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The inclusion of *Leucaena diversifolia* in a Colombian beef cattle production system: An economic perspective

Leucaena diversifolia *en un sistema de producción ganadera en Colombia: Una perspectiva económica*

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Abstract

Despite the great potential of legumes in cattle production, their adoption and use throughout the tropical world remain limited. While this is largely attributed to factors such as limited knowledge or access to credit, lack of information on the viability and profitability of the technology can influence the adoption decision. The objective of this study is to evaluate the profitability of including *Leucaena diversifolia*, accession ILRI 15551 in a Colombian beef cattle production system. For this purpose, we use data from a grazing experiment comparing a grass-legume association (*Brachiaria* hybrid cv. Cayman and *L. diversifolia*) with a grass monoculture (cv. Cayman) in the Valle del Cauca department, both with the purpose of beef production. We use a discounted cash flow model, developed with the simulation software @Risk, which considers inherent risk and uncertainty factors in these types of rural investment projects, under three different pasture degradation scenarios. The results indicate that the inclusion of *L. diversifolia* is financially profitable and substantially improves the associated risk and performance indicators. Profitability indicators increased in a range of 15–110%, and the probability of suffering economic losses decreased from 72% to 0%. The results were directly related to the increases in animal productivity (49%) and efficiency resulting from including the legume. This work shows that *L. diversifolia* has significant potential to increase both animal production and profitability, which is conducive to the sustainable intensification of beef production in grazing systems.

Keywords: Grass-legume systems, Monte Carlo simulation, risk analysis, shrub legumes, sustainable intensification.

Resumen

A pesar del gran potencial de las leguminosas para la producción ganadera, su adopción y uso siguen siendo limitados. Mientras que esto se atribuye en gran medida a factores como el conocimiento limitado o falta de acceso a crédito, también la información faltante sobre la viabilidad y rentabilidad de la tecnología puede influir en la decisión de adopción. Este estudio tiene como objeto evaluar la rentabilidad de la inclusión de *Leucaena diversifolia* accesión ILRI 15551, en un sistema de producción de ganado de carne, basado en el pasto *Brachiaria* híbrido cv. Cayman (Cayman), en el Departamento del Valle del Cauca, Colombia. Se usaron datos de un experimento de pastoreo para comparar la asociación Cayman-*L. diversifolia* con el monocultivo de Cayman. Se aplicó la metodología de flujo de caja libre descontado y un análisis de simulación Monte Carlo con el software de simulación @Risk, con el fin de incluir los factores de riesgo e incertidumbre en las variables identificadas como críticas, bajo tres escenarios de persistencia de las pasturas. Los resultados indican que la inclusión de *L. diversifolia* es financieramente rentable y permite mejorar sustancialmente todos los indicadores de riesgo y desempeño. Los indicadores de rentabilidad incrementaron en un rango del 15 al 110%, y la probabilidad de obtener pérdidas económicas pasó del 72.1 al 0%. Los resultados estuvieron directamente relacionados con el incremento en la productividad animal (49%) y eficiencia resultantes de la inclusión

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de la leguminosa. Este trabajo muestra que *L. diversifolia* tiene un potencial significativo para aumentar tanto la producción animal como la rentabilidad, lo cual es propicio para la intensificación sostenible de la producción de carne en sistemas bajo pastoreo.

Palabras clave: Análisis de riesgo, intensificación sostenible, simulación Monte Carlo, sistemas gramínea-leguminosa.

Introduction

The forage-based cattle sector plays a key role in tropical food production, food security and poverty alleviation (Peters et al. 2013; Capstaff and Miller 2018). However, along with the benefits, negative consequences on the environment can occur. Globally, it has been estimated that the sector contributes 14.5% of all anthropogenic greenhouse gas (GHG) emissions, mainly as methane (CH_4) from the enteric fermentation process (Gerber et al. 2013). In addition, the sector is being associated with problems of land degradation, deforestation, water pollution and depletion, and loss of biodiversity (Steinfeld et al. 2009). Under this perspective, and in the context of: scarce resources; increased global demand for food; and climate change (FAO 2017), governments, NGOs and other organizations have developed strategies to mitigate the sector's environmental impacts, increase its efficiency and improve its productivity. In this regard, improvements in animal feeding and sustainable intensification are considered to be among the most promising strategies to date (Gerber et al. 2013; FAO 2017).

Given this panorama, the inclusion of forage legumes in cattle production systems has the potential to achieve the aforementioned objectives. Firstly, legumes can increase both yield and nutritional value of the forage, and improve the efficiency in converting forage to animal protein (meat/milk) (Lüscher et al. 2014). Secondly, legumes can reduce enteric CH4 emissions from ruminants (Harrison et al. 2015) and increase the levels of nitrogen (N) in the soil through biological N fixation (Dubeux et al. 2017). For example, studies show that, when *Leucaena leucocephala* is sown into grass pasture, CH_4 emissions per kg of consumed dry matter can be reduced by 15% (Molina et al. 2016) and more than 75 kg N/ha/yr can be fixed (Shelton and Dalzell 2007). Other environmental benefits include: the improvement of soil fertility and carbon accumulation (Rao et al. 2015); the potential for mitigation of and adaptation to climate change (Schultze-Kraft et al. 2018); and a contribution to rehabilitating degraded pastures (Plazas and Lascano 2006).

Despite the great potential of tropical legumes in cattle production, their adoption and use by producers remain limited (Shelton et al. 2005). Among the limiting factors for widespread use are: economic factors that determine access to capital (e.g. size of the productive unit, access to credit); lack of knowledge and limited perceived benefits by the producer (Thomas and Sumberg 1995; Wortman and Kirungu 2000; Lapar and Ehui 2004); and aspects associated with risk aversion and uncertainty (Feder 1980; Marra et al. 2003). A key aspect for successful adoption of an innovation is personal sustainability, i.e. adoption will not occur unless the economic benefits of adopting exceed the costs for technological investment (Carey and Zilberman 2002; Pannell et al. 2006). Although adoption levels of forage legumes are still low in the tropics, some successful examples from different continents were reported by Shelton et al. (2005), highlighting their profitability and multipurpose benefits to farmers. However, this type of information is often scarce, making the decision making process difficult for the producer. Therefore, it is important to perform economic evaluations to generate information about the viability and profitability of the desired technology.

The objective of this study was to evaluate the profitability of including *Leucaena diversifolia* in a Colombian cattle production system. For this purpose, we compared a grass-legume association (*L. diversifolia* in a *Brachiaria* hybrid cv. Cayman pasture) with a grass monoculture (Cayman) in the Valle del Cauca department, Colombia, both with the purpose of beef production. The methodology is based on a discounted cash flow model, developed with the simulation software @Risk, and considers the inherent risk and uncertainty factors in these types of rural investment projects. The results provide a mechanism for improving the quality of the decision making process regarding adoption of legumes for cattle production systems.

Materials and Methods

Data source and study area

The data used in this study were obtained from field evaluations of: a) Cayman as a monoculture; and b) a Cayman-*L. diversifolia* association, carried out by the Tropical Forages Program at the facilities of the International Center for Tropical Agriculture (CIAT) in Palmira, Valle del Cauca, Colombia. The ecological classification of the study area, according to Holdridge (1967), corresponds to a pre-montane wet forest (bh-P), located at 1,001 masl, with average temperature, relative humidity and annual precipitation of 23.8 °C, 75% and 1,045 mm, respectively and a bimodal rainfall regime (March–April and October–November). The experiment was established on a fertile Mollisol with clayey texture (clay content between 40 and 60%; Howeler 1986), good drainage, pH (H_2O) 7.54, organic matter 4.85%, CEC 16.4 cmol/kg, P concentration 25 ppm and Ca, Mg and K concentrations 7.87, 6.17 and 0.82 cmol/kg, respectively. The pastures were established in August 2013 and until grazing commencement were maintained by cutting at 6 week intervals. Grazing was between August 2014 and August 2015, using 10 Colombian half-blood steers (zebu × Holstein, zebu × Normande, zebu × Jersey); liveweight gains were measured monthly. The steers were 12 months old and weighed 210±25 kg (±SD) at the start and 416 ±28 kg at the end of the evaluation. The data related to the costs were compiled using economic information collected during the establishment of the trial, and adjusted with the help of Colombian forage and livestock experts to avoid overestimation for research reasons. The prices were later updated to 2018 levels, according to the price bulletins of the Colombian Price Information System for the Agricultural Sector (SIPSA) and the Colombian Cattle Federation's (FEDEGAN) databases.

Description of the treatments

The treatments were: T1) Cayman monoculture (100%); and T2) Cayman-*L. diversifolia* association (in a proportion of 70:30 of DM at the beginning of the trial). Each treatment had an area of 9,900 m^2, divided into 3 plots of 3,300 m^2, under an experimental design of a randomized complete block. Each plot was divided with electric fences into 3 sub-plots of 1,100 m^2. The animals grazed under a rotational system with 6 days of occupation and 48 days of rest for each sub-plot. For T2, 2,000 *L. diversifolia* plants/ha had been established and distributed in twin rows separated by a distance of 8 m. The twin rows were separated by a distance of 1.5 m, and distance between plants within rows was 1 m. The initial stocking rate (SR) for both treatments was 2.3 animal units (AU = 450 kg) per hectare and by the end of the evaluation year SRs were 3.36 AU for T1 and 4.04 AU for T2. It is important to point out that during the time of the evaluation, observations on the selective behavior of the animals showed a high acceptance in the consumption of the legume. This explains, partly, the high liveweight gains and animal production in T2 (Table 1). Other factors contributing to the generally high forage and livestock production values are high soil fertility and the fact that the measurements refer to the initial 1–2 years of this production systems comparison trial.

Table 1. Forage dry matter production, nutritional quality and animal response data over 1 year for a *Brachiaria* hybrid cv. Cayman monoculture (T1) and a Cayman-*L. diversifolia* association (T2).

Parameter	Variable	T1		T2	
		(Mean ± SD)	CV (%)	(Mean ± SD)	CV (%)
DM production	Tonnes DM/ha/yr	22.5		32.2	
Nutritional quality	Protein (%)	6.7		8.25 (Cayman) 26.7 (*L. diversifolia*)	
	IVDMD (%)	65.5		64.9 (Cayman) 58.6 (*L. diversifolia*)	
Animal response	Mean stocking rate (AU/ha)	3.36		4.04	
	Weight gain (g/hd/d)	440 ± 41	9.3	657 ± 73	11.2
	Liveweight production (kg/ha/yr)	723 ± 68	9.3	1,078 ± 120[1]	11.2
	Time to reach sale weight (months)[2]	18		12	

DM = Dry matter; IVDMD = In vitro dry matter digestibility; AU = 450 kg animal.
[1]Statistically different at P<0.01.
[2]Period of time required to bring a calf with an average weight of 200 kg to a sale weight of 450 kg.

Economic risk and sensitivity analyses

The economic evaluation is based on a discounted cash flow model for the estimation of financial profitability indicators capable of measuring the viability of the 2 treatments. The evaluated indicators include the internal rate of return (IRR), net present value (NPV), cost:benefit ratio (C:B) and payback period. The evaluation was made based on the principles established by Park (2007) for each indicator. In addition, the minimum profitable area required to generate 2 integral Colombian Basic Salaries (CBS) on a monthly basis during the 10 year evaluation horizon (1 integral CBS = US$ 469/month in 2018) was estimated as an indicator for smallholder producers, who normally experience strong resource limitations.

The model includes a systematic categorization of the variable costs and the benefits associated with the 2 evaluated treatments. Specifically, the following categories of costs per hectare were considered: total cost of establishment; costs of renewal and maintenance of each treatment; capital opportunity costs during the establishment period for both treatments (T1: 3 months, T2: 8 months); and operational costs (e.g. purchase of animals, animal health, mineral supplementation, labor costs for permanent and occasional staff). The benefits derived from beef production in a cattle raising and fattening system, according to the animal response indicators, are presented in Table 1. The evaluation horizon for both treatments was 10 years, according to the lifespan of the grass (Holmann and Estrada 1997). Although it has been shown that *L. leucocephala* can remain productive for periods longer than 30 years in other regions of the tropics and subtropics (Jones and Bunch 1995; 2000), we decided to maintain a conservative scenario for T2, given the lack of data and information on the persistence of *L. diversifolia* in the specific study area. Additionally, a discount rate of 12%, and constant prices and flows for each treatment according to the respective release and fattening periods (T1: 18 months; T2: 12 months) were assumed for constructing the cash flow.

In order to include risk and uncertainty levels in the variables identified as critical for the model and to consider different scenarios, a quantitative risk analysis was carried out by running a Monte Carlo simulation in the software @Risk (Paladise Corporation). In such a simulation, random input variables are identified and represented by means of probability distributions, to later calculate the profitability indicators (outputs of the model). This process is repeated numerous times to obtain the probability distributions of these outputs (Park 2007). For this analysis 5,000 simulations were carried out for 3 pasture persistence scenarios and the following variables were randomly combined: liveweight gain/animal/year; investment costs; maintenance costs; sale price per kg live weight; and purchase price per kg live weight. For the 2 price variables, a correlation coefficient of 0.89 was determined. The simulation used a confidence level of 95%. Table 2 shows the probability distributions for the input variables.

Table 2. Probability distributions for input variables, parameters and risk factors.

Variable	Treatment	Distribution	Parameters			Distribution adjustment	Randomness
			p1	p2	p3		
Liveweight (LW) gain (kg/hd/yr)	T1	Pert (a,b,c)	139	161	174	Judgment of the researcher according to the availability of data and behavior of the variable according to literature (Gutiérrez et al. 2009).	Interaction between decision variables (e.g. type of feeding) and non-controlled ones (e.g. climatic conditions).
	T2	Pert (a,b,c)	205	239	268		
Sale price (US$/kg LW)[1]	T1 & T2	Lognormal (μ,σ)	1.64	0.33		Based on the best historical data adjustment, using the Akaike information criterion (AIC; Akaike 1974).	Varies as a result of factors associated with the supply and demand of the market.
Purchase price (US$/kg LW)[2]	T1 & T2	Lognormal (μ,σ)	1.36	0.22			
Investment costs (US$/ha)	T1	Triangular (a,b,c)	586	689	794	This distribution is recommended to specify situations that involve costs and investments.	Vary depending on the specific place where the establishment is made (e.g. the amount of tillage and level of fertilizer applied are determined by soil characteristics and rainfall regime) (Rincón and Caicedo 2010).
	T2	Triangular (a,b,c)	941	1,106	1,272		
Maintenance costs (US$/ha)	T1	Triangular (a,b,c)	134	148	163		
	T2	Triangular (a,b,c)	102	114	123		

a,b,c: minimum, most probable and maximum value, parameters of the Triangular and Pert distributions. [1]Exchange rate used: 1 US$ = 2,800 Colombian Pesos (COP). [2]Historical data taken from FEDEGAN (2018).

In both treatments, application of maintenance fertilizer and pasture renewal were assumed for Year 5 in T1 and Year 7 in T2, in order to maintain the level of production during the defined evaluation horizon. However, animals can cause physical damage to the legume or grass which can affect production. To include this factor in the model, 3 treatment persistence scenarios were built. These were determined by considering 3 annual degradation rates that decrease the total forage supply and therefore the carrying capacity. The rates were estimated according to criteria provided by several forage experts, under the assumption of adequate management in terms of fertilizer application, rotation and rest of the pasture, as follows: for T1 at 1% (S1), 3% (S2) and 8% (S3); and for T2 at 1% (S4), 3% (S5) and 5% (S6). In T2, the maximum rate of degradation is assumed to be lower than for T1, given the constant supply of N to the pasture contributed by the legume through the process of atmospheric N fixation. It should be noted that both the simulations and risk indicators do not capture effects of extreme (climatic) events or losses due to an extraordinary incidence of pests and diseases.

As decision criteria, the mean value and the variations of the obtained profitability indicators were used, 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 made, the average result will tend toward the expected value (Park 2007). On the other hand, sensitivity and scenario analyses were carried out in order to identify those variables with the strongest effects on the profitability indicators within the total set of variables defined as critical. The variables identified in the previous analyses were studied individually by means of a stress analysis, where the values of the distribution are restricted to the 10th percentile, and through which the changes in the NPV indicator were identified.

Results

The two treatments were compared in terms of their economic performance, considering the uncertainty of random variables identified for the estimation of profitability indicators. Table 3 shows the main results associated with the costs and income for each treatment. The costs of establishing T2 are 60% higher than those for T1. However, the evidenced animal production indicators for T2 allowed average annual increases per hectare of 66% in gross income and 119% in net profit, when compared with T1.

Table 3. Costs and income for fattening steers on *Brachiaria* hybrid cv. Cayman pasture (T1) and a Cayman-*L. diversifolia* association (T2).

Parameter	T1	T2
Investment costs		
Establishment of pasture (US$/ha)[1]	689	1,107
Pasture renewal (US$/ha)[2]	211 (Year 5)	153 (Year 7)
Electric fence (US$/ha/yr)[3]	750	752
Purchase of animals (US$/ha/cycle)	1,071	1,253
Operational costs		
Pasture maintenance costs (US$/ha)[4]	148	209
Permanent labor (US$/ha/yr)[5]	623	622
Animal health (US$/ha/yr)	20	22
Supplementation (US$/ha/yr)[6]	87	86
Gross income (US$/ha/yr)	2,190	3,199
Unit cost of production (US$/kg)[7]	1.2	1.21
Net income (US$/ha/yr)[8]	356	695

[1]For establishment, herbicide application and mechanical soil tillage were carried out. The sowing rate of Cayman was 8 kg/ha with a level of fertilizer of N, P, K, Mg and S of 100, 22, 41.5, 20 and 20 kg/ha, respectively. Two thousand *L. diversifolia* plants were established per ha. [2]Includes maintenance fertilizer, soil 2x plowing and replanting of Cayman at a sowing rate of 2 kg/ha. [3]Electric fence for a rotational grazing system. [4]Maintenance is carried out every 2 years and includes weed control, fertilizing with half the dose used for establishment (no N fertilizer in T2), and pruning of *L. diversifolia*. [5]Estimated: 2.5 permanent jobs required for every 100 animals in a cattle raising and fattening system (FEDEGAN 2018), and a legal minimum wage in force plus benefits in 2018 of US$ 469/month. [6]Supplementation with mineralized salt at a rate of 100 g/hd/d. [7]Unit cost of production: dividing total cost of the product by total production. [8]Net income: total income (sale price x yield) minus total costs.

The summary of the main financial results of the simulation for both treatments is presented in Table 4. The results suggest that the inclusion of *L. diversifolia* is financially profitable and would improve all risk and performance indicators when compared with Cayman as monoculture. The model shows a positive mean NPV for T2 that, according to the pasture degradation scenario, varies between US$ 1,716 and US$ 2,055, and an internal rate of return (IRR) to own resources of around 21%. In addition, the superior productive indicators for T2 allow reduction in the minimum profitable area required to generate 2 Colombian basic salaries from 6.54 ha to 3.76 ha, as well as reducing the payback period from 6 to 4 years. T1 shows a higher NPV variability than T2.

With regard to the probability of finding that the evaluated treatments were not financially feasible, Figure 1 shows the distributions for the NPV indicator, which reflects the amplitude of the variation for the NPV indicator. For T1, the indicator ranges from negative values close to US$ 1,506, to positive values close to US$ 948, with 72% probability of obtaining negative values. For T2, the inclusion of *L. diversifolia* shifts the distribution curve to the right, reducing the probability of losses to 0%, with values ranging from -US$ 61 to US$ 4,145.

Table 4. Summary of profitability indicators of the simulation model for fattening steers on *Brachiaria* hybrid cv. Cayman pasture (T1) and a Cayman-*L. diversifolia* association (T2).

Decision criterion	Indicator	T1			T2		
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
NPV (US$)	Mean[1]	(288)	(342)	(473)	2,055	1,881	1,716
	SD[2]	447	434	404	697	673	651
	CV	1.55	1.26	0.85	0.34	0.36	0.38
	CI (95%)[3]	(1,135)–558	(1,165)–481	(1,239)–292	743–3,389	610–3,172	484–2,965
IRR (%)	Mean	11	11	10	22	21	21
	CI (95%)	4–15	4–15	4–14	16–28	15–28	15–27
Benefit:Cost[4]	Mean	0.98	0.97	0.96	1.13	1.12	1.12
	CI (95%)	0.9–1.05	0.9–1.04	0.89–1.03	1.05–1.22	1.04–1.21	1.03–1.20
Payback period (years)	Mean	6	6	6	4	4	4
	CI (95%)	3–8	3–8	3–8	3–5	3–5	3–5
Minimum area (ha)[5]	Mean	6.54			3.76		

[1]Mean value of the NPV obtained in the simulation (5,000 iterations). [2]SD: Standard deviation of the NPV with respect to the mean value. [3]CI: Minimum and maximum values with a 95% confidence interval. [4]Quotient between benefits and discounted costs. [5]Minimum area (in ha) required for generating 2 basic Colombian salaries.

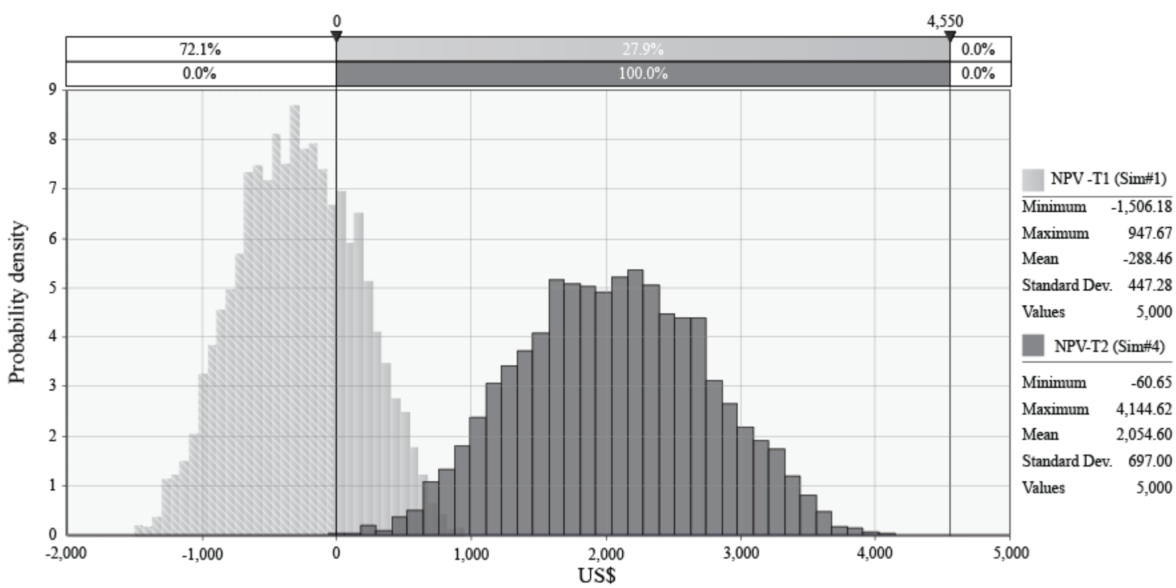

Figure 1. Probability and cumulative density distributions for NPV for fattening steers on *Brachiaria* hybrid cv. Cayman pasture (T1) and a Cayman-*L. diversifolia* association (T2).

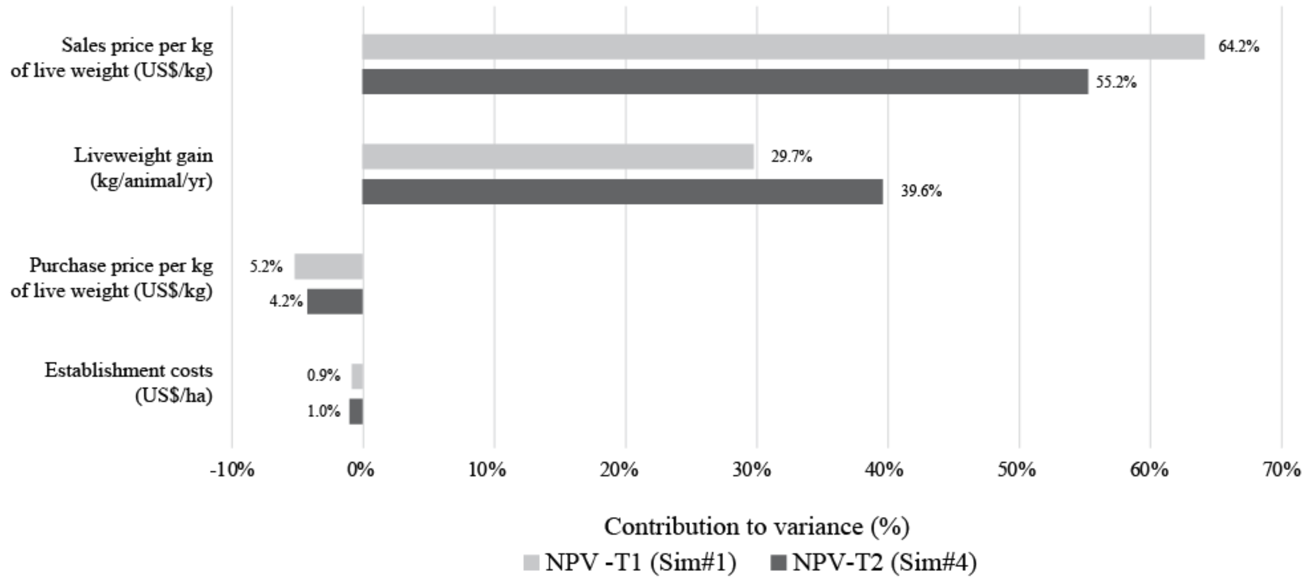

Figure 2. Contributions of random input variables to the variance of the NPV for fattening steers on *Brachiaria* hybrid cv. Cayman pasture (T1) and a Cayman-*L. diversifolia* association (T2).

The contribution of the input variables to the variance of the NPV is shown in Figure 2. The calculated correlation coefficients show that profitability is affected primarily by 2 variables: sale price per kg of live weight; and animal production. Increases in these variables have an effect on the variability in the forecast of the indicator as follows: Changes in sale price per kg of live weight lead to changes in the variance of 64.2% for T1 and 55.2% for T2. Similarly, changes in animal production modify the variance of the indicator by 29.7% for T1 and 39.6% for T2. When conducting a stress analysis in the 10th percentile for the 2 variables at the same time, negative changes with respect to the mean value of the NPV indicator can be observed for T1 (335%) and T2 (57%).

Discussion and Conclusions

The inclusion of *L. diversifolia* in a grazing system for beef production improved the productive and economic performance indicators under different scenarios of animal production and market conditions. In productive terms, the association of Cayman and *L. diversifolia* increased animal production by 49%, compared with a Cayman monoculture. The results are consistent with various experimental studies in a wide range of environments, which demonstrate the ability of *Leucaena* spp. to improve production and profitability in the tropics (Kennedy and Charmley 2012; Peck et al. 2012; Harrison et al. 2015). For example, in northern Colombia, associations of *L. leucocephala* with grass have been shown to increase animal production per hectare by 110%, a result of increased liveweight gain per animal (56.6%) and carrying capacity (43.4%), when compared with improved grass monoculture (Gaviria et al. 2012). In Queensland, Australia, liveweight gains on buffel grass (*Cenchrus ciliaris*)-*L. leucocephala* pastures were 38% higher than on buffel grass alone (Walton 2003).

However, these studies have been carried out mainly with different accessions of the species *L. leucocephala*, which has been widely acknowledged as having excellent yield and high forage quality leading to high liveweight gains in cattle, compared with other species of *Leucaena* (Lefroy 2002). For example, evaluations at Lansdown, north Queensland, Australia found differences in daily animal liveweight gains between *L. diversifolia* (532 g) and *L. leucocephala* (694 g), which were associated with greater in vitro dry matter digestibility and lower levels of condensed tannins in *L. leucocephala* (Jones et al. 1998). However, *L. diversifolia* has shown a greater range of adaptation to different edaphoclimatic conditions than *L. leucocephala*, in particular to higher soil acidity and cooler temperatures (Peters et al. 2011), allowing a wider use in tropical and subtropical regions.

In terms of animal response indicators, T2 showed superior performance to T1, which translates into better financial performance in all 3 evaluated degradation scenarios. The profitability of the system is improved when

L. diversifolia is associated with Cayman. These results are comparable with values reported in other studies, which have identified the potential of legumes to improve cattle profitability, livelihoods and resource use efficiency (Muir et al. 2017). In Queensland, *L. leucocephala* has been identified as the most productive and profitable legume, increasing liveweight production (both per hectare and per animal) by 2.5 times and doubling the gross margin/ha, when compared with perennial grasses (Bowen et al. 2016). At the regional level in Queensland, economic benefits from the adoption of *L. leucocephala* have been estimated to be more than US$ 69 million/yr for 2006 in a planted area of 150,000 ha (Shelton and Dalzell 2007). Profitability evaluations in Costa Rica, Michoacán (Mexico) and the Colombian Caribbean region report an IRR that oscillates around 33% for a *L. leucocephala*-grass association (Jimenez-Trujillo et al. 2011; González 2013; Murgueitio et al. 2015). The productive and economic indicators of sowing *L. diversifolia* presented in this study are a fundamental input to the discussion on how to reduce the need for expansion of land area required for agricultural production (FAO 2017), and show that *L. diversifolia* can become a potential option for sustainable intensification and for reducing the pressure on natural resources.

Improvements in the profitability indicators when including *L. diversifolia* in the system demonstrate a reduction in the risk of economic loss and less variance in changes in critical variables. In particular, the results of the sensitivity analysis showed that changes in the sale price of meat have stronger impacts on the profitability indicators for the Cayman monoculture, which suggests increased risk with respect to market conditions that cause price decreases. Although the price risk is also present after including *L. diversifolia*, it is much lower and this might be a key factor in encouraging adoption, since farmers, being naturally rather risk-averse (Marra et al. 2003), will most likely favor technologies with a relatively lower variance. In addition, its higher stability over the years in terms of forage production and the higher protein concentration, especially in dry seasons, compared with a grass monoculture (Tedonkeng Pamo et al. 2007), allow for stronger persistence and result in less variability when it comes to indicators of production.

In addition to the increased production and profitability highlighted in this research, several other studies have shown improvements in meat quality when *Leucaena* is being used. For example, Montoya et al. (2015) found that animals from systems incorporating *L. leucocephala* produced meat with superior tenderness, better pH and color, as well as higher carcass weights, when compared with animals from traditional grazing systems. Such quality attributes could contribute to product differentiation strategies and price premiums and therefore promote the adoption of legumes. We recommend that these additional benefits be included in the evaluation of legume-based cattle fattening systems. As mentioned in this paper, the inclusion of legumes also leads to important environmental benefits in the cattle system, such as the reduction of enteric methane emissions (Campbell et al. 2014) and overall greenhouse gas emissions (Kennedy and Charmley 2012; Harrison et al. 2015). These, among others, represent significant environmental benefits with economic and welfare impact at society level. We recommend that environmental benefits be included in future economic evaluation studies.

The authors of this research are aware that the data reported were obtained in an experiment under controlled conditions both in terms of animal and pasture management, following expert recommendations and constant monitoring schemes. This has to be taken into account when replicating the trial. Alterations to the reported values might occur under different settings and more so under real farming conditions, depending on the region, climate or soil conditions, animal breeds, or animal and pasture management, among others.

In conclusion, this study indicates that investing in the establishment of legumes in grass-legume associations, such as *L. diversifolia*, turns out to be a valuable option for improving both efficiency and profitability of the production system, and thus can contribute in a positive way to producer welfare. Providing livestock producers with such information is a first step towards overcoming barriers to technology adoption, i.e. towards decreasing the misconception by producers that there are limited benefits from planting pasture legumes (Shelton et al. 2005). However, for broader adoption to occur, providing this type of information on its own is not sufficient; improvements in the framework conditions are also needed. The establishment of such systems should be accompanied by specific training and extension programs, which in many cases would need to be developed (e.g. in the Colombian context), to overcome the lack of knowledge and experience in the use of tropical forage legumes. This should reduce uncertainties associated with technology adoption and increase adoption rates. At the same time, the access to and structure of necessary financial resources (e.g. credits), as well as the availability and access to seed or vegetative material, need to be improved in order to provide the necessary resources for technology adoption. This holds true especially for Colombia, where credit schemes do not respond to the producer reality (i.e. no credits available for pasture improvement, too short grace periods in livestock credits) and where a well-functioning legume seed system is non-existent.

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