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Economic evaluation of supplementation with *Canavalia brasiliensis* CIAT 17009 in a Colombian dual-purpose cattle system

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Introduction: In the dual-purpose cattle systems of the Colombian Caribbean region, the grass *Bothriochloa pertusa* (Colosuana) is predominant. Despite its overall good performance, its productivity and quality significantly decline during dry seasons, leading to feed shortages and production slumps. Supplementation with legumes and improvement of pasture conditions are effective measures to address these challenges, but their adoption remains low in the region, which, among others, is related to limited availability to information on both legume cultivation and conservation, seed scarcity, and financial constraints.

Methods: Against this background and with the purpose of contributing to closing the information gap, this study provides an economic assessment to determine the feasibility of adopting pasture improvement measures and legume hay supplementation. Based on information from agronomic evaluations conducted by AGROSAVIA, the economic analysis compares a traditional dual-purpose grazing system (*Bothriochloa pertusa* monoculture) with 3 improved systems that contemplate both pasture improvement of *Bothriochloa pertusa* and supplementation with hay of the legume *Canavalia brasiliensis* at 3 different inclusion levels (0.5, 1.0, 1.5% dry matter of animal liveweight).

Results and discussion: The results show that pasture improvement and supplementation significantly improve the productivity of the production system and thus its economic performance, as documented by improved financial indicators, such as the Net Present Value, Internal Rate of Return, or Benefit–Cost Ratio.

KEYWORDS

improved forages, legumes, dual-purpose cattle, profitability indicators, Monte Carlo simulation

1 Introduction

According to the 2022 Livestock Census, the cattle population in Colombia exceeds 29 million animals. At the departmental level, the main producers are the departments of Antioquia (11.2%), Córdoba (7.8%), Meta (7.8%), Caquetá (7.5%), Casanare (7.5%), Santander (5.7%), Magdalena (5.5%), and Cesar (5.5%) (ICA, 2022). In economic terms, the cattle sector contributes 1.3% to the national, 19.8% to the agricultural, and 47.2% to the livestock gross domestic products, respectively

(FEDEGAN, 2023). 57% of the cattle production systems are dual-purpose, 29% specialized in beef production, and 14% in dairy (Contexto Ganadero, 2020). Recent information shows a decrease in milk production, with an annual variation for the second quarter of 2022 of -2.5% , which is related to high production costs, especially in the highlands, and a change in the orientation of holdings towards the beef market (FEDEGAN, 2022). Regarding beef cattle, between January and August 2022, slaughter decreased by 6.2% , mainly caused by increases in beef prices and related reductions in demand, as well as by augmented slaughter weight (FEDEGAN, 2022). In the face of weakened market conditions, it is thus necessary to promote the development of more efficient, competitive, and high-quality production systems, and especially the incorporation of improved forage technologies is an important strategy for this purpose since feed contributes up to 70% of the total production costs (Strauch and Stockton, 2013).

In the Colombian Caribbean, the grass *Bothriochloa pertusa* has spread widely and is predominant in the dry savannas of the region (Tapia-Coronado et al., 2019; Mojica-Rodríguez, 2017; Cuadrado et al., 1998). This grass exhibits good performance during the rainy season but faces issues of forage production and quality during dry periods (Castro-Rincón et al., 2016), requiring the inclusion of supplemental feed in the cattle's diet (Cuadrado et al., 1998). Empirical evidence supports the effectiveness of legumes in this regard (Castro-Rincón et al., 2016; Ullrich et al., 1994; Vera et al., 1996; Holmann and Lascano, 2004). An example is the supplementation with *Canavalia brasiliensis* CIAT 17009 in dual-purpose cattle systems (Castro-Rincón et al., 2016).

With the aim of selecting the best legumes in terms of forage production, quality, and animal response, the Colombian Agricultural Research Corporation AGROSAVIA evaluated the use of *Canavalia brasiliensis* hay as a supplement to grazing with *Bothriochloa pertusa* in the department of César in 2013. Positive results were observed in terms of milk productivity during the dry season. Research assessing the economic viability of supplementation with *Canavalia brasiliensis* has not yet been conducted but clarity in that regard would help cattle farmers in adoption decision making and provide inputs for other actors supporting the adoption and dissemination process. Despite the advantageous attributes of *Canavalia brasiliensis*, their use as supplement does come with higher costs compared to the *Bothriochloa pertusa* grazing system. Consequently, it is crucial to furnish data regarding the profitability of these technologies to streamline their dissemination and adoption, recognizing their positive impacts on economic viability and financial metrics.

Against this background and based on data from the agronomic evaluations of AGROSAVIA, the objective of this study is to analyze the economic feasibility of implementing supplementation with *Canavalia brasiliensis* hay during the dry season, along with pasture improvement measures, in the Colombian Caribbean. For this purpose, a base scenario (100% grazing with *Bothriochloa pertusa*) was compared against 3 treatments, which involved both pasture improvements and supplementation with *Canavalia brasiliensis* hay (at inclusion levels of 0.5, 1.0, and 1.5% dry matter (DM) of the animals' liveweight, respectively). With a discounted free cash-flow model, considering cost and income flows for a period of 8 years, interest rates, producer price indices, market prices, and animal liveweight, economic indicators, such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit–Cost Ratio (B/C) were estimated for each treatment. In a second step, a Monte Carlo simulation and sensitivity analyses were conducted.

The article is structured as follows. Section 2 is composed of a description of the technology *Canavalia brasiliensis* along with the results of the agronomic evaluation conducted by AGROSAVIA. Section 3 presents the methodology for the economic evaluation. Section 4 presents the results for each treatment. Section 5 provides a discussion and Section 6 some important conclusions.

2 Description of the technology

2.1 Main characteristics and benefits of *Canavalia brasiliensis*

The legume *Canavalia brasiliensis* is a herbaceous plant with twining and trailing growth habits. It produces long pods measuring 10–12 cm in length. The plant has well-developed roots, and its seeds are light brown (Franco and Peters, 2007). In Latin America, it is also known by various other names, such as Calibolati, Frejolón, Frijol espada, Haba de playa, or Mata de playa (Cook et al., 2020). It is a multipurpose material, primarily used as feed for cattle supplementation and as green manure to improve soil structure (Franco and Peters, 2007; Cook et al., 2020; Douchamps et al., 2011). *Canavalia brasiliensis*, native to Latin America and the United States (Florida), thrives in regions receiving annual rainfall between 900 to 1,800 mm. It can endure periods of drought lasting 5–6 months and regenerates readily with the onset of rain. The species demonstrates adaptability to a wide range of climates and soil types, including clayey, sandy, low fertility, and alkaline soils (pH 4.3 to 8.0). It grows from sea level up to 1,800 meters above sea level (Cook et al., 2020; Peters et al., 2011).

Supplementing with legume hay brings benefits both to milk productivity and cattle liveweight gain (Castro-Rincón et al., 2016; Ullrich et al., 1994; Vera et al., 1996; Holmann and Lascano, 2004). *Canavalia brasiliensis* has shown positive results in complementing feed during the dry seasons of the Colombian Caribbean and, i.e., milk productivity gains of around 15% have been estimated in dual-purpose systems (Mojica-Rodríguez, 2017; Cuadrado et al., 1998; Castro-Rincón et al., 2016).

2.2 Supplementation of *Bothriochloa pertusa* with *Canavalia brasiliensis* at different inclusion levels: results of the agronomic evaluations of AGROSAVIA

Regarding the performance of *Canavalia brasiliensis*, Table 1 reports green forage production at 22,000 kg per hectare and year and dry matter (DM) at 6,160 kg, indicating a dry matter share of 28%.

As Table 1 on the nutritional quality indicators shows, *Canavalia brasiliensis* exhibits higher values for crude protein content, ether extract, and dry matter digestibility, while *Bothriochloa pertusa* surpasses in neutral and acid detergent fiber.

3 Materials and methods

The present study conducts an economic evaluation of supplementing *Bothriochloa pertusa* with the legume *Canavalia*

TABLE 1 Nutritional quality indicators for *Bothriochloa pertusa* and *Canavalia brasiliensis* and Productivity indicators for *Canavalia brasiliensis*.

Indicator	<i>Bothriochloa pertusa</i>	<i>Canavalia brasiliensis</i>
Crude protein content (%)	5.1	16.9
Neutral detergent fiber content (%)	72.1	55.8
Acid detergent fiber content (%)	43.3	39.4
Ether extract (%)	1.7	1.8
Dry matter digestibility (%)	43.9	55.2
Green matter production (kg ha ⁻¹)	NA*	22,000
Dry matter share (%)	NA	28
Dry matter production (kg DM ha ⁻¹)	NA	6,160

Source: Mojica-Rodríguez (2017). *NA, not applicable.

brasiliensis at different inclusion levels along with pasture improvement measures. The study is based on data obtained from AGROSAVIA from agronomic evaluations (AGROSAVIA, 2022).

3.1 Description of the treatments evaluated by AGROSAVIA

AGROSAVIA established the materials at the end of the rainy season in the second half of 2013 to have forage reserves during the dry season from January to March 2014. During this period, they measured technical and productivity indicators. The experiment took place at the San Carlos farm in the municipality of San Diego in the Department of Cesar, which is located within the Caribbean region of the lower Colombian tropics (<1,200 m.a.s.l.).¹ The average annual temperature, relative humidity, and average annual rainfall are 28.7°C, 70%, and 1,600 mm, respectively. The rainy season occurs from April to June and from September to November. The soils range from shallow to deep, with good drainage and intermediate to high fertility (Mojica-Rodríguez, 2017).

The evaluation was conducted for 4 treatments. The first treatment was the control or baseline technology, representing the traditional production system in the region, which is based solely on grazing *Bothriochloa pertusa* grass with limited investment in soil preparation (Mojica-Rodríguez et al., 2013). The 3 remaining treatments contemplated pasture improvement measures and supplementation with *Canavalia brasiliensis* hay at 3 different inclusion levels (Mojica-Rodríguez, 2017). Pasture improvement measures included mechanical soil preparation and chemical fertilization of the pasture. In these treatments, supplementation with

Canavalia brasiliensis hay was provided at 3 inclusion levels, i.e., 0.5, 1.0, and 1.5% DM of the animals' liveweight. Each of the 3 treatments was implemented on an area of 2 hectares and counted with 2 lactating Gyr x Brown Swiss cows (1 cow/ha). Rotational grazing was practiced, and for *Canavalia brasiliensis* hay production, 1 additional hectare was allocated, established in the second half of 2013, and conserved as hay for 90 days after germination. The baseline treatment was conducted with mixed-breed cows (7 colors) representative of the region (Mojica-Rodríguez et al., 2013), which are comparable to the Gyr x Brown Swiss cows used in the other treatments (Mojica-Rodríguez, 2017). Measurements were taken daily.

3.2 Main results of the agronomic evaluations conducted by AGROSAVIA

Table 2 presents a set of relevant indicators both for the traditional system with *Bothriochloa pertusa* and the 3 supplementation treatments. As can be observed, forage production in *Bothriochloa pertusa* significantly increases in the supplementation scenarios, which is due to the applied pasture improvement measures. The traditional system can only sustain 0.7 Tropical Livestock Units (TLU; 1 TLU = 450 kg) per hectare, whereas in the other treatments, it becomes possible to sustain a cow and its calf (equivalent to 1 TLU).

The treatments increased the total solids content of the milk, rising from 11.9 to 12.2 and 12.3%, respectively. In terms of milk protein content, there was a slight decrease from 3.3 to 3.2%. Previous trials by AGROSAVIA reflect the difficulty of increasing the milk protein content and supplementation is more effective in relation to the fat percentage and therefore on the total solids content of the milk. On the other hand, milk fat content increased from 3.4 to 3.9 and 4.0%, respectively. For the analyzed region, total solids are a relevant parameter in determining the price per liter of milk. Therefore, the intervention is expected to result in higher income for the producer. Finally, the average hay consumption for the 3 inclusion levels indicates that the animals did not consume the entire offered hay. For instance, when they had access to 1.5% DM of the animal liveweight, the average consumption was 0.81% DM. This is a significant finding, as it suggests that productivity gains can be achieved with lower amounts of supplementation.

In the traditional *Bothriochloa pertusa* monoculture grazing system, the average producible milk yield is 2.7 kg per day, with

¹ In the lower tropics (<1,200 m.a.s.l.), production is generally lower than in the upper tropics (>1,200 m.a.s.l.) (Cadena et al., 2019). The upper tropics, referred to as region 1, encompass the departments of Cundinamarca, Boyacá, Antioquia, Quindío, Risaralda, Caldas, Nariño, Cauca, and Valle del Cauca. The lower tropics, known as region 2, are comprised by the departments of Cesar, Guajira, Atlántico, Bolívar, Sucre, Córdoba, Chocó, Magdalena, Norte de Santander, Santander, Caquetá, Tolima, Huila, Meta, Orinoquia, and Amazonia. This classification is based on the definition provided by the Milk Price Monitoring Unit (Unidad de Seguimiento de Precios de Leche, USPL) (MADR, 2012, 2015a, 2015b).

TABLE 2 Productive system indicators per hectare.

Indicators	<i>Bothriochloa pertusa</i> traditional	Pasture improvement and supplementation with <i>Canavalia</i> <i>brasiliensis</i>		
		Inclusion levels 0.5%	Inclusion levels 1.0%	Inclusion levels 1.5%
Forage production colsuana (kg DM ha ⁻¹)	550	2,237	2,237	2,237
Stocking rate (TLU ha ⁻¹)	0.7	1	1	1
Liveweight (kg)*	450	450	450	450
Marketable milk production (kg d ⁻¹)	2.7	4.9	4.9	5.3
Milk consumption by calf (kg d ⁻¹)	ND**	1.5	1.7	1.9
Total milk production (kg d ⁻¹)	2.7	6.4	6.6	7.2
Total solids (%)	11.9	12.2	12.3	12.3
Protein (%)	3.3	3.2	3.2	3.2
Fat (%)	3.4	3.9	3.9	4
Hay consumption (kg DM animal ⁻¹ d ⁻¹)	NA**	0.46	0.5	0.81

Source: AGROSAVIA (2022). *In the traditional system, the weight is also 450 kg, but more space is required to accommodate 1 TLU and its calf, for which each treatment was conducted on 2 hectares. **ND, not determined; NA, not applicable.

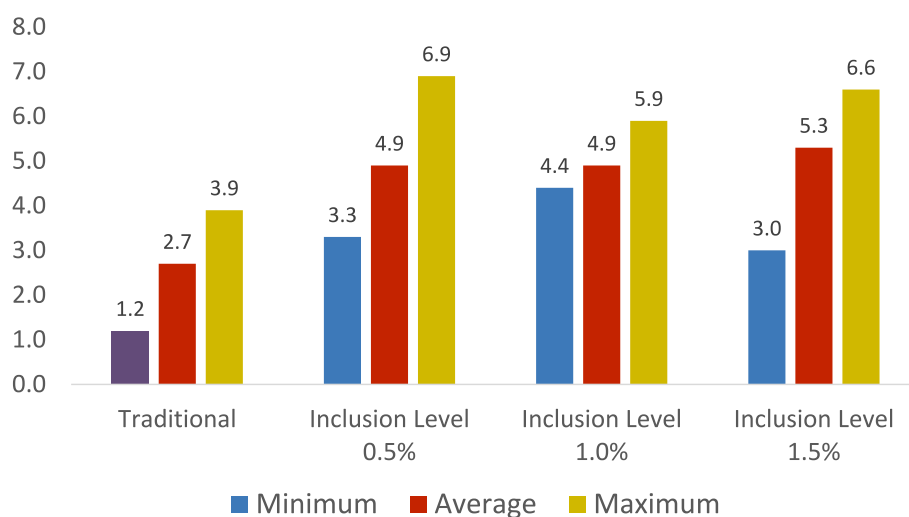


FIGURE 1

Marketable milk production by technology (kg d⁻¹ ha⁻¹). Source: Own elaboration based on data from AGROSAVIA (2022). Based on animals of 450 kg liveweight (1 TLU).

minimum and maximum values of 1.2 and 3.9 kg, respectively. With pasture improvement and under the 3 *Canavalia brasiliensis* supplementation treatments, average milk production increased to 4.9 kg at the 0.5 and 1.0% inclusion level. At the 1.5% inclusion level, the average production reaches 5.3 kg. During the evaluation period, the observed minimum value was 3.0 kg at the 1.5% inclusion level, while the maximum value occurred at the 0.5% inclusion level with 6.9 kg (see Figure 1). These results are consistent with similar evaluations of this legume in the region (Mojica-Rodríguez, 2017).

3.3 Discounted cash flow model

The method applied for determining the economic viability of the evaluated treatments is cash flow analysis, which systematically organizes

the outflows and inflows of a productive project for each analyzed period (Miranda, 2022). In our study, outflows represent the investments and costs necessary to establish the productive system and ensure its operation over time. Incomes, given the dual-purpose system production system, are derived from the sale of milk and meat. With these elements, net profit and profitability indicators were calculated for each of the 4 treatments, such as the Net Present Value (NPV), Internal Rate of Return (IRR), Benefit–cost Ratio (B/C), and payback period (PP), which help to identify the best possible option in terms of return on investment.

To project income and costs over time, a series of economic and technical assumptions were made:

3.3.1 Evaluation horizon

The obtained data from AGROSAVIA is from 2013/14 but for the purpose of this study, an evaluation horizon of 8 years was defined,

i.e., from 2022 to 2029, which is based on the productive lifespan of the cows under each treatment (7 Colors and Gyr x Brown Swiss). For this, the 2013/14 values on input and market prices provided by AGROSAVIA were updated to 2022.

3.3.2 Discount rate

Within this temporal analysis, a crucial element is the cost of capital. This concept can be understood as the minimum return expected from an investment (Moscoso et al., 2012). In other words, it is an interest rate or discount rate that generates sufficient incentives to participate in a productive project (Moscoso et al., 2012). For the Colombian agricultural sector, the reference discount rate is set by the portfolio of services and credit lines of the Fund for Financing the Agricultural Sector (FINAGRO). It is defined as the fixed-term deposit rate (DTF) + 5% effective annual rate (FINAGRO, 2021). The DTF is a weighted average of the rates of 90-day certificates of deposit and is considered an indicator of the cost of money over time (Banco de la República, 2023a). The existing DTF in mid-2021 (1.9%) was taken, which corresponds to the time of structuring the different investments for the establishment of the technologies. Therefore, the applied discount rate was 6.9%.

3.3.3 Labor

Since the evaluated treatments were small-scale, they did not demand permanent labor. However, the evaluation recorded the number of workers and the value of their wages for establishing and operating the productive systems. Regarding tax costs, income tax rates were not incorporated, since, in practice, tax benefits allow projects with these characteristics to be exempt (MADR, 2020).

3.3.4 Opportunity cost of land

The opportunity cost of land is also considered, which is the value of the lease that producers must pay to use the necessary land for their productive activity. In the region, the annual value for cattle is US\$ 130.90 per hectare, and for agriculture US\$ 96.96.² These prices correspond to the market values observed in the region and collected by AGROSAVIA (2022).

3.3.5 Inflation

Since money loses value over time, the cash flow must incorporate the effect of inflation on costs and revenues for each period. This means that nominal prices were used. For incomes, consumer price indices (CPI) for milk and meat were considered. Production costs were indexed with producer price indices (PPI) for agricultural inputs. The growth of the minimum wage and the general CPI were also considered (Banco de la República, 2022; DANE, 2022a, 2022b).

3.3.6 Meat and milk prices

The agronomic evaluations by AGROSAVIA did not measure animal liveweight gain since focus was set on milk production in a dual-purpose system. However, data for the traditional system in the

region indicate that, for the evaluated breeds, the average values for liveweight gain are 422 grams per animal and day and the average price is US\$ 1.82 per kg liveweight (AGROSAVIA, 2022). These values were thus used for all treatments. For the 3 inclusion treatments, a higher stocking rate was recorded than for the traditional system, which is reflected in the revenues. The milk price depends on the values defined by the Entity for Milk Price Monitoring Unit for region 2, corresponding to the Colombian lower tropics. This regulatory policy is a response to asymmetries in commercialization in a highly heterogeneous market. The price is positively related to the percentage of total solids in a liter of milk (MADR, 2012, 2015a, 2015b). Payments for hygiene, health, or other types of bonuses that dairy companies offer to producers were not considered in the analysis.

3.3.7 Pasture establishment, maintenance, and renewal

In the study region, *Bothriochloa pertusa* is the predominant grass used for grazing in dual-purpose cattle systems. The improvement treatments incorporated mechanical soil preparation and fertilization as pasture improvement measures. Likewise, pasture renewal was contemplated in year 5 of the operation to maintain productivity. On the other hand, the establishment of *Canavalia brasiliensis* for hay production was conducted on an additional hectare in the 3 improvement treatments. Since high-quality seeds were used, the land was mechanically prepared, and fertilizer applied, no renewal of *Canavalia brasiliensis* was contemplated. Establishment costs of *Bothriochloa pertusa* contained the items mechanized land preparation, seeds, fertilization, weed and pest control, and labor, and were valued at US\$ 319.98 per hectare for the traditional system and US\$ 455.24 for the improvement treatments. Pasture renewal in the fifth year includes resowing, labor, fertilization and weed control, and the costs were incorporated into the cash flow and adjusted for inflation. The costs of establishment and production of *Canavalia brasiliensis* hay amount to US\$ 993.16 per hectare.

3.3.8 Infrastructure

Infrastructure costs include all expenses for building the perimeter fence and accessories such as the drinking trough and saltlick. They amount to US\$ 953.70 per hectare for each of the 4 treatments.

3.3.9 Animal health management

Includes vaccines and other inputs that ensure the health and well-being of the cattle. Its value is US\$ 271.34 per cow and year for each of the 4 treatments.

3.3.10 Animal purchase, redemption value, lactating period, calving interval

The estimated cost of acquiring the dual-purpose 7 Colors and Gyr x Brown Swiss cattle is US\$ 969.64 per animal. The redemption value of US\$ 730.86 was indexed for inflation and added in the eighth year after the end of the lifespan of the animals. The lactating period was estimated at 255 days and the calving interval at 422 days.

3.4 Quantitative risk analysis

Any investment is subject to a level of risk. Costs, revenues, and benefits depend on market prices and the economic environment,

² For this analysis, conversion of Colombian Pesos to US\$ was applied using the average representative exchange rate for the end of 2021 and the course of 2022, which was 4,125.25 Colombian per US\$ (Banco de la República, 2023b).

over which the producer has no control. These are random variables (RV). Thus, profitability indicators are also RV and require a risk analysis. This contributes to decision-making with greater certainty (Park, 2007). For this purpose, a Monte Carlo simulation was employed, which generates a random sample for the variable of interest, given a probability distribution (Park, 2007). Monte Carlo simulation requires establishing systematic steps. The first is to have a model to evaluate, in our case, the cash flow. Second, RV are defined, such as prices, productivity, and profitability indicators. The third step is to establish the probabilistic distributions related to the variables of interest. The fourth step defines a pseudo-random number to generate the value of the RV. The fifth step sets the number of simulation repetitions. Finally, the calculations are conducted, and the results analyzed (Park, 2007; Herrera, 2020). The process is carried out using the software @Risk (Palisade Corporation). For our study, 5,000 simulations were generated with a confidence level of 90%.

Decision criteria in this probabilistic context are based on the average results of the Net Present Value (NPV) and the Internal Rate of Return (IRR). According to the law of large numbers, these values are the best possible estimates, as the average value tends to converge toward the expected value as the number of simulation repetitions increases. In other words, towards the actual average (Park, 2007). The NPV, Equation 1, brings the net cash flows (NCF) of the time periods to the present, adjusted according to the defined discount rate (i). The probabilistic version can be expressed as:

$$E[NPV] = \sum_{t=0}^T \frac{E(NCF_t)}{(1+i)^t} \quad (1)$$

Where $E[NPV]$ is the expected value of the NPV, $E(NCF_t)$ the expected value of the net cash flow for period t , and i the discount rate.

On the other hand, the IRR is the discount rate that equals the NPV to zero, denoted as i^* in Equation 2 (Miranda, 2022). Incorporating the probabilistic elements, it can be defined as:

$$\sum_{t=0}^T \frac{E(NCF_t)}{(1+i^*)^t} = 0 \quad (2)$$

The decision criteria for accepting an investment state that the NPV should be greater than 0, and the IRR should be greater than the market's discount rate. When comparing multiple investment alternatives, the one with the highest NPV and IRR should be chosen. The quantitative risk analysis also includes a sensitivity analysis, through tornado diagrams, which measure

the impact of key variables on profitability indicators (Enciso and Burkart, 2020).

4 Results

4.1 Cost and revenue structure

In the traditional system, the largest portion of establishment costs is allocated to inputs (45.45%), followed by land preparation (30.3%), and labor (24.24%). In terms of infrastructure expenses, the construction of fences represents the majority (75.24%), followed by labor (15.25%), and additional items like water troughs and salt licks (9.51%). As for the operational costs to maintain the animals within the system, the primary expenditure is on labor (65.22%), with the remaining percentages being utilized for medications (28.82%), mineralized salt (4.70%), and vaccines (1.26%). It is important to clarify that the expenses are the same for the 3 *Canavalia brasiliensis* treatments and only the hay inclusion levels in the animal diets vary. In terms of implementing the supplementation treatments, the highest cost share is attributed to inputs (59.53%), followed by land preparation (21.30%), and labor (19.17%). The distribution of costs for infrastructure and animal maintenance remains consistent with the traditional treatment. Lastly, the production of *Canavalia brasiliensis* hay required an additional hectare of land, with inputs constituting the most significant expense (65.40%), followed by land preparation (18.59%), and labor (16.01%). The cost of the hay amounted to US\$ 0.16 per kg DM.

The revenues are derived from the sale of milk and meat, given that it is a dual-purpose production system. The price per liter of milk was determined based on the total solids content (g/l) and the economic value assigned of this component in 2022 (US\$/g). This is in accordance with Resolution 017 of 2012 from the Ministry of Agriculture and Rural Development of Colombia (MADR), which provides the payment guidelines for the dairy enterprises in the region (MADR, 2012). For the traditional system, a price of US\$ 0.31 per liter is paid, and the income is US\$ 0.87 per cow and day. In the improved treatments, the price ranges between US\$ 0.321 and US\$ 0.324 per liter, and the income ranges between US\$ 1.62 and US\$ 1.77 per cow and day. It should be emphasized that the economic benefit in terms of meat comes from the increased animal stocking rate per hectare, i.e., from 0.7 to 1 TLU.

4.2 Profitability indicators

The results of the economic indicators are presented in Table 3. Both the traditional system and the 3 supplementation treatments

TABLE 3 Economic indicators for the 4 evaluated treatments.

Indicator	Traditional	Inclusion levels 0.5%	Inclusion levels 1.0%	Inclusion levels 1.5%
NPV (US\$)	2,994	23,007	23,372	26,988
IRR (%)	9.30	16.65	16.79	18.20
PP (years)	7.83	7.25	7.25	7.16
B/C	1.08	1.32	1.33	1.38

The discount rate used is 6.9%. The was conducted considering an 8-hectare system for each case.

have positive NPV and IRR higher than the discount rate. In other words, all alternatives are profitable. However, the effect of the 3 supplementation treatments is quite clear: The NPV increases by approximately 668 to 801%, and the IRR between 7.35 and 8.9%. This is the result of increased animal stocking rates, higher milk production, and better milk sales prices.

The PP is the time required to recover an investment, considering the value of money over time (Park, 2007). According to the discounted cash flows, the investment is recovered during the seventh year in all treatments, with improvements of several months in the 3 inclusion levels scenarios. The B/C is greater than 1 in all treatments, confirming their profitability. As can be seen, all economic indicators improve in the supplementation treatments.

4.3 Quantitative risk and sensitivity analysis

To provide further support to the analysis, the Monte Carlo simulation method was applied to the estimated profitability indicators. The results are reported in Table 4. The variables considered as the most important determinants of profitability, based on available

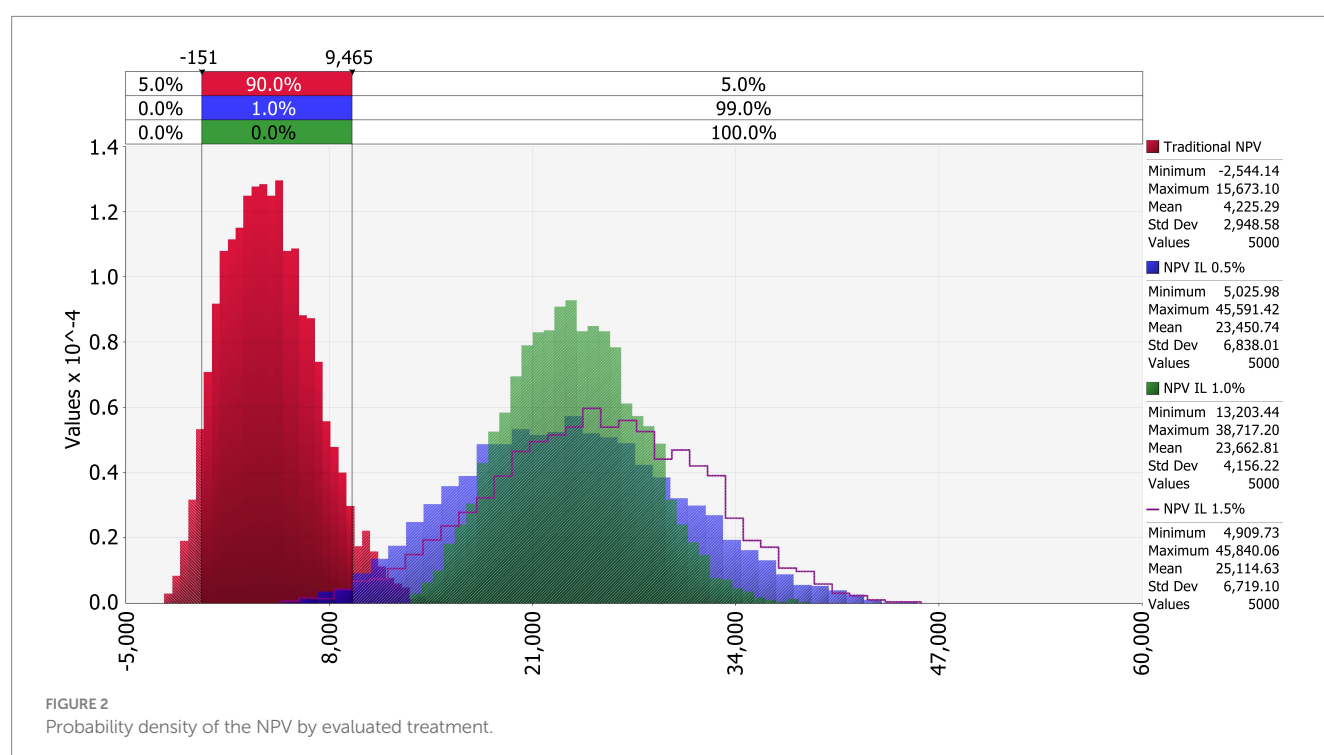
information, were the discount rate, productivity, and milk price. Since minimum, maximum, and most likely values were provided by experts, they were adjusted using a Pert distribution, which was identified as the most suitable for the simulations (Enciso et al., 2019; Nagel-Alne et al., 2014; Pena de Ladaga, 2017). Additionally, the Akaike, Bayesian, and Kolmogorov–Smirnov (K-S) tests were conducted, all of which supported the use of this probability distribution. All systems have a positive NPV and an IRR higher than the discount rate. The best indicators are found for the supplementation treatment with 1.5% inclusion levels, with an average NPV of US\$ 25,115 and an average IRR of 17.39%. The supplementation treatments with inclusion levels of 1.0 and 1.5% resulted in the estimates with the lowest dispersion, as evidenced by the lowest coefficients of variation (CV) (17.56 and 26.75%).

Figure 2 displays the probability distributions of the NPV for the evaluated treatments. It can be observed that in the traditional system (red color), values can range between US\$ -2,544.14 and US\$ 15,673.10. The probability of obtaining a negative NPV is 0.059. The probability distribution curves of the NPV in the 3 supplementation treatments shift to the right. As a result, their mean value increases from US\$ 4,225.29 in the traditional system to figures ranging from

TABLE 4 Results of the quantitative risk analysis.

Indicator	Measure	Traditional	Inclusion level 0.5%	Inclusion level 1.0%	Inclusion level 1.5%
NPV	Mean (US\$)	4,225.29	23,450.74	23,662.81	25,114.63
	SD*	2,948.58	6,838.01	4,156.22	6,719.10
	CV	69.78	29.16	17.56	26.75
	Prob (NPV < 0)**	0.059	0	0	0
IRR	Mean (%)	10.19	16.74	16.85	17.39

Estimated with @Risk. *SD, standard deviation; **Prob, probability.



US\$ 23,450.74 to US\$ 25,114.63 in the 3 supplementation treatments. At the 0.5% inclusion levels (blue color), values between US\$ 5,025.98 and US\$ 45,591.42 can occur. At the 1.0% level (green color), they range from US\$ 13,203.44 to US\$ 38,717.20, and at the 1.5% level (purple color) from US\$ 4,909.73 to US\$ 45,840.06. The probability of obtaining a negative NPV is zero for the 3 supplementation treatments.

The sensitivity analysis is summarized in Figure 3, which presents tornado diagrams for the 4 treatments. It reports the contribution of variance, which allows identifying the factors that have the most influence on the financial viability of the considered scenarios. The results indicate that milk productivity is the most influential variable on the NPV. In the traditional system and the 3 supplementation treatments, it explains 77.6, 74.8, 35.0, and 73.4% of the variations in the profitability indicator, respectively. The second most relevant variable is the discount rate, which on average explains 31.52% of the variation in the NPV.

The robustness of the sensitivity analysis is validated through the three scenarios constructed for the improved systems, which are consistent in identifying dairy productivity as the main determinant of profitability. In two of the three cases, it is the factor exerting the greatest influence on profitability.

5 Discussion

In various parts of the world, the inclusion of legumes in animal diets has driven more efficient cattle systems in terms of both productivity and environmental impact. Legumes contribute to climate change mitigation through reducing the use of chemical fertilizers, increasing per hectare productivity, and reducing the unit product carbon footprint. Likewise, they contribute to climate change adaptation through increasing resilience, i.e., when it comes to drought. In some cases, legumes also promote animal health by

reducing the use of drugs. The inclusion of legumes thus also contributes to reducing production costs (Lüscher et al., 2014; Hassen et al., 2017; Muir et al., 2017; Castro-Montoya et al., 2019). The present study provides an economic evaluation of supplementation with the legume *Canavalia brasiliensis* in a traditional dual-purpose grazing system with the grass *Bothriochloa pertusa* in Colombia.

The agronomic evaluation of supplementation using hay from the legume *Canavalia brasiliensis*, along with improvements in pasture management, proved effective in enhancing the animal diet in a dairy cattle system during dry seasons. This intervention increased milk productivity by 137–167%, total solids content in milk by 2.5–3.4%, milk fat content by 14.7–17.6%, and animal stocking rates by 43%. The increased total solids content is especially interesting, since it helps dairy producers to obtain higher milk prices in the market. The profitability analysis confirmed the viability of implementing these technological changes. Particularly the NPV increases by 668–801%, the IRR by 79–96%, and the B/C ratio by 22–28 points. The financial analysis indicates that the change towards supplementation is a highly profitable endeavor for dual-purpose farmers in Colombia – independent from the inclusion rate of *Canavalia brasiliensis* (0.5–1.5%). Our analysis also shows that supplementation at any of the 3 inclusion levels reduces the risk of obtaining negative NPV from 0.059 to 0%, indicating that the implementation of such feeding strategy – if done as recommended – is a low-risk endeavor. These findings are consistent with similar assessments conducted for dairy or dual-purpose cattle systems in Colombia across various geographical areas. For instance, supplementation in a *Cenchrus clandestinus* (Kikuyu grass) grazing system with the legume *Avena sativa* AV25-T (Altoandina) as silage during dry periods in the Boyacá (Andean region) department leads to increased milk productivity in Holstein cows (82–220%) and improved profitability indicators, as well as reduced investment risk (Enciso and Burkart, 2020; Lüscher et al., 2014; Hassen et al., 2017; Castro-Montoya et al.,

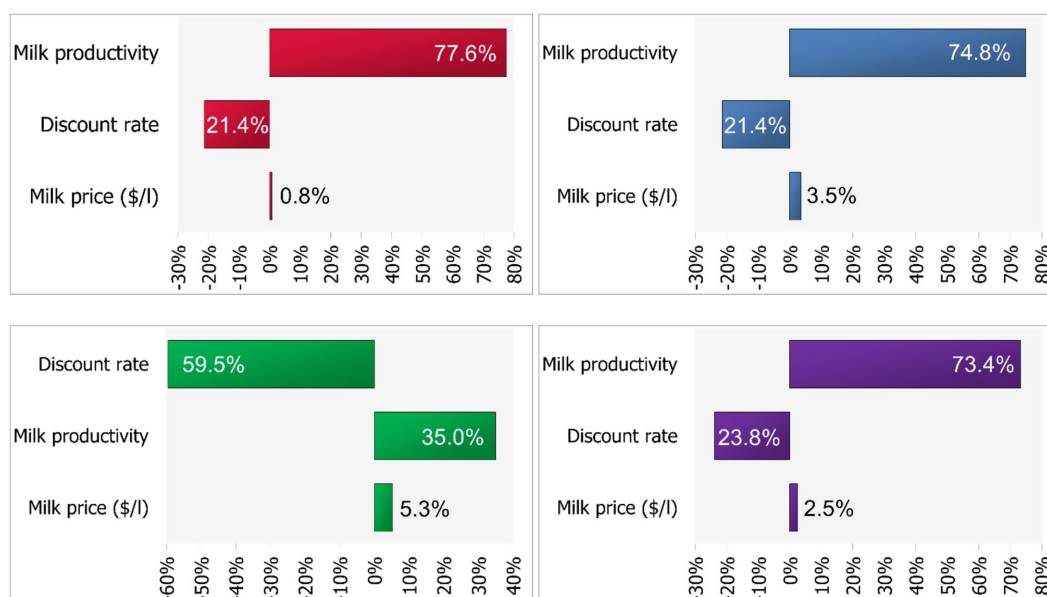


FIGURE 3

Sensitivity Analysis of the NPV for the evaluated treatments - contribution to variance. Upper left: traditional treatment; upper right: pasture improvement and 0.5% IL; lower left: pasture improvement and 1.0% inclusion level; lower right: pasture improvement and 1.5% inclusion level.

2019; Enciso et al., 2021). A similar situation was observed in the Colombian Orinoquia region (Eastern Plains region) where the integration of the legume *Arachis pinto* in a grazing system with *Urochloa humidicola* (syn. *Brachiaria humidicola*) helped to increase animal stocking rates (33%) and milk productivity (52%), which, like for the present study, was the primary determinant of profitability in the analyzed dual-purpose cattle production system, leading to improved profitability indicators and reduced investment risk (Enciso and Burkart, 2020; Enciso et al., 2021). In Nariño (Andean and Pacific regions), legumes also showed a positive response during drought seasons, particularly in the case of *Trifolium repens*, *Trifolium pratense* L., and *Vicia sativa* L. (Portillo-López et al., 2019). Existing regulations that aim to correct market failures and provide a fairer milk price to primary producers thus play a significant role in the profitability of these systems, emphasizing the importance of increasing productivity and quality, i.e., the total solids content since it is used for determining the milk price in the market (MADR, 2012, 2015a, 2015b).

Other studies focused on different supplementation strategies for beef cattle fattening systems. Among them, supplementation with hydroponic green forage in cattle breeding and fattening systems with *Urochloa decumbens* in the eastern plains of Colombia, has proved to increase profitability by doubling the NPV of a traditional system without supplementation (Navarro, 2016). Another study focused on evaluating the inclusion of the legume *Leucaena diversifolia* in a beef cattle grazing system with *Urochloa* hybrid cv. Cayman in the Cauca Valley (Pacific zone), reporting increased profitability by 15 to 110% and reduced probability of financial (from 72 to 0%) when compared to a grass monoculture system with *Urochloa* hybrid cv. Cayman only. In this case, the sale price per kilogram of cattle liveweight had the greatest influence on profitability (Enciso et al., 2019). This indicates potential of supplementation strategies not only for the dairy but also the beef sector, and, above all, dual-purpose production systems, which are predominant in Colombia.

Our results also reveal that the animals consume less *Canavalia brasiliensis* hay than what was made available across the 3 evaluated inclusion levels. In the 0.5% inclusion levels, a relatively small share of 8% of the hay was left, while in the 1.0 and 1.5% inclusion levels, these shares significantly increased to 50 and 46%, respectively. This information is important for managing the production system, as it provides guidance on parameters that can be adjusted to optimize the use of resources. This coincides with an evaluation from Valenca, Brazil, on protein-energy supplementation (using soybean meal, corn meal, urea, and white salt) in *Urochloa decumbens* pastures with crossbred Nellore heifers, which found that lower supplement consumption resulted in higher efficiency of feed conversion to liveweight gain, leading to reduced costs and improved profitability indicators (Santos et al., 2018; Silva et al., 2019).

Other studies have documented the economic and environmental benefits of integrating forage legumes into broader livestock systems, particularly in silvo-pastoral arrangements. For instance, in the Colombian Eastern Plains, a silvo-pastoral system using improved pastures of *Urochloa humidicola* cv. Llanero, *Urochloa brizantha* cv. Toledo, and the legume *Pueraria* has shown Benefit–Cost ratios of 1.57 and 1.32, with very low probabilities of economic loss, ranging from 0 to 1.7% (Flórez et al., 2024). Similarly, analyses in the Colombian Cauca department have demonstrated a 40% reduction in carbon footprint when using silvo-pastoral systems integrating forage

legumes (Gonzalez Quintero et al., 2024). In Brazil, silvo-pastoral systems with eucalyptus trees have yielded profitability of around 20% (Santos and Grzebieluckas, 2014), while in Mexico, trials with *Leucaena leucocephala* in association with *Cynodon dactylon* estimate a profitability of 27.9%, which increases to 30.4% when monetizing carbon sequestration (Cuevas-Reyes et al., 2020).

Beyond economic benefits, legumes also play a critical role in improving environmental performance. Nitrogen fixation through legumes can reduce reliance on chemical inputs, leading to more sustainable farming practices. For example, significant differences have been found between monocultures of *Cynodon plectostachyus* and systems that include *Leucaena leucocephala*. In the latter, nitrogen fixation increased from 0 to 400 kg ha⁻¹ year⁻¹, carbon sequestration rose from 120 to 220 t ha⁻¹ year⁻¹, and CH₄ emissions decreased from 85 to 68 kg animal⁻¹ year⁻¹ (Bacab et al., 2013). Further studies have estimated strong reductions in CO₂, CH₄, and N₂O emissions in silvo-pastoral systems using similar legume-based interventions (Murgueitio et al., 2016). For instance, in a comparison of silvo-pastoral systems with *Leucaena leucocephala* versus monocultures of *Urochloa brizantha* cv. Toledo and *Urochloa* hybrid cv. Cayman, CO_{2eq} emissions were reduced by 8%, resulting in a monetary saving of US\$ 6.12 per head of cattle (Sandoval et al., 2023).

In summary, the integration of legumes into cattle systems not only improves economic outcomes but also leads to environmental benefits. These complementary objectives – enhanced productivity and reduced environmental impact – are key to developing sustainable and profitable cattle farming practices across Latin America (Bussoni et al., 2021). Although our study did not focus on valuing the environmental benefits or ecosystem services associated with legume supplementation, this area warrants further investigation in future research.

In Colombia and much of the tropical regions of Latin America, dual-purpose cattle systems are integral to livestock production, accounting for 43.3 and 75% of cattle herds, respectively (FEDEGAN, 2022; Turcios Samayoa, 2008). The tropical regions of Latin America house 80% of the region's cattle, with dry tropics, such as Colombia's Caribbean region, playing a particularly prominent role (Rearte, 2022). Moreover, climate change poses significant challenges to cattle systems across the region (Nardone et al., 2010). A key trend across Latin America is the improvement of cattle systems through the diversification of cattle diets with legumes, particularly during dry spells and droughts. This approach has been shown to boost milk and meat production, reduce reliance on nitrogen fertilizers and nutritional supplements, and restore lands degraded by extensive monoculture farming (Molina-Rivera et al., 2019). Legumes like *Leucaena leucocephala*, when incorporated into silvo-pastoral systems, have been demonstrated to double or even triple animal stocking rates, thereby strengthening these systems in regions such as Mexico, Colombia, Costa Rica, and Guatemala (Bacab et al., 2013; Turcios Samayoa, 2008). On the policy front, countries like Mexico, Guatemala, and Costa Rica are promoting dual-purpose cattle systems and their associated value chains through Nationally Appropriate Mitigation Actions (NAMAs) programs (FAO, 2023). The results from this study are thus not only relevant to the specific context of Colombia but also have broader applicability to other regions across Latin America and beyond. Given the prevalence of similar agroecological zones and cattle systems in tropical areas of Central and South America, as well as in other tropical and subtropical regions worldwide, the findings could serve as a model for improving

cattle farming practices globally. The demonstrated benefits of legume incorporation into cattle systems – such as increased productivity, reduced costs, and enhanced sustainability – can be applied to a wide range of systems facing similar environmental challenges, supporting the sustainable intensification of cattle farming across diverse agroecological zones.

Supplementation with legumes in its various forms is part of a broad range of technologies and management strategies for the cattle sector. As shown by our results, as well as similar studies, supplementation can help increase productivity, quality, and profitability of dairy, beef, and dual-purpose production systems. Likewise, it contributes to climate change mitigation and adaptation. Despite these advantages, it is not broadly used in Colombian cattle systems (Enciso et al., 2021; Muir et al., 2017), which can be attributed to numerous factors, such as (i) limited legume seed availability and accessibility; (ii) high establishment costs, limited cash-flow of the producers and access to financing (e.g., credits); (iii) lack of information on the benefits, selection, establishment, and management of legumes, as well as conservation (hay, silage) and supplementation strategies; and (iv) socio-cultural burdens, i.e., supplementation and legumes not being part of traditional cattle farming in Colombia. To overcome the legume seed bottleneck, it is essential to incentivize seed companies to invest in legume seed production on the one hand, but also to find solutions to some biological challenges, such as low seed production potential in some tropical perennial legumes, indeterminate flowering, prostrate inflorescences, and dehiscent pods. Likewise, legume seed production knowledge should be generated among farmers to either incentivize them investing in seed production for on-farm use or as a business model to supply seeds at the local level (Muir et al., 2005; Muir et al., 2017; Akinola and Agishi, 1989; Raghu et al., 2005; Chauhan and Pandey, 2014; Muir and Pitman, 1991). Regarding the generation and dissemination of knowledge about legumes and supplementation, stronger collaboration among research institutions, NGOs, the public sector, and private seed companies should be encouraged, so that synergies can be harnessed, duplications reduced, and homogeneity in the information itself increased, by this contributing also to the removal of socio-cultural burdens. Likewise, new, digital channels for information dissemination should be explored. A good example for this is the Tropical Forages Selection Tool developed by leading forage experts for the tropics (Cook et al., 2020). To overcome limitations with financing, the positive effects of legume supplementation on climate change mitigation should be further explored, so that instruments for payments for ecosystem services can be adjusted to support economic incentives for adoption. Likewise, credits particularly focused on legume establishment and conservation could help to overcome financial burdens to investing. Positive examples for Colombia can be found for silvo-pastoral systems, where a credit line for purchasing seeds is available since 2022 (Burkart et al., 2022; Moreno-Lerma et al., 2022) and options are being explored regarding payments for ecosystem services (Diaz et al., 2019a, 2019b).

6 Conclusion

Improvements in the *Bothriochloa pertusa*, along with the supplementation of *Canavalia brasiliensis* hay during the dry season, helps optimizing the performance of dual-purpose cattle systems in Colombia, as evidenced by both the productive and economic indicators

provided in this study. When compared with a traditional production system based solely on grazing *Bothriochloa pertusa* grass, supplementation and pasture improvement help to increase stocking rates, milk productivity, and total solids and fat contents in milk. This, in turn, leads to more beef and marketable milk produced by the farmer that can be sold at higher prices to the dairy companies, since premium prices are paid for higher total solids contents. As a result, improvements in the economic indicators were observed, i.e., NPV, IRR, and B/C, indicating that for a dual-purpose farmer in Colombia, it is financially viable and of low risk to implement supplementation with *Canavalia brasiliensis* along with pasture improvement strategies. The suggested supplementation and pasture improvement strategies thus lead to higher incomes for the producers and reduce their risk of feed shortages, i.e., in the face of climate change and prologued droughts.

This analysis provides both dual-purpose farmers with necessary information for adoption decision making and other actors involved in the dissemination and adoption process of legumes in Colombia. Since the adoption of both supplementation strategies and legumes is still limited in the country, the study thus helps in closing the information gap. Additional efforts are, however, required to support technology uptake and include, e.g., the development of a formal legume seed production system, support for local seed production among farmers, financial incentives and new credit instruments, as well as increased collaboration among the key actors involved in technology development, information generation and dissemination, and commercialization.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JJ: Conceptualization, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. JM: Conceptualization, Resources, Writing – original draft, Writing – review & editing. MS: Resources, Writing – original draft, Writing – review & editing. EC: Resources, Writing – original draft, Writing – review & editing. SB: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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