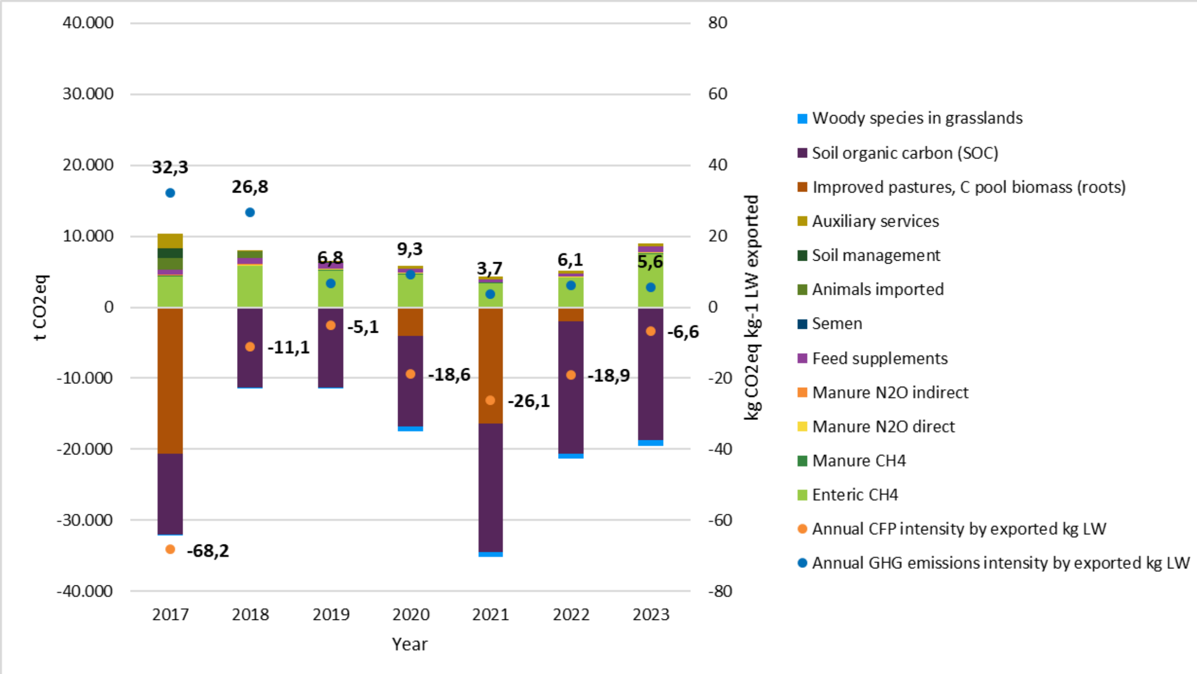


Figure 2.9. Primary y-axis: annual greenhouse gas (GHG) emissions and removals (t CO_2eq) in HSJ during 2017 - 2023. Secondary y-axis: annual GHG and carbon footprint (CFP) intensity by exported kg live weight (LW).

The annual GHG emissions and removals present high variations through the years. GHG emissions were due to:

i. Differences in livestock emissions because of the herd consolidation. The LW is doubled from 2017 to 2023.
ii. Imported animals in 2017 and 2018 supporting the establishment of the herd.
iii. High emissions in the soil management caused by the soil amendment.
iv. High emissions in the auxiliary services mainly from the construction of the three sheds.

Regarding GHG removals, the variations came from the C uptake in the below-ground biomass, i.e. the roots of the pastures plant species, which were computed during the year of introduction and expansion of pastures. A modest increase of GHG removals can be observed as C uptake in the woody species in grasslands, reflecting introduction of *Eucaplytus pellita* in 2020 and the native trees planned in 2023. The GHG and CFP intensities showed an important decrease from 2017 to 2023 produced by the fivefold increase of the exported LW of HSJ. It is expected that with the consolidation these figures achieve a constant level.

Table 2.7. Cumulative greenhouse gas emissions and removals (t CO_2eq) in the BL scenario of HSJ.

Source/sink	2017	2018	2019	2020	2021	2022	2023
Enteric CH_4	4,349	10,138	15,334	20,001	23,426	27,556	35,036
Manure CH_4	58	137	207	270	317	373	475
Manure N_2O direct	107	251	381	497	567	657	816
Manure N_2O indirect	53	123	186	244	278	322	400
Feed supplements	680	1,515	2,336	2,839	3,158	3,601	4,313
Semen	0.5	1	1	1	2	2	3
Embryos	5	11	20	28	36	43	52
Animals imported	1,698	2,648	2,648	2,648	2,648	2,648	2,648
Soil management	1,366	1,414	1,461	1,509	1,557	1,605	1,653
Auxiliary services	2,002	2,146	2,290	2,625	3,013	3,402	3,791
Improved pastures (roots)	-20,683	-20,683	-20,683	-24,774	-41,217	-43,221	-43,221
Soil organic carbon (SOC)	-11,338	-22,676	-34,014	-46,684	-64,708	-83,385	-102,062
Woody species in grasslands	-54	-109	-163	-864	-1,565	-2,266	-3,079
Total GHG emissions	10,319	18,383	24,864	30,663	35,003	40,208	49,186
Total GHG removals	-32,075	-43,467	-54,860	-72,323	-107,490	-128,872	-148,361
Total CFP	-21,757	-25,084	-29,995	-41,659	-72,488	-88,664	-99,175

Cumulative results 2017 - 2023

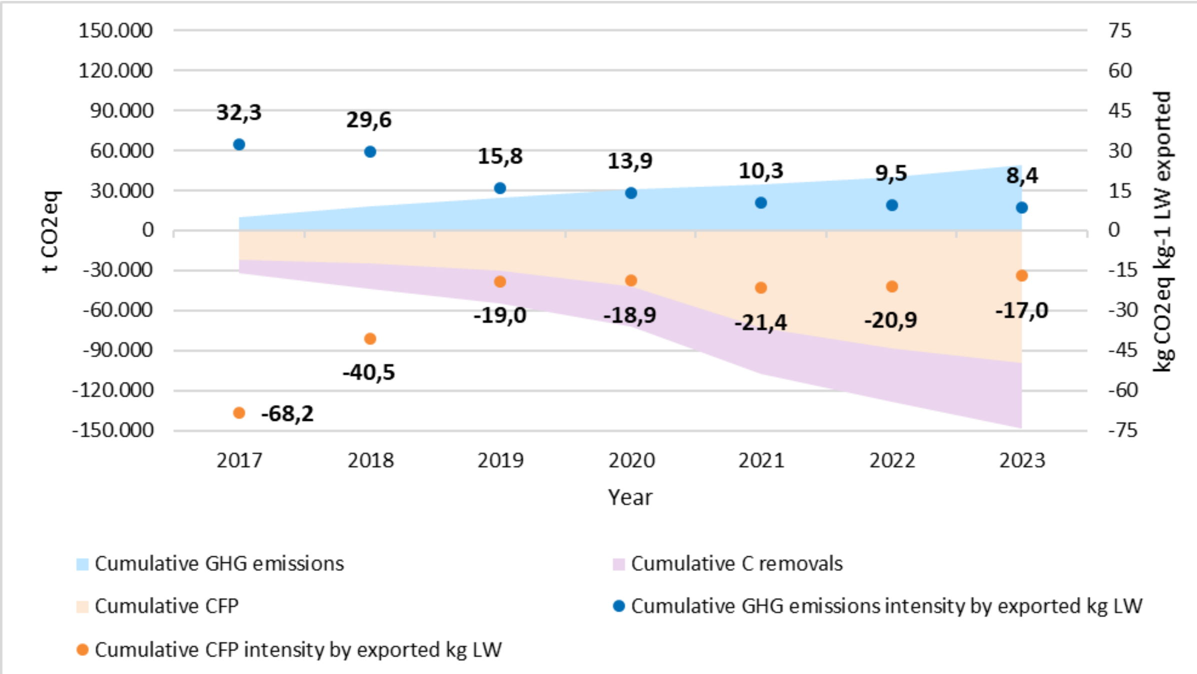


Figure 2.10. primary y-axis: cumulative greenhouse gas (GHG) emissions and removals (t CO_2eq) in HSJ during 2017-2023. Secondary y-axis: cumulative GHG and carbon footprint (CFP) intensity by exported kg live weight (LW).

In order to make the fluctuations relative, Table 2.7 and Figure 2.10 show the cumulative GHG emissions and removals, the resulting CFP of the BL scenario, and the corresponding GHG and CFP intensities by kg exported LW of HSJ. During the seven-year period, the total GHG emissions, removals and CFP account for approximately 49,186, -148,361 and -99,175 t CO_2eq. This means that HSJ has removed more C than GHG released to the atmosphere. However, it should be noted that while livestock emissions will increase constantly over time, GHG removals will achieve a new steady-state. The cumulative GHG and CFP intensity of the exported LW is 8.4 and -17.0 kg CO_2eq kg^{-1} LW exported.

Contribution analysis: GHG emissions

The cumulative contribution of the GHG emissions by source are presented in Figure 2.11.

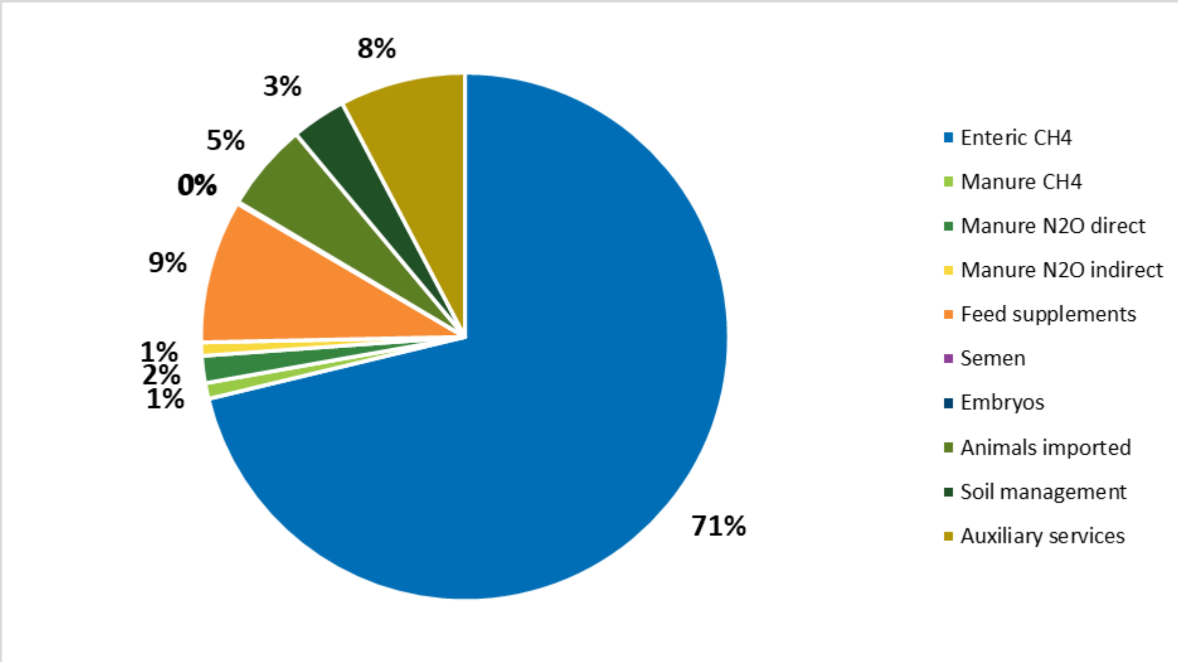


Figure 2.11. Share of cumulative contribution of the GHG emissions by source in the period 2017 to 2023.

As expected, the main contributor to the GHG emissions of HSJ is the enteric CH_4 with 71%. The manure GHG emissions together contribute 3.4%. Feed emissions constitute an important share with 9%, due to high emissions of soybean and maize. It has to be noted that datasets used might differ from the actual emissions occurring in Colombia, where raw materials are currently being purchased: soybean meal dataset comes from Brazil and that for maize comes from the rest of the world. The GHG emissions from the auxiliary services, with an 8% contribution, come mainly from the construction of three sheds and transport of the inputs such as raw materials for the feed supplements and fertilizers. Genetic resources, such as embryos and semen units contribute 0.1%.

Contribution analysis: GHG removals

The cumulative contribution of the GHG removals by sink are presented in Figure 2.12. With 102,062 t CO_2eq, SOC is the main contributor to the GHG removals in HSJ. This high C storage is highly influenced by the SOC reference in the HSJ site. The measurements undertaken in this study showed a value of 79.9 t C ha^{-1} for the 0-30 cm soil depth. This is almost 40% and 50% higher than the reference default value for this climate zone and soil type provided by the IPCC (52 ±6% t C ha^{-1}; IPCC, 2019) and FAO-GSP-Glo SIS Global (42.7

±5.8 t C ha^{-1} mean; 29.3 min - 56.2 max; FAO 2021). It is worth noting that after the assumed accumulation period of 20 years (IPCC default value) the system comes to a new equilibrium, meaning that possibly no additional C will be accumulated. After that it is unclear what will be the SOC dynamics: it might keep increasing, remain stable or even start decreasing. Further explanation on the results can be found in the section of Workstream 1 and the Info Note "Soil carbon stocks in tropical pasture systems in Colombia's Orinoquía region: supporting readiness for climate finance" (Villegas et al. 2021).

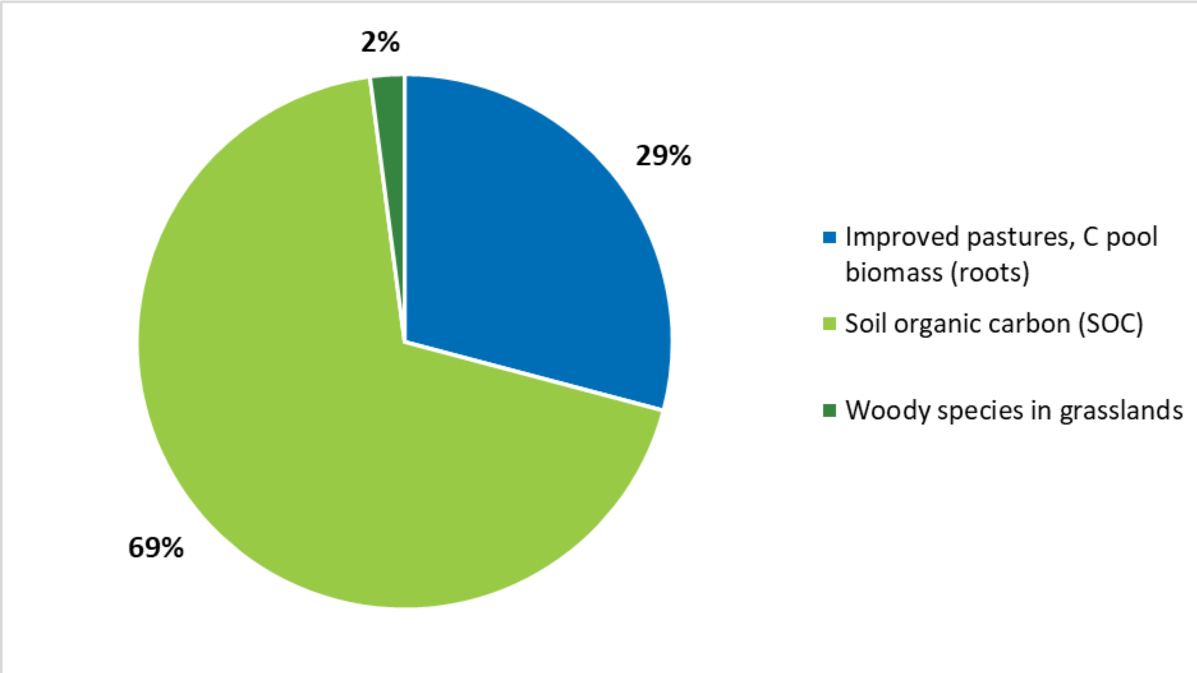


Figure 2.12. Share of cumulative contribution of the GHG removals by sink in the period 2017 to 2023.

Additional GHG removals occur in the pastures' roots (43,221 t CO_2eq) once they achieve their maximum growth potential. The woody species show a modest share of 2% to the GHG removals. The HSJ team observed good functionality of the introduced *Eucalyptus pellita*. This species captures approximately 8 times more CO_2 on an ha^{-1} yr^{-1} base than the native trees (IDEAM et al. 2018).

Effect of the reproductive parameters of the cattle breeds in HSJ

The breed short-cycle Nelore is characterized by earlier precocity, shorter reproductive cycles and higher daily LW gains (Table 2.4). Because the conventional calculation of the GHG intensity of cattle farms is based on annual figures as shown in the previous sections, the effect of this higher performance on the GHG emissions cannot be represented as it does not cover the complete life cycle of the animal (Figure 2.13).

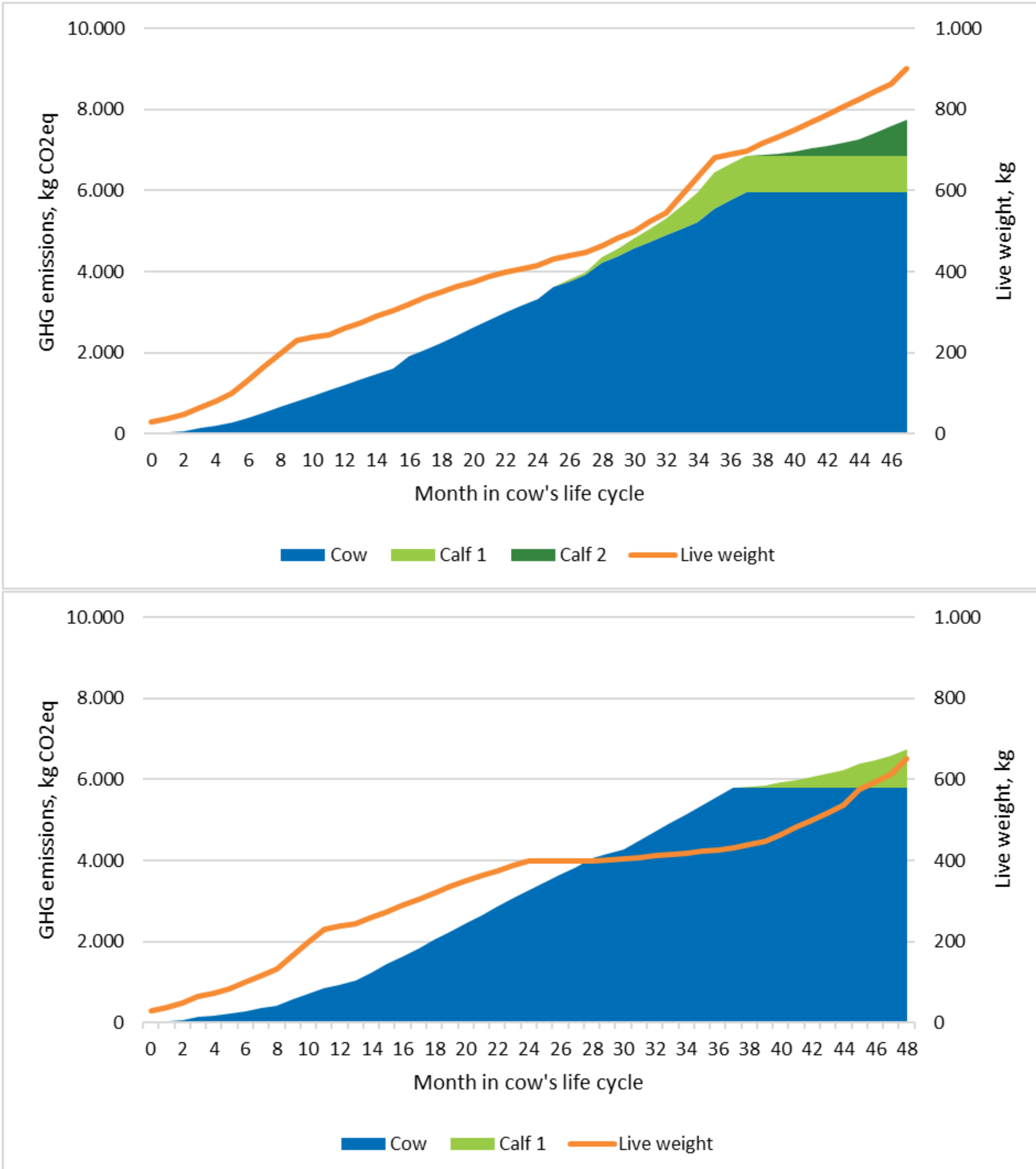


Figure 2.13. Life cycle of cows used to produce offspring for meat, emitted greenhouse gases (GHG) and produced live weight (LW). Up: short-cycle Nelore, down: Brahman.

Approximately in 46 months, the life cycle of a cow of the short-cycle Nelore breed produces 900 kg LW, namely two 250 kg calves and its own LW of 400 kg. At the same time, the Brahman produces 650 kg LW (one calf and its own LW) because it achieves precocity one year later. The total GHG emissions of the life cycle of the female Brahman and short-cycle Nelore account for approximately 6,742 kg CO_2eq and 7,740 kg CO_2eq, respectively. Due to the higher LW, the GHG intensity of the first is 10.4 kg CO_2eq kg^{-1} LW, i.e. 21% higher than the short-cycle Nelore (8.6 kg CO_2eq kg^{-1} LW).

Reference scenario (REF)

The reference scenario was a hypothetical cow-calf farm producing the same functional unit defined for the study: the annual production of the exported animal LW of HSJ, represented by the reference unit 1 kg LW during the period 2017 to 2023, as shown in Figure 2.4. Table 2.8 summarizes the characterization of the BL and REF scenarios of the study. A hypothetical reference farm was built selecting the conventional practices of those from the farms located in the department of Meta, in the Eastern plains of Colombia, a region near Vichada (Figure 2.14). The data was retrieved from the database of the Sustainable Colombian Cattle Ranching (GCS, Spanish initials) and the Livestock Plus (L+) projects (see details in Part 3 of the report, section "Detailed description of the farms for the REF scenario"). In the Meta department, the cow-calf farms are characterized by large natural open pastures, use of traditional-extensive grazing systems, low stocking rates, and diets based on native forages species with a small share of improved forages, leading to low productivity rates (González-Quintero et al. 2020, 2021).

Table 2.8. Characterization of the BL and REF scenarios

Descriptor	BL	REF
Cattle breed	Short-cycle Nelore	Cebu (Brahman) Cebu x Pardo Cebu x Creole
Species of pastures	Improved pastures: *Urochloa humidicola* cv. Humidicola *Urochloa brizantha* cv. Marandú *Urochloa humidicola* cv. Llanero *Urochloa* hybrid cv. Cayman *Megathyrsus maximus* cv. Mombasa	Native pasture Guaratara - *Axonopus purpusii*
Diet	Specific mix by animal sub-category of improved pastures, mineral salt, mineral salt (+protein) and concentrate	Native pasture Guaratara - *Axonopus purpusii,* and mineral salt
Grazing strategy	Rotational system	Large areas
Savannah burning	No	Yes
Level of grassland management	Improved grassland	Nominally managed (non–degraded)
Woody species in grasslands	Variety of native trees and introduction of *Eucalyptus pellita*	No
Forest	Conservation	No
Electricity supply	Solar photovoltaic panels	No
Raw materials for feed supplements	Outsourced	Outsourced

From the 2,618 farms surveyed by the GCS and L+ projects, 38 cow-calf farms from Meta department were identified and included in the reference scenario. To build this scenario, historical and projected LW produced per year by HSJ from 2017 to 2023 were considered. The current herd structure and daily LW gain of farms from Meta were kept constant, to identify how many animals per category would be required to produce the annual LW produced by HSJ from 2017 to 2023. Assumptions included the presence of Guaratara grass species in these farms and one burning event per year occurs in the whole grazing area. GHG emissions from animals and pastures were estimated considering the hypothetical animal numbers, LW gains, and grazing areas, as well as the bromatological characteristics of Guaratara (Corpoica 2018). For the reference scenario, total GHG emissions, emission intensities, and contributions of emissions by source were calculated as the average for the 38 farms.

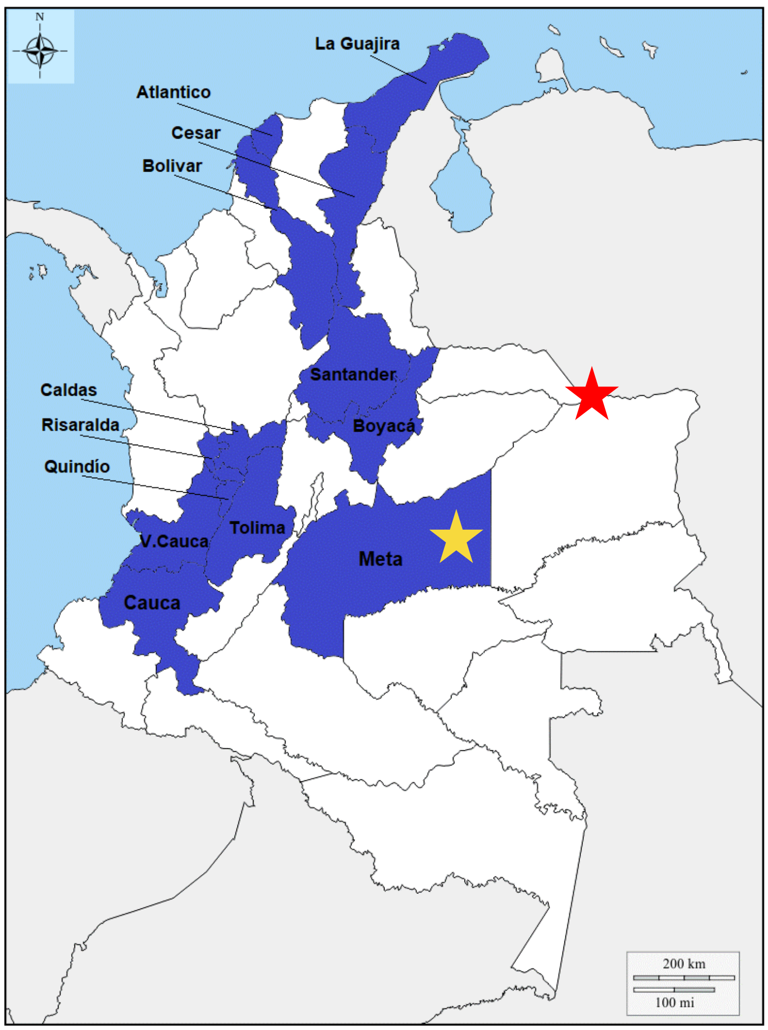


Figure 2.14. Departments where surveyed farms were located. The red star indicates the location of HSJ. The yellow star highlights the department from which the conventional practices for the REF scenario were taken.

Table 2.9 shows the total GHG emissions (t CO_2eq) generated by the reference farm for each year from 2017 to 2023. Variations in GHG emissions by year are directly correlated with variations of live weight production per year.

Table 2.9. cumulative greenhouse gas emissions and removals (t CO_2eq) of the BL vs. the REF scenario.

Source/sink	BL	REF	Delta, %
Enteric CH_4	35,036	43,994	↑ 26
Manure CH_4	475	555	↑ 17
Manure N_2O direct	816	652	↓ 20
Manure N_2O indirect	400	342	↓ 14
Feed supplements	4,313	1,004	↓ 77
Semen	3	n/a	
Embryos	52	n/a	
Animals imported	2,648	n/a	
Soil management	1,653	17,478	↑ 560
Auxiliary services	3,791	200	↓ 88
Improved pastures (roots)	-43,221	n/a	
Soil organic carbon (SOC)	-102,062	n/a	
Woody species in grasslands	-3,079	n/a	
Total GHG emissions	49,186	64,226	↑ 31
Total GHG removals	-148,361	0	
Total CFP	-99,175	64,226	↑ 165

n/a: not available, N.A. not applicable

The cumulative contribution of GHG emissions in the reference scenario for the period 2017 to 2023 by source is presented in Figure 2.15. Enteric CH_4 and manure deposited on pastures were primary sources contributing to total GHG emissions and 68% of cumulative emissions. CO_2 emission from burning ranked as the second source of emissions, contributing to 27%, while direct and indirect N_2O emissions from manure deposited on pastures, and secondary emissions from feed supplementation contributed to a lesser extent.

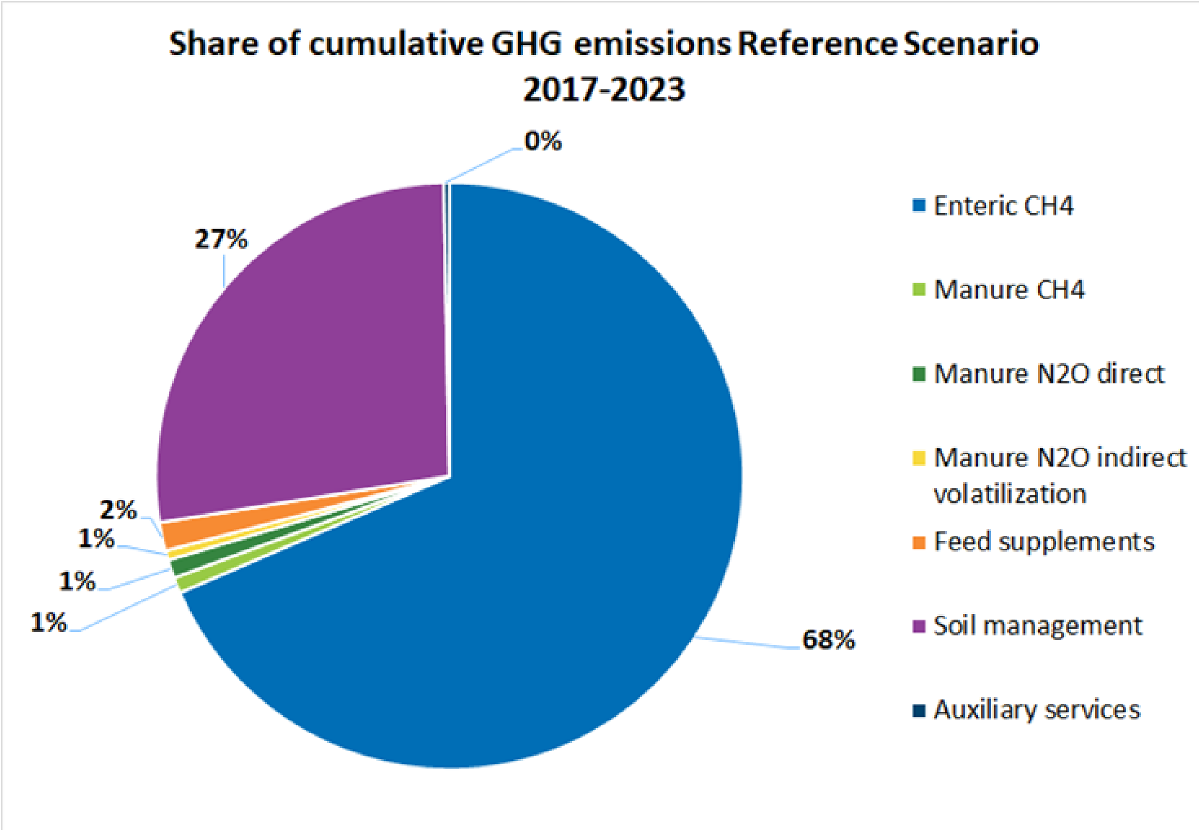


Figure 2.15. Share of cumulative GHG emissions Reference Scenario 2017-2023

Figure 2.16 shows the cumulative GHG emission intensities by exported kg LW (kg CO_2eq kg^{-1} LW exported) for the BL and REF reference scenario. The GHG emission intensity for the reference farm was higher than in HSJ, primarily influenced by the lower LW productivity, the higher % of unproductive animals in the herd, and the savannah burning. It was noted that the savannah burning can increase even more than the results shown in this study because according to the HSJ team, there might be two or three burning occurrences instead of one, as assumed in this study.

GHG removals do not take place in the reference farm as i) the highest share of the pastures are native savannahs and ii) animals graze in large areas.

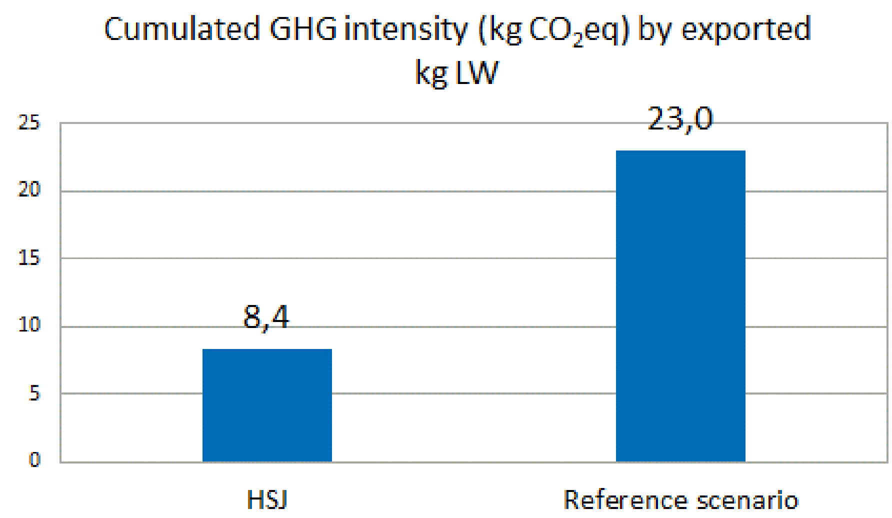


Figure 2.16. Cumulative GHG emission intensities (kgCO_2) by exported kg live weight for HSJ and the reference scenario

Explorative scenarios

Four explorative scenarios with further mitigation options were designed and compared with the BL scenario: i) supplementation of the feed additive 3-nitroxypropanol (3-NOP), ii) expansion of live fences (LF), iii) introduction of legumes (LEG), and iv) own maize production (SELF). Table 2.10 summarizes the characterization of the BL and the explorative scenarios of the study.

Table 2.10. Characterization of the BL and REF scenarios. Empty cells mean no changes compared to the BL scenario.

Scenario	BL	3-NOP		LF	LEG	SELF	
Descriptor	Level of adoption	1	2			1	2
Cattle breed	Short-cycle Nelore						
Species of pastures	Improved pastures: Humidicola, Marandú, Llanero, Cayman, Mombasa						
Diet	Specific mix by animal sub-category of improved pastures, mineral salt, mineral salt (+protein) and concentrate	All animals were simulated to consume a diet that contains 3-NOP at all life cycle stages	Only cows during the life cycle stages between 350 and 400 kg LW.				
Grazing strategy	Rotational system						
Savannah burning	No						
Level of grassland management	Improved grassland						
Woody species in grasslands	Variety of native trees and introduction of *Eucalyptus pellita*			Perimeter and internal fences	10% of area covered with Humidicola		
Forest	Conservation						
Electricity supply	Solar photovoltaic panels						
Raw materials for feed supplements	Outsourced					Own maize production	Intercropping of maize with Humidicola

BL: Baseline scenario; 3-NOP: 3-nitroxypropanol; LF: Live fences; LEG: legumes; SELF: Self-sufficiency. 1 and 2 are adoption levels of mitigation practices.

Enhanced diet (3-NOP)

The 3-NOP scenario was designed with the additive 3-nitroxypropanol (3-NOP, DSM Nutritional Products Ltd., Kaiseraugst, Switzerland). 3-NOP is a synthetic compound that inhibits an enzyme (Methyl-coenzyme Mreductase) crucial to the final step of CH_4 synthesis in the rumen (Duin et al. 2016). The feed additive 3-NOP has been shown to be an effective enteric CH_4 mitigant from high-forage fed beef cattle, with constant influences across studies regardless of animal species and diet composition (Dijkstra et al. 2018). 3-NOP was selected as a viable strategy for HSJ because of its high mitigation potential (about 30% of CH_4 emissions with no negative effects on DMI or LW gain) and due to its feasibility for adoption in HSJ. Recently, 3-NOP – under the commercial name Bovaer - was approved in Latin American countries such as Brazil and Chile. Following conversations with the provider, it is anticipated that 3-NOP will also soon be commercially available in Colombia. In discussions with the HSJ team, they expressed their interest in testing the additive.

Two levels of adoption were suggested: in level 1, all animals were simulated to consume a diet that contains 3-NOP at all life cycle stages for 2023, whilst in level 2, all short-cycle Nelore cows were simulated to consume a diet that contains 3-NOP only during the life cycle stages between 350 and 400 kg LW. The basal diets were the same as in the BL and 3-NOP was supplemented at a rate of 100 mg kg^{-1} DM in both levels of adoption. The indirect GHG emissions related to production and transport of 3-NOP were assumed to be 47.9 kg CO_2eq kg^{-1} (Alvarez-Hess et al. 2019).

Table 2.11 shows the total GHG emissions and removals for the BL and 3-NOP scenarios for the year 2023.

Table 2.11. Annual greenhouse gas emissions and removals (t CO_2eq) of the BL vs. the 3-NOP scenario for the year 2023.

Source/sink	BL	3-NOP_1	Delta, %	3-NOP_2	Delta, %
Enteric CH_4	7,479	5,236	↓ 30	5,642	↓ 25
Manure CH_4	102	102		102	
Manure N_2O direct	160	160		160	
Manure N_2O indirect	78	78		78	
Feed supplements	712	768	↑ 8	758	↑ 6
Semen	0.5	0.5		0.5	
Embryos	9	9		9	
Animals imported	0	0		0	
Soil management	48	48		48	
Auxiliary services	389	389		389	
Improved pastures (roots)	0	0		0	
Soil organic carbon (SOC)	-18,677	-18,677		-18,677	
Woody species in grasslands	-812	-812		-812	
Total GHG emissions	8,977	6,790	↓ 24	7,186	↓ 20
Total GHG removals	-19,489	-19,489		-19,489	
Total CFP	-10,512	-12,700	↓ 21	-12,303	↓ 17
GHG intensity, kg CO_2eq kg^{-1} LW exported	5.6	4.2	↓ 24	4.5	↓ 20
CFP intensity, kg CO_2eq kg^{-1} LW exported	-6.6	-7.9	↓ 21	-7.7	↓ 17

Main assumption: Supplementation with 3-NOP, will decrease by 30% with no negative effects on DMI or ADG. The scenarios with 3-NOP include indirect carbon dioxide emissions from the production and transport of 47.9kg CO_2eq kg as suggested by (Alvarez-Hess et al. 2019).

The total annual GHG emissions from BL, 3-NOP levels 1 and 2 were 8,977, 6,790, and 7,186 t CO_2eq, respectively, with percentage reduction of total GHG emissions for level one and two were 24 and 20%. The main changes seen upon adoption of this scenario were reflected in enteric CH_4 and feed supplements emissions. Enteric CH_4 emissions were calculated at 5,236 and 5,642 t CO_2eq for the 3-NOP level of adoption 1 and 2. 3-NOP supplementation showed a reduction of CH_4 emissions by 30 and 25% (levels 1 and 2 respectively) compared to BL, due to the inhibition effect of 3-NOP on CH_4 production.

Using 3-NOP for all animals (whole herd) at all growing stages only reduced 5% more compared to limiting 3-NOP supplementation to short-cycle Nelore cows during the life cycle stages between 350 and 400 kg LW. The slight change in mitigation effect of CH_4 emissions of level 1 compared to level 2 was due to cows between 350 and 450 kg LW representing most of the population. Supplementing this specific group of animals in HSJ by 2023 could have a similar effect as to supplementing the whole herd.

Finally, the total CFP associated with 3-NOP supplementation for levels 1 and 2 were -12,700 and -12,303 t CO_2eq, which was a change of 21% and 17% compared to their BL. By feeding 3-NOP both whole herd or only the short-cycle Nelore cows between 350 and 400 kg LW), the total CFP of HSJ could be reduced.

Live fences (LF)

Live fences is a non-intensive silvopastoral system using lines of trees instead of dead posts to support barbed or electrified wire on paddock boundaries and divisions. Among benefits, species used as LF could capture and fix N into the soil, have CH_4 reduction factors, ecosystem services and store more C in the soils. This practice also improves animal welfare since it provides shade and rest areas for livestock.

Based on previous discussions with the HSJ team, areas where LF can be built were delimited. Its northern and southern limits already have existing living barriers. It has been suggested to construct LF in a manner that it connects ecosystems through corridors (Figure 2.17).

Figure 2.17. Geographical representation of the intervention with perimeter and internal live fences. Where the solid red line is the external boundary of the HSJ and the dotted yellow lines are the location of the live fences.

According to the GIS analysis and the specifications received, this practice has an intervention potential of approximately 51.04 km, which would result to mitigation of approximately 12.8 t CO_2eq yr^{-1}, attributed to the GHG sink "Woody species in grasslands" (Table 2.12).

Table 2.12. Annual greenhouse gas emissions and removals (t CO_2eq) of the BL vs. the LF scenario for the year 2023.

Source/sink	BL	LF	Delta, %
Enteric CH_4	7,479	7,479	
Manure CH_4	102	102	
Manure N_2O direct	160	160	
Manure N_2O indirect	78	78	
Feed supplements	712	712	
Semen	0.5	0.5	
Embryos	9	9	
Animals imported	0	0	
Soil management	48	48	
Auxiliary services	389	389	
Improved pastures (roots)	0	0	
Soil organic carbon (SOC)	-18,677	-18,677	
Woody species in grasslands	-812	-825	↓ 2
Total GHG emissions	8,977	6,790	
Total GHG removals	-19,489	-19,502	↓ 0.1
Total CFP	-10,512	-10,525	↓ 0.1
GHG intensity, kg CO_2eq kg^{-1} LW exported	5.6	4.2	
CFP intensity, kg CO_2eq kg^{-1} LW exported	-6.6	-7.9	↓ 0.1

The most suitable species for the construction of live fences will be Eucalipto (*Eucalyptus pellita*), Caña fisto (*Cassia fistula*), Yopo (*Anadenanthera sp*.), Simarua (*Simarouba sp*.), Melina (*Gmelina arborea*) (Figure 2.18). HSJ expressed interest in testing this mitigation practice with the Melina (*Gmelina arborea*) species.

a b

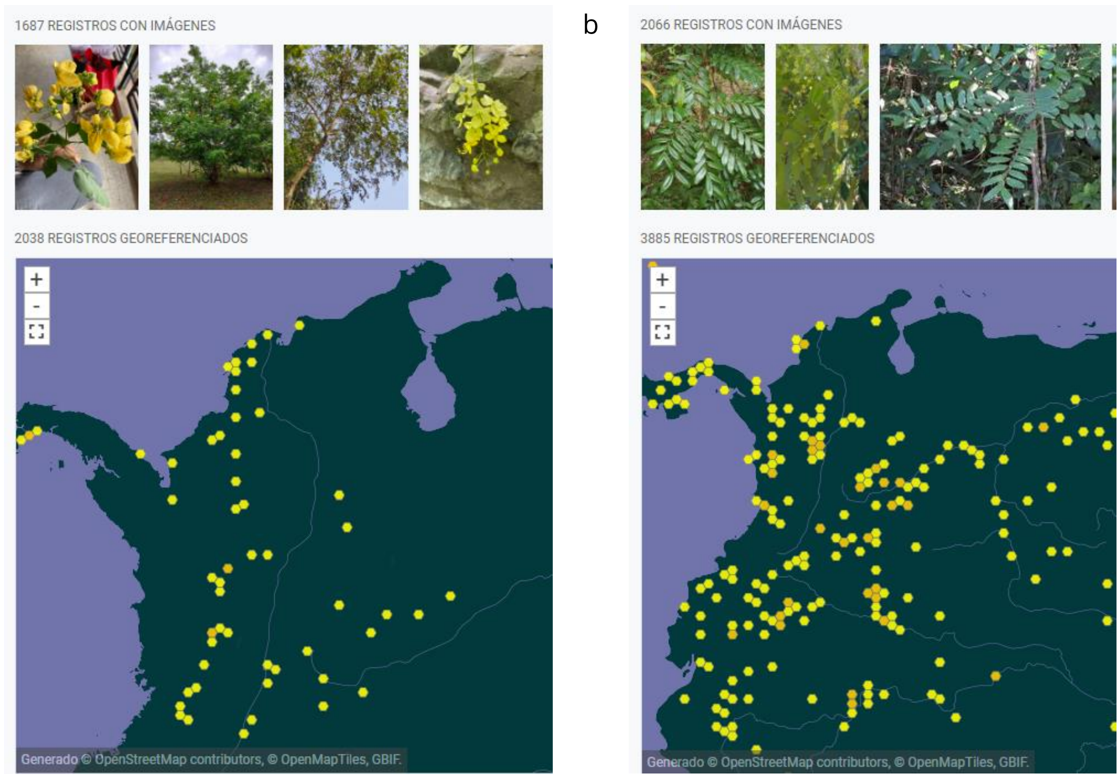


Figure 2.18. Points of presence of potential species usable as live fences. (a) Cassia fistula; (b) Simarouba sp. Source: Global Biodiversity Information Facility (GBIF).

Legumes (LEG)

Implementation of legume species could provide a wide range of adaptation to soil fertility and humidity conditions. Other benefits include a high resistance to pests and diseases, high digestible protein content, good palatability, economic returns (Enciso-Valencia et al. 2021) and a promissory potential to mitigate GHG emissions. Different studies have shown the importance of including legumes in the livestock diet; Rincón et al. (2021) quantified 50% more crude protein from diets based on grass-legume association, in comparison to those based on grass monoculture. Additionally, Pereira et al. (2019) showed that a mixed pasture of *A. pintoi* with Marandu grass promoted a beef cattle production equivalent to, or better than, the grass monoculture with fertilization of 120 kg N ha^{-1}. Moreover, Dubeux Jr et al. (2017) observed a significant biological N fixation among cultivars of *A. pintoi.* All these studies place the *A. pintoi* species as an alternative which - not only improves animal productivity but also mitigates GHG emissions. The results of the LEG scenario - by planting in an area corresponding to 10% of the *Urochloa humidicola* crop, are shown in Table 2.13.

Table 2.13. Annual greenhouse gas emissions and removals (t CO_2eq) of the BL vs. the LEG scenario for the year 2023.

Source/sink	BL	LEG	Delta, %
Enteric CH_4	7,479	7,444	↓ 0.5
Manure CH_4	102	102	
Manure N_2O direct	160	160	
Manure N_2O indirect	78	78	
Feed supplements	712	712	
Semen	0.5	0.5	
Embryos	9	9	
Animals imported	0	0	
Soil management	48	48	
Auxiliary services	389	389	
Improved pastures (roots)	0	-4,282	↓
Soil organic carbon (SOC)	-18,677	-20,577	↓ 10
Woody species in grasslands	-812	-812	
Total GHG emissions	8,977	8,941	
Total GHG removals	-19,489	-25,678	↓ 32
Total CFP	-10,512	-16,736	↓ 59
GHG intensity, kg CO_2eq kg^{-1} LW exported	5.61	5.59	↓ 0.4
CFP intensity, kg CO_2eq kg^{-1} LW exported	-6.6	-10.5	↓ 59

Results showed that enteric CH_4 emissions decrease due to the consumption of the legume by the animals. The major mitigation contribution can be attributed to growth of the roots and the roots turnover which leads to accumulation of SOC. Overall the reduction of the total GHG removals in the year 2023 would be 32%. As a consequence, the CFP and CFP intensity decreases by 59%.

The most suitable species for implementation of legumes will be *Arachis pintoi* due to its adaptability and suitability in the region where HSJ is located (Figure 2.19). HSJ is keen to explore this mitigation practice and introduce in their farm.

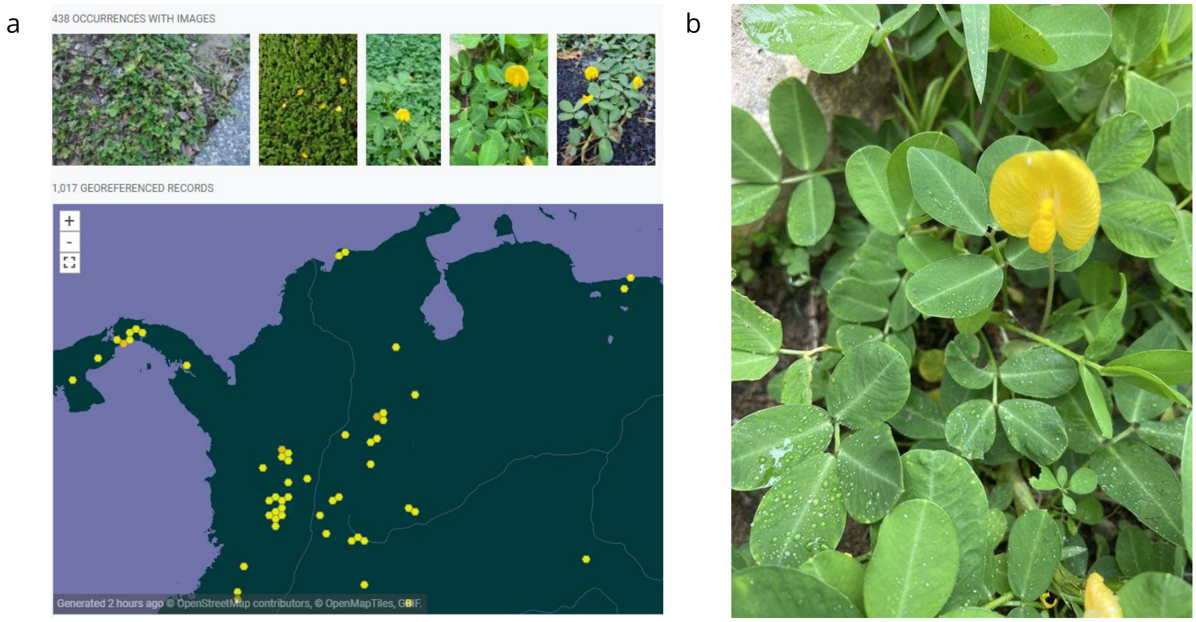


Figure 2.19. (a) points of presence of *A. pintoi* in Colombia; this distribution includes the east plains where HSJ is located. Source: Global Biodiversity Information Facility (GBIF). (b) *Arachis pintoi.*

Self-sufficiency (SELF)

HSJ planted approximately 30 ha of maize, to prepare cattle feed supplements. This constitutes level 1 of the scenario SELF (Table 2.14).

Previous research projects at CIAT have demonstrated that the integration of *Urochloa* pastures in the cropping system may deliver benefits at the productive and environmental level (Karwat et al. 2017). In a research station in the Orinoquia region, N use efficiency of maize was two-fold greater in a rotation system of maize with *U. humidicola,* in comparison to continuous maize cultivation. The need for N fertilization was reduced by half in the rotation. Additionally, experiences in Brazil showed that intercropping maize with *Urochloa* pastures (both grass and crop components occurring at the same time) have yielded results in GHG reduction.

For the level 2 of the SELF scenario, an intercropping system will be considered. Planting maize requires high amounts of soil amendments and the HSJ team remarked that they do not intend to repeat this operation. However, they showed interest in testing the intercropping.

Table 2.14. Annual greenhouse gas emissions and removals (t CO_2eq) of the BL vs. the LEG scenario for the year 2023.

Source/sink	BL	SELF_1	Delta, %	SELF_2	Delta, %
Enteric CH_4	7,479	7,479		7,479	
Manure CH_4	102	102		102	
Manure N_2O direct	160	160		160	
Manure N_2O indirect	78	78		78	
Feed supplements	712	862	↑ 21	773	↑ 8
Semen	0.5	0.5		0.5	
Embryos	9	9		9	
Animals imported	0	0		0	
Soil management	48	48		48	
Auxiliary services	389	351	↓ 10	351	↓ 10
Improved pastures (roots)	0	0		0	
Soil organic carbon (SOC)	-18,677	-18,677		-18,677	
Woody species in grasslands	-812	-812		-812	
Total GHG emissions	8,977	9,089	↑ 1	9,001	↑ 0.3
Total GHG removals	-19,489	-19,489		-19,489	
Total CFP	-10,512	-10,400	↑ 1	-10,488	↑ 0.2
GHG intensity, kg CO_2eq kg^{-1} LW exported	5.61	5.68	↑ 1	5.62	↑ 0.3
CFP intensity, kg CO_2eq kg^{-1} LW exported	-6.57	-6.50	↑ 1	-6.55	↑ 0.2

GHG emissions from "Feed supplements" increased by 21% in the scenario level SELF_1 due to the amendments needed to prepare the soil for the maize. Auxiliary services decreased by 10% as transportation of maize to HSJ was reduced. Overall, the GHG emissions and CFP for the year 2023 increased by 1% compared to the BL scenario.

For scenario level SELF_2, the GHG emissions of the feed supplements can be reduced compared to the SELF_1, using the observations of Canisares et al. (2021). They showed that the specific EF for direct N_2O emissions can be reduced by 18% in tropical maize production through intercropping of maize with Humidicola. The results were very similar to the BL scenario, suggesting that by intercropping Humidicola with maize, additional GHG emissions produced due to the application of amendments can be offset in one year. Furthermore, specific GHG emissions of the production of 1 kg maize decrease from 1.22

to 1.07 kg CO_2eq because the maize yield can increase 10%, i.e. from 150,000 to 165,000 kg yr^{-1}. Further trials can be performed to estimate potential decrease in N-fertilizer demand.

Assessing cost-effectiveness of mitigation practices of explorative scenarios

The analyses showed the possibility to understand important differences between scenarios (annual climate impact for the year 2023): both in mitigation potential and in costs per unit of C abated. However, it is necessary to clarify that the analysis does not judge the analyzed practice. Rather - the proposed scenarios according to their implementation potential and system conditions. Under different scenarios, one mitigation practice may be less or more effective than another and its particular results cannot be generalized.

Introduction of legumes (LEG) showed the highest mitigation capacity, representing the highest cost-effectiveness (green column in Figure 2.20) at an investment of $141 per ton CO_2eq and a mitigation potential close to 632 ton CO_2eq. Secondly, the introduction of 3-NOP to the whole herd scenario (yellow column) presented an important mitigation capacity, but at a higher cost per unit of C ($183 per ton CO_2eq and a mitigation potential close to 225 ton CO_2eq).

It should be noted that some mitigation practices require a higher initial investment than others and subsequent maintenance costs, e.g. the LEG scenario will require a high investment cost and lower maintenance costs. However, the 3-NOP scenario will always require the same annual investment. This suggests that medium and long term assessments should be made achieve the most cost-effective scenario.

Establishment of live fences had a low performance in both mitigation and cost-effectiveness (blue column) ($220 per ton CO_2eq and less than 1 ton of CO_2eq) as the layout where they can be established is not significant compared to HSJ's area. It is important to consider larger areas for this practice in order to reach a high potential and achieve multiple benefits such as animal welfare and forest by-products, etc.

SELF scenarios - *Own maize production* and *intercropping of maize with humidicola* demonstrated to have resulted to an opposite effect compared to what was expected from a mitigation scenario. These two scenarios indicated negative mitigation values and the highest abatement costs, compared to all evaluated scenarios. The first one would require an investment of $257 per ton CO_2eq and the second one of $127; both with no potential to mitigate under the modelled conditions.

This does not mean that these scenarios should be eliminated. However it is recommended that new levels of intervention be assessed. Additionally, these scenarios may bring co-benefits that may not have been included in the present analysis.

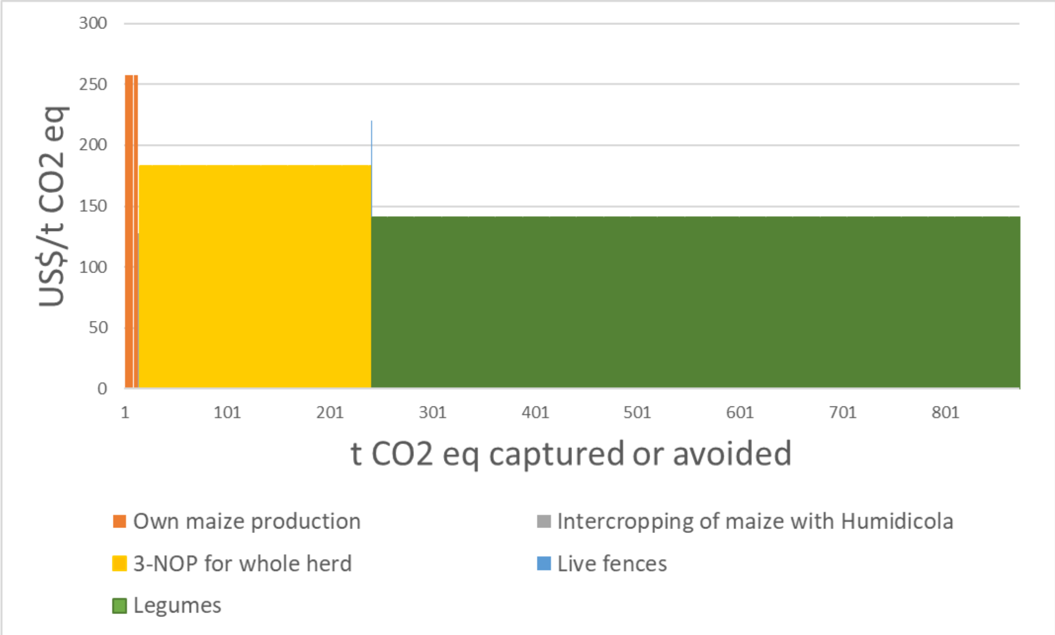


Figure 2.20. Cost-effectiveness of the technologies evaluated in the explorative scenarios.

Part 3: Description of activities, methods, and data within the workstreams of the study

Workstream 1: Soil organic carbon (SOC) analyses

The main objectives of WS 1 were to measure the reference SOC stocks in the native savannahs of HSJ, to assess SOC change over time from introduction of improved pastures in the grazing area, and to explore the simulation of soil C dynamics. The planned tasks and their current status are shown in Table 3.1.

Table 3.1. Description and status as of December 20, 2021 of the tasks in WS1

Task	Description	Status
1.1	Identification of study sites and definition of sampling units (plots and pits), which should be representative of the whole pasture area of HSJ in terms of topography, drainage, and management	Finished
1.2	Excavation of soil pits up to 100 cm and soil sampling at different depths in native and improved pasture following	Finished
1.3	Analysis of SOC by dry combustion method, and physical-chemical characterization of soils at CIAT and UC Davis laboratories	Finished
1.4	Calculation of soil C stocks in each pasture type and determination of the level of improvement due to management	Finished
1.5	Evaluation of suitable models for simulation of soil C dynamics. Assessment of the dataset generated. Simulation of SOC-N dynamics over changing climate and management scenarios.	Finished

The research results of the tasks 1.1 to 1.4 are described below. Findings have also been reported in the CCAFS Info Note[2], "*Soil carbon stocks in pasture systems in Colombia's Orinoquia region: supporting readiness for climate finance*", which can be accessed here: hdl.handle.net/10568/116231.

[2]This info note is not peer-reviewed brief reports on interim research results fostered by the CGIAR research program on climate change, agriculture, and food security (CCAFS). They do not express the opinion of the donors and are used for communication purposes only. They are hosted in the public CGIAR repository (CGSPACE) with a permanent link under copyright license.

Box 3.1. Key findings from the assessment of soil carbon stocks in pasture systems in Hacienda San José

- Using field measurements, it has been observed that pastures in clay soils in HSJ can store more than 200 t C ha^{-1} (0-100 cm), indicating 40% higher storage capacity than IPCC default values (0-30cm).
- Close to 30% of the total SOC stock were found in the top 0-20 cm soil layer, highlighting the importance of analyzing deeper soil layers in SOC assessments.
- Improving pasture systems have the potential to accumulate SOC, especially in the topsoil layer. This may be a consequence of higher forage production in improved pastures and cattle waste depositions.
- Clay soils in HSJ demonstrated a huge potential for SOC sequestration through pasture improvement (~2.0 t C ha^{-1} yr^{-1}; 0-20 cm). This rate should be reduced overtime once SOC stocks approach a new steady-state. Therefore, future monitoring is critical to validate findings and better understand SOC changes in the region.

Methods

Soil sampling and analysis

In August 2021, soil was sampled at HSJ in two pasture areas: unmanaged native savannah (NS) and improved pasture (IP), and used a completely randomized design (n=5) for the quantification of total organic carbon, bulk density (BD), and chemical and physical characteristics. These two pasture areas (NS and IP) were located in close proximity (next to each other) and presented similar topographic and edapho-climatic conditions. The IP area was introduced 6.5 years ago (2015) through conversion of the same native savannah into *U. humidicola*. These areas represented a chronosequence, in which NS preceded IP in a land use succession (Table 3.2).

Table 3.2. Location and characteristics of native savannah (NS) and improved pasture (IP) soil sampling sites at HSJ, Colombia.

	Native Savannah (NS) 	Improved Pasture (IP) 
Location	Orinoco region (Orinoquia), La Primavera, Colombia	
Lat/Lon	5°54’52.48” N 69°37’12.54” W	
Climate classification	The climate zone defined by the IPCC (2006a) is “Tropical, wet”.	
Soil characteristics(0-20cm)	Order: Ultisols and Oxisols (IGAC 2012); pH: 4.5; Texture: Silty clay loam (8% Sand, 55% Silt, 37% Clay) “Low activity clay (IPCC 2006a)”; Organic matter: 43.8 g kg^{-1}; BrayII-P: 1.3 mg kg^{-1}; Al: 2.9 cmol kg^{-1}	
Pasture details	The unmanaged native savannah (NS) in which the research was carried out has been free of burning and cattle grazing for more than 7 years.	The improved pasture (IP) of *U. humidicola* was established in 2015 (~6.5 years ago). Rotationally grazed with cattle at approximately 1 head per hectare.

In both pasture areas (NS and IP), soil samples were collected from five trenches (replicates; n=5) which were arranged in a random transect along the pasture area, ~250-400 meters apart from each other. Soil samples were collected at 0–5, 5–20, 20–60 and 60–100 cm soil depth. In each sampling location and soil depth, two sub-samples were collected on two sides of the trench, which were further analysed and combined to account for SOC spatial variability. A total of 40 soil samples per area were collected. Samples from the 5–20, 20–60 and 60–100 cm soil layers were taken from the middle part of the corresponding soil layer.

Soil samples were air-dried and then sieved at 2 mm. From each sample, 10 g were ground and sieved at 0.25 mm for determination of total C content that was determined by dry combustion through a Carbon Analyzer - LECO CN-2000. For the determination of soil BD, samples of undisturbed areas were collected using a steel cylinder (5 x 5 cm) for subsequent evaluation of dry soil weight (at 110 °C) and determination of soil BD.

The soil sampling approach used in this work has been applied in several agricultural SOC assessments (e.g., Carvalho et al. 2010; Costa Jr et al. 2013). For a more in-depth examination of changes, defining the number of samples may require pre-analysis of the SOC variation of the area (World Bank 2021b). Although this condition is not always possible due to time and financial constraints, it is recommended to be pursued in future assessments.

Soil C stock calculation

For each soil layer, the study calculated C stocks by multiplying the concentration of the soil C (g kg-1) by soil density (g cm^{-3}) and soil layer thickness (cm). As samples were collected from fixed layers, the stock calculation needed to be adjusted for variations in BD after the conversion of NS (reference area) into IP. The methodology described in Ellert and Bettany (1996) was used to adjust soil C stocks to an equivalent soil mass. For that, the depth of the IP area was adjusted for the same soil mass as the corresponding layer (0–100cm) in the NS.

Statistical analysis

Statistical data analyses were processed with consideration to a completely randomized design with five pseudo-replicates in each evaluated area. The use of pseudo-replicates is a procedure commonly applied in ecological studies. It is described in detail by Hurlbert (1984). Two-way Analysis of variance (ANOVA) was applied to the results regarding SOC stocks whereby pasture type and soil depth were considered as fixed factors. The Tukey HSD test ($\alpha = 0.05$) was applied to the comparison of mean values between the areas evaluated in each case study. All statistical analyses were processed using the "r-companion" package of the R software.

Results and discussion

Soil bulk density, carbon content and carbon stocks

Both NS and IP areas showed the same pattern of soil C distribution over different soil layers. The highest soil C content was found in the upper 0–5 cm soil layer with a decrease in the deeper layers. These values were higher under IP compared to NS. Soil BD showed an opposite trend, with results showing an increase with soil depth and a decrease under IP compared to NS (Figure 3.1).

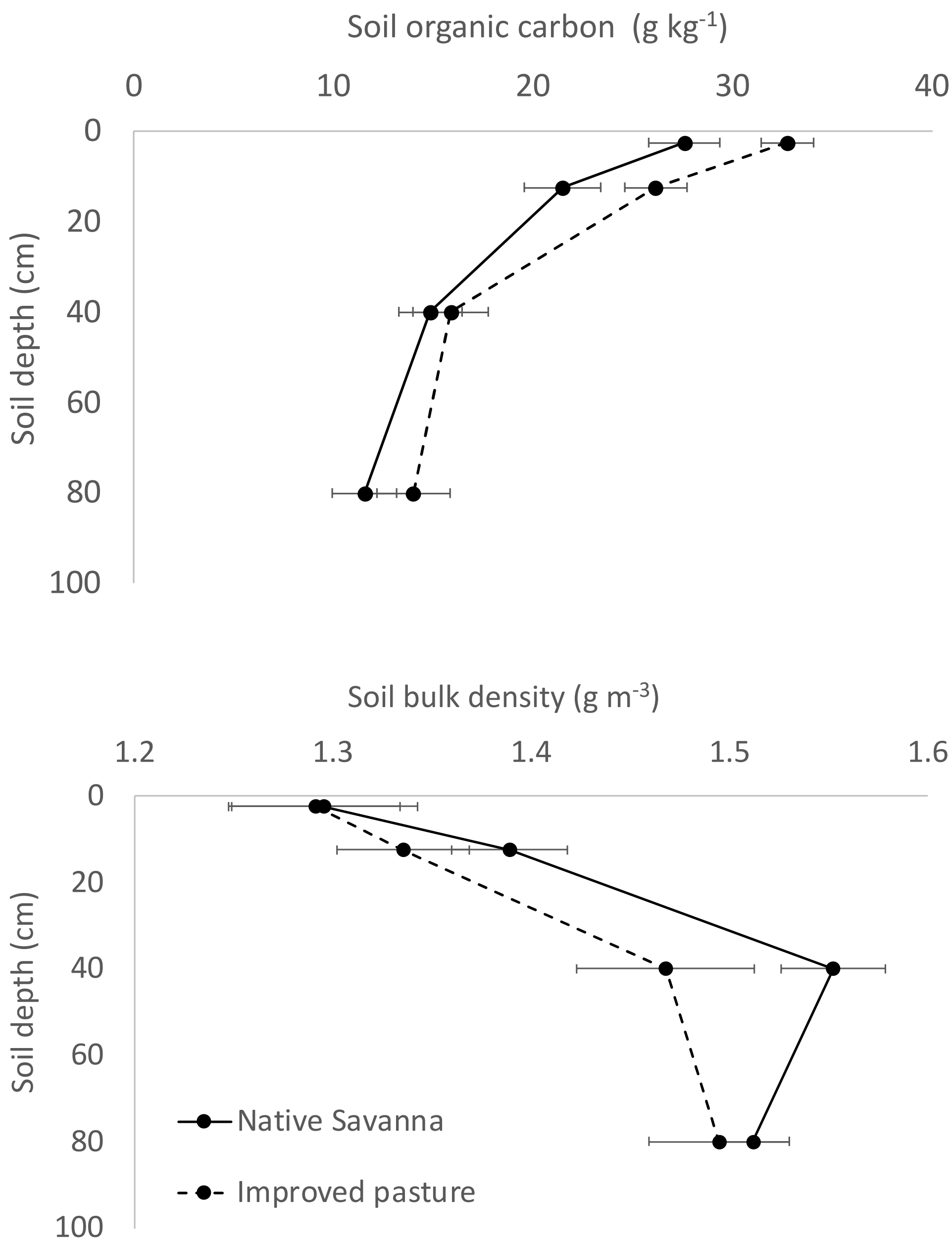


Figure 3.1. Soil carbon content (g kg^{-1}) and soil bulk density (g cm^{-3}) of soil layers in HSJ.

The estimated total SOC stocks of the 0-100 cm layer were 224.8 and 259.0 t C ha^{-1} for the NS and IP, respectively (Figure 3.2). In both NS and IP areas, close to 10% and 30% of the total SOC stock (0-100 cm) concentrated in the top 0-5 cm and 0-20 cm soil layers, (Figure 3.2). The SOC stock (0-100 cm) was 15% higher in IP compared to the NS. However, significant differences were only found in the upper layers, 0–5 and 0-20 cm. Differences between treatments suggested an accumulation of 3.3 and 13.1 t C ha^{-1} or 0.5 and 2.0 t C ha^{-1} yr^{-1} in the 0–5 and 0-20 cm soil depths, respectively, over ~6.5 years.

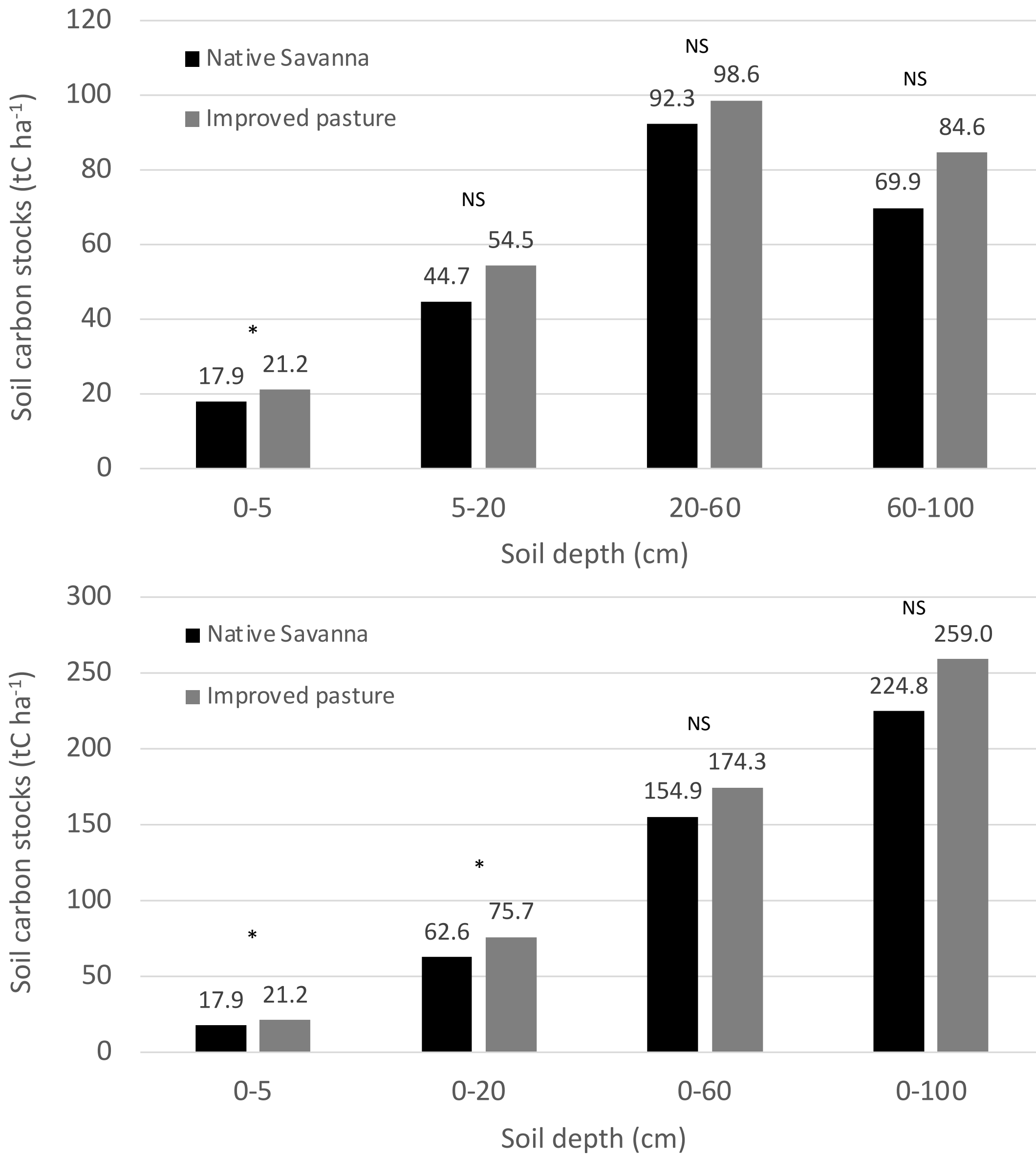


Figure 3.2. Soil carbon stocks (t C ha^{-1}) of soil layers in HSJ. Asterisk (*) represent significant differences according to the Tukey test at 5% level. 'ns' represent no significant differences.

The introduction of *U. humidicola* in previous NS areas impacted SOC accumulation and soil quality of the improved pasture area through its abundant root system and its turnover, further influenced by pasture productivity and management (i.e., rotational grazing). Field evaluations at HSJ show that forage DM production in IP is 14% higher annually than NS (7.2 vs. 6.3 t DM ha^{-1} yr^{-1}) and almost 8 times higher in the dry season (2.5 vs. 0.3 t DM ha^{-1}) compared to the published values for native savannah vegetation. The higher plant biomass productivity in IP, together with the introduction of grazing animals depositing urine and dung have likely increased the deposition of organic residues, especially on the soil surface, with subsequent percolation into the soil profile.

It is highly likely that significant changes in SOC stocks will occur in deeper soil layers in the coming years (below 20 cm soil depth) if the current management continues or improves. Otherwise, accumulated SOC could decline over time in the absence of adequate management (Costa et al. 2022; Fisher et al. 2007).

Comparison with other studies

The magnitude of C stocks found in this work (>200 t C ha^{-1}) was higher compared to other studies for the same land use, management and soil depth (0-100 cm). For example, Fisher et al. (1994) measured approximately 200 t C ha^{-1} researching in the same region as this work; Corazza et al. (1999) found 150 Mg C ha^{-1} in soils cultivated with *Brachiaria decumbens* pasture in the Brazilian savannah; and Battle-Bayer et al. (2010) reported SOC stocks of 123- 209 t C ha^{-1} in different types of Brazilian savannahs.

The rates of SOC accumulation (~2.0 t C ha^{-1} yr^{-1} for the 0-20 cm and ~5.5 t C ha^{-1} yr^{-1} for the 0-100 cm), were also in the high-end values found in the literature (e.g Fisher et al. 1994 and others), including those in the Orinoquia region. Variation may be attributed to differences in soil texture, pasture management, forage grass type and time of implementation as well as soil sampling design and SOC stock calculation (e.g., correction for the same soil mass).

After ~7 years of *U. humidicola* implementation over native savannah on the same eastern plains of the Colombia's Orinoquia region, Fisher et al. (1994) estimated a lower SOC accumulation of ~1.0 t C ha^{-1} yr^{-1} for the 0-20 cm soil layer, but a similar rate when considering deeper soil layers (~4.0 t C ha^{-1} yr^{-1} for 0-80 cm). Another similar study evaluating 9 farms in the Orinoquia region reported much lower rates of ~0.4 (0-20 cm) and ~1.0 t C ha^{-1} yr^{-1} (0-100 cm), but after ~29 years of implementation of *U. humidicola* over native savannah (CIAT-Agrosavia; unpublished data). These authors suggested that higher SOC sequestration in the first study (Fisher et al.1994) was related to adequate management of the introduced pasture under experimental condition (e.g., with fertilization and rotational grazing), which did not have the same status in the second case (CIAT-Agrosavia; unpublished data). This situation most likely prevented proper forage development and limited the amount of below and above-ground organic residues absorbed by the soil. In addition, after almost 30 years, the SOC stock could be just reaching a new-steady state after peaking its accumulation in the first decade of the pasture implementation.

In the Brazilian savannah (Cerrado region) at introduction of pastures, SOC accumulation rates were also more conservative than the level observed in this study. Bustamante et al. (2006), reported that the conversion of native vegetation to pasture showed a mean SOC accumulation of 1.23 t C ha^{-1} yr^{-1} (from -0.9 to 3.0 t C ha^{-1} yr^{-1}). Maia et al. (2009) observed variations in SOC after conversion of native vegetation (Cerrado and Amazon

Forest) into pasture of -0.28 t C ha^{-1} yr^{-1} (degraded pastures), 0.03 t C ha^{-1} yr^{-1} (non-degraded pastures) and 0.61-0.72 t C ha^{-1} yr^{-1} (improved pasture) (0-20 cm)., By modelling (DayCent) the SOC impact, Damian et al. (2021) estimated an increase in SOC of 0.04-0.95 t C ha^{-1} yr^{-1} from improving and diversifying pasture management in Brazil (e.g., integrated crop-livestock and forest-livestock systems). Out of 115 studies evaluating SOC stock changes in introduced pasturelands globally, Conant et al. (2001) found 74% SOC increase in cases between 0.11-3.04 t C ha^{-1} yr^{-1}. However, only 35% of those cases showed significant differences.

Although improved pastures assessed in this workstream did not receive any maintenance fertilization after establishment, higher SOC sequestration rate found in this work could also be attributed to higher clay content of the sampled area (~40% of clay content; Table 3.2), which represents less than 50% of the Orinoquía region. The majority would have around 25% content of clay (mid texture soil), and therefore less potential to accumulate SOC. The relationship between SOC and soil texture have been attributed to a chemical stabilization of SOC by soil clay/mineral surface (Feller and Beare, 1997). These relations suggest that soils with high clay content have more potential for SOC storage than sandy soils and, therefore, the percentage of clay content is a good indicator of SOC content and its potential accumulation (Nichols et al. 1984).

Differences in SOC accumulation rate can be further associated with climatic differences, where high temperatures and rainfall in Colombia favor *U. humidicola* to root deeper and consequently, accumulate more SOC (Fisher et al. 2007). Furthermore, the conversion to IP is relatively recent (6.5 years). Thus, the soil is likely to still be developing its SOC accumulation curve. This rate is expected to reduce overtime as suggested by other studies in the same region.

Finally, the errors associated with non-identical initial soil conditions in the NS and IP chronosequence (e.g., land history) of fields make this approach less accurate for the determination of rates of SOC accumulation compared to a diachronic approach (Costa Jr et al. 2013).

Comparison to the IPCC default values

The SOC stock found in NS represents 79.9 t C ha^{-1} for the 0-30 cm soil depth (linear regression analysis not shown), which is almost 40% and 50% higher than the reference default value for this climate zone and soil type provided by the IPCC (52 ±6% t C ha^{-1}; IPCC 2019) and FAO-GSP-Glo SIS Global (42.7 ±5.8 t C ha^{-1}; 29.3 Min - 56.2 Max).

Using the IPCC Tier 2 SOC stock change method to estimate SOC sequestration with improved practices and using an adjusted reference SOC stock (from 52 to 79.9 t C ha^{-1}) (IPCC 2019), this study estimated a total SOC accumulation of 13.6 t C ha^{-1} for the 0-30 cm, similar to the values found in this work (12.7 t C ha^{-1} for the 0-30 cm). However, according to the IPCC (2019), this level of SOC accumulation is expected to happen in 20 years' time (equivalent to a new steady-state for this stock). Here the study estimated that this change was achieved after only six years. These results underscore the importance of field measurements to improve local-specific SOC data, but especially the necessity of SOC monitoring to better understand and validate SOC stock variations over time.

Limitations

High rates of SOC accumulation found in this workstream and although in line with previous study in the region (Fisher et al. 1994), may raise questions regarding adequacy of the soil sampling design to accurately detect SOC changes, as well as the duration how long this situation can be sustained.

Although the soil sampling approach used has been applied in several other SOC assessment, future research could further consider the effect of land stratification in assessing SOC variation and reducing uncertainties (World Bank 2021b). The soil sampling could also be extended to a NS used under a similar grazing management of the IP in HSJ to decouple the impact of the type of forage from the management practice.

Furthermore, more moderate rates of SOC accumulation are expected to be found when using diachronic sampling (when measurements are made over time on the same location) rather than the field chronosequence approach as it is challenging to eliminate all non-wanted sources of soil C variation (e.g., soil texture, land-use history) through analyses of soil C accumulation in a chronosequence (synchronic approach) (Costa Jr et al. 2013).

On the capacity of SOC accumulation, accrual potentials remain unclear. IPCC guidelines assume 20 years as the default period in which new SOC stocks approach a new steady-state. This also enables comparison of results between regions and countries and with other estimation methods (IPCC 2019). Nevertheless, a meta-analysis of field studies has suggested that SOC sequestration can continue for over 40 years before reaching a new equilibrium (Minasny et al. 2017), depending on management practices, soil type and climate condition (e.g., rainfall and temperature).

Conclusions

The conversion of NS into a cultivated and well-managed pasture with *U. humidicola* on the Colombian Orinoquia increased SOC stocks of the superficial soil layer (0-20 cm), with a tendency to increase stocks at deeper layers (0-100 cm).

The large SOC sequestration capacity in improved pasturelands in soils with high clay content in the Orinoquia region (~2 t C ha^{-1} yr^{-1}), while increasing production of food (i.e., meat and milk), may be attractive for climate finance opportunities.

Results reported in this workstream provide valuable information for future monitoring of SOC changes in Colombia under different pasture systems that may support climate finance considerations for low GHG emissions development in beef cattle production systems.

Box 3.2. Additional measurements: plant root biomass

In addition to the results already presented in workstream 1, plant root biomass was also sampled in HSJ to understand differences in SOC accumulation under various conditions. Unfortunately, due to space limitation during the air travels, this limited the amount of samples transported, only one pit was made in each system (Figure 3.3). Soil samples were taken in a 15 x 15 cm surface at different depths (0-5, 5-20, 20-60 and 60-100 cm) to quantify the root content. The soil with roots was diluted with water and sieved with a 0.5 mm mesh to obtain the roots. This is then oven-dried at 65°C for 72 hours and weighed. The total root biomass from 0-80 cm in *U. humidicola* was approximately double than that of the native savannah (Table 3.3). This fact is remarkable considering that the new grass was established only around 6.5 years ago. Additionally, major differences in root biomass were observed in the topsoil 0-5 cm layer, where the *U. humidicola* had six times more root biomass than the native savannah. If these results could be confirmed following a more robust experimental design and considering various replications, this outcome could support observed differences in SOC accumulation, for which abundant and deep root systems are key.

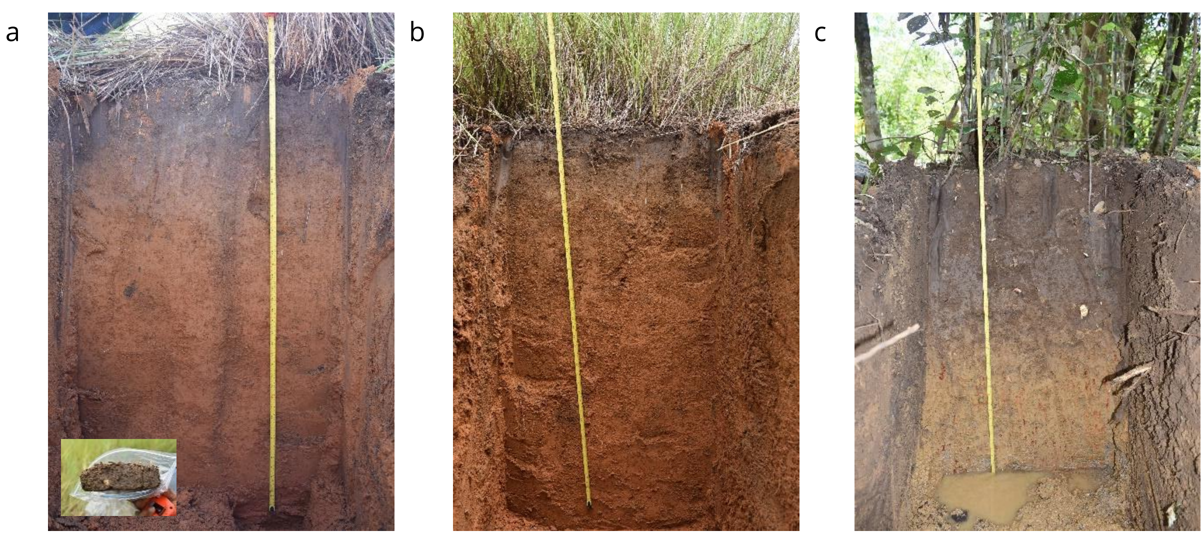


Figure 3.3. Soil pits made in each system to quantify the amount of roots in the soil. (a) native savannah. (b) *U. humidicola*. (c) Forest.

Table 3.3. Root weight at different soil depths in three land covers (native savannah, *U. humidicola* and forest). DM: Dry matter

	Roots (g DM soil depth^{-1})				
Land cover	0-5 cm	5-20 cm	20-60 cm	60-80 cm	Total
Native savannah	1.12	1.92	1.89	0.65	5.58
U. humidicola	7.20	2.00	1.13	0.27	10.60
Forest	4.16	8.79	14.51	0.36	27.82

Task 1.5. Evaluation of suitable models for simulation of soil C dynamics. Assessment of the dataset generated. Simulation of SOC-N dynamics over changing climate and management scenarios.

For task 1.5, after evaluation of suitability of three different models for simulation of C dynamics (Table 3.4) the DNDC (DeNitrification-DeComposition) model was selected.

Table 3.4. Major process-based models used for SOC accounting in voluntary carbon market (VCM) projects (Costa Jr et al. 2021)

Model	Definition	Key input data required
Century/ DayCent	The Century model simulates carbon and nitrogen fluxes and interactions in the atmosphere, vegetation, and soil. DAYCENT is the daily time-step version of the CENTURY biogeochemical model.	• Climate (precipitation and temperature daily/monthly basis) • Use of farming inputs (e.g., timing and amount of N-fertilizer used); • Soil characteristics (e.g., density, texture, and pH) • Soil management (e.g., no-tillage)
DNDC	The DeNitrification-DeComposition model (DNDC) is a family of models for predicting plant growth, soil C sequestration, GHG emissions and nutrient fluxes for cropland, pasture, forest, wetland, and livestock operation systems.	
Roth-C	Models the turnover of SOC in topsoil, allowing for the effects of soil (i.e., type, temperature, moisture), plant and agriculture management characteristics during the turnover process.	

The DNDC model is a process-based model of C and N biogeochemistry in agricultural ecosystems for predicting crop yield, C sequestration, nitrate leaching loss, and emissions of C and N gases in agroecosystems.

DNDC was used to simulate C and N dynamics tailored to HSJ conditions with a 50-year timeframe. Three types of variables were used as inputs to the model. Climate information and management practices were obtained from HSJ, whereas soil physical and chemical parameters were measured from soil samples collected in the farm during field visits to HSJ and analysed in the CIAT laboratory. One single climate file (1 year information) was used for the modelling since significant gaps were found in the meteorological dataset of the farm.

Results indicated that the major C inputs to the cropping system are the pasture shoots and roots, whereas major C outputs were CO_2 emissions and root exudation. Soil CH_4 emissions and leached C were negligible (Figure 3.4). During the first two years since the establishment of the new cropping system, a negative SOC balance was observed (i.e. C loss). Such behaviour is expected to occur due to land use change which results to soil disturbance and where bare soil patches remain until the new crop reaches a homogeneous coverage in the field. By the fifth year, the system reached the maximum increase in SOC in the 0-50 cm layer, in the magnitude of 3.4 t C ha^{-1} yr^{-1}. After that point forward, the rate of improvement of SOC with new management practices resulted to a reduction to about 0.7 t C ha^{-1} yr^{-1} until the 10^{th} year, to 0.2 t C ha^{-1} yr^{-1} until the 20^{th} year, and 0.04 t C ha^{-1} yr^{-1-} by the 30^{th} year. Carbon losses were then observed on the 37^{th} year at a pace of -0.001 t C ha^{-1} yr^{-1}, and reaching -0.03 t C ha^{-1} yr^{-1} in the 50^{th} year.

According to the model, the C balance of the cropping system become less advantageous with time, and indeed, between the 10^{th} and 20^{th} year of continuous cropping, the C balance become almost neutral as the C input by plant biomass C is offset by the increase of CO_2 emissions. This could have been triggered by pasture degradation from mining of nutrient pools. It would be advisable to renew the pasture (progressive re-sowing) to re-establish the nutrient cycling dynamics and maintain biomass production.

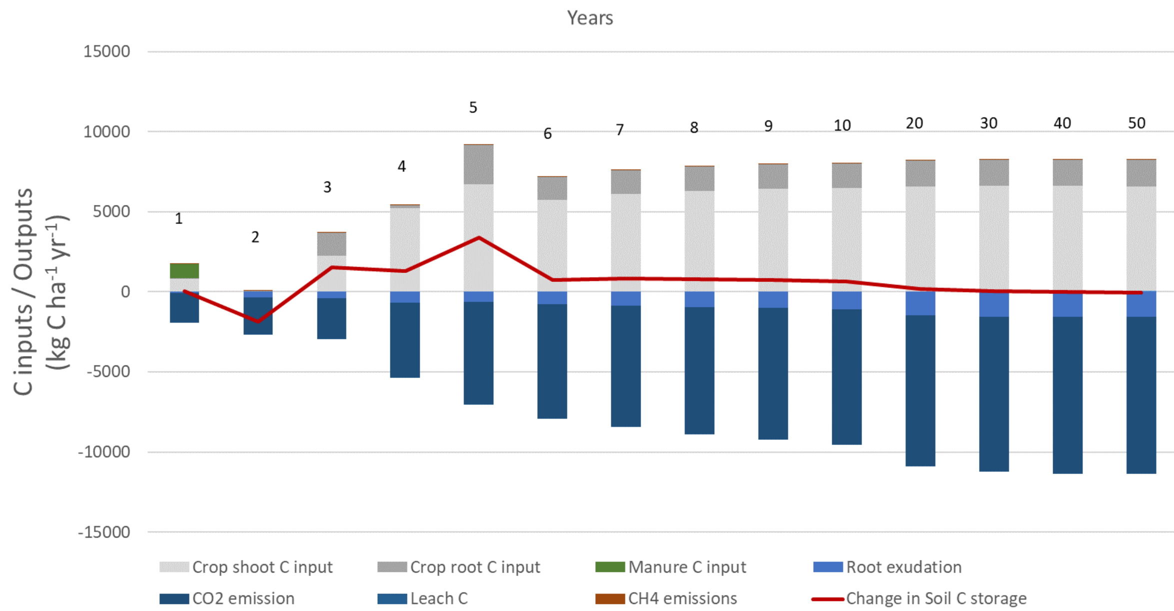


Figure 3.4. Carbon inputs and outputs of the cropping system simulated over 50 years following the conditions of HSJ.

The modelled SOC stocks from improved management were consistent with the SOC stocks measured *in situ* in the farm. Seven years after implementation of this practice, the SOC stock in the 0-50 cm soil layer was estimated in 145 t C ha^{-1}, with a yearly accumulation of 0.9 t C ha^{-1}, whereas the measured SOC stock resulted in 142 t C ha^{-1}, with a yearly accumulation of 2 t C ha^{-1}.

Using the DNDC, CIAT team was able to carry out a modelling exercise to simulate C dynamics in HSJ obtaining estimations comparable with real data. However, it is important to highlight that results are exploratory and more data is needed to validate the model. The use of a single climate file for the whole simulated period can be inaccurate and more information is needed on the feed supplementation of cattle and grazing regimes to accurately account for manure C in the pasture C dynamics.

This task was a first step towards structuring a model to estimate changes in SOC stocks in HSJ based on improved pasture management. To this end, the study concludes that DNDC has potential to model SOC in HSJ. These findings can serve as a basis for future studies to feed the model, which must be accompanied by *in situ* SOC monitoring, which is recommended to be undertaken every five years.

Workstream 2: Exploration of best practices through assessment of reduction of N_2O soil-born emissions

The objectives of WS2 were to provide options and recommendations for quantification of N_2O soil-borne emissions after deposition of animal urine in soil and to measure the N_2O emissions from native savannahs and mitigation potential from specific grass species (i.e. *Urochloa humidicola, syn. Brachiaria humidicola or commonly known as Humidicola*).

Tasks of WS 2 and current status are shown in Table 3.5.

Table 3.5. Description and status as of December 20, 2021 of the tasks in WS 2

Task	Description	Current status
2.1	Development of options and recommendations for quantification of N_2O soil-borne emissions for the task team's consideration	Finished
2.2	Installation of closed static chambers for measurement of N_2O in the paddocks previously identified as in workstream 1 (Task 1.1).	Finished
2.3	Measurement of N_2O emissions before, and 30 days after animal urine application. Urine to be applied to the soil will be collected on the farm	Finished
2.4	Calculation of daily fluxes and cumulative N_2O emissions over the sampling period.	On-going
2.5	Simultaneous collection of soil samples to evaluate the transformation of mineral N in the soil (NH_4+ and NO_3-), measurement of soil temperature, and water content	Finished

Representative points were defined for the native savannah, *U. humidicola* and forest systems (land cover). Along each land cover, seven PVC measurement chambers were installed in the soil burying half depth of the ring and coupling PVC caps of the same size, each day that gas accumulation was measured. In each land cover seven chambers were used, of which four chambers were applied with urine, and three with water (zero-Nitrogen control). The PVC rings and chambers had a diameter of 26 cm and were installed at a distance of 20 meters from each other. Urine was manually collected from cows (400 kg of weight) in the farm and cooled before distributing in the chambers. A subsample of 50 mL of urine was collected, adding 1% v/v of H_2SO_4, frozen via volatilization to avoid N losses, then urine-N concentration was measured in the laboratory.

In each measurement site (PVC rings) 0.5 L of urine or water were applied in each chamber and its surrounding soil surface covering an area of 0.25 m^2. Sampling was performed at 16 time points, with basal measurements (before simulated urination event which included pasture cut) and 21 days after urine and water (control) application (see Figure

3.5). Gas sampling was performed using Gasmet DX4040 portable FTIR multigas analyser following the static chamber method in previous studies (Teutscherova et al. 2019). Cumulative fluxes N_2O were calculated and differences between systems were analysed for GHG emissions reduction from soil (Brummell et al. 2012; Stewart et al. 2012; Villegas et al. 2020).

Simultaneously every day, temperature and soil moisture were measured in each chamber. After sealing the chambers with an elastic band, the measurement was monitored every 20 seconds for 8 minutes. The cumulative flux was calculated for each treatment by interpolating the N_2O concentration during the 21-day sampling period (Figure 3.6).

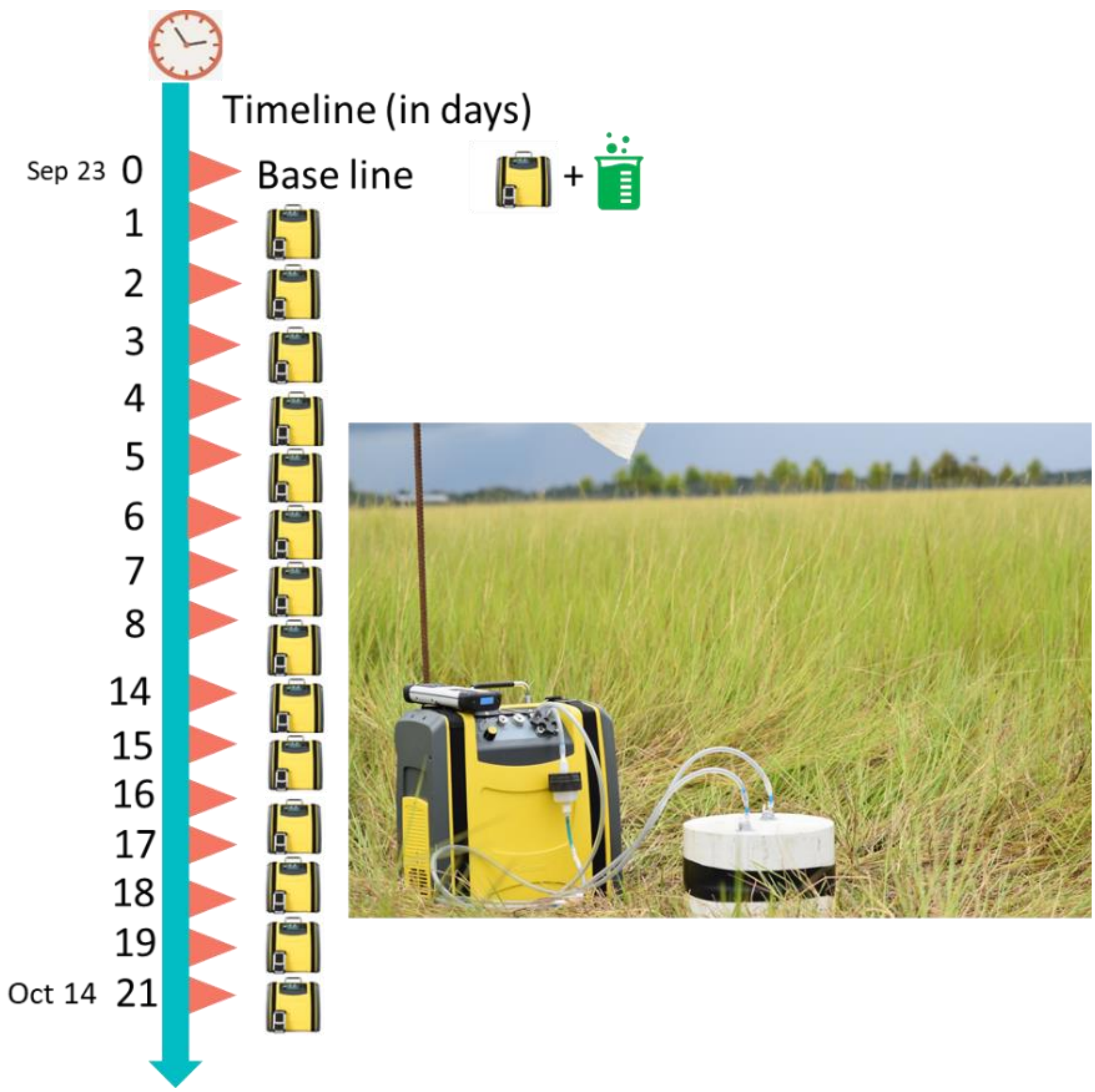


Figure 3.5. Nitrous oxide (N_2O) measurements in one of Hacienda San Jose paddock using portable FTIR Gasmet DX4040.

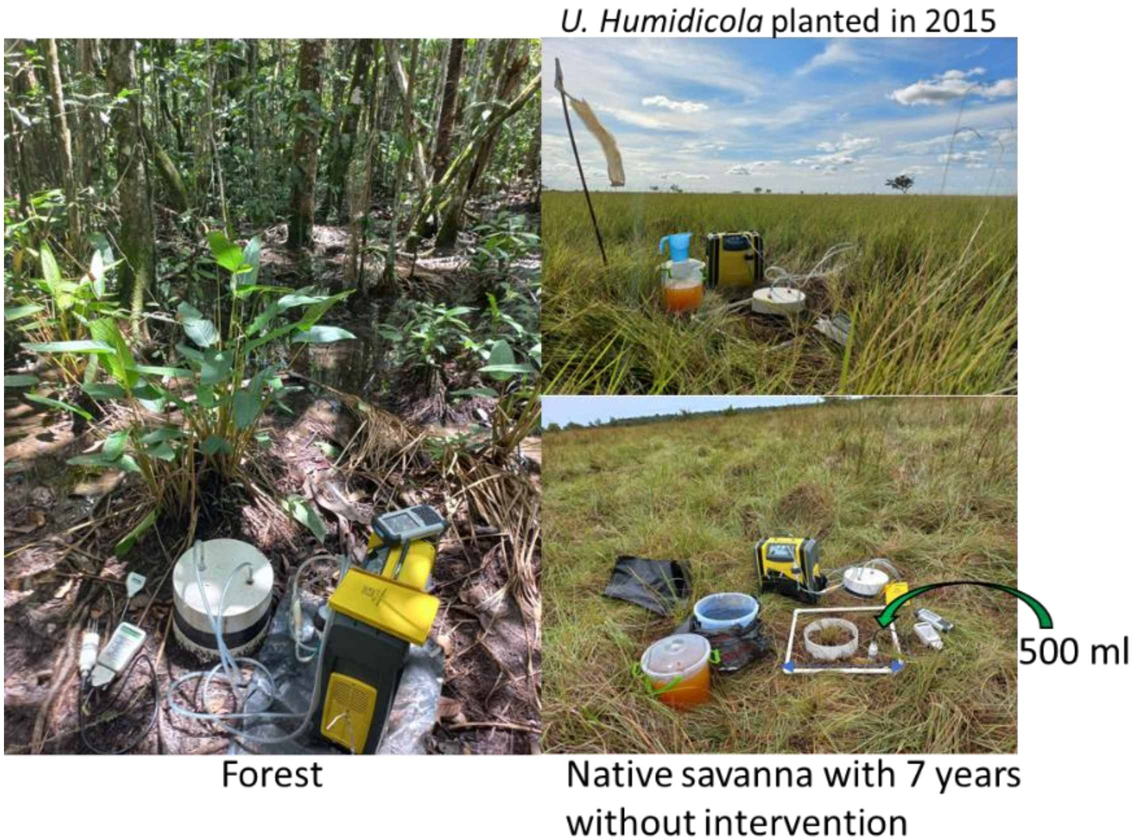


Figure 3.6. Application of urine and water on the soil (in an area of 0.25 m^2), and installation of chambers for N_2O measurement.

Irrespective of land cover analysed, the emissions of N_2O in the treatments with urine application were higher than with water application (control). During the whole sampling period, daily N_2O emissions were continuously highest in the native savannah, followed by the *U. humidicola*, and forest (Figure 3.7). The peaks of N_2O emissions were consistent with the precipitation observed during our measurements (Figure 3.8). According to Robertson and Groffman (2007), water-filled pore space (WFPS) plays a dominant role in determining to which extent N transformations are driven by nitrification or denitrification processes, both dependent on soil moisture. For the case of N_2O, it is an anaerobical process – meaning, when WFPS reaches above 80-90%, and oxygen is reduced, production of N_2O becomes encouraging.

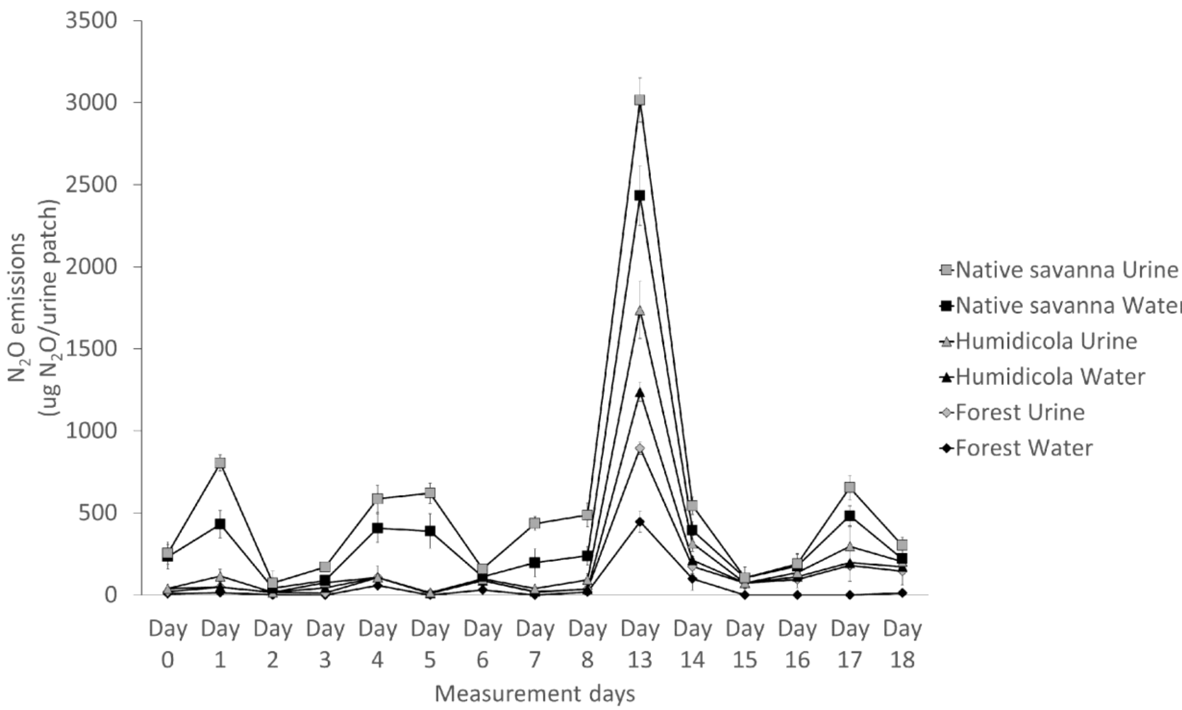


Figure 3.7. Daily N_2O fluxes in forest, native savannah, and *U. humidicola* with the water and urine application.

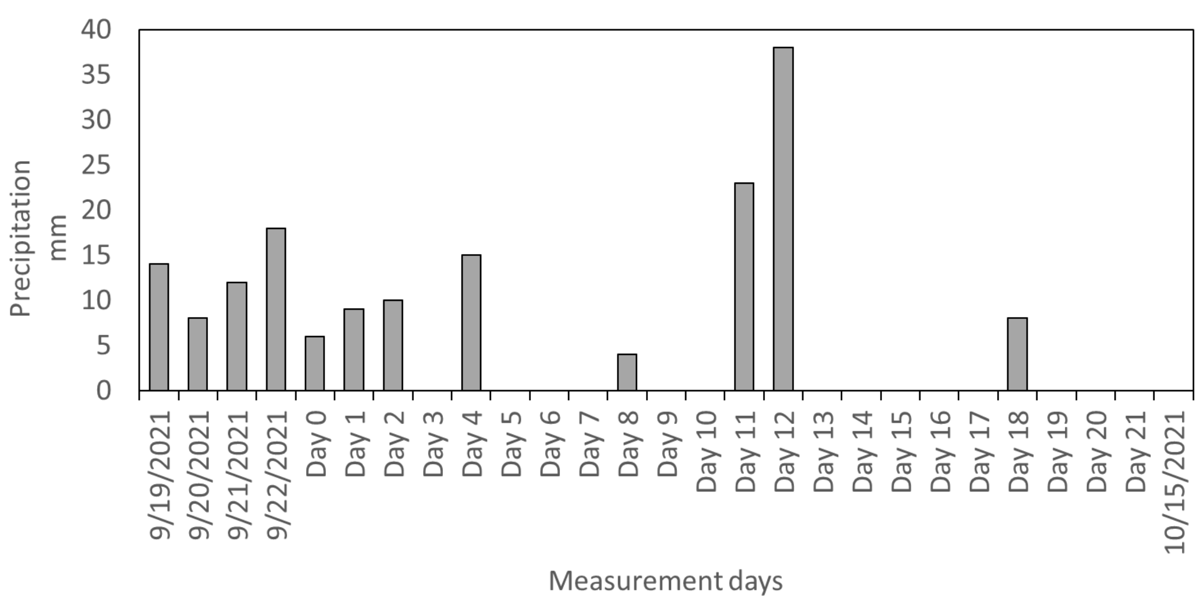


Figure 3.8. Registered rainfall during N_2O measurement campaign.

Carbon sequestration in agricultural land has been widely acknowledged as a strategy to mitigate climate change. However, recent studies (both measuring and modelling soil organic C and N dynamics) have reported that alongside with increase in SOC accumulated, N_2O emissions are likely to increase and may offset the C sequestered, either partially or even suggests additional emissions with respect to the baseline scenario (Qiu et al. 2009). Thus crucial to determine if the capacity of biological nitrification inhibition of *U. humidicola* could mitigate the expected increase in emissions, and to calculate specific emission factors for direct N_2O-N emissions from animal manure to refine the CFP model of HSJ.

Results indicated that there is a corelation between grassland improvement (introduction of *U. humidicola*) and the reduction of N_2O emissions. The improved *U. humidicola* pasture showed the lowest N_2O emissions among the treatments analysed after application of urine and water. Soils under native savannah emitted 10 times more N_2O than the improved pasture after application of water and 2.5 times more N_2O after simulation of urine deposition (Figure 3.9). The capacity of biological nitrification inhibition (BNI) has been acknowledged as the plant's natural strategy to avoid N losses in controlled environments, which also produces a number of environmental and physiology benefits, triggered by specific root compounds like 'brachialactone' (Subbarao et al. 2009).

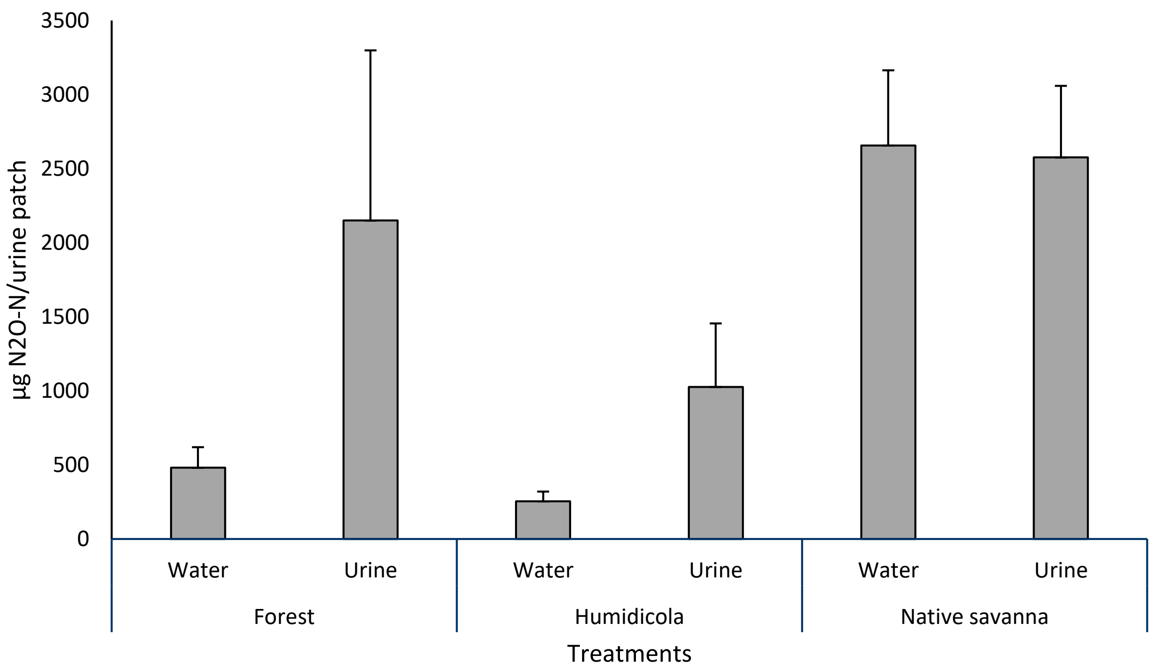


Figure 3.9. Cumulative N_2O fluxes in three systems: forest, native savannah and *U. humidicola*.

For the second part of the objective (calculation of EF), the following formula was used:

$$EF\ (\%) = \frac{N_2O\ emitted\ by\ treatment - N_2O\ emitted\ by\ control}{N\ applied\ (kg)}$$

The urine N concentrations observed in the samples obtained in the farm and analysed at CIAT yielded extraordinarily low N values. Whereas other authors have reported that normal ranges of urine N are around 1 to 10 g N L^{-1}, the N concentration measured in this sample was considerably lower than 1 g N L^{-1}. Given the structure of the formula for the calculations of the EF, independently on the difference of emissions in the treatment and the control, the lower the divisor (N applied) the lower the N applied, then the higher the EFs. The calculated EFs for this task were about 0.05 kg N_2O-N kg^{-1} N, whereas the IPCC default EF is almost ten times lower, 0.006 kg N_2O-N kg^{-1} N. The analysis of N concentration in urine samples stored for various days proved to be challenging as N can be easily vaporized. To ensure that the calculated EFs did not result to experimental error during sample storage, new materials and instructions were sent to HSJ to re-sample urine from the same type of animals originally used and were then sent to CIAT for new analysis in the laboratory.

By the time this report is submitted (20th Dec 2021), thanks to the collaboration spirit of the HSJ and due diligence, the new urine samples have already been sent to the CIAT laboratory.

Workstream 3: Farm level life cycle-based model and scenario analyses

Objectives of WS 3 were to consolidate the previously developed life cycle-based model of HSJ with the measurements from WS 1 and 2, and to identify scenarios for HSJ at farm level to improve potential climate impact of its operations.

The execution of the WS 3 was undertaken in close coordination with HSJ. Lengthy discussions were exchanged between stakeholders on the definition of explorative scenarios. The objective was to identify management practices and adoption levels feasible to the conditions and interests of HSJ. Indicators used to characterize the scenarios are presented below. Subsequently, the data collected during the inventory compilation is presented in the Tables referenced in Part 2 of this report.

Screening of mitigation practices for scenario design

Based on previous data on management practices already implemented in HSJ, a screening was made on management practices with the potential to mitigate HSJ's climate impact. These practices were categorized by two types of strategies "production efficiency" and "land-based carbon removal" (Cusack et al. 2021). An additional strategy on "energy management" was included for a potential transition to renewable energies (Table 3.6). The criteria for selection of mitigation practices was based on the following:

- High: reductions greater than 30%
- Medium: reductions between 10 to 30%
- Low: reductions lower than 10%

Table 3.6. Screening of mitigation practices and viability of adoption in HSJ

Strategy	Management practice	Potential mitigating effect	Viability of adoption in HSJ
Production efficiency	Increased forage quality	Low to medium (potential CH_4 emissions reduction between 5 to 30 %). Improving forage quality by increasing forage digestibility is an effective mitigation strategy.	The improvements in grazing management adopted by HSJ and the dietary supplementation received by the different animal categories are probably contributing to lower GHG emissions. *This is not considered a possible scenario for the farm because it is already being developed.*
	Feed additives (electron receptors, ionophores antibiotics, chemical inhibitors, etc.)	High (reduction in CH_4 emissions > 30%) Ionophores (e.g. monensin) have a high mitigation potential. However, the inhibitory effects of ionophores on methanogenesis are not always persistent over time and affect the dry matter intake of animals.	In general, mitigation options include electron receptors, ionophores, antibiotics, chemical inhibitors may offer opportunities to reduce enteric methane emissions; however, the results in literature have been inconsistent and have little success in grass-based systems (the main limitation). Furthermore, individual supplementation is required. *Unviable practice for scenario development for HSJ.*
	Supplementing micro and macroalgae (seaweeds)	Medium to high. Micro-algae *Asparagopsis taxiformis* (the most studied species) has high efficacy in CH_4 emissions reduction. However, some studies suggest that feed intake and animal performance can be reduced with high levels of supplementation.	Expensive and require the development of cultivation techniques (high infrastructure investment). The use of seaweed has greater viability in coastal areas. Limitation: difficult access and production. It is expected that in two or three years the microalgae will be on the market. *Unviable practice for scenario development for HSJ.*
	Supplementing 3-nitrooxypropanol (3-NOP).	High (reduces CH_4 emissions by 30% dairy cows and up to 90% in beef cows).	Animal supplementation in pasture-based systems is limiting. However, further studies are planned to refine

		3-NOP, marketed by DSM under the name Bovaer®, is a very specific inhibitor that suppresses an enzyme (Methyl Coenzyme M Reductase) that is responsible for the last step of methanogenesis. 21 Bovaer® is an effective methane inhibitor that has been extensively evaluated mixed into rations in beef cattle feedlots.	promising formulations and to establish their methane reduction potential for pasture-fed cattle. Advantage: Bovaer has long-term mitigation effects on enteric CH_4 emissions with no compromising effect on diet digestibility. No negative impact on animal welfare, feed consumption or performance has ever been identified. *Viable practice for scenario development for HSJ.*
Land-based carbon removal	Live fences	Medium to high Potential to capture carbon in biomass and soil 30% greater than the traditional use of fences.	HSJ management plan already includes perimeter live fences. It is possible to incorporate paddock subdivisions with this practice. *Viable practice for scenario development for HSJ.*
	Low and medium density silvopastoral systems	Medium to high 23.4% lower methane yields compared to traditional grazing systems. 50.1% lower methane yields than those from degraded pastures	This technology involves a high capital investment and experts at HSJ tell that they have had previous negative experiences. *Unviable practice for scenario development for HSJ.*
Energy management	Substitution of fossil fuels	Low GHG emissions of combustion of liquefied petroleum gas (LPG): 1.6 t CO_2eq $(m^3)^{-1}$ GHG emissions of electricity from diesel generator: 0.3 kg CO_2eq kWh^{-1}	Necessary investments to be identified replacement of gas by electric stoves in the kitchens replacement of diesel generators in the facility for the production of feed supplements *Viable practice for scenario development for HSJ.*
	Sale of electricity surplus	Low GHG emissions of electricity from diesel generator: 0.3 kg CO_2eq kWh^{-1}	There is no electricity grid and the next town/facility is approximately 50 km away *Unviable practice for scenario development for HSJ.*

Data collected during the inventory compilation of HSJ operations

Table 3.7. Coefficients and emission factors used in the Tier 2 equations of IPCC (2019) by AFOLU sector

Source and climate impact	Tier	IPCC equation	Coefficient/Emission factor	Value	Source
Forest Land C uptake in total biomass: C offset	1	2.9	CF: carbon fraction of dry matter, t C t^{-1} DM	0.47 (0.44 – 0.49)	IPCC (2019), Table 4.3. Domain: Tropical and subtropical. Part of tree: All. Ecological zone: Tropical moist deciduous forest. Continent: North and South America. Status: Primary
		2.10	G_W: Average annual above-ground biomass growth for a specific woody vegetation type, t DM ha^{-1} yr^{-1}	0.4 (2.1; SD)	IPCC (2019), Table 4.9. Domain: Tropical. Ecological zone: Tropical moist deciduous forest. Continent: North and South America. Status: Primary
			R: Ratio of below- to above-ground biomass for a specific woody vegetation type, t DM below-ground biomass t^{-1} DM above-ground biomass	0.24 (±4%)	IDEAM et al. (2018), Annex 14. Category: Natural forest. Region: Orinoco basin
Grassland, improved pastures C uptake in below-ground biomass: C removal	2	2.9	CF, t C t^{-1} DM	0.47	IPCC (2006b), Volume 4, Chapter 6, Page 9. Default value for herbaceous biomass
		2.10	G_W, *U. humidicola* cv. Humidicola (CIAT 679), t DM ha^{-1} yr^{-1} G_W, *U. brizantha* cv. Marandú (CIAT 6780), t DM ha^{-1} yr^{-1} G_W, *U. humidicola* cv. Llanero (CIAT 6133), t DM ha^{-1} yr^{-1} G_W, *U. hybrid* cv. Cayman (CIAT BR02 1752), t DM ha^{-1} yr^{-1} G_W, *Megathyrsus maximus* cv. Mombasa (CIAT 6962), t DM ha^{-1} yr^{-1}	7.16 3.46 6.30 3.50 9.50	Primary HSJ data, Boviplan (2020, 2021)
			*G_W, Guaratara - *Axonopus purpusii*, t DM ha^{-1} yr^{-1}	6.26	Peñuela et al. (2011), Table 5
			R, Humidicola, Cayman, Mombasa, Guaratara, t DM below-ground biomass t^{-1} DM above-ground biomass	0.62 (50%)	IDEAM et al. (2018), Annex 14. Category: Pastures. Region: National
			R, Marandú, Llanero, t DM below-ground biomass t^{-1} DM above-ground biomass	0.5	Cardoso (2020, personal communication)
Grassland, soil C sequestration in soil due to root turnover: C removal	1	2.25	D: Time dependence of mineral SOC stock change factors which is the default time period for transition between equilibrium SOC values, yr	20	IPCC (2019), Volume 4, Chapter 6, Page 5
			F_{LU}: Stock change factor for mineral SOC land-use systems or sub-systems for a particular land-use	1	IPCC (2019), Table 6.2. Level: All. Climate regime: All.
			F_{MG}: Stock change factor for mineral SOC for management regime	1.17 (±9%)	IPCC (2019), Table 6.2. Level: Improved grassland. Climate regime: Tropical.
Grassland, Woody species C uptake in total biomass: C removal	2	2.4	ΔC_G: Annual increases in biomass C stocks due to biomass growth in land remaining in the same land-use category, fruit orchards and native trees, t C ha^{-1} yr^{-1}	1.35 (±7%)	IDEAM et al. (2018), Annex 18. Factor for "Mango".
			CO_2 uptake due to biomass growth, *Eucalyptus pellita*, t CO_2 ha^{-1} yr^{-1}	61.6 (±10%)	IDEAM et al. (2018), Annex 16.

Enteric fermentation GHG emissions from livestock	2	10.3	C_f: Coefficient for calculating NE for maintenance NE_m, lactating cows, MJ d^{-1} kg^{-1}	0.386	IPCC (2019), Table 10.4.
			C_f, bulls, MJ d^{-1} kg^{-1}	0.370	
			C_f, non-lactating cows, calves and heifers after 55 days, MJ d^{-1} kg^{-1}	0.322	
		10.4	C_a: Coefficient corresponding to animal's feeding situation, pasture, MJ d^{-1} kg^{-1}	0.17	IPCC (2019), Table 10.5.
			C_a, grazing large areas*, MJ d^{-1} kg^{-1}	0.36	
		10.6	C: Coefficient for calculating NE for growth NE_g, females, calves and heifers after 55 d	0.80	IPCC (2019), Volume 4, Chapter 10, Page 24.
			C, bulls	1.2	
		10.8	Milk: Amount of milk produced, L d^{-1}	3.5	Primary HSJ data.
			Fat: Fat content of milk	3.5%	IDEAM et al. (2018), Annex 12. Cows used to produce offspring for meat.
		10.13	$C_{pregnancy}$: Pregnancy coefficient	0.1	IPCC (2019), Table 10.7. Animal category: Cattle and Buffalo.
		10.14	DE: Digestibility of feed expressed as a fraction of gross energy, Humidicola	49.50%	Primary HSJ data, Corpoica (2018)
			DE, Marandú	50.54%	
			DE, Llanero	52.38%	
			DE, Cayman	52.82%	
			*DE, Guaratara	50.37%	
			†TDN: Total digestible nutrients, Mombasa sillage	55.43%	Primary HSJ data, Boviplan (2019)
			†TDN DE^{-1} ratio, Mombasa silage	0.91	Agrosavia (2020)
			†DE, Mombasa silage	60.86%	Own calculation
		10.16	DMI: Dry matter intake, Humidicola, % LW d^{-1}	2.3%	Primary HSJ data, Boviplan (2020)
			DMI, Marandú, % LW d^{-1}	2.4%	
			DMI, Llanero, % LW d^{-1}	2.2%	
			DMI, Cayman, % LW d^{-1}	2.4%	
			ED: Energy density of the feed, Humidicola, MJ kg^{-1} DM	16.82	Primary HSJ data, Corpoica (2018)
			ED, Marandú, MJ kg^{-1} DM	16.83	
			ED, Llanero, MJ kg^{-1} DM	16.69	
			ED, Cayman, MJ kg^{-1} DM	16.72	
			ED, Guaratara , MJ kg^{-1} DM	16.78	
			†WMI: Wet matter intake, Mombasa, kg WM AU^{-1} d^{-1}	18 – 25	Primary HSJ data, Boviplan (2020)
			†DM content, Mombasa,	25%	Agrosavia (2020)
		10.21	Y_m: Methane conversion factor	7	IPCC (2019), Table 10.12. Livestock category: Non-dairy and multi-purpose Cattle and Buffalo. Description: >75% forage. Feed quality digestibility DE ≤ 62%

			Y_m, bulls receiving feed concentrate	6.3	IPCC (2019), Table 10.12. Livestock category: Non-dairy and multi-purpose Cattle and Buffalo. Description: Rations of >75% high quality forage and/or mixed rations, forage of between 15 and 75% the total ration mixed with grain, and/or silage. Feed quality digestibility DE 62-71%
			Y_m, calves until age 55 d	0	Ramírez-Restrepo et al. (2019)
Manure management GHG emissions from livestock	2	10.23	B_0: Maximum methane producing capacity for manure produced by livestock category, m^3 CH_4 kg^{-1} VS MCF: Methane conversion factor for manure management system	0.19 0.47%	IPCC (2019), Table 10.17. System: Pasture/Range/Paddock.
		10.24	UE: Urinary energy as fraction of the GE	0.04	IPCC (2019), Volume 4, Chapter 10, Page 64.
			ASH: Ash content of feed as fraction of the DM, Humidicola ASH, Marandú ASH, Llanero ASH, Cayman *ASH, Guaratara	7.7% 8.5% 10.1% 10.5% 8.7%	Primary HSJ data, Corpoica (2018)
		10.32	CP: Percent crude protein in DM, Humidicola CP, Marandú CP, Llanero CP, Cayman *CP, Guaratara	2.5% 3.7% 5.3% 6.9% 4.9%	Primary HSJ data, Corpoica (2018)
		11.5	MS: Fraction of total annual N excretion that is deposited on pasture, range and paddock	95%	IDEAM et al. (2018), Page 420.
		11.1	$EF_{3PRP,CPP}$: N_2O emissions from manure management for cattle, poultry and pigs, kg N_2O kg^{-1} N	0.006 (0.000-0.026)	IPCC (2019), Table 11.1. Disaggregation: Wet climate.
Emissions from biomass burning in grasslands Avoided GHG emissions from improved practice	2	2.27	M_B: Mass of fuel available for combustion, Guaratara, t DM ha^{-1}	3.72	Peñuela et al. (2011), Table 5, rain season
			C_f: Combustion factor	0.95	Etter et al. (2010), Table 1. Ecosystem code: Sandy savannahs.
			$G_{ef}CO$: EF, g kg^{-1} DM burnt $G_{ef}CH_4$:, g kg^{-1} DM burnt $G_{ef}N_2O$:, g kg^{-1} DM burnt $G_{ef}NOx$:, g kg^{-1} DM burnt	65 (±20) 2.3 (±0.9) 0.2 (±0.1) 3.9 (±2.4)	IPCC (2019), Table 2.5. Category: Savannah and grassland
Liming GHG emissions from soil management	1	11.12	$EF_{Dolomite}$, t C t^{-1} dolomite	0.13	IPCC (2006b), Volume 4, Chapter 11, Page 27.

Urea application GHG emissions from soil management	1	11.13	EF_{Urea}, t C t^{-1} urea	0.20	IPCC (2006b), Volume 4, Chapter 11, Page 34.
Direct N_2O emissions from managed soils GHG emissions from soil management	1	11.1	EF_1: N_2O emissions from N additions from synthetic fertilizers, kg N_2O-N kg^{-1} N input	0.016 (0.013-0.019)	IPCC (2019), Table 11.1. Disaggregation: Synthetic fertilizer inputs in wet climates.
Indirect N_2O emissions from managed soils	1	11.9	$FRAC_{GASF}$: Fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, urea, kg N volatilized kg^{-1} N applied	0.15 (0.03-0.43)	IPCC (2019), Table 11.3. Disaggregation: Urea.
			$FRAC_{GASF}$: DAP, kg N volatilized kg^{-1} N applied	0.08 (0.02-0.30)	IPCC (2019), Table 11.3. Disaggregation: Ammonium-based.
			EF_4: N_2O-N emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$	0.014 (0.011-0.017)	IPCC (2019), Table 11.3. Disaggregation: Wet climate.
	1	11.10	$FRAC_{LEACH-(H)}$: Fraction of all N added to managed soils in regions where leaching runoff occurs that is lost through leaching and runoff, kg N kg N^{-1} additions or deposition by grazing animals EF_5: N_2O-N emissions from leaching runoff, kg N_2O-N kg^{-1} N leaching runoff	0.24 (0.01-0.73) 0.011 (0.00-0.02)	IPCC (2019), Table 11.3.
Indirect N_2O emissions from manure management GHG emissions from livestock	2	10.26	$FRAC_{GASM}$: Volatilization from dung and urine deposited by grazing animals (kg NH_3-N + NOx-N) kg N^{-1} deposited	0.21 (0.00-0.31)	IPCC (2019), Table 11.3.
		10.28	EF_4: N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$	0.014 (0.011-0.017)	IPCC (2019), Table 11.3. Disaggregation: Wet climate.

NE: Net energy, LW: Live weight, VS: Volatile solid excreted, PRP: Pasture/Range/Paddock, DM: Dry matter, WM: Wet matter, EF: Emission factor, DAP: Diammonium phosphate, SD: Standard deviation.

NOTES: If available, uncertainty is indicated in brackets. Coefficients used as reference situation of the management practices in HSJ are marked with a *. Coefficients used in other equations but within the same context are marked with a †.

Table 3.8. Herd characterization and animal inventory in HSJ by animal subcategory

Animal category (IPCC 2019)	Animal subcategory by breed, LW, lactation and pregnancy	Initial LW, kg	Mature LW kg	Avg LW, kg	Avg LW gain, kg d^{-1}	2017	2018	2019	2020	2021	2022	2023
Cows used to produce offspring for meat	N-sc_cow_350_lact_preg	230	350	290	0.00	38	146	241	0	0	0	0
	N-sc_cow_400_lact_preg	350	400	400	0.00	0	87	152	773	912	808	673
	N-sc_cow_350_lact_non_preg	230	350	290	0.00	79	38	74	0	0	0	0
	N-sc_cow_400_lact_non_preg	350	400	400	0.00	0	23	47	159	187	166	139
	N-sc_cow_350_non_lact_preg	230	350	290	0.47	22	213	218	346	316	776	2,099
	N-sc_cow_400_non_lact_preg	350	400	400	0.47	0	0	0	58	223	477	3,158
	N-sc_cow_350_non_lact_non_preg	230	350	290	0.47	46	56	68	72	65	160	430
	N-sc_cow_350_non_lact_non_preg					2	0	0	0	0	0	0
	N-sc_cow_400_non_lact_non_preg	350	400	400	0.47	0	0	0	13	46	98	648
Bulls used principally for breeding purposes	N-sc_bull_for_reproduction_350	250	350	300	1.10	23	50	161	196	129	141	1,841
	N-sc_bull_for_reproduction_460	350	460	405	0.43	0	0	0	0	0	0	0
	N-sc_bull_for_reproduction_550	460	550	505	0.60	3	13	9	123	85	170	223
Calves pre-weaning	N-sc_heifer_100	30	100	65	0.44	0	208	356	0	0	0	0
	N-sc_heifer_230	100	230	165	1.05	105	0	0	785	852	672	408
	N-sc_calf_100	30	100	65	0.50	0	86	158	0	0	0	0
	N-sc_calf_250	100	250	175	0.99	12	0	0	147	247	302	404
Cows used to produce offspring for meat	B_cow_350_lact_preg	230	350	290	0.00	0	0	0	0	0	0	0
	B_cow_400_lact_preg	350	400	400	0.00	449	390	364	0	0	0	0
	B_cow_350_lact_non_preg	230	350	290	0.00	0	0	0	0	0	0	0
	B_cow_400_lact_non_preg	350	400	400	0.00	534	574	452	190	67	41	0
	B_cow_400_lact_non_preg					31	32	0	0	0	0	0
	B_cow_350_non_lact_preg	230	350	290	0.42	299	604	476	32	0	0	0
	B_cow_400_non_lact_preg	350	400	400	0.42	251	173	515	0	0	0	0
	B_cow_350_non_lact_non_preg	230	350	290	0.42	151	538	308	540	0	0	0
	B_cow_350_non_lact_non_preg					136	169	0	0	0	0	0
	B_cow_400_non_lact_non_preg	350	400	400	0.42	1,754	1,947	1,626	2,079	1,359	1,335	0
Bulls used principally for breeding purposes	B_bull_for_reproduction_350	250	350	300	0.99	437	867	0	88	70	80	0
	B_bull_for_reproduction_350					8	1	0	0	0	0	0
	B_bull_for_reproduction_460	350	460	405	0.38	269	294	316	0	0	0	0
	B_bull_for_reproduction_460					137	0	0	0	0	0	0
	B_bull_for_reproduction_500	460	500	480	0.54	18	18	7	222	71	40	0
Calves pre-weaning	B_heifer_100	30	100	65	0.39	0	293	134	0	0	0	0
	B_heifer_230	100	230	165	0.95	488	162	33	0	0	0	0
	B_calf_100	30	100	65	0.45	0	344	131	0	0	0	0
	B_calf_250	100	250	175	0.89	495	165	518	190	67	41	0

N-sc: short-cycle Nelore, B: Brahman, LW: Live weight. **Notes:** Values for the F1 crossbreed are computed under the breed Brahman. Rows in blue contain the data of imported animals.

Table 3.9. Characterization and price (2021) at the farm gate of the co-products of HSJ.

Co-product	Age, months	LW, kg	Price, USD kg^{-1} LW*	Price, USD $head^{-1}$*
Breeding stock (f)	20	360	n/a	1,900
Breeding stock (m)	24	550	n/a	3,100
Weaned heifer	12	230	n/a	5,000
Weaned calf	12	250	1.5	370
Cull cow	36	400	1.2	600
Cull bull	24	500	1.2	620
Cull bull used principally for breeding purposes	96	550	1.2	690
Embryos	n/a	n/a	n/a	370†
Semen	n/a	n/a	n/a	9†

LW: Live weight, n/a: not applicable.
*Exchange rate: 4,005.9 COP$ USD^{-1} (xe.com, 14.12.21).
†The prices for embryos and semen are given by unit

Table 3.10. Exported embryos and semen units from HSJ during 2017 - 2023.

Genetic resource	2017	2018	2019	2020	2021	2022	2023
Embryos	0	20	568	986	600	600	600
Semen units	0	1,959	7,277	14,800	15,000	15,000	15,000

Table 3.11. Annual area (ha) by land use type in HSJ during 2017 - 2023.

Land use type	2017	2018	2019	2020	2021	2022	2023
Native savannah	3,655	3,655	3,655	3,110	960	698	675
Improved pastures	4,553	4,553	4,553	5,088	7,238	7,500	7,500
Woody species	11	11	11	21	21	21	44
Riparian forest	430	430	430	430	430	430	430
Infrastructure	21	21	21	21	21	21	21
Total	8,670	8,670	8,670	8,670	8,670	8,670	8,670

Table 3.12. Activity data and emission factors of the soil management in HSJ.

Parameter	Value	Activities (ecoinvent 2019) and further sources
Fertilized area, ha	32	Cultivar Mombasa
Annual amount of urea applied to soils, kg ha^{-1} yr^{-1}	250	Urea, as N {RoW}| production
N content in urea, %	46	YARA (2014)
Annual amount of DAP applied to soils, kg ha^{-1} yr^{-1}	200	Phosphate fertilizer, as P2O5 {RoW}| diammonium phosphate production; Nitrogen fertilizer, as N {GLO}| market for
P_2O_5 content in DAP, %	46	YARA (2014)
N content in DAP, %	18	YARA (2014)
Annual amount of potassium chloride applied to soils, kg ha^{-1} yr^{-1}	150	Potassium chloride, as K2O {RoW}| potassium chloride production
K_2O content in potassium chloride, %	60	YARA (2014)
Soil amendment area 2017, ha	5,027	
Dolomite applied to soils 2017, kg ha^{-1}	550	Dolomite {RoW}| production
Phosphate rock applied to soils 2017, kg ha^{-1}	250	Phosphate rock, as P2O5, beneficiated, dry {RoW}| phosphate rock beneficiation, dry
Gypsum applied to soils 2017, kg ha^{-1}	200	Gypsum, mineral {RoW}| gypsum quarry operation

RoW: rest of the world, DAP: diammonium phosphate.

Table 3.13. Activity data and emission factors of the land use "Infrastructure" in HSJ. If available, uncertainty is indicated in brackets.

Parameter	Value	Activities (ecoinvent 2019) and other sources
Sheds area, m^2	1,824	Shed {RoW}| construction.
Sheds amount, n	3	
Solar panels area, m^2	125	Photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted, on roof {RoW}
Solar panels capacity, kW	17.4	
Solar panels utilization 2017-2022, %	74	
Solar panels, utilization 2023, %	100	
Electricity production 2017-2022, kWh	20,000	Electricity, low voltage {RoW}
Electricity production 2023, kWh	27,000	
LPG, m^3	3.3	Natural gas, liquefied {RoW}| production
Gasoline 2017-2019, gal	1,853	Transport, passenger, motor scooter {RoW}| processing
Gasoline 2020-2023, gal	5,025	
Specific fuel consumption motor scooter, L 100 km^{-1}	3.5	
Diesel pick-ups 2017-2019, gal	1,591	Transport, passenger car, large size, diesel, EURO 4 {RoW}
Diesel pick-ups 2020-2023, gal	4,135	
Specific fuel consumption pick-up, L 100 km^{-1}	7.0	statista (2021)
Diesel, agricultural machinery 2017-2019, gal	2,386	Diesel, burned in agricultural machinery {GLO}
Diesel, agricultural machinery 2020-2023, gal	6,202	
EF_{CO2} for combustion of LPG, kg TJ^{-1}	63,100 (61,600-65,600)	IPCC (2006b), Table 1.4.
EF_{N2O} for combustion of LPG, kg TJ^{-1}	0.5	Jungbluth (1997), Table 8.
Net calorific value LPG, TJ Gg^{-1}	47.3 (44.8-52.2)	IPCC (2006b), Table 1.2.
Density LPG, kg $(m^3)^{-1}$	522.2	OECD et al. (2004), Table A3.8
Transport of inputs (raw material for feed supplements, fertilizers, amendments), km	450	Transport, freight, inland waterways, barge {RoW}

LPG: Liquified petroleum gas, EF: Emission factor, RoW: Rest of the world.

Table 3.14. Feed supplements by animal sub-category in HSJ.

Animal subcategory	Feed supplement	Amount
Adult animals	Mineral salt enhanced with protein	0.1% kg LW d-1
Lactating females	Mineral salt	0.027% kg LW d-1
Bulls, >18 months	Concentrate	1.5% kg LW d-1
	Mombasa silage	4.8% kg LW d-1

Table 3.15. Composition of the feed supplements in HSJ

Raw material	Mineral salt	Mineral salt (+ protein)	Concentrate	Activities (ecoinvent 2019) and other sources
Sea salt	38%	22%	1%	Sodium chloride, powder {RoW}
Monocalcium phosphate	29%	7%	0%	Mineral supplement, for beef cattle {GLO}
Calcium carbonate	27%	10%	2%	Calcium carbonate, precipitated {RoW}
Sulfur	2%	2%	0%	Sulfur {CO}
Salt (6% P)	5%	0%	0%	Mineral supplement, for beef cattle {GLO}
Protein core	0%	5%	1%	Soybean meal {RoW}
Rice, polished, broken	0%	4%	29%	Rice feed meal, at processing (Agri-footprint 5)
Maize	0%	30%	40%	Maize grain, rainfed {RoW}
Urea	0%	12%	2%	Urea, as N {RoW}
Soybean meal	0%	10%	25%	Soybean meal {BR}

RoW: Rest of the world, GLO: global, CO: Colombia, BR: Brazil, P: phosphor

Table 3.16. Chemical composition of the feed supplements in HSJ and datasets used

Raw material	Dry matter (DM), %	Digestibility of feed (DE), %	Energy density, Mcal kg^{-1} DM	Ash, %	Crude protein, %
Sea salt	100.0[b]	0.0[b]	0.0[e]	98.0[f]	0.0[f]
Monocalcium phosphate	100.0[b]	0.0[b]	0.0[c]	81.7[c]	0.0[c]
Calcium carbonate	100.0[b]	0.0[b]	0.0[c]	99.5[c]	0.0[c]
Sulfur	100.0[b]	0.0[b]	0.0[e]	n/a	n/a
Salt (6% P)	100.0[a]	0.0[a]	0.0[e]	98.0[g]	0.0[g]
Protein core	94.9[a]	87.9[d]	5.1[d]	6.6[d]	50.5[d]
Rice, polished, broken[c]	87.6	86.8	4.3	1.0	9.2
Maize[c]	86.3	87.2	4.5	1.4	8.8
Urea[c]	99.4	100.0	2.5	0.03	28.7
Soybean meal[c]	93.2	87.9	5.1	6.6	47.0

a: bromatological studies available at HSJ
b: own assumption based on the characteristics of the salt (6%)
c: INRAE et al. (2021)
d: own assumption that it's a material similar to soybean meal
e: own assumption based on the characteristics of the monocalcium phosphate and calcium carbonate
f: FEDNA tables, (Blas et al. 2019)
g: own assumption based on the characteristics of the sea salt
n/a: not available

Table 3.17. Enteric CH_4 emissions by animal subcategory in kg CO_2eq head^{-1} d^{-1} and two methodological approaches, average 2017 – 2023.

Animal subcategory	Tier 2 (IPCC default coefficients)	Tier 3 (actual DMI)
N-sc_cow_350_lact_preg	6.65	4.24
N-sc_cow_400_lact_preg	6.65	4.23
N-sc_cow_350_lact_non_preg	8.92	4.20
N-sc_cow_400_lact_non_preg	8.92	4.24
N-sc_cow_350_non_lact_preg	7.11	5.78
N-sc_cow_400_non_lact_preg	7.11	5.77
N-sc_cow_350_non_lact_non_preg	9.58	5.78
N-sc_cow_400_non_lact_non_preg	9.58	5.78
N-sc_bull_for_reproduction_350	11.39	4.40
N-sc_bull_for_reproduction_550	11.75	9.86
N-sc_heifer_100	4.80	0.98
N-sc_heifer_230	8.79	1.88
N-sc_calf_100	4.35	0.98
N-sc_calf_250	9.15	1.73

DMI: dry matter intake.

Detailed description of the farms for the REF scenario

The hypothetical reference farm was built by selecting regional conventional practices corresponding to HSJ management practices (Table 2.3). Data was retrieved from the database of the Sustainable Colombian Cattle Ranching (GCS, Spanish initials) and the Livestock Plus (L+) projects.

The GCS project conducted surveys in 2,011 farms characterized as either cow-calf, cattle-fattening, dual-purpose, full cycle, or specialized dairy livestock farms, selected based on environmental attributes, existence of globally important ecosystems, and proximity to protected areas. Livestock farms surveyed were located in the departments (in parenthesis, the number of municipalities surveyed): Atlántico (13), Bolívar (4), Boyacá (12), Caldas (2), Cesar (10), La Guajira (5), Meta (10), Quindío (9), Risaralda (2), Santander (4), Tolima (6), and Valle del Cauca (7) (Figure 2.14). A ten-component questionnaire was used per farm: (1) general information, (2) herd composition and management, (3) pasture management practises, (4) livestock production and reproduction data, (5) animal health, (6) environmental information, (7) social information, (8) organizational and relationship with the external environment information, (9) incomes from livestock, and (10) financial information.

The L+ project conducted a survey among farms located in the Meta Piedmont (municipalities of Cumaral and Restrepo), Meta high plains (Puerto Gaitán and Puerto López), and Cauca dry valley of Patía (El Bordo and Mercaderes). Surveys were conducted in 607 livestock farms: Piedmont (150), High Plains (147), and dry valley of Patía (310). The questionnaire focused on eight components: (1) general information, (2) administrative information, (3) land-use information, (4) technical assistance, (5) production and trade system characteristics, (6) association membership, (7) financial information, and (8) climate events.

Workstream 4: Comparative analysis of HSJ's value chain expansion scenario and Colombian beef value chains

This workstream aims to provide an overview of the potential climate impact of future farms (satellite cow-calf farms and fattening farms) and activities (cattle transport and slaughterhouse operations) included in the value chain expansion of HSJ. The system boundary presented in Workstream 3 was expanded to "Cradle to slaughterhouse-gate" (Figure 3.10), excluding satellite cow-calf farms. Some primary data was gathered from HSJ. Gaps were filled with information from desk research. The estimation of the GHG emissions and C removals from the satellite cow-calf and fattening farms were made under the same methodological approach to the one applied for HSJ.

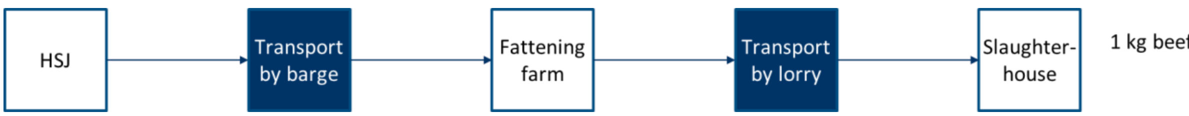


Figure 3.10. Activities included in the product system "Cradle to slaughterhouse-gate".

Satellite cow-calf farms

The first part of the value chain expansion consists in the establishment of satellite cow-calf farms operating with the same productive and environmental standards. The system boundary is similar to HSJ's "cradle to farm-gate". Two of the farms will start operations in 2022 and 148 more will be established by 2035. Each farm has an area of 927 ha planted with *Urochloa humidicola* cv. Humidicola (CIAT 679). Table 3.18 summarizes the herd characterization and animal inventory of the farm.

Table 3.18. Herd characterization and animal inventory of a satellite cow-calf farm by animal subcategory.

Animal category (IPCC 2019)	Animal subcategory by breed, LW, lactation and pregnancy	Initial LW, kg	Mature LW kg	Avg LW gain, kg d^{-1}	2022	2023	2024
Cows used to produce offspring for meat	cow_350_non_lact_preg	275	350	0.467	122	72	62
	cow_350_non_lact_non_preg	275	350	0.467	62	216	125
	cow_450_lact_preg	350	450	0	371	379	360
	cow_450_non_lact_non_preg	350	450	0.470	221	207	283
Calves pre-weaning	calf_210	100	210	0.99	92	92	92
	heifer_275	100	275	1.05	522	515	564
Total herd, AU					903	967	968
Grazing area, ha					927	927	927
Stocking rate, AU ha^{-1}					0.97	1.04	1.04

LW: Live weight, AU: 450 kg LW

The economic activity of the satellite cow-calf farm is the production of weaned heifers and calves, which are sold with the same price by kg (Table 3.19) in the market of cattle fattening farms. The resulting cull cows also satisfied this market with a slightly lower price than the weaned calves.

Table 3.19. Characterization and price (2021) at the farm gate of the co-products of the satellite cow-calf farm.

Co-product	Age, months	LW, kg	Price, USD kg^{-1} LW*	Price, USD $head^{-1}$*	2022	2023	2024
Weaned heifer	12	275	1.5	411.9	0	212	335
Weaned calf	7	210	1.5	314.5	0	92	92
Cull cow	20	380	1.3	502.8	0	36	10
Cull cow	>29	450	1.3	595.4	33	155	165

LW: Live weight. *Exchange rate: 4,005.9 COP$ USD^{-1} (xe.com, 14.12.21)

Figure 3.11 shows the annual animal inventory and exported LW, respectively, during the first three years of operation, the period for which data is currently available.

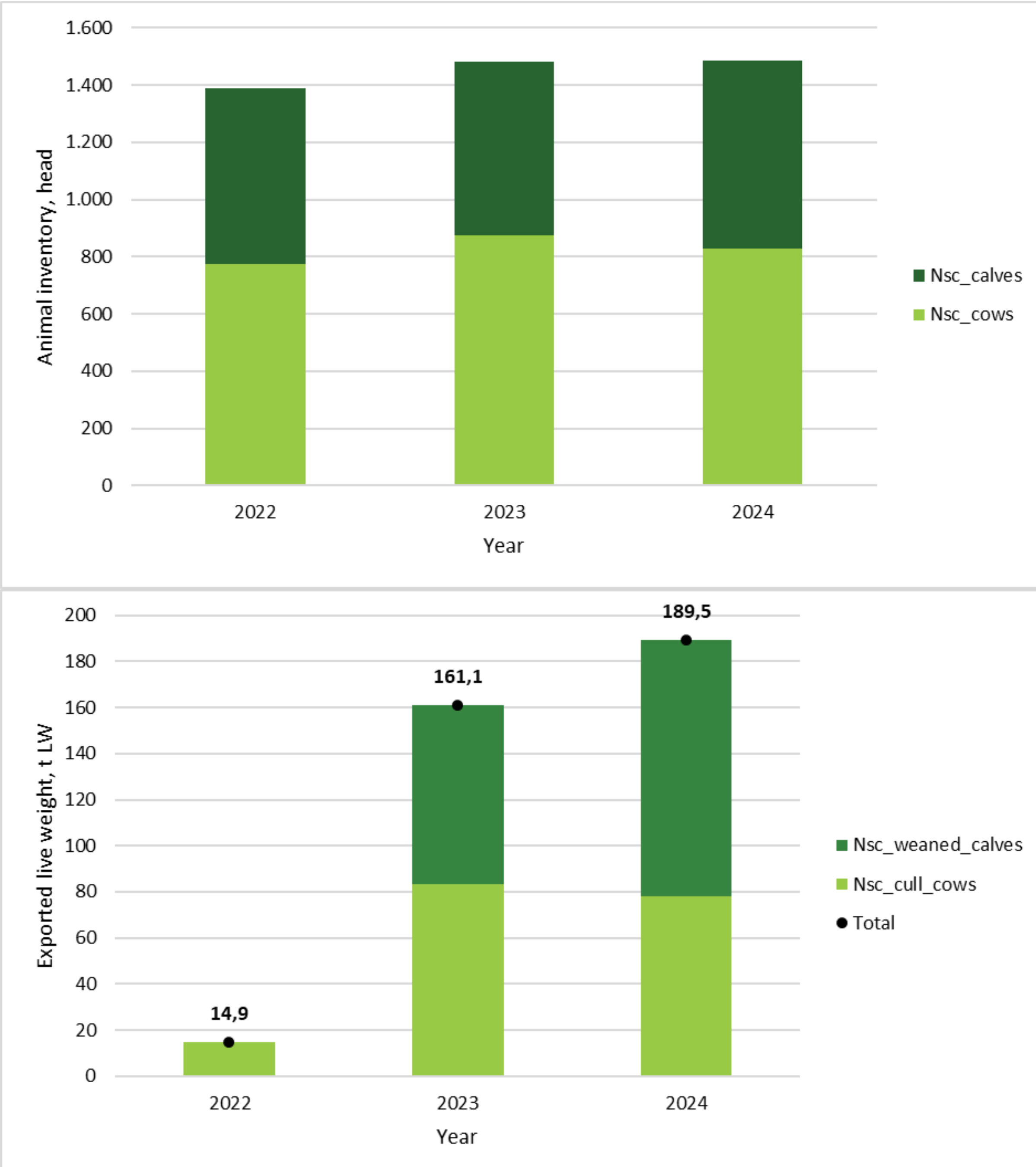


Figure 3.11. Annual animal inventory (up) and exported live weight (LW) (down) of a satellite cow-calf farm.

Compared to HSJ, all animals in the satellite cow-calf farms belong to the breed short-cycle Nelore, moving directly from the breeding farm HSJ. The herd structure is simpler, consisting only of cows and calves. Cows represent between 56 and 59% of the herd, while in HSJ it ranges from 66 to 73% (see Figure 2.3). During the first year of operation, the exported LW is modest with 14.9 t LW. In 2023 this figure is approximately 10.8 times higher leading to a high variability of the annual CFP as shown in Figure 3.12.

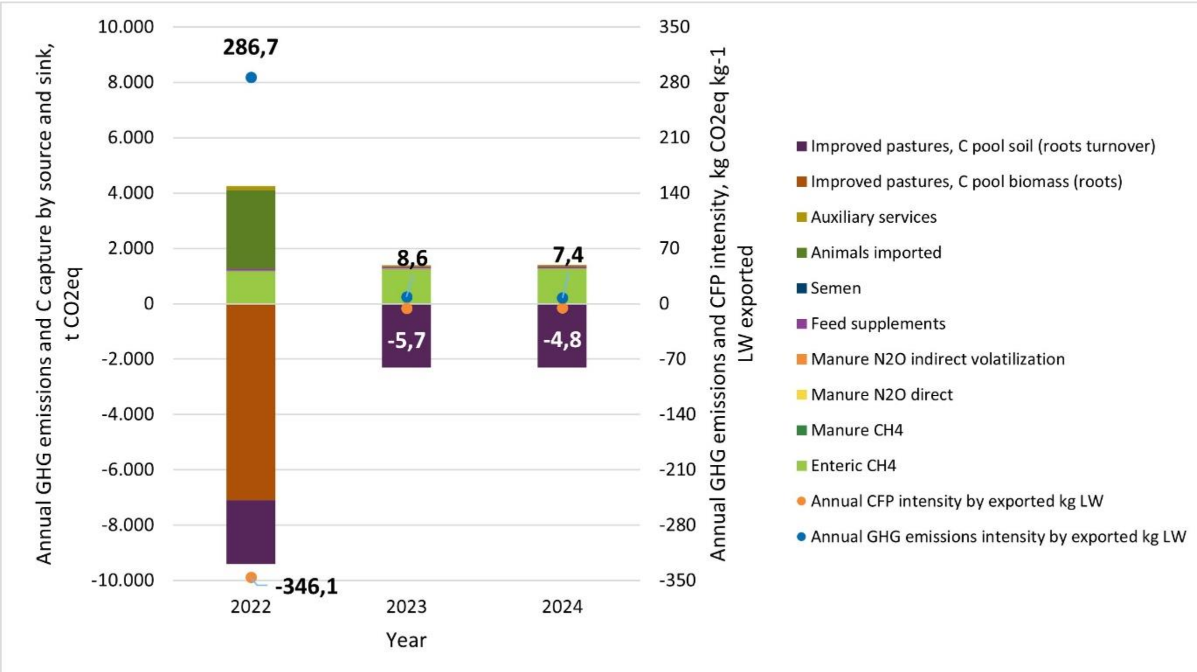


Figure 3.12. Annual greenhouse gas (GHG) emissions and carbon (C) capture by source and sink of the satellite cow-calf farms. Primary y-axis: absolute figures. Secondary y-axis: intensity figures by kg live weight (LW) exported.

The primary contributors of GHG emissions in 2022 were imported animals aimed at establishing the herd. However, if the complete system is to be assessed, i.e. HSJ as a breeding farm plus the satellite cow-calf farm, these GHG emissions have to be removed from the latter to avoid double accounting. In this case, the GHG emissions structure of the satellite cow-calf farm is presented in Figure 3.13 (up) and compared to that of HSJ (down).

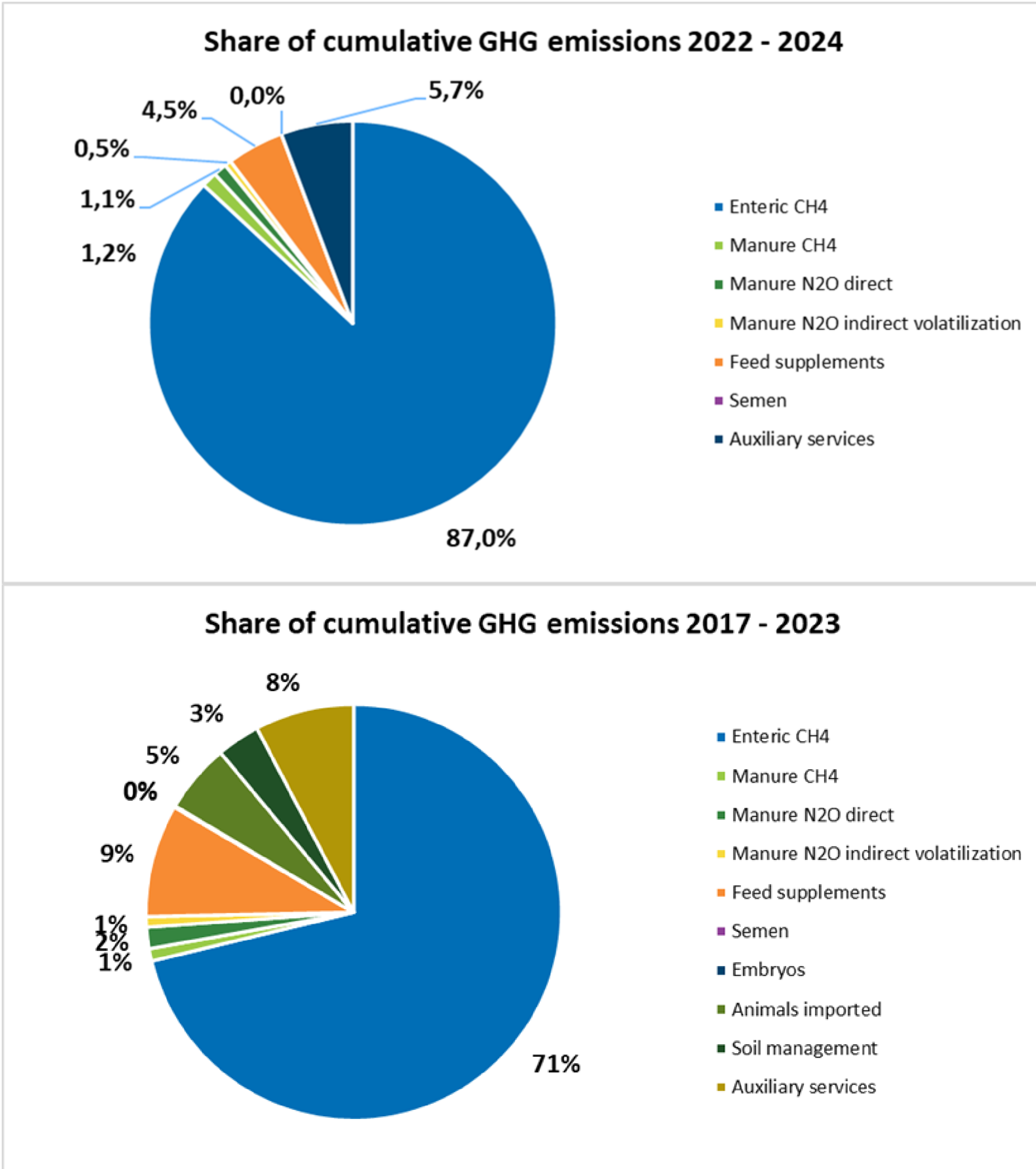


Figure 3.13. Structure of cumulative greenhouse gas (GHG) emissions by source of the satellite cow-calf farms in the period 2022 to 2024 (up) and of HSJ between 2017 to 2023 (down).

The GHG emissions structure of the satellite cow-calf farm is less complex than that of HSJ whereby enteric CH_4 emissions present a higher share (87 vs. 71%). The contribution of the feed supplements of the satellite cow-calf farm is lower due to the absence of males consuming the concentrate used in HSJ (usually with high GHG emissions from maize and soybean meal). The auxiliary services also show a lower share as the shed in the satellite cow-calf farm is shared by four of these units. This means that only a quarter of the GHG emissions are assigned to one farm. In contrast, HSJ has 3 sheds. In the satellite cow-calf farms there are no GHG emissions from soil management as improved pastures are introduced without any amendment. The team of HSJ explained that they didn't see any considerable benefit for the pastures upon applying soil amendments.

The C capture in the satellite cow-calf farms occur in the pastures' roots and in the soil. The first are computed in 2022, year of implementation of the pastures, reflecting the roots' growth. Once its full growth potential is achieved, the biomass growth and turnover enter a steady-state equilibrium, if the pasture is steadily managed properly. Thus, this C accumulation is modelled as one single event. The parameters on above-ground biomass productivity, ratio to below-ground biomass and C content were the same as those for Humidicola in HSJ (Table 3.7) and resulted in 7,089 t CO_2 captured in the 927 ha of grazing area. SOC is a different case where C stock change occurs yearly during a default time of 20 years (IPCC 2019) and accounted for 2,308 t CO_2 yr^{-1} in the 927 ha of grazing area. Again, the parameters used were the same as for HSJ. It's recommended to undertake some field measurements on these farms to validate if they behave in the same way as HSJ.

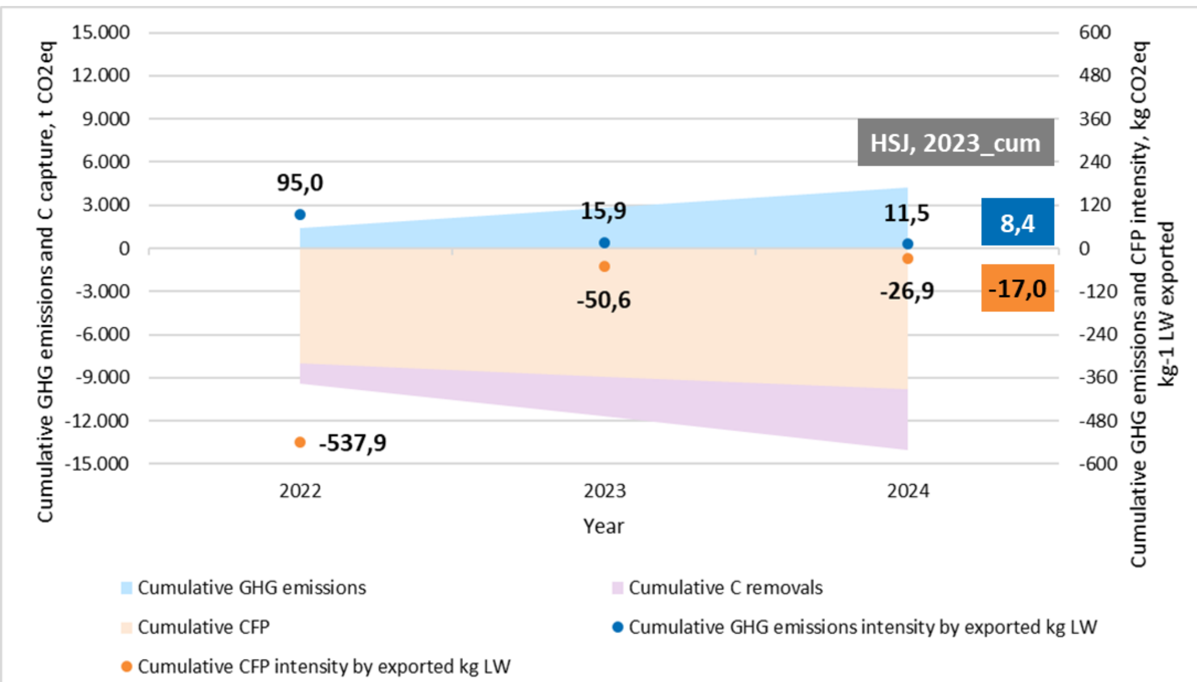


Figure 3.14. Cumulative greenhouse gas (GHG) emissions, carbon (C) capture and carbon footprint (CFP) of the satellite cow-calf farms in the period 2022 to 2024. Primary y-axis: absolute figures. Secondary y-axis: intensity figures by kg live weight (LW) exported. The blue and orange squares show the GHG and CFP intensity, respectively, of the exported LW of HSJ.

Figure 3.14 displays the cumulative GHG emissions (light blue), C capture (light violet) and CFP (light orange) of the satellite cow-calf farms in the period 2022 to 2024. The GHG intensity resulted to 11.5 kg CO_2eq kg^{-1} LW exported, i.e. 37% higher than that of HSJ (8.4 kg CO_2eq kg^{-1} LW exported. This difference lies on the higher animal inventory of HSJ. High shed emissions which occur during the first year of operations are amortized in a period of seven years for HSJ but only three for the satellite cow-calf farms.

Fattening farms

It is foreseen that one fattening farm will start operations in 2028 and 19 more between 2029 to 2033. The fattening farm will have an area of 3,007 ha seeded with Humidicola. The herd structure of the fattening farm is displayed in Table 3.20, and consists of fattening males at different ages. Considering the average daily LW gain corresponding to 0.49 kg $head^{-1}$ d^{-1}, and to the animal inventory, the annual LW production would be around 785.3 t. Farms will use neither fertilizers nor undertake soil amendments.

Table 3.20. Herd structure of the fattening farm

Animal Category	Heads of cattle
Calves (8-20 months)	1,500
Young bulls (20-32 months)	1,455
Young bulls (> 32 months)	1,411

GHG emissions distributed by source is shown in Figure 3.15. The primary source relates to animals, with CH_4 from enteric fermentation the main contributor of total GHG emissions, followed by N_2O emissions from manure deposited on pastures, and finally CO_2 emissions from manufacturing of mineralized salt. There are no GHG emissions arising from soil management due to exclusion of fertilizer and amendments during the establishment and maintenance of pastures. The C capture occurred in the pastures' roots and in the soil, but its contribution was small compared to the total C balance.

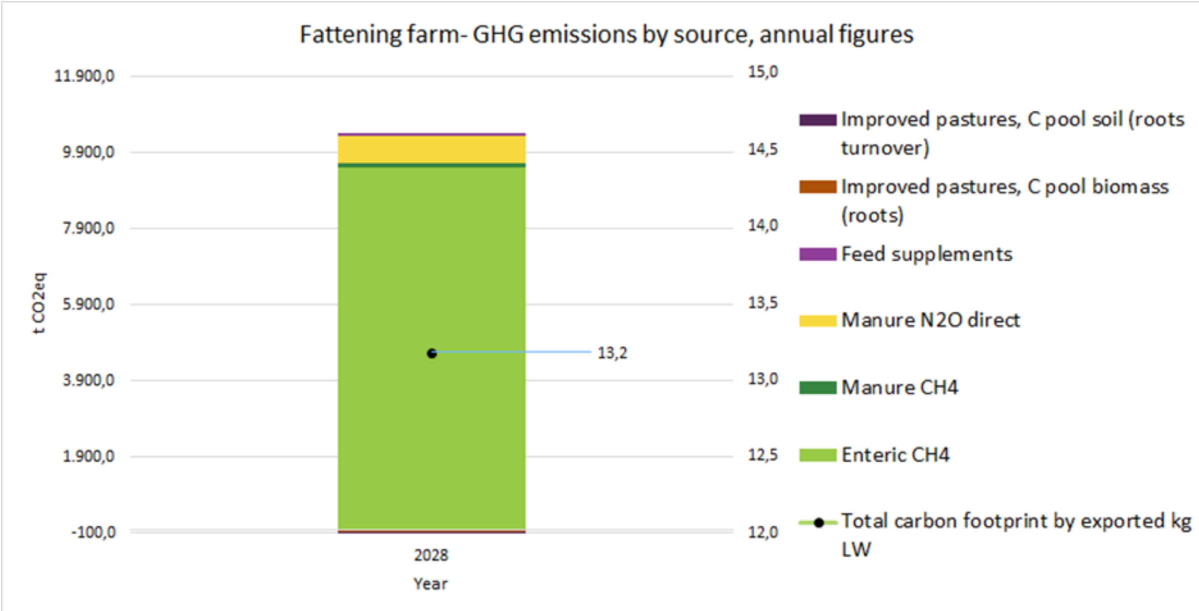


Figure 3.15. Greenhouse gas emissions by source of the fattening farm.

Considering annual GHG emissions, C captures and annual LW produced, the CFP for the fattening farm resulted to 13.2 kg CO_2eq kg^{-1} exported LW. Fattening farms in Colombia are characterized for being extensive, where animals graze on large plots, under low stocking rates, and receive diets that usually include native forage species, leading to low productivity rates. It has been reported a CFP of 18.7 kg CO_2eq kg^{-1} LW exported for Colombian fattening farms (González-Quintero et al. 2021). Differences in CFP between fattening systems (Figure 3.16) are primarily driven by the higher productivity of the fattening farm (0.49 kg head^{-1} d^{-1}) than the average productivity of Colombian fattening farms (0.43 kg head^{-1} d^{-1}), influenced by the inclusion of a pasture of higher quality by the fattening farm. In addition, the fattening farm does not have unproductive animals in the herd, which also positively influenced its CFP.

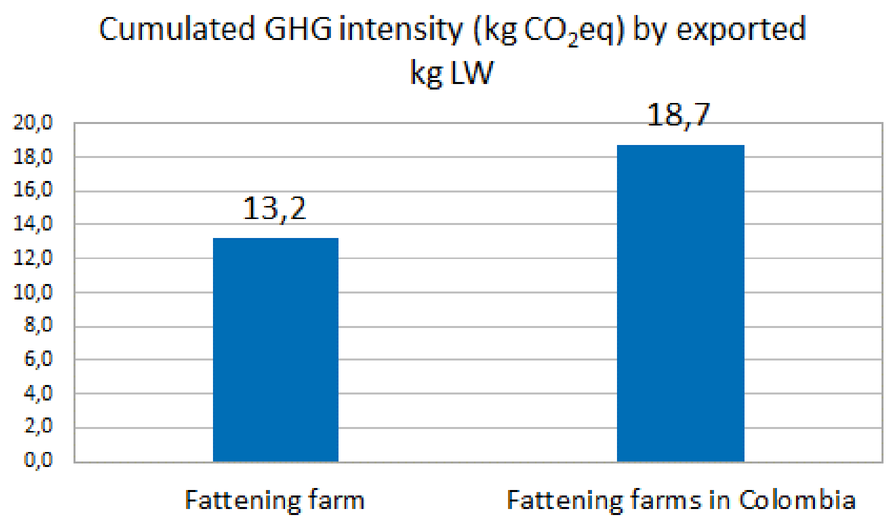


Figure 3.16. Cumulative greenhouse gas (GHG) emission intensities by exported kg live weight (LW) for the fattening farm vs. Colombian fattening farms.

Slaughterhouse activities

Slaughterhouses represent a major source of GHG emissions, and this is the rational for inclusion in the Sustainable Livestock NAMA (Nationally Appropriate Mitigation Actions): there is no concrete data on their EFs because there is no management standard. Waste from this system is usually partially treated and deposited in water bodies or in oxidation lagoons, extending their emitting time. Having biodigesters are recommended in order to produce biogas for heating boilers and producing a by-product called biol, which is rich in N (Comité NAMA Bovina 2021).

Energy use is the most important source of GHG emissions in slaughterhouse operations (Desjardins et al. 2012; Mogensen et al. 2016; Presumido et al. 2017). There is consensus that the slaughter process consumes heat, electricity, water and generates wastewater that goes to treatment. However, very few reports still detail the emissions in each of these process stages. Additionally, the existing reports are not uniform in the methodology, coefficients, and EFs they use, making it very difficult to distinguish them (Mogensen et al. 2016).

Slaughtered animals are processed into four types of products: edible products, hides, a variety of other by-products that can be utilized, and specified risk materials (SRM) that need to be destroyed. Adequate disposal or use of waste, for example, the use of by-products and hides should thus be included in the calculations. Finally, total GHG emissions can become neutral or negative as the net environmental burden decreases through proper management practices (Mogensen et al. 2016).

Although Mogensen et al. (2016) found emissions from slaughterhouse operations ranging from 0.1-0.2 kg CO_2eq kg^{-1} edible product, given the scarcity and lack of uniformity of the few existing data, it has been inferred that GHG emissions from transport and slaughterhouse operations are close to 2% of the total emissions produced during the animal production cycle (Desjardins et al. 2012; Mogensen et al. 2016; Presumido et al. 2017).

Cattle transportation

In the product system "Cradle to slaughterhouse-gate" the animals are transported twice: from HSJ to the fattening farm and from the fattening farm to the slaughterhouse. Table 3.21 shows the corresponding activity data.

Table 3.21. Activity data for cattle transport.

Transport	Distance, km	Days	LW loss, % LW , best case[a]	LW loss, % LW, worst case[a]	Activity (ecoinvent 2019)
HSJ to fattening farm in Puerto Lopez	600	4	3%	7%	Transport, freight, inland waterways, barge {RoW}
Fattening farm to slaughterhouse	90	0.5	3%	7%	Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}

LW: live weight, d: day, RoW: rest of the world.
a: The assumptions for the best and worst case were made based on Bavera (2006), Carnetec (2018) and Gallo (2001)

During transport, cattle lose weight due to the energy spent by animals to cope with stressful situations to which they are exposed. These losses occur mainly via withdrawal of the intestinal content, urine excretion, perspiration, and elimination of water through the lungs (Bavera 2006). The reviewed literature focuses on one day journeys (Bavera 2006, Carnetec 2018, Gallo 2001). The transport from HSJ to the fattening farm however, takes four days. The assumption was made that the major part of weight loss occurs at the beginning of the transport as it corresponds to the withdrawal of the intestinal content. Further weight from the tissues can get lost (Bavera 2006) but they are not expected to be as large as the beginning (expert judgement at CIAT). To tackle this uncertainty, two alternatives were calculated: a best and a worst case - with weight loss during the transport of 3 and 7%, respectively. According to information gathered from HSJ, the animals are fed with pasture cuts from the farm leading to some cattle GHG emissions (described in Part 2 of this report).

Greenhouse gas emissions "Cradle to slaughterhouse-gate"

The EFs calculated in the previous sections for the activities within the product system "Cradle to slaughterhouse-gate" come together in Figure 3.17. Additionally, the EF for HSJ operations, i.e. 8.4 kg CO_2eq kg^{-1} LW (cumulative of the BL scenario) (see Part 2).

The mass flow of LW needed to produce 1 kg beef is displayed above the arrows as follows: 0.88 kg LW leaves HSJ and is transported by a barge run by diesel 600 km over the river "Meta". The LW loss is assumed to be 7% resulting in 0.82 kg LW arriving at the fattening farm. The ratio of the input:output LW was calculated based on the data reported by HSJ, i.e. 2.6 (210 kg LW input and 550 kg LW output). The mature LW of 2.15 kg leaves the fattening farm by a diesel-engine lorry, where again 7% is lost. The conversion efficiency at the slaughterhouse is assumed to be 50% resulting in the production of 1 kg beef. The green values in Figure 3.17 indicates the results under the best case assumption of 3% LW lost during the transport.

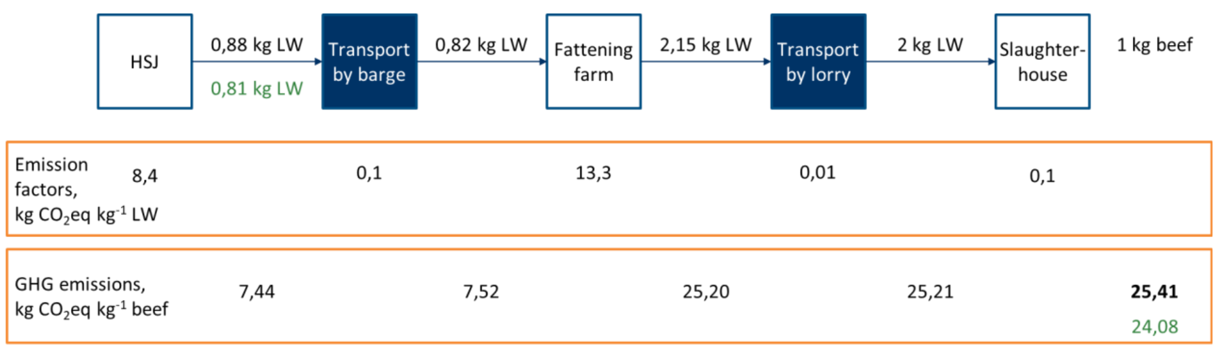


Figure 3.17. Greenhouse gas (GHG) emissions of the product system "Cradle to slaughterhouse-gate". LW: live weight.

The total specific GHG emissions intensities are 25, 42 and 24.08 kg CO_2eq kg^{-1} beef, assuming 7 and 3% LW loss at transport. Results are not comparable in Colombia as this is the first time that the GHG emissions are calculated until the slaughterhouse gate. Mogensen et al. (2016) report 30 – 45 kg CO_2eq kg^{-1} beef for young animals of beef systems in Denmark. In the database Agrifootprint v.5 the GHG intensity for 1 kg beef in Ireland can be found, at 35 kg CO_2eq. Given the multiple assumptions made for the calculation in this study, it would be premature to compare these results directly. However, the figures are in the same order of magnitude and constitute as a basis for further analysis. The C removals associated to this product system will be those from the farms shown in the previous sections.

Carbon footprint at the corporate level

GHG emissions were also assessed at the corporate level, specifically transport to HSJ of employees and business partners to the farm as it is associated with fossil fuel burning. Authors of this study however, did not receive data on this matter. The compliance to some standards like e.g. the Greenhouse Gas Protocol (WRI and WBC 2004; 2011) and ISO 14064-1:2018 “Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals” may be needed for certain climate certification schemes. Depending on HSJ plans, travel data is crucial, as well as that of energy consumption and infrastructure of the administrative activities of the company. Carbon neutrality claims should integrate operations of the whole organization (Finkbeiner and Bach 2021).

References

Agrosavia. 2020. AlimenTro. Colombian Corporation for Agricultural Research. alimentro.agrosavia.co, (checked on 9/3/2020).

Albrecht A; Kandji ST. 2003. Carbon sequestration in tropical agroforestry systems. Agriculture, Ecosystems and Environment 99(1–3):15–27. doi: 10.1016/S0167-8809(03)00138-5

Alvarez-Hess PS; Little SM; Moate PJ; Jacobs JL; Beauchemin KA; Eckard RJ. 2019. A partial life cycle assessment of the greenhouse gas mitigation potential of feeding 3-nitrooxypropanol and nitrate to cattle. Agricultural systems 169:14–23. doi: 10.1016/j.agsy.2018.11.008

Ayala Prieto KJ; Melo Velandia AA; Zuluaga Salazar AF; Chica Sepúlveda DM; Gómez Botero JC; Uribe Trujillo F; Chará Orozco JD; Alvarado Cortés C. 2017. Manual de usos de la tierra. Proyecto Ganadería Colombiana Sostenible, Bogotá, Colombia. bit.ly/3JjR2rs

Battle-Bayer L; Batjes NH; Bindraban PS. 2010. Changes in organic carbon stocks upon land use conversion in the Brazilian Cerrado: A review. Agriculture, Ecosystems and Environment,137: 47–58. doi: 10.1016/j.agee.2010.02.003

Bavera GA. 2006. Debaste o merma. Cursos de Producción Bovina de Carne. Universidad Nacional de Río Cuarto. Córdoba, Argentina. bit.ly/3GHg2XO (checked on 12/15/2021).

Blas C de; García-Rebollar P; Gorrachategui M; Mateos GG. 2019. Tablas FEDNA 2019, 4ª edición. Fundación Española para el Desarrollo de la Nutrición Animal, Madrid, España. fundacionfedna.org/ingredientes-para-piensos (checked on 10/17/2021).

Brummell ME; Farrell RE; Siciliano SD. 2012. Greenhouse gas soil production and surface fluxes at a high arctic polar oasis. Soil Biology and Biochemistry 52:1–12. doi: 10.1016/j.soilbio.2012.03.019

Burke K. 2021. Soil carbon sequestration on farms alone won't absolve our daily emission sins. The Guardian. bit.ly/33bQhkO (checked on 12/20/2021).

Bustamante MMC; Corbeels M; Scopel E; Roscoe R. 2006. Soil carbon and sequestration potential in the Cerrado Region of Brazil. In: Lal R; Cerri CC (eds.) Carbon Sequestration in soils of Latin America. pp. 285–304. doi: 10.1201/9781482298031

Canisares LP; Poffenbarger H; Brodie EL; Sorensen PO; Karaoz U; Villegas DM; Arango J; Momesso L; Crusciol CAC; Cantarella H. 2021. Legacy effects of intercropping and nitrogen fertilization on soil N cycling, nitrous oxide emissions, and the soil microbial community in tropical maize production. Frontiers in Soil Science 1:746433. doi: 10.3389/fsoil.2021.746433

Carnetec. 2018. El efecto de la merma en el sacrificio animal. CONtexto ganadero. https://bit.ly/3LubibA. (checked on 12/15/2021).

Carvalho JLN; Raucci GS; Cerri CEP; Bernoux M; Feigl BJ; Wruck FJ; Cerri CC. 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil and Tillage Research 110: 175–186. doi: 10.1016/j.still.2010.07.011

Comité NAMA Bovina. (2021) Acción de mitigación nacionalmente apropiada NAMA de la ganadería bovina sostenible en Colombia. Gobierno de Colombia, Bogotá, Colombia. hdl.handle.net/10568/114685.

Conant RT; Paustian K; Elliott ET. 2001. Grassland management and conversion into grassland: effects on soil carbon. Applied Ecology 11(2):343–355. doi: 10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Corazza EJ; Silva JE; Resck DVS; Gomes AC. 1999. Behavior of different management systems as a source or sink of C-CO_2 in relation to Cerrado type vegetation. Revista Brasileira de Ciência do Solo 23:425–432. (In Portuguese). doi: 10.1590/S0100-06831999000200025

Corpoica (Corporación Colombiana de Investigación Agropecuaria). 2018. Results of laboratory tests of herbaceous biomass in Hacienda San Jose. Corpoica, Bogotá, Colombia.

Costa C Jr, Villegas DM, Bastidas M, Rubio NM, Rao I and Arango J (2022) Soil carbon stocks and nitrous oxide emissions of pasture systems in Orinoquía region of Colombia: Potential for developing land-based greenhouse gas removal projects. Front. Clim. 4:916068. doi: 10.3389/fclim.2022.916068

Costa Jr C; Corbeels M; Bernoux M; Píccolo MC; Siqueira Neto M; Feigl BJ; Cerri CEP; Cerri CC; Scopel E; Lal R. 2013. Assessing soil carbon storage rates under no-tillage: comparing the synchronic and diachronic approaches. Soil and Tillage Research 134:207–212. doi: 10.1016/j.still.2013.08.010.

Costa Jr C; Seabaeur M; Schwarz M; Dittmer K; Wollenberg E. 2021. Scaling soil organic carbon sequestration for climate change mitigation. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Wageningen, The Netherlands. hdl.handle.net/10568/114846

Cusack DF; Kazanski CE; Hedgpeth A; Chow K; Cordeiro AL.; Karpman J; Ryals R. 2021. Reducing climate impacts of beef production: A synthesis of life cycle assessments across management systems and global regions. Global Change Biology 27(9):1721–1736. doi: 10.1111/gcb.15509

Desjardins RL; Worth DE; Vergé XP; Maxime D; Dyer J; Cerkowniak D. 2012. Carbon footprint of beef cattle. Sustainability 4(12):3279-3301. 10.3390/su4123279

Dijkstra J; Bannink A; France J; Kebreab E; Van Gastelen S. 2018. Antimethanogenic effects of 3-nitrooxypropanol depend on supplementation dose, dietary fiber content, and cattle type. Journal of Dairy Science 101(10):9041–9047. doi: 10.3168/jds.2018-14456

Dubeux Jr. JCB; Blount ARS; Mackowiak C; Santos ERS; Pereira-Neto JD; Riveros U; Garzia L; Jaramillo DM; Ruiz-Moreno M. 2017. Biological N_2 fixation, belowground responses, and forage potential of rhizoma peanut cultivars. Crop Science 57:1027–1038. doi: 10.2135/cropsci2016.09.0810

Duin EC; Wagner T; Shima S; Prakash D; Cronin B; Yáñez-Ruiz DR; Duval S; Rümbeli R; Stemmler RT; Thauer RK; Kindermann M. 2016. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. Proceedings of the National Academy of Sciences 113(22):6172–6177. doi: 10.1073/pnas.1600298113

ecoinvent. 2019. ecoinvent data v3.6. Zürich, Switzerland. www.ecoinvent.org.

Ellert BH; Bettany JR. 1996. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Canadian Journal of Soil Science 75(4):529–538. doi: 10.4141/cjss95-075

Enciso-Valencia KJ; Rincón-Castillo Á; Ruden DA; Burkart S. 2021. Risk reduction and productivity increase through integrating *Arachis pintoi* in cattle production systems in the Colombian Orinoquía. Frontiers in Sustainable Food Systems 5:666604. doi: 10.3389/fsufs.2021.666604

Etter A; Sarmiento A; Romero MH. 2010. Land use changes (1970–2020) and carbon emissions in the Colombian Llanos. In Hill MJ; Hanan NP, eds. Ecosystem function in Savannas: Measurement and modeling at landscape to global scales. CRC Press, Boca Raton, FL, USA. p. 383–402. doi: 10.1201/b10275-32

FAO. 2012. Global ecological zones for FAO forest reporting: 2010 update. Forest Resources Assessment Working Paper 179. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. fao.org/3/ap861e/ap861e00.pdf (checked on 2/16/2021).

FAO. 2021. GloSIS Country Driven Global Datasets. Food and Agriculture Organization of the United Nations (FAO). 54.229.242.119/GloSIS

Fisher MJ; Braz SP; Santos RSM dos; Urquiaga S; Alves BJR; Boddey RM. 2007. Another dimension to grazing systems: Soil carbon. Tropical Grasslands 41:65–83. bit.ly/34T1ze7

Fisher MJ; Rao IM; Ayarza MA; Lascano CE; Sanz JI; Thomas RJ; Vera RR. 1994. Carbon storage by introducing deep-rooted grasses in the South American savannas. Nature 371:236–238. doi: 10.1038/371236a0

Gallo C; Espinoza MA; Gasic J. 2001. Efectos del transporte por camión durante 36 horas con y sin período de descanso sobre el peso vivo y algunos aspectos de calidad de carne en bovinos. Archivos de Medicina Veterinaria 33(1):43–53. doi: 10.4067/S0301-732X2001000100005

Godde CM; Boer IJM de; Ermgassen E zu; Herrero M; van Middelaar CE; Muller A; Röös E; Schader C; Smith P, van Zanten HHE; Garnett T. 2020. Soil carbon sequestration in grazing systems: managing expectations. Climatic Change 161:385–391. doi: 10.1007/s10584-020-02673-x

González-Quintero R; Sánchez-Pinzón MS; Bolivar-Vergara DM; Chirinda N; Arango J; Pantevez HA Correa-Londoño G; Barahona-Rosales R. 2020: Technical and environmental characterization of very small, small, medium and large cow-calf operations in Colombia. Revista Mexicana de Ciencias Pecuarias 11(1):183–204. doi: 10.22319/rmcp.v11i1.4902

González-Quintero R; Bolívar-Vergara DM; Chirinda N; Arango J; Pantevez H; Barahona-Rosales R; Sánchez-Pinzón MS. 2021: Environmental impact of primary beef production chain in Colombia: Carbon footprint, non-renewable energy and land use using Life Cycle Assessment. Science of The Total Environment 773:145573. doi: 10.1016/j.scitotenv.2021.145573

Hurlbert SH, 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs 54:187–211. doi: 10.2307/1942661

IDEAM; PNUD; MADS, DNP; Cancillería. 2018: Inventario nacional de gases de efecto invernadero (GEI) de Colombia. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM); Programa de las Naciones Unidas para el Desarrollo (PNUD); Ministerio de Ambiente y Desarrollo Sostenible (MADS); Departamento Nacional de Planeación (DNP); Ministerio de Relaciones Exteriores. Bogota, Colombia. https://bit.ly/3BjGOom

IGAC. 2012. Regiones geográficas de Colombia. Instituto Geográfico Agustín Codazzi (IGAC), Bogotá, Colombia.

INRAE; CIRAD; AFZ. 2021. Tables of composition and nutritional values of feed materials INRAE CIRAD AFZ. French National Research Institute for Agriculture, Food, and Environment (INRAE); French agricultural research and cooperation organization (CIRAD); French association for animal production (AFZ). feedtables.com (checked on 11/20/2021).

IPCC (Intergovernmental Panel on Climate Change). 2006a. IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use. Institute for Global Environmental Strategies (IGES), Hayama, Japan. ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC (Intergovernmental Panel on Climate Change). 2006b. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Institute for Global Environmental Strategies (IGES), Hayama, Japan. ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013. The physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, MA, USA. ipcc.ch/report/ar5/wg1

IPCC (Intergovernmental Panel on Climate Change). 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. IPCC. Switzerland. ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories

ISO 14021:2016, 2016-07: Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling). iso.org/standard/66652.html

ISO 14026:2017, 2018-12: Environmental labels and declarations – Principles, requirements and guidelines for communication of footprint information. iso.org/standard/67401.html

ISO 14040:2006, 2009-11: Environmental management – Life cycle assessment – Principles and framework. iso.org/standard/37456.html

ISO 14044:2006, 2006-10: Environmental management - Life cycle assessment - Requirements and guidelines. iso.org/standard/38498.html

ISO 14064-1:2018, 2016-06: Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. iso.org/standard/66453.html

ISO 14067:2018, 2019-02: Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification. iso.org/standard/71206.html

Jungbluth N. 1997. Life-Cycle-Assessment for stoves and ovens. UNS Working Paper No. 16. Umweltnatur- und Umweltsozialwissenschaften, Zürich, Switzerland. bit.ly/3suIKWW (checked on 1/26/2021).

Karwat H; Moreta D; Arango J; Núñez J; Rao I; Rincón Á; Rashe F; Cadish G. 2017. Residual effect of BNI by *Brachiaria humidicola* pasture on nitrogen recovery and grain yield of subsequent maize. Plant and Soil 420(1–2):389–406. doi: 10.1007/s11104-017-3381-z

Kesicki F; Strachan N. 2011. Marginal abatement cost (MAC) curves: confronting theory and practice. Environmental Science & Policy 14(8):1195–1204. doi: 10.1016/j.envsci.2011.08.004

Kristensen T; Mogensen L; Knudsen MT; Hermansen JE. 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livestock Science 140(1–3):136–148. doi: 10.1016/j.livsci.2011.03.002

Maia SMF; Ogle SM; Cerri CEP; Cerri CC. 2009. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Groso states, Brazil. Geoderma 149(1–2):84–91. doi: 10.1016/j.geoderma.2008.11.023

Minasny B; Malone BP; McBratney AB; Angers DA; Arrouays D; Chambers A; Chaplot V; Chen ZS; Cheng K; Das BS; Field DJ; Gimona A; Hedley CB; Hong SY; Mandal B; Marchant BP; Martin M; McConkey BG; Mulder VL; O'Rourke S; Richer-de-Forges AC; Odeh I; Padarian J; Paustian K; Pan G; Poggio L; Savin I; Stolbovoy V; Stockmann U; Sulaeman Y; Tsui CC; Vågen TG; van Wesemael B; Winowiecki L. 2017. Soil carbon 4 per mille. Geoderma 292:59–86. doi: 10.1016/j.geoderma.2017.01.002

Mogensen L; Nguyen TLT; Madsen NT; Pontoppidan O; Preda T; Hermansen JE. 2016. Environmental impact of beef sourced from different production systems - focus on the slaughtering stage: input and output. Journal of Cleaner Production 133:284–293. doi: 10.1016/j.jclepro.2016.05.105

Muñoz I; Schmidt JH. 2016. Methane oxidation, biogenic carbon, and the IPCC's emission metrics. Proposal for a consistent greenhouse-gas accounting. The International Journal of Life Cycle Assessment 21(8):1069–1075. doi: 10.1007/s11367-016-1091-z

Neira FH; Turriago JD; Berrio V. 2017. Estimation of reference soil organic carbon (SOC) for mineral soils of Colombia. In FAO (Ed.): Proceedings of the Global Symposium on Soil Organic Carbon. Rome, Italy, 21–23 March 2017. p. 80–86. fao.org/3/i7565e/i7565e.pdf

OECD; IEA; Eurostat. 2004: Energy Statistics Manual. Organisation for Economic Cooperation and Development (OECD); International Energy Agency (IEA): Statistical Office of the European Communities, Paris, France. https://bit.ly/3stbGyo (checked on 26.01.21).

Peñuela L; Fernandez AP; Castro F; Ocampo A. 2011. Uso y manejo de forrajes nativos en la sabana inundable de la Orinoquia. The Nature Conservancy (TNC); Fundación Horizonte Verde (FHV), Bogotá, Colombia. bit.ly/365ltmO

Pereira JM; Rezende CP; Borges AMF; Homem BGC; Casagrande DR; Macedo TM; Alves BJR; Sant'Anna SAC de; Urquiaga S; Boddey RM. 2019. Production of beef cattle grazing on *Brachiaria brizantha* (Marandu grass)—*Arachis pintoi* (forage peanut cv. Belomonte) mixtures exceeded that on grass monocultures fertilized with 120 kg N/ha. Grass and Forage Science 75:28–36. doi: 10.1111/gfs.12463

Presumido PH; Sousa FR de; Gonçalves A; Dal Bosco T; Feliciano M. 2017. Pegada de carbono da produção de carne bovina no Nordeste de Portugal: comparação entre dois sistemas produtivos. Livro de atas do III Congresso Ibero-Americano de Empreendedorismo, Energia, Ambiente e Tecnología. p. 303-308. hdl.handle.net/10198/16012

Qiu J; Li C; Wang L; Tang H; Li H; Van Ranst E. 2009. Modeling impacts of carbon sequestration on net greenhouse gas emissions from agricultural soils in China. Global Biogeochemical Cycles 23(1):GB1007. doi: 10.1029/2008GB003180

Ramírez-Restrepo CA; Vera RR; Rao IM. 2019. Dynamics of animal performance, and estimation of carbon footprint of two breeding herds grazing native neotropical savannas in eastern Colombia. Agriculture, Ecosystems & Environment 281:35–46. doi: 10.1016/j.agee.2019.05.004

Rincón A; Villalobos M. 2021. Animal production in three *Urochloa decumbens*-legume pastures in the Eastern Plains of Colombia. Tropical Grasslands-Forrajes Tropicales 9(2):192–205. (In Spanish). doi: 10.17138/TGFT(9)192-205

Robertson GP; Groffman PM. 2007. Nitrogen transformations. In: Paul EL, ed. Soil Microbiology, Ecology and Biochemistry, 3rd edn. Academic Press, Cambridge, MA, USA. p. 341–364. doi: 10.1016/B978-0-08-047514-1.50017-2

Smith P. 2014. Do grasslands act as a perpetual sink for carbon? Global change biology 20(9):2708–2711. doi: 10.1111/gcb.12561

statista (2021): Durchschnittlicher Kraftstoffverbrauch der in Deutschland zugelassenen Pkw in den Jahren von 2010 bis 2019. (in Liter/100 Kilometer). bit.ly/3I7LRed (checked on 27.01.21).

Stewart KJ; Brummell ME; Farrell RE; Siciliano SD. 2012. N_2O flux from plant-soil systems in polar deserts switch between sources and sinks under different light conditions. Soil Biology and Biochemistry 48:69–77. doi: 10.1016/j.soilbio.2012.01.016

Subbarao GV; Nakahara K; Hurtado MP; Ono H; Moreta DE; Salcedo AF; Yoshihashi AT; Ishikawa T; Ishitani M; Ohnishi-Kameyama M; Yoshida M; Rondon M; Rao IM; Lascano CE; Berry WL; Ito O. 2009. Evidence for biological nitrification inhibition in *Brachiaria* pastures. Proceedings of the National Academy of Sciences 106(41):17302–17307. doi: 10.1073/pnas.0903694106.

Teutscherova N; Vazquez E; Arango J; Arevalo A; Benito M; Pulleman M. 2019. Native arbuscular mycorrhizal fungi increase the abundance of ammonia-oxidizing bacteria, but suppress nitrous oxide emissions shortly after urea application. Geoderma 338:493–501. doi: 10.1016/j.geoderma.2018.09.023

UPME (Unidad de Planeación Minero energética). 2019: Sistema de Transmisión Nacional Energía Eléctrica Plan Actual. UPME, Bogotá, Colombia. https://bit.ly/3HSHcfK (checked on 9/13/2021).

Villegas D; Arevalo A; Nuñez J; Mazabel J; Subbarao G; Rao I; De Vega J; Arango, J. 2020. Biological nitrification inhibition (BNI): Phenotyping of a core germplasm collection of the tropical forage grass *Megathyrsus maximus* under greenhouse conditions. Frontiers in Plant Science 11:820. doi: 10.3389/fpls.2020.00820

Villegas DM; Bastidas M; Matiz-Rubio N; Ruden A; Rao I; Hyman G; Arango J, Baedeker T, Cando L, Ramirez Diaz M, Teillard F, Costa Jr C. 2021. Soil carbon stocks in tropical pasture systems in Colombia's Orinoquía region: supporting readiness for climate finance. CCAFS Info Note. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Wageningen, The Netherlands. hdl.handle.net/10568/116231

World Bank. 2021a. Opportunities for climate finance in the livestock sector: Removing obstacles and realizing potential. World Bank, Washington, DC, USA. hdl.handle.net/10986/35495

World Bank. 2021b. Soil organic carbon MRV sourcebook for agricultural landscapes. World Bank, Washington, DC, USA. hdl.handle.net/10986/35923

WRI; WBCSD (2004): The greenhouse gas protocol. A corporate accounting and reporting Standard, Revised edition. Washington, DC, USA; Conches-Geneva, Switzerland. ghgprotocol.org/corporate-standard

WRI; WBCSD (2011): Corporate value chain (Scope 3) accounting and reporting standard. Supplement to the GHG Protocol Corporate Accounting and Reporting Standard. Washington, DC, USA; Conches-Geneva, Switzerland. ghgprotocol.org/standards/scope-3-standard

YARA (2014): Technical Data Sheets. Granular Urea. Granular Potassium Chloride. Diammonium Phosphate. Yara Colombia.

Bioversity International and the International Center for Tropical Agriculture (CIAT) are part of CGIAR, a global research partnership for a food-secure future.

Bioversity International is the operating name of theInternational Plant Genetic Resources Institute (IPGRI).

The Americas Hub

Km 17 Recta Cali-Palmira, CP 763537
P.O. Box 6713
Cali, Colombia
Tel. +57 2 445 0000

www.bioversityinternational.org
www.ciat.cgiar.org
www.cgiar.org

Rev. 2022/02/28