Ex-Ante Evaluation of Economic Impacts of Adopting Improved Forages in the Colombian Orinoquía

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Forage-based cattle systems play a key role in rural economies of developing countries in terms of food security and poverty alleviation. However, they can generate negative environmental impacts by contributing to increased greenhouse gas emissions, land degradation, and reduction of biodiversity. As a result of that, large amounts of resources have been allocated to research and development (R&D) in forage material improvement and a broad range of improved materials were released showing superior characteristics in terms of productivity and environmental impacts compared to native or naturalized materials. However, data are still scarce on both the economic and environmental "yields" of investments in R&D activities around improved forage materials. Through an ex-ante evaluation, this study aims at estimating the potential "yields" of the investment in R&D and diffusion activities of the improved forage variety *Brachiaria brizantha* 26,124 cv. Agrosavia Caporal in the Colombian Orinoquía region. The analysis used two evaluation methodologies: 1) a combined discounted free cash flow model and Monte Carlo simulation using the simulation software @Risk to determine the impact on individual welfare, and 2) an economic surplus model an risk analysis to determine the potential social benefits of the technologies and their distribution among producers and consumers, considering changes in adoption rates, productivity levels and probability of success. The results suggest that the evaluated material presents important economic benefits for the study region and results in a positive return on the investments made in R&D activities. The results are a key input for decision making processes among public and private institutions involved in funding and executing the development of improved forage materials and will help to set research priorities and resource allocation.

Keywords: agricultural research and development, priority setting, technological change, economic surplus analysis, decision making, funding allocation for research, sustainable intensification (SI), conservation

INTRODUCTION

The Cattle Sector in the Colombian Orinoquía

Cattle production is one of the main agricultural activity in Colombia and plays a major role in the achievement of the Sustainable Development Goals in the region, as it holds a large potential for economic, social and environmental improvements. The Colombian cattle sector contributes with 21.8% of the agricultural Gross Domestic Product of the country and generates approximately 6% of the national and 19% of agricultural employment, respectively (FEDEGAN, 2018). Its importance

also lies in its impact on a social level. Cattle farming is mainly carried out by small-scale farmers (81% of the cattle farms in Colombia possess less than 50 animals, with an average of 18 animals per farm) (ICA, 2020). Additionally, it is estimated that 44% of the cattle producer households live in conditions of poverty (DANE-CNA, 2014; UPRA, 2019, 2020). According to the Food and Agriculture Organization of the United Nations (FAO, 2018), the sector has the potential to contribute to the goals of income and poverty reduction, reducing the environmental footprint, enhancing the provision of ecosystem services and promoting peace and social stability, among others. Over 20% of the total agricultural production from developing countries comes from this sector, and the increasing demand for animal source foods, coupled with changing diets and decreased availability of suitable land, pose major pressures on increasing the efficiency of the sector in ways that are inclusive, environmentally responsible and improve food security. In Colombia, its environmental relevance is primary, as cattle production generates 16% of the greenhouse gas emissions of the Colombian Agriculture, Forestry and Other Land Use sector (AFOLU), and is also one of the principal activities associated with deforestation and the expansion of the agricultural Frontier (IDEAM and MADS, 2016).

The Orinoquía region is of special importance for the country's cattle sector, as it holds approximately 20% of the total national cattle inventory (ICA, 2020), with nearly 55% of its agricultural land destined to cattle grazing (UPRA, 2015a; UPRA, 2015b; UPRA, 2015c). Although the average farm size in the region is rather large (534 ha), this is biased by a small number of large-scale farmers while the region is dominated by small-scale cattle farms with an inventory of less than 50 animals (ICA, 2020). The sector faces important challenges, as the expansion of cattle production threatens biodiversity and strategic ecosystems in the region, such as natural savannas, gallery forests, foothills or flooded forests. Additionally, forage supply is highly dependent on the marked water seasonality of the region (excessive rainfall and drought), directly affecting cattle production and making the sector more vulnerable to climate change. Investments in more intensive cattle production systems, considering the specific environmental conditions, water dynamics and presence of strategic ecosystems in the region, therefore, have been the main approach for achieving a sustainable development of the regional cattle sector (CIAT and CORMACARENA, 2018).

To advance towards sustainable intensification of cattle farming in the Orinoquía, institutions such as the Colombian Agricultural Research Corporation (AGROSAVIA, before Corpoica) and the International Center for Tropical Agriculture (CIAT) have been commissioned to carry out research on new forage materials. Government and research institutions consider the region as strategic for forage research and development (R&D), due to high soil acidity and low fertility - both key for carrying out adaptation and productivity trials with new and promising materials (Peters et al., 2013; Rao et al., 2015). Research has been aimed at identifying new forage materials with better productive characteristics, a greater range of adaptation to extreme conditions and higher resistance to local pests and diseases. Among the released materials, the grasses *Brachiaria*

humidicola CIAT 679 cv. Humidicola, *Brachiaria brizantha* CIAT 26110 cv. Toledo and, more recently, *Brachiaria brizantha* CIAT 26124 cv. Agrosavia Caporal stand out as superior alternatives to the traditional *Brachiaria decumbens* cultivars mainly used in the Orinoquía (Miles et al., 1996).

Processes of identification and release of new forage materials represent the first step towards sustainable intensification (improving efficiency without the need to further expand pasture areas), increasing food security and decreasing environmental trade-offs (including greenhouse gas emission intensities of the cattle sector). Under the right enabling conditions (e.g., subsidized credit, technical assistance, protective tariffs and land tenure security), sustainable intensification can help in achieving the objective of liberating areas with potential for crop cultivation, reforestation, conservation or landscape recovery.

Research on new varieties for the agricultural sector is recognized as a powerful instrument to accelerate economic growth and development (The World Bank, 2008; Stads and Beintema, 2009), but this process requires steady financing to maintain and enhance the necessary scientific, technical and technological capacities and infrastructure. In particular, most resources for agricultural research come from public funds, making it of special importance that the technologies derived from R&D processes are profitable and viable. Ex-ante impact evaluations allow estimating the possible benefits of R&D investments, providing information for prioritization and more strategic decision-making (Maredia et al., 2014).

Studies on the evaluation of impacts generated by the development of new forage materials in Colombia are scarce and date back to the 1990s and early 2000s. They focus on new *Brachiaria* hybrids and accessions adapted to different regions of the country (e.g., Vera et al., 1989; Seré et al., 1993; Rivas and Holmann, 2004a, 2004b), providing consistent results on the positive economic impacts derived from the adoption in cattle systems. No recent studies, however, evaluate the potential benefits of new forage materials. New grasses and legumes -- including cv. Agrosavia Caporal, the most recent technology to be delivered to Colombia's cattle producers–lack economic evaluation. *B. brizantha* cv. Agrosavia Caporal will be the third *Brachiaria brizantha* material released in the country, after the La Libertad (CIAT 26646) and the Toledo varieties released in 1987 and 2002, respectively. This material has been evaluated since 1986 and was identified as a promising alternative to improve cattle production in well-drained soils of the Orinoquía. In this sense, the objective of this study is to evaluate the impact of R&D and adoption of the new variety *Brachiaria brizantha* 26,124 cv. Agrosavia Caporal (Agrosavia Caporal from here on) in the Colombian Orinoquía region, with emphasis on the beef raising and fattening production system. For this purpose, we applied models at two aggregation scales - the micro and macro level. At the micro or farm level, a cost-benefit analysis was performed using a discounted free cash flow model and a Monte Carlo simulation analysis. This model was used to evaluate and analyze potential impacts on the primary producer and to determine if the adoption of the technology is economically feasible. At the macro level or the regional scale, an

economic surplus model was used in order to estimate and analyze the potential added benefit for the society and its distribution among two different social groups: producers and consumers. The economic surplus model is the most widely used model for measuring ex-ante impacts of technological innovations, providing a consistent theoretical basis with minimum data requirements. Although there are other more precise models (e.g., the IMPACT model), we aimed at maximizing the precision of our estimates, considering budget limitations, time constraints and access to available data.

Agrosavia Caporal has already been developed, but it is not yet available to producers (planned year of release: 2022). One of the aims of this study is, therefore, to not only guide the decision-making process of investing in the development of future varieties, but to also provide evidence on the potential benefits of other endeavors with similar contexts. This study also attempts to highlight some of the minimal conditions in terms of adoption levels and expected benefits, necessary to make such investments profitable both at the individual and social levels. The article is structured as follows: First, we present the theoretical framework on adoption processes at the micro and macro level, a literature review on previous studies on the subject and the empirical methodology we applied. In Section *Results*, we present our results. Section *Discussion* discusses these results considering previous studies on the subject and on-going adoption processes in the region. The final section presents the conclusions of the article.

Review on Economic Evaluations of *Brachiaria* in Latin America

In the context of adopting improved forages, impact evaluation studies were conducted mainly at the end of last century, and especially regarding *Brachiaria* hybrids and accessions in different regions of Latin America (e.g., Seré and Estrada, 1982; Rivas and Holmann, 2004a; Rivas and Holmann, 2004b). Seré and Estrada (1982) evaluated the profitability of cattle fattening under different feeding scenarios (with improved forages) in various locations of the Orinoquía, finding Internal Rates of Return (IRR) of between 10.7 and 30.4% (Vera et al., 1989). calculated that the use of *Antropogon gayanus* (Carimagua I) is 33% more profitable than traditional (naturalized) forages in the Orinoquía region and 78% the northern Caribbean of Colombia, respectively. Seré et al. (1993) examined the profitability of tropical forages released by CIAT and its local partners in Latin America, identifying an IRR of between 20 and 100%. Rivas and Holmann (2004a) evaluated the potential impact of new *Brachiaria* hybrids resistant to spittlebug in the eastern Orinoquía region and the Caribbean coast of Colombia, and estimated benefits for 2004 of US$960 million, which was equivalent to 43% of the country's meat and milk production value in 2003 (direct impact on the livestock sector). More recent studies on the subject were found for the African continent, where the impact of higher-yielding *Brachiaria* varieties was estimated. Elbasha et al. (1999), for example, evaluated the impact of different planted forages in West Africa during the period from 1977 to 1997 and estimated economic benefits of

approximately US$11.8 million, which represents an internal social rate of return on investments of 38% over a 20-year period. Schiek et al. (2018) evaluated the potential economic impact of the development and release of improved *Brachiaria* varieties in six East African countries, using an economic surplus model. According to their results, investment in a forage research program is a low risk endeavor with a high probability of obtaining positive results at a minimum adoption rate of 10%.

Most of the described studies used the economic surplus method as main approach for impact evaluation. In general, across all reviewed studies, positive results were found regarding the benefits of research on forage alternatives with better productive characteristics as strategy for intensifying cattle production. Although some of the past studies focused on the impacts of improved forages in different regions of Colombia, neither more recent ex-ante evaluations were found, nor particular studies regarding the species *Brachiaria brizantha* or micro-level studies that include quantitative risk assessments, which give more robust results and improve decision-making at the primary producer level. This document is intended to be a contribution to the literature in that sense, and provides useful information to donors and decision-makers regarding the potential yields of investing in forage research for the Colombian Orinoquía.

MATERIALS AND METHODS

Data Sources

Productivity data for the Agrosavia Caporal variety were obtained from field trials carried out by AGROSAVIA and CIAT in the Colombian Orinoquía region. Evaluations were carried out at the Taluma experimental station and the Carimagua Research Center under well-drained soil conditions. The average temperature at the site is 26°C and the average annual rainfall 2,500 mm. Productivity was calculated as the average of the accumulated live weight gain over a year in a cattle raising and fattening system. These measurements were carried out on a monthly basis between 2011 and 2015, with six groups of young crossbred bulls in a rotational grazing design, with 14 days of occupation and 28 days of recuperation. Information on the traditional technology (reference technology) used in the region was obtained through interviews with AGROSAVIA researchers and from past field evaluations conducted in the region. The ex-ante impact analysis seeks to compare a novel technology with a technology traditionally used in the study region. In our case, *Brachiaria decumbens* as monoculture is the technology with the largest area in the Colombian Orinoquía, with important characteristics in terms of productivity and adaptability to well-drained soils in the region (Rincón et al., 2010). The grass *Brachiaria decumbens*, was introduced and used massively in the country in the 1970s. The scenario assumes adequate management practices in terms of fertilization and rotation, to avoid overestimating the benefits associated with the adoption of the new variety.

Information related to economic and technological assumptions, as well as the R&D costs used in the economic

surplus model, was obtained through expert consultation and literature review. Section 2.6.1 shows the data sources corresponding to each parameter used. The establishment and management costs of the evaluated technologies were calculated based on the economic information collected during the trials, which was adjusted with the help of forage and livestock experts according to the conditions of a typical beef cattle raising and fattening farm in the Orinoquía region. Prices were updated to 2018 according to the price bulletins of the Colombian Price Information System of the Agricultural Sector SIPSA/DANE (2020) and databases of the Colombian Cattle Farmer Federation, FEDEGAN, (2019a).

Characteristics of the New Technology

B. brizantha cv. Agrosavia Caporal is a new forage alternative coming directly from the species *Brachiaria brizantha*, which was collected in Karuzi (Burundi, Africa) in 1985. CIAT researchers collected this material in collaboration with the Burundian national agricultural research institution (ISABU) (Rincón et al., 2021). Agrosavia Caporal is a perennial grass that grows in clumps, with decumbent stems of a height of 60–150 cm, capable of rooting in the ground and favoring soil coverage, persistence and lateral displacement of the grass. Its leaves are lanceolate with little pubescence, reaching up to 60 cm in length and 2.5 cm in width. It grows well in tropical conditions up to altitudes of 1,800 m above sea level. It develops best at temperatures between 20 and 35°C, with the highest forage production occurring during rainy season and in conditions with annual rainfall between 1,600 and 3,500 mm (Rincón et al., 2021). Although the variety was targeted to the Orinoquía region, it holds the potential for broader adoption in other regions of Colombia, given its adaptation potential to different climates (humid and sub-humid tropics) and soils (medium to good fertility) (M. Sotelo, personal communication, May 17, 2020).

The first evaluation records of *B. brizantha* cv. Agrosavia Caporal in Colombia date back to 1986, when antibiotic resistance to spittlebug was evaluated among 400 accessions of *Brachiaria*. Accession 26,124 was part of a group of 27 materials which were selected for presenting greater resistance compared to the commercial material *Brachiaria brizantha* cv. Marandú (CIAT, 1991). In 1997, it was one of the materials selected for presenting better drought resistance in trials established at the Carimagua research station in the Colombian Orinoquía (CIAT, 1997). In 1999, it was introduced for agronomic evaluation in different locations across Colombia (CIAT, 1999), and in 2000, in the Orinoquía (CIAT, 2001). In a participatory evaluation exercise, Agrosavia Caporal was selected by producers as a promising material for cattle production in the Orinoquían savannas, due to its good stem-leaf ratio, soft leaves, rooting behavior and rapid recovery after grazing (CIAT, 2001).

In 2011, in an inter-institutional agreement between AGROSAVIA and CIAT, forage germplasm evaluations under well-drained soils were started in the Orinoquía with the establishment of 58 materials and the aim of selecting the five most promising ones. The Agrosavia Caporal accession was identified as one of these materials, and was included in

animal feeding trials carried out at two locations in the Orinoquía (Taluma experimental station and Carimagua Research Center), where it was compared with *Brachiaria decumbens* - the control material predominant in the region. The main characteristics that made Agrosavia Caporal an outstanding alternative for animal feeding, and especially compared to other evaluated accessions such as Toledo (*Brachiaria brizantha* CIAT 26110), are its high forage productivity and quality, drought resistance (i.e., avoiding cattle weight losses during dry season) and grazing persistence (Rincón et al., 2021). *B. brizantha* cv. Agrosavia Caporal also shows good tolerance to water stress during the rainy season, as well as to different spittlebug species (*Aeneolamia varia* and *Zulia pubescens*) present in the region (Rincón et al., 2021).

Table 1 provides a summary of the main productive indicators of cv. Orinoquía, as well as the reference technology (*Brachiaria decumbens*) for comparison. The adoption of Agrosavia Caporal increases the total available forage biomass by 23% and the protein content by 28% compared to the reference technology, reflected also in the animal response, with average annual live weight gains per hectare of 226 kg for Agrosavia Caporal versus 198 kg for *Brachiaria decumbens*. According to the daily live weight gain data, the raising and fattening cycle until reaching the final sales weight (from 200 kg to 450 kg) is 19 months for Agrosavia Caporal and 24 months for *Brachiaria decumbens*.

Methodological Approach: Cost-Benefit Analysis

Through a cost-benefit analysis, we estimated the impact of investing in the establishment of Agrosavia Caporal in a cattle raising and fattening system at the micro level (from a primary producer's point of view) in the Colombian Orinoquía. This methodology was used as it allows to analyze the market viability of an investment project in a reliable way, considering all the relevant costs and benefits in a process of technology adoption at the farm level, the lifespan of the technology, productivity flows and relevant market prices. Such analysis is being applied when a comparison has to be made between a traditional technology and a new one, in order to determine the changes in costs and income associated with the new technology. In our case, the comparison is made with the reference technology–a monoculture pasture of *Brachiaria decumbens* (A. Rincón, personal communication, February 12, 2021).

The cost-benefit analysis is based on a discounted free cash flow model to estimate financial profitability indicators and to determine the viability of the different investment options. Profitability indicators include the Internal Rate of Return (IRR), Net Present Value (NPV), Benefit/Cost ratio (B/C) and investment payback period (PRI). The model includes a systematic categorization of the variable costs and benefits associated with the two evaluated options. Specifically, the following per hectare cost categories have been considered: establishment costs, renovation and maintenance costs, opportunity costs of capital during the establishment period (3 months, from establishment until first grazing), and operating costs (e.g., purchase of animals, animal health,

TABLE 1 | Dry matter production, nutritional quality and animal response of the evaluated grasses.

Parameter	Variable	Brachiaria brizantha 26,124 cv. Agrosavia caporal	Brachiaria decumbens (reference technology)
Biomass production	DM (ton ha^{-1} y^{-1})	7.1	5.8
Nutritional quality	Crude protein (% DM)	9.6	7–8
	IVDMD (%)	65	62
Animal response	Animal carrying capacity (AU)	1.4	1.2
	Live weight gain (g AU^{-1} d^{-1})	418	345
	Animal productivity (kg ha^{-1} y^{-1})	226	198
	Raising and fattening period (months)[1]	19	24

IVDMD = In Vitro Dry Matter Digestibility; 1 AU (Animal Unit) = 400 kg/animal; DM = Dry Matter; 1 Period of time required to bring an animal of 200 kg average weight to a sales weight of 450 kg.

TABLE 2 | Variables simulated with the Monte Carlo model.

#	Variable	Distribution	Most likely value	Minimum value	Maximum value
1	Meat price (US$ kg^{-1})	Triangular[1]	1.26	1.21	1.31
2	Live weight gain Agrosavia Caporal (g AU^{-1} d^{-1})	PERT[2]	226	199	262
3	Live weight gain References technology (g AU^{-1} d^{-1})	PERT[2]	198	128	227
4	Establishment costs Agrosavia Caporal (US$ ha^{-1})	Triangular	341	273	409
5	Establishment costs References technology (US$ ha^{-1})	Triangular	306	245	368

[a]Prices in US$–/US$/COP XRT: Average 2020; [1]This triangular distribution is an average of the three values and is recommended to specify situations that involve costs and investments; [2]A PERT distribution is a weighted average of the three values with greater emphasis on the center of the distribution and was selected by judgment of the researchers according to data availability.

supplementation, permanent and occasional labor). On the other hand, the benefits are derived from beef production in a cattle raising and fattening system, according to the obtained animal response indicators (**Table 1**). For the construction of the cash flow we assumed constant prices and an evaluation horizon of 10 years according to the estimated lifespan of pastures (Riesco and Seré, 1985). The cost of financing is chosen as the discount rate according to the rural credit lines of the Colombian Fund for the Financing of the Agricultural Sector (FINAGRO), and considered as the opportunity cost of capital, associated with a risk factor present in the activities of the rural sector. The following discount rate was, therefore, established: Fixed-term deposit rate (DTF) + 5% effective annual interest rate. The investment is assumed to happen in year 0, and from year one to year 10, the income and expenses associated with each technology are generated. It is important to mention that, although data were obtained at an experimental level, we expect the differences to the real conditions of the region to be insignificant, if the producers follow the technical recommendations for pasture management (e.g., fertilization plans, periods of pasture occupation and recovery) and if the material is established under agroecological conditions similar to those recommended (e.g., altitude, soil type, precipitation regime). In addition, at a methodological level, different scenarios are applied for the returns of each of the evaluated technologies (**Table 2**).

To include risk and uncertainty levels and consider different scenarios, a quantitative risk analysis was performed using a Monte Carlo simulation with the software @Risk (Paladise Corporation). In this simulation, values of the variables identified as critical (meat price, live weight gain, establishment costs) are randomly assigned, according to their probability distribution functions, to later calculate the determined profitability indicators (model outputs). This process is repeated numerous times to obtain the probability distributions of said outputs (Park, 2007). In our study, 5,000 simulations or iterations were carried out, where the variables live weight gain (per animal and day), investment costs, and sales price (per kg live weight) were randomly combined. The simulation used a 95% confidence interval. The probability distributions for the input variables are presented in **Table 2**.

The decision criteria are the mean values and the variations of the profitability indicators resulting from the simulation, as well as the probability of success (NPV>0). The use of the mean value criterion is based on the law of large numbers, which states that if many repetitions of an experiment are carried out, the average result will tend towards the expected value (Park, 2007). Additionally, a sensitivity analysis was performed using a tornado diagram, which displays each variable according to its impact on the variance of the model result. The diagram identifies the variables defined as critical and those with greater effects on the profitability indicators.

Methodological Approach: Economic Surplus Model

The equation system for the economic surplus model is based on Alston et al. (1995) (**Figure 1**). It proposes to model and measure the economic effects of technological changes induced by research in market environments, through parallel and linear

shifts of the supply and demand curves. In this case, the product in question (beef) is a perishable good that is not closely linked to international markets and therefore, equations for a closed economy are used.

The annual change in total surplus is defined as:

$$\Delta ET = K_t P_0 Q_0 \left(1 + \frac{1}{2} Z_t n\right) \quad (1)$$

where P_0 and Q_0 are the equilibrium prices and quantities, respectively; Z_t is the proportional price decrease in year t, defined as:

$$Z_t = \frac{K_t \varepsilon}{\varepsilon + n} \quad (2)$$

and K_t is the supply displacement factor associated with technological change, and its value is variable over time, depending on the dynamics of the adoption process; n is the absolute value of demand elasticity and ε the supply elasticity:

$$K_t = \left[\frac{E(Y)}{\varepsilon} - \frac{E(C)}{1 + E(Y)}\right] p A_t \delta_t \quad (3)$$

where $E(Y)$ is the average proportional yield increase per hectare, with ε being the supply elasticity used to convert the gross output effect of R&D-induced performance changes into a gross unit production cost effect; $E(C)$ is the average proportional change in variable costs per hectare required to achieve the increased yield; p is the probability of success in the technology adoption process; δ_t is the depreciation factor of the technology; A_t is the adoption rate in year t, and is determined by a logistic curve:

$$A_t = \frac{A_{MAX}}{1 + e^{-(\alpha + \beta t)}} \quad (4)$$

Amax is the maximum adoption rate, and the parameters α and β control displacement and slope, respectively and are determined by both the duration of research and adoption.

The annual change in consumer surplus is defined as:

$$\Delta EC_t = Z_t P_0 Q_0 \left(1 + \frac{1}{2} Z_t n\right) \quad (5)$$

The change in producer surplus is defined as:

$$\Delta EP_t = \Delta ET_t - \Delta EC_t \quad (6)$$

The economic benefits associated with the change in surpluses are expressed as annual flows of net benefits and the NPV is estimated. The NPV of the new R&D technology is calculated as:

$$NPV = \sum_{t}^{T} \frac{\Delta ET_t - k_t}{(1 + r)^t} \quad (7)$$

The aggregate IRR was calculated as the discount rate that equates the aggregate NPV to zero as follows:

$$\sum_{t}^{T} \frac{\Delta ET_t - k_t}{(1 + TIR)^t} = 0 \quad (8)$$

Additionally, for the estimation of the ex-ante evaluation model, the following assumptions are considered (Alston et al.,

1995): 1) There are no policy distortions such as subsidies, production quotas, or others; 2) markets are competitive; 3) the supply equals the demand for the good, since prices are adjusted to reach equilibrium quantities, 4) the change in total surplus is a measure of the change in social welfare; and 5) the shift in the supply curve is only the result of technological change.

Model Parameters
To estimate the social benefits of forage varieties by means of the surplus model, it is necessary to consider different technical and economic parameters. Technical parameters allow identifying the magnitude of the shift in the supply function and the behavior of the adoption curve over time and are related to: 1) changes in productivity levels, 2) year of technology launch and duration of the diffusion period, 3) speed and intensity of the adoption process, and 4) R&D levels. The economic parameters define the markets under analysis in terms of: 1) type of economy, 2) initial equilibrium quantities and prices, and 3) price elasticities of supply and demand.

Table 3 presents a summary of the parameters related to both the market and the technology used to estimate the model in the basic scenario, as well as the respective data sources. The impact calculations at the national level were made assuming values of productivity increases and a potential area determined by the current rate of adoption of the *Brachiaria brizantha* species at the national level, given its high adaptation potential. Technology adoption behavior and the estimation of R&D costs are further explained in the subsequent sections. R&D costs occur from the initial year of research until the release of the new technology (2011–2022). After its release, the technology is acquired by the private sector (in this case a seed production and marketing company from Brazil) who assumes the subsequent costs associated with seed production, marketing and distribution. As these costs do not correspond to public research institutions or governmental institutions, they are excluded from the calculations in our study.

In order to examine the sensitivity of the model results, three analysis scenarios have been considered: basic (B), optimistic (O) and pessimistic (P). The parameters that vary between scenarios are productivity, maximum expected adoption rate, and probability of success (**Table 4**). The probability of success is defined as the success of developing a technology for commercial use, as well as the annual adoption rate being met at a defined percentage. Although Agrosavia Caporal has already been developed, it is not yet commercially available to producers. According to preliminary agreements with seed producing companies, it will be commercialized in 2022. Additionally, heat maps were elaborated to analyze the effect of the variation simultaneal of the first two variables on the IRR indicator.

Cost of Research and Development
The R&D costs for the evaluation and selection of the new Agrosavia Caporal variety were estimated according to the requirements of scientific personnel in a process of improvement by selection, and the annual budgets approved under the macroproject *Evaluación y desarrollo de materiales*

TABLE 3 | Description of the key parameters and data sources for the analysis of economic surpluses in the basic scenario.
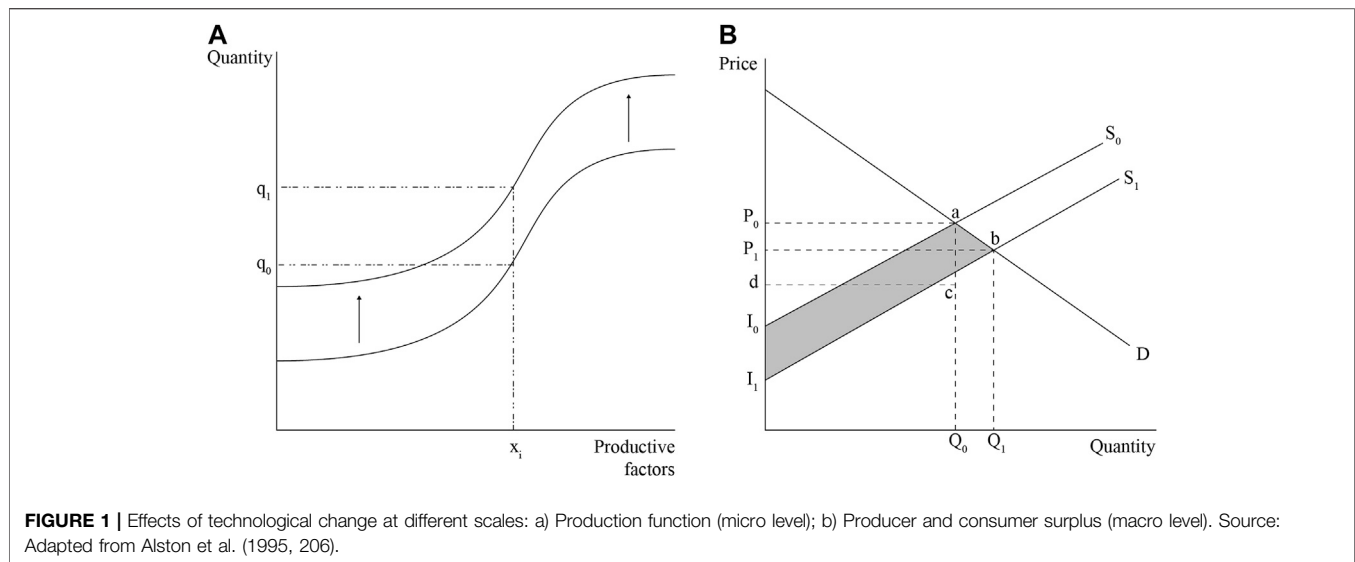
Parameter	Value	Description	Source
Economic assumptions			
Economy type	Closed	Beef from the Orinoquía region is destined for the local and extra-regional market (mainly Bogotá, Cúcuta and Bucaramanga). At the national level, 93% of the beef produced is destined for internal consumption	Own estimate based on data from DANE (2021)
Supply elasticity	0.7	The offered quantities vary less than proportionally to price changes	Rivas and Holmann (2004a)
Demand elasticity	−1.17	According to Ramirez (2012), the long-term elasticity of the beef demand is relatively elastic (>1). The estimates of cross elasticity with the other types of meat (chicken, pork) show a high substitution effect regarding price changes	Ramirez (2012)
Regional initial production (tons)	200,560		Own estimate based on data from FEDEGAN (2019a) and ICA (2020)
National initial production (tons)	932,813		FEDEGAN (2019a)
Initial price (US$/ton)	2,376		Own calculations based on data from FEDEGAN and Bogota (2019b)
R&D costs (US$)	563,243		Expert estimation based on R&D budgets involved in the selection process of a new forage variety
Technical assumptions			
R&D period (years)	5 (2011–2015)	Evaluations for the selection of promising materials under the agreement AGROSAVIA-CIAT.	
Diffusion period (years)	27	The diffusion period can vary between 25 and 30 years, depending on the agro-ecosystem and the production system	Rivas and Holmann (2004b)
Year of release	2022	The initial year of introducing *Brachiaria brizantha* 26,124 cv. Agrosavia Caporal has been set for 2022, since AGROSAVIA is currently in the process of producing basic seed and in negotiations with seed companies in Brazil for seed production at a commercial level	(A. Rincón, personal communication, February 12, 2021)
Effects on productivity (%)	+14	Better animal response associated with the best characteristics in terms of nutritional quality and biomass production of the new variety compared to traditional technologies in the region	Estimates according to agronomic and animal response trial data
Changes in costs (%)	0	There are no changes in production costs associated with the new material	Information provided by livestock and forages experts
Probability of success of research (%)	80	As a basic scenario, the assumptions used in the model are expected to be fulfilled by 80%	Judgment of the researchers according to expert opinion regarding the success of other research programs in other countries and regions
Discount rate (%)	12	Social rate recommended by the National Planning Department for public investment projects in Colombia	DNP (2013)
Adoption profile	Logistic adoption curve	Behavior of the adoption-diffusion process of agricultural technologies	Alston et al. (1995)
Initial adoption rate (%)	0.001	A logistical distribution is assumed	Alston et al. (1995)
Maximum expected adoption rate (%) - Regional	2.22	Percentage of area grown with *Brachiaria brizantha* in the Colombian Orinoquía region	Labarta et al. (2017)
Maximum expected adoption rate (%) - National	2.8	Percentage of area grown with *Brachiaria brizantha* in Colombia	Labarta et al. (2017)

TABLE 4 | Scenarios for the sensitivity analysis of the economic surplus model for *Brachiaria brizantha* 26,124 cv. Agrosavia Caporal.

Scenario	Regional			National		
	P	B	O	P	B	O
Changes in productivity (%)	10	14	20	10	14	20
Probability of success (%)	70	80	100	70	80	100
Expected final adoption rate (%)	1.11	2.22	3.33	1.4	2.8	4.2

P: pessimistic scenario; B: basic scenario; O: optimistic scenario.

forrajeros para integrarlos a los sistemas de producción ganaderos de la Orinoquía, financed by the Colombian Ministry of Agriculture and Rural Development (MADR), and executed by AGROSAVIA and the International Center for Tropical Agriculture (CIAT). In this project, 58 forage accessions were evaluated in the Orinoquía region in order to identify five promising varieties adapted to the local edaphoclimatic conditions. The R&D period was 5 years, from 2011 to 2015. The project had an annual budget of US$65,000, where 30% was allocated for the evaluation of Agrosavia Caporal. This included

FIGURE 1 | Effects of technological change at different scales: a) Production function (micro level); b) Producer and consumer surplus (macro level). Source: Adapted from Alston et al. (1995, 206).

operational expenses for the establishment, maintenance and evaluation of the trials, such as agricultural inputs, agricultural services (e.g., labor for field work), equipment and machinery, transportation, travel expenses, and laboratory analysis.

Personnel requirements were estimated from the percentages of time devoted by scientists, researchers, technicians and workers in a process of improvement by selection. This process consists of five main stages: 1) evaluation of the visual characteristics of the materials (height, coverage, dynamometer, vigor, pests and diseases); 2) evaluation of visual characteristics, dry matter production (DM) and nutritional quality (e.g., protein content, digestibility, neutral detergent fiber) of the pre-selected materials in (i); 3) evaluation of plant-animal interaction of the materials identified in (ii), which are established on a larger scale to determine palatability, material persistence and animal productivity (meat or milk); 4) evaluation of the plant-animal interaction of the materials identified in (iii); and 5) establishment of the selected materials in different locations depending on whether they are for release at the regional or national level. Prior to these stages, the costs associated with processes of application, reception, and field establishment of the seed for multiplication, as well as institutional costs and equipment depreciation were also included. The total duration of the evaluation process was five consecutive years (2011–2015). Since 2016, some evaluations have continued, mainly at the Taluma experimental station, with an approximate annual budget of US$2,708. This includes the costs associated with the maintenance of the trials and administrative expenses. In the years 2014–2016, multiplication of basic seed was carried out CIAT's facilities in Palmira, Colombia, and the associated costs were also included. The total estimated R&D cost for the variety was estimated with US$563,243.

Technology Adoption and Diffusion

Before any economic impact associated with technical change can occur, a process of adoption and diffusion of the new technology needs to happen. By adoption we mean, in the context of

technological innovations, the individual decision-making process about the acceptance of a previously unknown innovation, which implies learning through the acquisition of information and its incorporation into the production function. On the other hand, diffusion refers to the process of acceptance of a technology by a set of individuals in time and for a given region (Rogers, 2003).

Empirical evidence on adoption/diffusion processes of new agricultural technologies shows that it normally follows a logistic or sigmoid pattern (Mansfield, 1961; Mahajan and Peterson, 1985). On the subject of pastures, although literature is scarce, the studies of Jarvis (1981) confirm that adoption adjusts to a logistic model, meaning that the adoption curve is characterized by three stages: 1) early adoption, 2) exponential growth, and 3) the transition phase. In the first stage, the technology has a low adoption rate since only the least risk averse producers, or in other words, those who are more innovative, decide to invest in a new technology (in our case a new forage variety). After that, the benefits of the new technology begin to be known and a stage of rapid growth starts, characterized in turn by two sub-stages (2a) an early majority and (2b) a late majority. In the latter stage, adoption continues to grow, but each time at lower rates, as the process approaches its upper limit.

To estimate the adoption curve, we make use of ex-post data on the adoption of varieties similar to the new Agrosavia Caporal. Data were obtained from a nationally representative adoption study carried out by Labarta et al. (2017) in Colombia. Their results indicate that 2.2 and 2.8% of the total area, respectively at regional and national levels, are planted with the variety *Brachiaria brizantha* cv. La Libertad. Considering that this grass was introduced to the country 50 years ago, it is plausible to assume that the adoption-diffusion process is already in a maturation stage. This rate is considered, therefore, as the maximum level of adoption for the basic scenario. For the pessimistic and optimistic scenarios, we expect the adoption rate to be 50% below/above the maximum adoption rate expected for the basic scenario, indicating a minimum rate of 1.11% and a maximum rate of
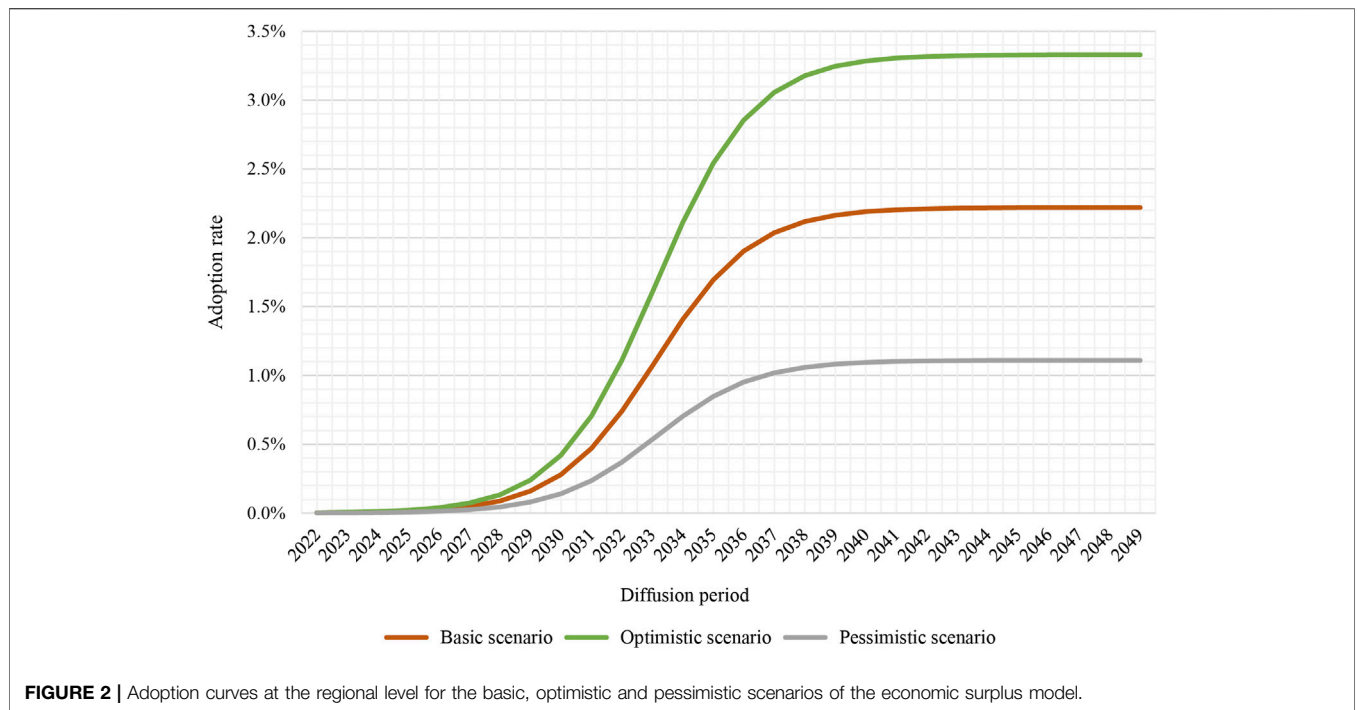
FIGURE 2 | Adoption curves at the regional level for the basic, optimistic and pessimistic scenarios of the economic surplus model.

TABLE 5 | Costs and income for cattle raising and fattening under both evaluated technologies.

Parameter	*Brachiaria brizantha* 26,124 cv. Agrosavia caporal	*Brachiaria decumbens* (reference technology)
Investment costs		
Establishment (US$ ha^{-1})	341	306
purchase of animals (US$ ha^{-1} cycle^{-1})	284	244
Operational costs		
Maintenance costs (US$ ha^{-1})[1]	182	182
Permanent labor (US$ ha^{-1} yr^{-1})[2]	89	84
Animal health (US$ ha^{-1} yr^{-1})	6.51	5.56
Supplementation (US$ ha^{-1} yr^{-1})[3]	14.1	12.03
Other costs	8.60	7.93
Gross income (average US$ ha^{-1} yr^{-1})	583	456
Unit cost of production (average US$ kg^{-1})[4]	1.027	1.029
Net income (average US$ ha^{-1} yr^{-1})[5]	112	94

[1]*Maintenance is carried out every 2 years and includes weed control, fertilizing with half the dose used for establishment;* [2]*Estimated: 2.5 permanent jobs required for every 100 animals in a cattle raising and fattening system (FEDEGAN, 2003), and a legal minimum wage in force plus benefits in 2020 of US$375.* [3]*Supplementation with mineralized salt at a rate of 50 g ha^{-1} d^{-1}.* [4]*Unit cost of production: dividing total cost of the product by total production.* [5]*Net income: total income (sales price x yield) minus total costs.*

TABLE 6 | Profitability indicators of the simulation model.

Decision criterion	Indicator	*Brachiaria brizantha* 26,124 cv. Agrosavia caporal	*Brachiaria decumbens* (reference technology)
NPV (US$)	Mean[a]	328	182
	SD[b]	95	134
	IC (95%)[c]	(30)-622	(223)-509
IRR (%)	Mean	21%	18%
Payback period (years)	Mean	5	5

[a]*Mean value of the NPV obtained in the simulation (5,000 iterations).*
[b]*SD: Standard deviation of the NPV with respect to the mean value.*
[c]*IC: Minimum and maximum values with a 95% confidence interval.*
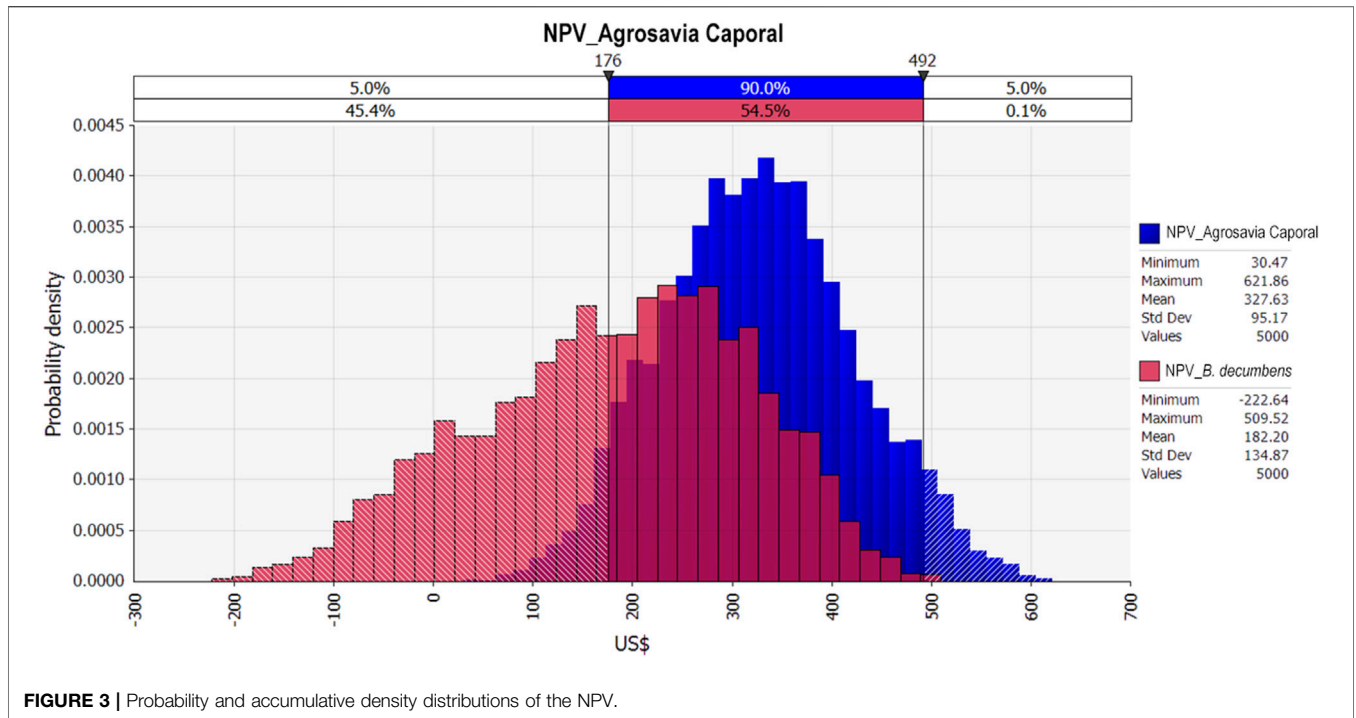
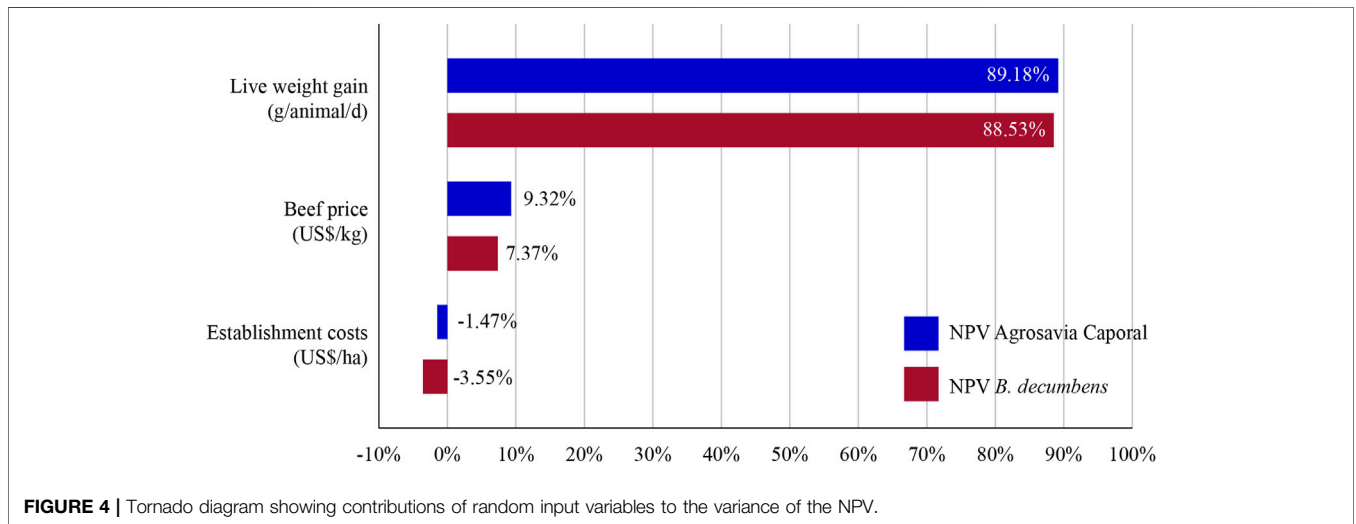**FIGURE 3 |** Probability and accumulative density distributions of the NPV.

FIGURE 4 | Tornado diagram showing contributions of random input variables to the variance of the NPV.

3.3% at the regional level, and a minimum rate of 1.4% and a maximum rate of 4.2% at the national level, respectively (**Figure 2**). In both cases, the aim is to examine the changes in the net social benefits when a successful dissemination process is assumed or when a process with serious difficulties is considered. However, much higher rates could be expected in an optimistic scenario, given adoption rates for other *Brachiaria* species, such as *Brachiaria dictyoneura* cv. Llanero and *Brachiaria decumbens*, which register adoption levels of 10.7 and 12.87%, respectively (Labarta et al., 2017). Nevertheless, in order to avoid, as far as possible, the overestimation of potential benefits coming along with adopting the new Agrosavia Caporal variety, we preferred to make more conservative estimates.

The total period of diffusion and adoption is 27 years (2022–2048), the maximum adoption rate will be reached in year 20 (2041), and from there on, a constant behavior is assumed.

RESULTS

Cost-Benefit Analysis

Table 5 provides an overview on the per hectare costs and income for both the Agrosavia Caporal and the reference technology. Regarding the direct production costs, the purchase of animals, pasture establishment and labor make up the highest shares.

TABLE 7 | Economic surplus model results (values in thousand US$).

Level	Scenario	Change CS	Change PS	Change TS	NPV	IRR (%)	B/C
Regional	B	1,184	1,979	3,165	903	19	8
	O	2,540	4,246	6,786	1,573	20	18
	P	444	742	1,186	-36	11	3
National	B	7,115	11,893	19,008	5,087	26	50.3
	O	15,261	25,508	40,768	11,342	30	108
	P	1,905	3,184	5,089	1,085	19	13.5

CS: Consumer Surplus, PS: Producer Surplus, TS: Total Surplus.

These three items participate with more than 80% of the total value. The unit cost per kilogram of beef produced was US$1.027 for the Agrosavia Caporal variety and US$1.029 for the reference technology. As a result of the better animal response indicators of the Agrosavia Caporal, the average gross income per year increased by 28% and the net profit by 19%.

The summary of the main financial results of the simulation is presented in **Table 6**. Under the assumptions used in this model, Agrosavia Caporal proves to be financially profitable and allows the improvement of all risk and performance indicators when compared to the reference technology. For Agrosavia Caporal, the model estimates an average NPV of US$328 and an IRR to equity of 21% per hectare. Regarding the probability of not obtaining financial feasibility of the evaluated technologies, **Figure 3** shows the NPV indicator distributions, which reflect the amplitude of its variation. For the reference technology, the indicator could range between US$-90 and US$540, with a probability of obtaining negative values of 13%. For Agrosavia Caporal, the improvement in productivity allows a shift to the right of the distribution curve, reducing the probability of losses to 0%, with values ranging from US$52 to 708.

The contribution of the input variables to the NPV variance is shown in the tornado diagram in **Figure 4**. The correlation coefficients calculated between the input values and the NPV variance show that profitability is affected mainly by two variables: liveweight gain and beef sales price. Increases in these variables have a positive effect on the variability of the indicator as follows: changes in the animal productivity variable modify the variance of the indicator by 89 and 90% for the new variety and the reference technology, respectively. Similarly, changes in the beef sales price lead to changes in the variance of 9 and 6%, respectively. Under the reference price of US$1.24 kg^{-1}, animal productivity below 0.174 tons ha^{-1} year^{-1} (equivalent to a live weight gain of 126 kg AU^{-1} year^{-1}) are not profitable for Agrosavia Caporal. Under the same reference price, the threshold for the base technology is a productivity level of 0.155 tons ha^{-1} year^{-1} (equivalent to a live weight gain of 129 kg AU^{-1} year^{-1}).

Economic Surplus Model

The results of the economic surplus model are presented in **Table 7**. At both the regional and national levels, the potential benefits of Agrosavia Caporal are positive in the three analyzed scenarios. Under the basic scenario, at the regional level, a total benefit of US$3,165,000 is estimated, which represents an internal social rate of return on investments of 19%. At the national level,

the results are similar to the ones at regional level, except that their magnitude is greater as a result of the increase in the expected adoption rate and affected production volume. The distribution of benefits is concentrated on the producers, who would receive 62.5% of the surplus. In the absence of international trade, the surplus production generated by the use of the new variety must be absorbed by the domestic market. Given that the demand curve is elastic (E_D =1.17), the new equilibrium point is reached through small price variations, increasing beef sales and producer incomes significantly while reducing consumer prices. The increase in production and reduction in consumer prices, in particular, favor low-income consumers who are more sensitive to price changes and thus contribute to improving food and nutritional security of the population.

Under the optimistic scenario, the new variety could achieve productivity increases of 16%, and cover 3.33% of the total Orinoquía region, respectively 4.2% of the national territory, leading to expected benefits of US$6,786,000 and US$40, 768, 000, respectively. Under this scenario, the investments in the development of Agrosavia Caporal would be very profitable, since the IRR would be >30% and the benefit/cost ratio would indicate that around US$108 are generated from every US$ invested. Under the pessimistic scenario, changes in yields of 12%, a regional adoption rate of 1.11% and a probability of success of 70% were considered, which would yield total benefits of US$1,186,000 for the Orinoquía region. Likewise, the estimated profitability would be 11% and thus lower than the social discount rate of 12%, meaning that the total surpluses generated at the regional level would not be sufficient to compensate the spent R&D costs. These results show a latent risk that the R&D investment spent for developing the material might not exceed the additional benefits and, therefore, in such scenario, an investment would not be recommended. For an investment to become socially and economically profitable, a series of requirements must be met that go beyond the R&D phase and the release of a material with outstanding characteristics, such as the development of efficient technology promotion and dissemination strategies (including the availability of commercial seed, distribution networks, communication strategies and competitive costs) that lead to both higher adoption levels than the projected 1.11% and productivity changes superior than 12%. In addition, since a probability of success of >70% is necessary, it is important that the developed technologies, in addition to their differentiating technical characteristics, are cost efficient and provide sufficient

TABLE 8 | Heat map for the sensitivity of the IRR (total surplus basis) with respect to changes in the adoption rate and productivity level.

	Adoption rate (regional level)									
Change in productivity	18.8%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
	5%	8.9%	12.5%	14.7%	16.3%	17.5%	18.6%	19.5%	20.3%	21.0%	21.7%
	10%	12.5%	16.3%	18.6%	20.3%	21.7%	22.8%	23.8%	24.7%	25.5%	26.2%
	15%	14.7%	18.6%	21.0%	22.8%	24.3%	25.5%	26.5%	27.4%	28.2%	28.9%
	20%	16.3%	20.3%	22.8%	24.7%	26.2%	27.4%	28.5%	29.4%	30.2%	31.0%

	Adoption rate (National level)									
Change in productivity	26%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
	5%	14.9%	18.3%	20.4%	22.0%	23.2%	24.2%	25.1%	25.8%	26.5%	27.1%
	10%	18.3%	22.0%	24.2%	25.8%	27.1%	28.2%	29.1%	29.9%	30.7%	31.3%
	15%	20.4%	24.2%	26.5%	28.2%	29.5%	30.7%	31.6%	32.5%	33.2%	33.9%
	20%	22.0%	25.8%	28.2%	29.9%	31.3%	32.5%	33.4%	34.3%	35.1%	35.8%

seed for multiplication. At the national level however, the IRR would be 19% given the higher overall adoption and total production affected by potential yield increases, suggesting that the R&D investment would be profitable at the national level–even under the pessimistic scenario.

To verify the robustness of the estimates for impacts and return on investment estimates, a sensitivity analysis was carried out with respect to the reference scenario. In particular, the variables of maximum expected adoption rate and productivity level were examined. **Table 8** shows heat maps corresponding to the changes of these variables and their effects on the IRR under basic scenario assumptions (probability of success of 80%, 2.8% adoption rate at regional and 2.2% at national level, respectively). The results suggest that, at the regional level, the technology is profitable when productivity increases greater than 5% occur and with an adoption rate of 1%. Although the results of the analysis are clearly sensitive to these two variables, investing in this alternative is highly profitable under most of the assigned values.

DISCUSSION

The material *Brachiaria brizantha* 26,124 cv. Agrosavia Caporal was identified as a promising variety for release, given its good characteristics in terms of nutritional quality, biomass production and persistence during dry season. Planting the variety leads to beef yield increases of around 14% when compared to *Brachiaria decumbens* (reference technology). This is consistent with the findings of Pardo and Pérez (2010), and Lascano et al. (2002), who have shown the potential of integrating new *Brachiaria brizantha* accessions in different areas of the Colombian Orinoquía to increase cattle productivity. These studies conclude that, compared to traditional technologies, the new accessions allow increasing meat production per hectare between 9 and 100%. According to our results, the higher productivity can improve the net returns of beef cattle production at a farm level by an average of 19%, as consequence of higher daily live weight gains, which reduce the length of the fattening cycle and generate faster and more frequent income flows. This translates into better financial indicators compared to the reference technology, with a

79% increase of the NPV and a 16% increase of the IRR, respectively. With an average NPV of approximately US$328 and an IRR of 21%, the technology appears as a viable alternative to improve both efficiency and profitability of the region's cattle farms.

Agrosavia Caporal also presents a reduction in the probability of obtaining economic losses (0 versus 13% for the reference technology), resulting from its higher productivity and lower yield variability (between 199 and 262 kg ha^{-1} year^{-1}). This is essential for regions such as the Orinoquía, where high water seasonality affects cattle production and the general availability of food. The region is projected to experience important difficulties due to climate change, with reductions in annual precipitation as well as increases in maximum temperatures (IDEAM et al., 2015). These increasing risks, coupled with changes in market conditions (e.g., sales and input price variations), substantially affect long-term investment decisions at the producer level, such as the adoption of new technologies. In this sense, forages that can guarantee a lower risk–such as Agrosavia Caporal–provide additional incentives for adoption (Marra et al., 2003). It is important to note that for both evaluated technologies, the productivity parameters used assume adequate pasture management. Inadequate management will inevitably translate into pasture degradation and affect the feasibility of the system, undermining the technology's potential as a promising material and affecting the environment by increasing carbon dioxide (CO_2) emissions. According to Rincón (2006), degraded pastures in the region cause a reduction in beef and dairy production of more than 50%, directly associated with a loss of biomass production, soil compaction, weed invasion and erosion, among others, making it essential to provide training to the primary producer through specific extension and technology transfer programs, focusing i.e., on establishing and maintaining the pasture.

Despite the previously mentioned benefits, pastures under monoculture remain significantly exposed to changes in production and quality throughout the year (Tedonkeng et al., 2007). The association of improved grass varieties with trees and legumes should be promoted as a technological package, since they can reduce heat stress in animals, contribute to increasing

pasture persistence (due to nitrogen fixation) and improve the provision of ecosystem services (e.g., contribution of organic matter to pastures, improvement of soil quality and soil carbon accumulation, temperature regulation) (Harrison et al., 2015; Reckling et al., 2016; Dubeux et al., 2017). Cohn et al. (2014) found that policy instruments, such as taxes on cattle from conventional systems or subsidies for production in diversified, more sustainable systems, might be effective methods to promote such technological and cultural changes among farmers and strengthen the long-term sustainability, while reducing greenhouse gas emissions.

At a macro level, the results from the economic surplus model show that, on average, investing in the development of more productive forages, such as Agrosavia Caporal, can be highly profitable from a social point of view, given the significant performance gains and the particular conditions of the cattle sector in both the Orinoquía and Colombia. We found that, if adopted, the forecasted productivity increases obtained with Agrosavia Caporal could generate a shift in beef supply, associated with significant economic benefits. The estimated NPV of the social benefits for the period from 2022 to 2048 would be approximately US$903,000 and US$11.3 million at the regional and national levels, respectively. These results are consistent with other studies that evaluated the impact of improved forage varieties in the country and identified internal social rates of return on investments of up to 100% (Vera et al., 1989; Rivas and Holmann, 2004a, 2004b). The results of the economic surplus model depend mainly on the variables *maximum expected adoption rate* and *productivity*. Under the pessimistic scenario, with an adoption rate of <1.11% (equivalent to 144,000 ha in the Orinoquía) and yield increases of <10%, the R&D investment would become unfeasible at a regional level. This has important implications both the R&D and dissemination processes. The use of new forage varieties that do not provide sufficient benefits at a social level may be economically feasible at a farm level but not justify a new R&D process. Even if reasonably larger productivity and risk reduction gains were to be expected, a strong dissemination process should be ensured so that the expected adoption levels can be reached. This includes a strong seed system that also focuses on communication, information and training. Success in that regard will depend entirely on the capacity of and coordination among institutions, which include actors from the public, private and mixed sectors. To ensure adoption, other barriers that need to be addressed include the access to credit and inputs, land tenure insecurity, market instability and inadequate infrastructure (e.g., Lapar and Ehui, 2004; Wunscher et al., 2004; Dill et al., 2015).

Regarding the social distribution of potential benefits, our study shows that they are mostly concentrated in the primary sector (supply side). Within the primary sector, it is not clear, however, how these benefits will be distributed among or concentrated within different segments (e.g., small, medium or large producers). Given that the micro level analysis reveals that the investment can be feasible even at minimum scales (1 ha), and considering the producer typology in the Orinoquía (53.4% of the producers have <50 animals (ICA, 2020)), we assume a large share of the potential beneficiaries will be small producers. These results, however, may be ambiguous: Labarta et al. (2017) describe a direct relationship between the adoption of improved forages in the region and the access to resources (e.g., credit, labor, level of wealth), making resource-rich producers the main group of potential adopters. Yet at the same time, when it comes to actual adoption, large producers are described as less likely to adopt, presumably due to scale limitations, security concerns, and lack of infrastructure. To the above-mentioned considerations, a series of structural factors can be added, such as land prices or local wage levels, that may or may not encourage the adoption of improved forages in the region.

Regarding environmental aspects, greenhouse gas emissions and deforestation are the main concerns for the Orinoquía cattle sector, with widespread adoption of improved forages potentially contributing to generating positive outcomes. But these improved forages also pose additional challenges and risks. Cattle production is one of the main sources of greenhouse gas emissions, resulting from the ruminant digestion process that generates methane (CH_4) and nitrous oxide emissions (CIAT and CORMACARENA, 2018). Higher quality forages allow increasing animal productivity and feeding efficiency (conversion of forage to animal protein), reducing CH_4 emissions per unit of product (Knapp et al., 2014; Zubieta et al., 2021). Cardoso et al. (2016) estimate that increased quality and quantity of forage can potentially decrease greenhouse gas emissions per kg carcass weight by 50%, principally resulting from a reduction of CH_4 emissions. The expansion of areas for cattle production is one of the main drivers of deforestation, a process that also generates high amounts of greenhouse gas emissions and is particularly problematic in the Orinoquía region, which holds various key ecosystems, such as natural savannas, flooded forests, humid forests or foothills (CIAT and CORMACARENA, 2018). In this regard, the effects of increasing productivity of agricultural systems on forest conservation can be ambiguous: it can incentivize the expansion of production in the agricultural Frontier through the clearing of forest areas, but it can also be used as an indirect tool to reduce the pressure of expanding the agricultural Frontier, an idea known as the Borlaug effect.

In the Orinoquía, the introduction of *Brachiaria* grasses since the end of the 1960s (*Brachiaria decumbens*, Rincón et al., 2010) has been a subject of debate, mainly in environmental terms. The adoption of these varieties occurred spontaneously and massively by the producers and was associated with several desirable traits that increased productivity, such as a high biomass production and nutritional quality, adaptation to marginal lands and low fertility soils (Rao et al., 1998). Different studies for the region have reported that the adoption of *Brachiaria* varieties resulted in productivity increases from 18 to 37 kg ha^{-1} year^{-1} (no adoption) to 294–402 kg ha^{-1} year^{-1} (with *Brachiaria*), resulting in important impacts at the productive, economic, environmental and social levels (Pérez and Vargas, 2001; Rincón et al., 2010). Positive impacts include the reduction of land degradation and pressure on the native savanna, methane emissions reductions due to increased feeding efficiency, greenhouse gas emissions reductions associated with native savanna burning (Smith et al., 1997), better soil cover and improved soil quality parameters (better water infiltration and reduced soil erosion), and higher nitrogen and carbon fixation to the soil (Boddey et al., 1998). These positive impacts are, however, often conditioned to the (proper) management of the pastures. Negative impacts are

mainly associated with the degradation of native savannas, threats to biodiversity, soil erosion, deforestation for expanding grazing areas and increased greenhouse gas emissions (Peñuela et al., 2011; Peñuela et al., 2014; CIAT and CORMACARENA, 2018). Various studies evaluated the conditions in which both scenarios are more likely to occur. In Brazil (Cohn et al., 2014), and De Oliveira Silva et al. (2016) have estimated a large greenhouse gas mitigation potential through cattle ranching intensification when coupled with no deforestation scenarios, taxes on conventional pastures and subsidies for semi-intensive systems. Some studies have found that land use changes derived from agricultural intensification are strongly linked to the characteristics of a particular area and the land tenure conditions. Decreasing deforestation patterns were found when intensification occurs in consolidated agricultural regions, and increasing deforestation when it occurs on marginal lands (Maertens et al., 2006; Barretto et al., 2013) and land with unclear land tenure (Kubitza et al., 2018). A meta-study of 60 cases conducted by Rasmussen et al. (2018) found that there are scant cases where agricultural intensification has had simultaneously a positive effect on well-being and ecosystem services. These studies suggest that holding the sustainability claims of cattle ranching intensification would likely require a combination of various policy and market mechanisms, such as effective monitoring and control, law enforcement, taxes, subsidies and land tenure rights, among others. In areas where land is not a constraining factor, as is the case of the Colombian Orinoquía, there is a greater pressure to expand, making this a major threat and topic to consider. While there are initiatives in the country seeking to prevent deforestation derived from the cattle sector (such as the National Zero Deforestation Agreements), it is still too early to provide evidence that can support their effectiveness, and further research is advised.

As mentioned in the methodology section, our evaluation is based on a partial equilibrium model and does therefore neither include potential impacts on other economic sectors nor on natural resources. Our study demonstrates, however, the importance of new pasture technologies, their high potential to produce social benefits, and the need to develop mechanisms to take advantage of this potential. Both our study and other previously conducted ex-ante studies (reviewed at the beginning of this document), were carried out after the investments in R&D have already happened and just before the release of the particular technology. It is recommended, however, to conduct such studies before making decisions on R&D investments, so that the results can serve in the decision-making process and for the allocation of ever scarce funds. Despite this, our results still provide insights into the potential benefits at the regional level and serve for justifying future R&D processes of new forage varieties for other regions of the country. When interpreting our results, it is important to bear in mind that the economic surplus model used is a minimum data approach that simplifies reality. Given data limitations, production estimates affected by technical change are based on average yields at the regional and national levels. Likewise, the model assumes that yield increases are the same for all producers, without considering existing heterogeneities among them, e.g.,

in technological terms. Transaction costs that occur once the variety is released, i.e., related to its adoption, dissemination and promotion, and that are assumed by the private seed sector were ignored in our study, since they are not part of the publicly-funded R&D process. These simplifications can lead to an overestimation of the estimated net benefits. To mitigate such limitations, we made conservative estimations based on expert consultations. Our model does not consider additional benefits that could derive from, e.g., an increase in milk production (since we evaluated the technologies in a dual-purpose system) and other technical parameters in the region (e.g., interval between births, birth rates). Nevertheless, these could substantially increase the benefits of the new variety for the region. Hence, research should be conducted to quantify such additional benefits.

As mentioned before, the variety Agrosavia Caporal is the third *Brachiaria brizantha* variety released in the area after Toledo and La Libertad. These cultivars, together with the new variety, are materials with characteristics superior to the traditional technology predominantly used in the area (*Brachiaria decumbens*). There are, however, differences between them in both desirable forage characteristics and limitations. Toledo, for example, has shown to present better dry matter yields compared to Agrosavia Caporal (Lascano et al., 2002), and better characteristics in terms of tolerance to humidity, recovery after grazing, and vigor of the plant compared to La Libertad (Lascano et al., 2002). Agrosavia Caporal, on the other hand, has shown resistance to different species of spittlebug, while Toledo and La Libertad are more susceptible (Lascano et al., 2002), and has better palatability and drought tolerance in the dry season (A. Rincón, personal communication, August 06, 2021). In this sense, they are materials with differentiating characteristics that could also have different economic impacts associated with their adoption. It is recommended, therefore, to evaluate each of these technologies to determine their viability in terms of R&D and to identify the forage attributes that could have the greatest economic impact.

CONCLUSION

Our study shows the economic feasibility both at the primary producer level and at the social level of adopting a new forage technology with superior productive characteristics. The new Agrosavia Caporal variety, which will be released in 2022, shows very good animal response parameters that increase the economic viability of cattle raising and fattening systems in the Colombian Orinoquía region. At the social level, technology adoption could generate an outward shift in the supply of meat, which would be associated with important benefits at both the regional and national levels. However, the potential success of Agrosavia Caporal, as well as of other potential new varieties with superior characteristics, is highly conditioned to the adoption level and to proper technology management that allows maintaining expected productivity levels. Therefore, it is essential to develop adequate support mechanisms during the release and adoption process, in order to provide farmers with solid extension strategies and training programs that focus, for example, on planting and cultivar management. Likewise, it is crucial that

commercial seed availability of the material is guaranteed in the release, adoption and diffusion processes.

The cattle sector in the Colombian Orinoquía region is not only important at an economic or social level but also plays a significant role at an environmental level. It is recognized for being one of the main contributors to the country's greenhouse gas emissions, and one of the main drivers of deforestation, affecting the different strategic ecosystems present in the Orinoquía. The sector is also highly dependent on and affected by water seasonality, a situation that could further aggravate under the forecasted climate change scenarios for the region. Sustainable intensification of the cattle sector is considered to be the route to reducing negative environmental impacts while improving per area productivity, and forages with superior characteristics play an important role in this sense. The inclusion of trees and legumes in cattle systems, which improve the provision of ecosystem services and animal welfare, however, should be considered as add-on in order to move towards more sustainability and away from grass monocultures. The superior nutritional characteristics of Agrosavia Caporal can have positive effects on the environmental impacts of the local cattle systems. Reduced CH_4 emissions and the release of areas can be expected, given the higher intensification and better digestibility. In order to achieve the economic, social and, above all, the environmental benefits of this new technology, coordinated efforts of the involved actors will be required. Extension campaigns need to provide information on the importance of sustainable intensification (focused on liberating areas for conservation) and conserving strategic ecosystems present in the region. Public policies and monitoring systems are needed in order to prevent an unwanted spread of the new technology (and any other new technology in the future) to protected areas or ecosystems of the region.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: Data is from another project/institution and still restricted. Requests to access these datasets should be directed to SB, s.burkart@cgiar.org

AUTHOR CONTRIBUTIONS

SB, KE, AC, and ARC: Conceptualization. KE, AC, ARC, and SB: Methodology. KE, AC, and ARC: Formal analysis. KE, AC, ARC, and SB: Writing the original draft and review and editing. AC, KE, ARC, and SB: Resources. SB: Supervision and funding acquisition. SB: Project administration. All authors contributed to the article and approved the submitted version.

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