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Impact of regenerative agricultural practices on forage maize (*Zea mays* L.) yield under semiarid conditions

Impacto de las prácticas agrícolas regenerativas en el rendimiento del maíz forrajero (*Zea mays* L.) en condiciones semiáridas

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ABSTRACT

Forage production is crucial for livestock in dry tropical regions due to its adaptability and nutrient content, especially during the dry season when pastures deteriorate. In this context, it is necessary to evaluate sustainable production practices that improve forage yield in semi-arid conditions. A field experiment was conducted under dry Caribbean conditions in Cesar, Colombia, during 2023 to evaluate the regenerative production system of forage maize (*Zea mays* L.) 'AGROSAVIA V-117', which was planted at a density of 100,000 plants/ha. The experiment included six treatments: control fertilization (FNC), FNC + amendment, FNC + biofertilizer, FNC + amendment + biofertilizer, FNC + amendment + biofertilizer + cover, and FNC + 20%. The results revealed that green forage production ranged from 79.92 to 92.89 t/ha for FNC + biofertilizer and FNC + 20%, respectively. The traditional fertilization + amendment + biofertilizer + cover crop treatment resulted in the highest ear production value (20.64 t/ha). Regarding forage dry mass accumulation, the 20% improvement in conventional fertilization yielded the highest value (25.48 t/ha), followed by the conventional fertilization + biofertilizer treatment (24.86 t/ha). Although no significant differences were observed between treatments, the results exceeded national averages, highlighting the potential to incorporate regenerative, economically viable, and environmentally sustainable practices into livestock production systems under semiarid conditions.

Keywords: biofertilizers; biomass; cover crops; dry tropics; fertilizers; forage mass; organic amendments

RESUMEN

La producción de forrajes es crucial para la ganadería en regiones secas tropicales debido a su adaptabilidad y suministro de nutrientes, especialmente durante la estación seca cuando los pastos se deterioran. En este contexto, resulta necesario evaluar prácticas productivas sostenibles que permitan mejorar el rendimiento forrajero en condiciones semiáridas. Para evaluar el sistema de producción regenerativa de maíz forrajero (*Zea mays* L.) "AGROSAVIA V-117", sembrado a una densidad de 100.000 plantas/ha, se realizó un experimento de campo en condiciones del Caribe seco en Cesar, Colombia, durante el año 2023. El experimento se planteó con seis tratamientos: Fertilización Control (FNC), FNC + Enmienda, FNC + Biofertilizantes, FNC + Enmienda + Biofertilizantes, y FNC + 20%. Los resultados mostraron una producción de forraje verde que osciló entre 79,92 y 92,89 t/ha para FNC + biofertilizante y FNC + 20%, respectivamente. La fertilización tradicional + enmienda + biofertilizante + cultivo de cobertura alcanzó los valores más altos de producción de mazorcas (20,64 t/ha). En cuanto a la acumulación de masa seca de forraje, la fertilización convencional mejorada al 20% tuvo el valor más alto con 25,48 t/ha, seguida de la fertilización convencional + biofertilizante con 24,86 t/ha. Aunque no se observaron diferencias estadísticamente significativas entre los tratamientos, los resultados superaron los promedios nacionales, lo que destaca el potencial de incorporar prácticas regenerativas, económicamente viables y ambientalmente sostenibles en los sistemas de producción ganadera en condiciones semiáridas.

Palabras clave: biofertilizantes; biomasa; cultivos de cobertura; trópico seco; fertilizantes; masa forrajera; enmiendas orgánicas

INTRODUCTION

The livestock sector faces numerous challenges, including climate variability and changes in eating habits, with the risk of discouraging production as a result of erroneous models and a lack of knowledge and information; however, there is global agreement that food production must increase to meet the demands of a population growing in number and longevity and at the same time, minimize negative environmental impacts (OCDE/FAO, 2020; Rao *et al.*, 2015). Although Colombia has a recent colonial history linked to agricultural development, livestock has spread inland from the Caribbean coast (Bolivar, Guajira, Cesar, Valledupar, and Magdalena). Livestock constitutes an economic sector that contributes to the country's development and more specifically, to the rural sector, providing food, animal traction for agriculture, and transportation, among other benefits (Govaerts *et al.,* 2019; Cuenca *et al.,* 2008). These activities have undergone technological advances through various processes. Institutional and trade-union policies compensate for technological and infrastructure deficiencies, driving greater sustainability in the livestock sector.

In Latin America, the scarcity of high-quality forage is among the main constraints on livestock production (Faji *et al.,* 2021). However, this sector continues to grow economically, particularly in Colombia, where improved management practices are being promoted. These strategies include the integration of both local and introduced fodder crops, as well as agroforestry systems, mixed systems, and silvopastoral approaches. These practices aim to optimize livestock diets, limit agricultural frontier expansion, safeguard biodiversity, and ensure agricultural sector sustainability (Rao *et al.,* 2015).

Agricultural production relies on favorable and stable climatic conditions and ecosystem services that regulate nutrient cycling, water, and biodiversity (White, 2020). The growing population drives food production and encourages an agricultural system that places pressure on natural resources, thus threatening life on the planet. Therefore, agricultural systems with a systemic, holistic approach to minimize environmental damage without limiting production are urgently needed. Within this framework, regenerative agriculture promotes sustainable management, emphasizing soil rehabilitation, environmental balance, health, and agricultural output. A priority is establishing transitional systems that protect and restore degraded agroecosystems. In this context, regenerative agriculture offers a range of integrated tools and techniques that promote the conservation of natural resources and the restoration of degraded systems (Pulleman *et al.,* 2024; White, 2020). Thus, reducing greenhouse gas emissions, soil degradation, and biodiversity loss while improving the resilience of agricultural production systems to climate change is essential for their long-term viability.

In this context, livestock farming is integral to agricultural production. Regenerative agriculture promotes soil health (Khangura *et al.,* 2023), fertility, biodiversity, and carbon capture, fostering better practices and enhancing soil care while maintaining or improving production and ecosystem services (Jayasinghe *et al.,* 2023; Naranjo & Ruiz-Buitrago, 2020). It creates synergy in terms of sustainability and supports the health of rural communities (Cañet-Prades *et al.,* 2022; Cusworth *et al.,* 2022). The Food and Agriculture Organization (FAO) advocates for responsible soil management to mitigate ecosystem degradation without sacrificing agricultural output, particularly in light of the rising demand for animal protein, necessitating more efficient and inclusive food systems (Cañet-Prades *et al.,* 2022).

In this context, the quantity and quality of fodder are crucial for livestock feed (Gantner, *et al*., 2021) since rural productive units supply between 60 and 75% of the world's meat and dairy products, respectively, which should increase by 180% by 2050 (Yitbarek, 2019). The use of alternative production methods (including regenerative agriculture) can contribute to better environmental outcomes and ecosystem services with higher profits and increased food production (Kumar *et al.,* 2019; Mahapatra *et al.,* 2021; Rowntree *et al.,* 2020).

In this sense, “AGROSAVIA V-117” was the maize variety selected by the National Federation of Cereal Producers -FENALCE, International Corn and Wheat Improvement Center -CIMMYT, and the Colombian Agricultural Research Corporation–Agrosavia to encourage its production through the “Maize for Colombia Vision 2030” agenda (Govaerts *et al.,* 2019). This species is recognized by livestock farmers as a source of green forage, is palatable, has good nutritional value, and is widely accepted in the area (García Botina, 2021). It is essential to supply the demand for feed in the region where livestock activity contributes 56% of GDP, followed by permanent crops with 31% and transitory crops with 13%.

Therefore, it is essential to develop production models that include strategies that enable the sector to be competitive with a balanced and permanent livestock diet.

In this regard, this study aimed to implement several principles of the regenerative production system of forage maize under dry Colombian Caribbean coastal conditions.

MATERIALS AND METHODS

Study area

This study was carried out at the National Learning Service’s Agricultural Centre (SENA) in the department of Cesar (Valledupar), Colombia (10° 24’ 05” N 73°14’10” W) (Figure 1). The location is situated at an altitude of 169 m above sea level, with a mean annual temperature of 29 °C, 900 mm of annual precipitation and 1800 mm of evapotranspiration, and conditions that originate in a hot dry semiarid climate (González-Álvarez *et al.,* 2019) where evapotranspiration exceeds precipitation, making it necessary to implement irrigation to avoid crop stress (Terán-Chaves *et al.,* 2023), mainly during the germination and ear filling stages.

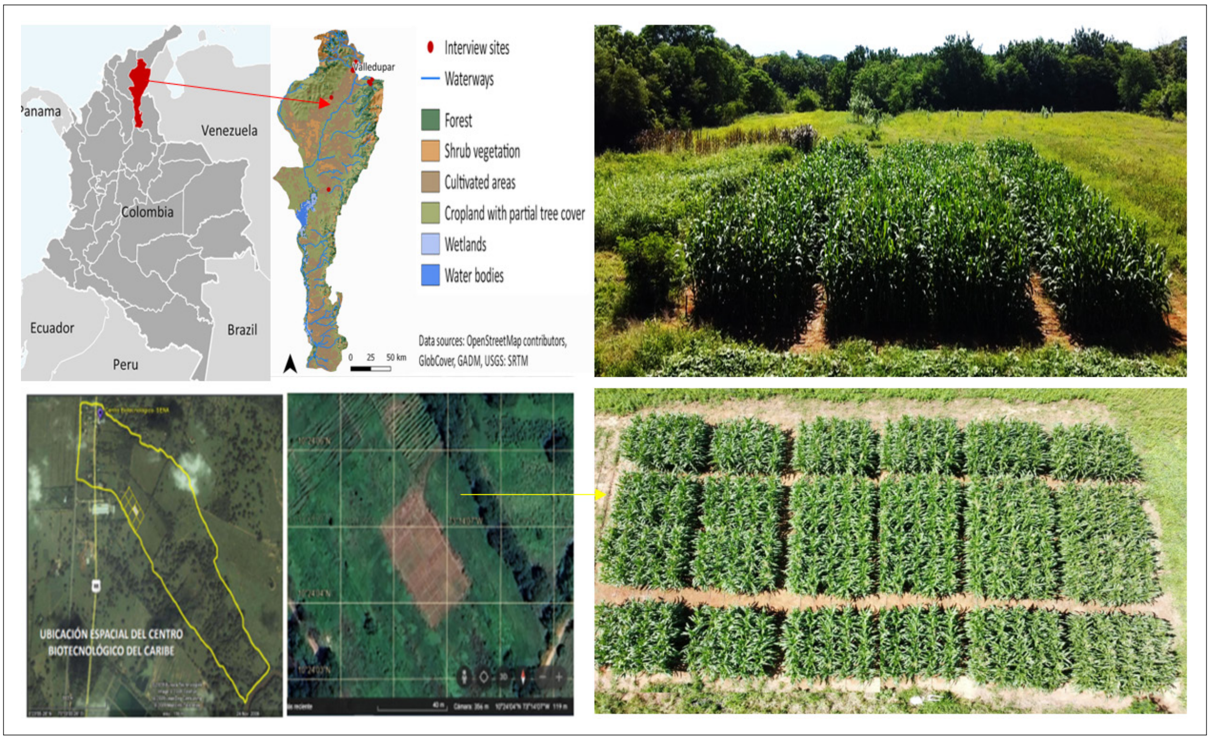

Figure 1. *Location and general view of the experimental field in the Colombian Caribbean Region*

Design of the trial. During 2023, a randomized complete block design was established with six treatments and four replications. The experimental unit consisted of 5*5 m plots, with five furrows at 0.8 m distance, and plants every 0.125 m (8 seeds per linear meter) for a planting density of 100,000 seeds/ha. The total area of each plot was 25 m².

Plot selection. The plot selected for the trial was previously cultivated with *Vigna unguiculata* (family Fabaceae), commonly known as cowpea. A disk plow and harrow were used for soil preparation. Once the soil had been prepared, composite samples were collected at a depth of 25 cm for soil physical and chemical characterization.

Agronomic management*.* Forage produced from the maize (*Zea mays* L.) AGROSAVIA V-117 variety was sown at a planting density of 100,000 plants per hectare under a regenerative agricultural system. Thus, it was not necessary to control for pests or diseases. Irrigation was provided by surface drip irrigation according to the species requirements and the area for each treatment. Weed management was conventional (before planting, atrazine® was applied as a selective preemergent herbicide at a dosage of 1.0 kg/ha).

The cover crop residue of *V. unguiculata* from the previous semester was used in the treatments where organic mulch was used. The results of the germination test verified that the seed quality and number of vigor days before sowing were greater than 90%.

Treatments

The treatments were based on the matrix in Table 1, where combinations of the factors' amendment, cover, and inoculation were applied. The nutrient doses needed to achieve high species yields were calculated using the soil analysis results obtained before planting. The FENALCE (FNC) nutritional package (Coral Eraso, *et al*., 2021) was used as a reference, recommending the application of 150 kg/ha of nitrogen (N), 70 kg/ha of phosphorus (P), 120 kg/ha of potassium (K), 20 kg/ha of sulfur (S), and 25 kg/ha of magnesium (Mg), along with 1.1 kg/ha of boron (B) and 2.0 kg/ha of zinc (Zn). These recommendations were established in Pelaya, Cesar, where grain yields exceed 8.0 t/ha, serving as the basis for the control treatment.

Based on the above, combinations were made between amendment, cover, and inoculation using the signs - and + for both factor levels (Table 1).

Table 1. *Effects of treatments used to evaluate regenerative agricultural practices on forage maize growth, biomass production, and yield*

Treatment	Description	Amendment	Biofertilizer	Coverage
T_1	Control Fertilization (FNC)	-	-	-
T_2	FNC + Amendment	+	-	-
T_3	FNC + Biofertilizers	-	+	-
T_4	FNC + Amendment + Biofertilizers	+	+	-
T_5	FNC + Amendment + Biofertilizers + Cover	+	+	+
T_6	FNC+20%	-	-	-

Note. FNC: Fertilization recommended by FENALCE. Amendment: 1.92 t/ha of vermicompost. Biofertilizer: (*Azospirillum* sp. + *Pseudomonas* sp.). Mulching: 4 t/ha cowpea (*Vigna radiata*) legume residue. FNC+20%: Fertilization recommended by FENALCE increased by 20%.

Measured Variables

Number of plants per hectare (NP): The total number of plants and ears per treatment was counted seven days before cutting or harvesting and then extrapolated to the number of plants/ha.

Tipping (NPC): The number of fallen plants was counted for each treatment and is expressed as the number of fallen plants/ha.

Plant height (PH) (cm): An average of 20 plants was randomly selected from the middle part of the central furrow of each plot. The measurement was made from the soil to where spike branching begins (Castellanos-Navarrete et al., 2017). These observations were carried out seven days before harvest.

Green forage yield (GF) (t/ha): The forage yield was evaluated according to the methodology proposed by CIMMYT (Verhulst et al., 2012). For this purpose, the biomass yield was obtained from the total mass of the green forage in three linear meters of the central furrow of each plot and then extrapolated to obtain the value in t/ha.

Fresh ear weight PMz (t/ha): Fresh ear weight in kg per furrow and its conversion to yield in t/ha.

Dry matter yield (DM t/ha): The dry matter (DM) yield per hectare was estimated based on the GF yield and %DM and its conversion to t/ha (Buchelt et al., 2021).

Finally, an economic analysis was performed to establish the production costs in US$/t/ha for each alternative evaluated, which is an essential aspect of the farmer's adoption of the technology. In this analysis, the costs associated with land preparation, fertilizer, amendment application, seed, and irrigation were considered following the parameters of the study carried out by Bueno et al. (2003) and adapted to this work's prices, inputs, and conditions.

Statistical analysis

Data generated for the variables studied were meticulously tabulated in Microsoft Excel® v.2104. The values obtained for each variable were calculated with precision as the mean and standard deviation, and were subjected to a rigorous analysis of variance ($p<0.05$) followed by a post hoc test of minimum significant difference at 5% probability to establish differences between the treatments applied. Next, Pearson's correlation test ($p<0.05$) was used to determine the associations between the variables evaluated and forage production. The statistical R Core Team (2016) program was used to ensure the accuracy and reliability of the results.

RESULTS

The soil analysis results in the preplanting plot are shown in Table 2. As can be seen, the pH level was optimal for the availability of nutrients; therefore, applying fertilizers could improve soil quality. The soil in question had low organic carbon, optimal Ca^{+2}, medium to low K^+ and Mg^{+2}, and high P contents. These parameters informed the fertilization necessary to maintain the NO_3^-: NH_4^+ ratio in a range of 75:25 (Peng *et al.,* 2019) and thus to favor the absorption of other macro- and micronutrients.

Table 2. *Soil chemical properties in which the experiment was established*

Parameter	Unit	Value
pH	unid	6.74
Organic carbon OC	%	0.53
NH_4^+	mg/kg	5.00
NO_3^-	mg/kg	54.0
Ca^{+2}	$Cmol_{(+)}$/kg	6.52
K^+	$Cmol_{(+)}$/kg	0.22
Mg^{+2}	$Cmol_{(+)}$/kg	1.43
Na^+	$Cmol_{(+)}$/kg	0.30
P	mg/kg	66.0
Effective Cation Exchange Capacity CECe	$Cmol_{(+)}$/kg	8.50

Plants per hectare (NP), plant height (PH), and tipping (NPC)

In this study, plant survival was evaluated before harvest. The average NP across treatments was 97,569 (p = 0.045). With respect to plant density and plant height, PH (Table 3) and T5 (FNC + Amendment + Biofertilizers + Mulching) resulted in the highest population with 100% germination success. No lodging was observed in any of the treatments (tipping).

Table 3. *Survival (number of plants/ha) and height of forage maize (cm) «AGROSAVIA V-117» in a regenerative agriculture System*

Treatment	Survival (No. plants/ha)	Plant Heigh (cm)
T_1	96875	233.6
T_2	97917	249.9
T_3	97917	247
T_4	93750	238.1
T_5	100000	236
T_6	98958	238.3
ρ value	0.0045	0.533

Plant height was evaluated at the end of the vegetative development phase. T5 resulted in the highest survival rate (100,000 plants/ha), whereas T2 resulted in the tallest plants (249.9 cm). The control (T1) had the lowest plant height, and T4 had the lowest survival (93,750 plants/ha).

Green Forage yield (GF), yield in the green ear (PMz), and dry mass (DM) yield

The results revealed no significant differences among the treatments for green forage (p = 0.8471), green ear yield (p = 0.523), and dry matter yield (p = 0.470). However, clear trends were observed: GF ranged from 79.92 t/ha in T1 to 92.89 t/ha in T3 (Figure 2 A and B); in terms of green ear yield, T2, T4, T5, and T6 outperformed T3 and T1 (Figure 2C); and in terms of dry matter, regenerative practices increased production by 2.5 to 5 t/ha compared with the control (T1) (Figure 2D).

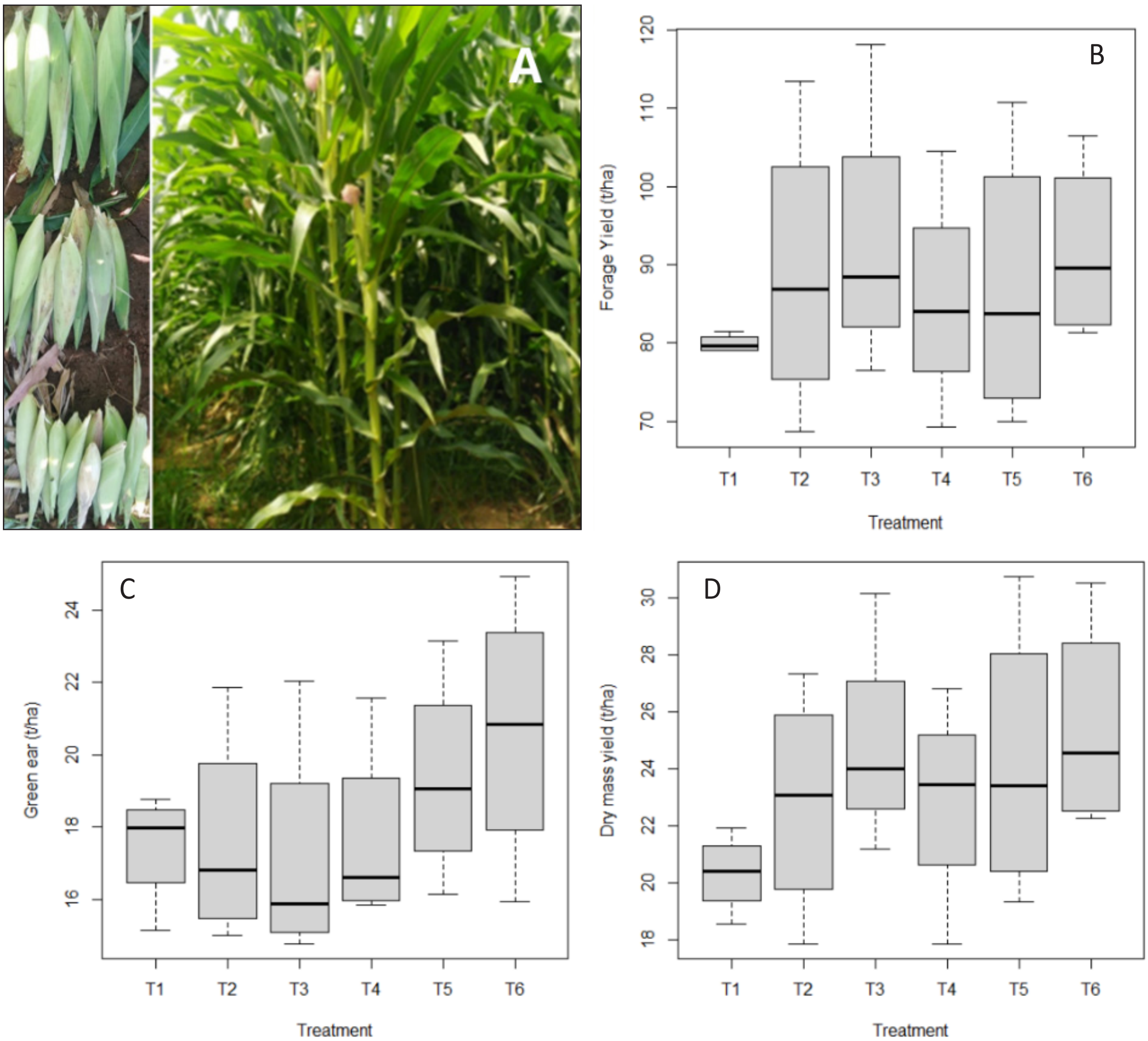

Figure 2. *A) Preliminary view of leaf and ear production; B) green forage yield (p=0.8471), green ear yield (p=0.523), and dry matter yield (p= 0.470) obtained by applying different regenerative agricultural treatments.*

Economic analysis

Table 4 shows the establishment costs and the value per ton of green forage produced. No differences were observed between treatments ($p > 0.25$). T3 achieved the lowest cost per ton ($21.21 USD/t) associated with the highest forage production (92.89 t/ha).

The values recorded for fertilization stand out due to the increase in inputs in general, especially mineral fertilizers, in the first half of 2023.

Table 4. *Establishment and maintenance costs of one hectare of forage maize across production systems in 2023*

Item/Treatment	T_1	T_2	T_3	T_4	T_5	T_6
Soil preparation	$ 270.550	$ 270.550	$ 270.550	$ 270.550	$ 270.550	$ 270.550
Fertilizer. (NPK - S-Mg)	$ 834.081	$ 834.081	$ 834.081	$ 834.081	$ 834.081	$ 1.028.64
B+Zn	$ 73.786	$ 73.786	$ 73.786	$ 73.786	$ 73.786	$ 110.680
Amendment	$ 0.000	$ 531.262	$ 0.000	$ 531.262	$ 531.262	$ 0.000
Biofertilizer	$ 0.000	$ 0.000	$ 24.595	$ 24.595	$ 24.595	$ 0.000
Mulch	$ 0.000	$ 0.000	$ 0.000	$ 0.000	$ 211.521	$ 0.000
Seed	$ 118.058	$ 118.058	$ 118.058	$ 118.058	$ 118.058	$ 118.058
Maintenance (Irrigation)	$ 649.320	$ 649.320	$ 649.320	$ 649.320	$ 649.320	$ 649.320
Total	**$ 1,945.8**	**$ 2,477.06**	**$ 1,970.39**	**$ 2,501.65**	**$ 2,713.18**	**$ 2,177.25**
Production GF (t/ha)	79.92	88.98	92.89	85.48	87.06	91.74
Cost t/ha forage	**$ 24.347**	**$ 27.838**	**$ 21.212**	**$ 29.266**	**$ 31.164**	**$ 23.733**

The results (Table 4) present a detailed analysis of the costs and production of forage maize (*Zea mays* L.) under different treatments in the framework of regenerative agricultural practices. Each treatment resulted in significant variations in input costs and forage production, suggesting that the choice of specific practices can influence crop yield and economic viability.

T2 had the highest total cost ($2,477.06 USD), which was correlated with high forage production (88.98 t/ha). T6 had a competitive total cost of $2,177.25, with a yield of 91.74 t/ha and a cost of $23,733/ton. T3, with a lower total cost than T2 ($1,970.39), resulted in the highest forage production (92.89 t/ha). Finally, T1 (control) had the lowest cost ($1,945.80 USD), as well as the lowest yield (79.92 t/ha).

In addition to immediate production costs, the economic viability of regenerative practices must be assessed through medium-term sustainability indicators. A cost-benefit analysis across 3-5 growing cycles suggests that treatments incorporating biofertilizers and organic amendments (T3, T4, and T5) could reduce synthetic fertilizer dependency by 15-25% by improving soil nutrient cycling and microbial activity (Liu *et al*., 2025; Smith *et al*., 2023). This effect aligns with the economic resilience framework proposed by Pretty (2018), which posits that regenerative systems buffer against input price volatility. Additionally, incorporating ecosystem service evaluation — such as soil carbon sequestration (estimated at 0.5 to 1.2 t C/ha/year in similar systems) and reduced erosion — would further improve the financial attractiveness of these practices (Sanderman *et al*., 2017; Schreefel *et al*., 2020). Future economic assessment should include metrics such as net present value (NPV), return on investment (ROI), and payback period to better inform farmer adoption and policy incentives.

Associations between the variables evaluated for forage production

Pearson's correlation analysis revealed positive associations between plant height and green forage production (r = 0.48), between ear mass and plant height (r = 0.71), and between dry mass and plant height, ear mass, and green forage yield (r = 0.56, 0.57, and 0.95, respectively). These results highlight the importance of these variables in achieving high forage yields.

DISCUSSION

Plants per hectare (NP), plant height (PH), and tipping (NPC)

The results obtained in this study demonstrate the positive impact of regenerative agricultural practices on the establishment and development of AGROSAVIA V-117 forage maize. T5 (FNC + amendment + biofertilizers + mulching) achieved the highest survival rate, with 100,000 plants/ha, whereas T2 (FNC + amendment) presented the greatest average height (PH), with a value of 249.9 cm. In contrast, the T1 control treatment (control, using conventional fertilization according to FNC) had the lowest PH, and T4 had the lowest survival rate, with 93,750 plants/ha and a plant height of 238.1 cm. These findings indicate that the incorporation of organic amendments together with inoculation techniques substantially enhances plant resistance to abiotic stressors, particularly under semiarid conditions in the Colombian Caribbean.

The survival rate emerged as a critical metric for assessing the effectiveness of the applied agricultural practices, with the T2, T3, and T5 treatments providing significantly more favorable conditions for crop establishment.

The average plant height achieved by the AGROSAVIA V-117 variety (240.5 cm) under the evaluated conditions—although below the reference range reported by Agrosavia (260–300 cm)—represents a significant advance in agronomic management, which includes components of regenerative agriculture such as mineral fertilizers, organic fertilizers, biofertilizers, and mulches (Singh *et al*., 2024). Historically, plant heights exceeding 180 cm have not been achieved in this area, likely due to low soil fertility, inadequate management practices, and adverse climatic conditions characteristic of the dry Caribbean (Aguirre Forero *et al*., 2022). The implemented technological package, which included high-density planting, irrigation, and a fertilization program, based on soil analysis and crop requirements, underscores its relevance to regional conditions.

The positive effect on plant height—a parameter associated with forage yield and fresh ear weight—indicates that appropriate agronomic management enhances the productive potential of a variety. This outcome may be attributed to the greater number of leaves and branches that increase total biomass, as reported by Faji *et al*. (2021), while simultaneously improving plant anchorage. Such structural reinforcement enabled effective resistance to the strong winds occurring at the end of the field phase, resulting in zero lodging of the crop material.

These results are consistent with those reported by Salazar-Sosa *et al*. (2010) in their study on high-density maize management, where plant survival was attributed to factors such as soil moisture, nutrient availability, and plant vigor during early developmental stages. Those authors reported a correlation between treatments with higher manure application rates (40 and 80 t/ha) and improved survival, in contrast to the lower values in the untreated control. These findings align with those of the present study, in which treatment combining amendment and biofertilizer application resulted in superior values for both plant height and survival rate (98%).

The green forage yield (GF), yield in the green ear (PMz), and dry mass (DM) yield

The results for green forage yield indicate that treatments that increase plant nutrient supply through fertilizers, and the combination of fertilizers with organic amendments and biofertilizers, increase both forage production and quality. In this context, Gutiérrez-León *et al*. (2023) reported that, although biofertilizers contain relatively low nutrient concentrations, they hold considerable potential for improving nutrient assimilation, as they report favorable forage yields and quality at relatively low nitrogen doses between harvests. Those authors reported the best results when nitrogen fertilizers and biofertilizers were combined, resulting in higher biomass and crude protein yields. Similar results were also reported by Khatun *et al*. (2019), who worked on saline soils, which are typical in the study area.

Organic amendments and biofertilizers have long been applied in agroecological and organic production systems, with significant effects on soil fertility, because they supply essential nutrients and organic matter, thereby improving both nutrient and moisture retention (Soro *et al*., 2015). Under the conditions of Agustín Codazzi, Cesar, the "AGROSAVIA V-117" variety has been reported to produce green forage yields ranging from 30 to 55.2 t/ha (Tapia *et al*., 2020; Gómez-Ramírez *et al*., 2023).

The low soil OC content (0.53%) corresponds to a reduced availability of N (<0.005%), a condition commonly found in dry tropical areas. However, fertilization with nitrogen sources combined with the application of organic amendments and biofertilizers led to improved soil conditions and a promising increase in crop yields across all treatments, as also noted by Rehberger *et al*. (2023).

The results obtained in this study highlight the benefits of the production system, as reflected in enhanced green forage yield (average across treatments: 87.7 t/ha), greater ear mass (18.3 t/ha), and increased dry matter content (23.4 t/ha) in the final forage.

These values substantially exceeded the regional averages reported for the AGROSAVIA V-117 variety, representing yield increases between 77% and 104% in treatments that incorporated regenerative agricultural practices.

Ears constitute a key component within the system, as they increase protein content and digestibility, thus providing forage with high nutritional value that enhances animal productivity (Bueno *et al.,* 2003). T5 and T6 achieved the highest values, which were 20.4 and 19.35 t/ha, respectively, surpassing those of the control (T1) by 3.14 and 1.85 t/ha, respectively.

Economic analysis

The economic assessment revealed substantial variation in cost–benefit ratios across treatments. Despite incurring a lower total cost than T2 ($1,970.39), T3 achieved the highest forage yield (92.89 t/ha). These findings resulted in production costs of $21,212 per ton of forage, which were the lowest among all the treatments, indicating superior cost efficiency.

The investment in amendments ($531,262) in T2 constituted a key factor contributing to the increase in yield, as amendment application enhanced soil health, improved nutrient availability, and optimized plant growth. In contrast, the T4 and T5 treatments, which combined amendments with mulching, presented higher costs (up to $211,521 for T5) without achieving yields comparable to those of T3 and T2.

These results demonstrate that not all inputs are equally effective under these conditions, emphasizing the need to carefully evaluate fertilization strategies in relation to crop performance. The total cost of the conventional T1 treatment was $1,945.80, with a yield of 79.92 t/ha, indicating that while conventional practices may involve lower expenditures, their productivity and cost efficiency are generally less competitive than those of regenerative approaches.

Notably, treatments involving vermicompost application incurred higher costs due to the commercial price of the amendment. Nevertheless, in the medium to long term, these costs may be mitigated through on-farm vermicompost production and the progressive improvement in soil organic matter content.

Associations between the variables evaluated and forage production

In Colombia, maize is the third most common crop in terms of cultivated area, following coffee and rice. Nevertheless, the country ranks first in South America and seventh worldwide in terms of import volume. The increasing demand for this cereal is attributable mainly to its use in animal feed. However, owing to the multiple edaphoclimatic constraints present in Colombia, *Zea mays* L. exhibits relatively low yields, resulting in a substantial gap between production and demand; consequently, this demand must be met through imports (Govaerts *et al*., 2019).

Given this situation, the national objective of achieving food security remains hindered, underscoring the urgent need for strategies aimed at improving yield performance. The findings of this study, with an average green forage yield of 87.68 t/ha, provide strong evidence of the productive potential of maize under adequate management. Beyond the quantitative results, these outcomes are relevant for demonstrating that yield improvement is not necessarily incompatible with the implementation of best agricultural practices. This observation is particularly significant, as it highlights the viability of regenerative agriculture as a sustainable alternative for forage production, thereby contributing to productivity in the livestock sector while aligning with environmental stewardship.

The cob represents a key component within the system, as it contributes to increased protein content and digestibility, thereby increasing the nutritional value of the forage and ultimately improving animal productivity (Bueno *et al*., 2003). The T5 and T6 treatments resulted in the highest yields, which were 20.64 and 19.35 t/ha, respectively, surpassing those of the control treatment (T1) by 3.14 and 1.85 t/ha, respectively. In terms of dry matter (DM) accumulation in forage maize, the highest values were recorded for the T6 and T3 treatments, which exceeded the T1 treatment by 20% and 18%, respectively.

The results of this study are particularly promising when the average yield for the green forage maize variety AGROSAVIA V-117 in the Caribbean region reported by Agrosavia ranges between 40 and 50 t/ha. These findings demonstrate a substantial increase in production, ranging from 77% to 104%, in treatments incorporating regenerative agricultural practices. These outcomes are consistent with the observations of Salazar-Sosa *et al*. (2010), who reported a residual effect over six years of continuous bovine manure application on forage maize yield and soil fertility parameters.

The results obtained in this study surpass the average yields reported for the region and contribute to territorial development, as higher mean values were recorded across the evaluated variables. These findings highlight the positive influence of intensive maize management in low-fertility soil in the Colombian dry Caribbean through the application of water on the basis of hydric balance, fertilizer fractionation, and dosage adjustment according to crop requirements, as well as the incorporation of biofertilizers and soil amendment practices that complement a regenerative agricultural system.

The results further demonstrate that the incorporation of soil organic matter (organic residues and bio inputs) enhances nutrient cycling, thereby increasing forage production (Ogunleye, 2022). Research efforts in the dry tropics remain incipient; however, maize (*Zea mays* L.) genotypes with acceptable fresh and dry forage yields for these environments have been identified, with the “Agrosavia V-117” variety used in this study being one such example.

The yield improvements observed, although not statistically different, align with international findings where regenerative practices enhance soil health and system resilience over time. In semi-arid systems of Sub-Saharan Africa, similar integrations of organic amendments and microbial inoculants have shown progressive yield increases over 3-5 years, driven by improved soil organic carbon and water retention (Mkomwa *et al*., 2022; Thierfelder *et al*., 2018). These results suggest that under Colombian dry Caribbean conditions, repeated applications of vermicompost and biofertilizers could similarly drive long-term improvements in soil fertility, potentially reducing future fertilizer needs —a pattern documented in long-term trials in Mexico and Kenya (Salazar-Sosa *et al*., 2010; Paul *et al*., 2023; Singh *et al*., 2024).

Furthermore, the replicability of this regenerative model to other forage crops, such as sorghum (Sorghum bicolor), and to drought-tolerant legumes (*Cajanus cajan*, *Vigna unguiculata*) appears promising, given shared agronomic constraints and microbial synergies reported in diversified cropping systems (Stagnari *et al*., 2017; Fan e*t al*., 2025). Future research should test these practices across crop rotations and integrated livestock systems to assess their broader applicability and cumulative ecological benefits.

Paul *et al*. (2023) reported that livestock farms may play a pivotal role in the sustainable transformation of agri-food systems in Africa. Their study along the Kenyan coast illustrates the potential of livestock systems to enhance soil health and landscape restoration while contributing to carbon sequestration through improved pastures and vegetation cover. Nevertheless, drought and inadequate grazing management remain the most significant challenges to these systems. Accordingly, these authors recommended planting forage crops for silage during the dry season as a strategy to ensure feed availability for livestock.

These conditions are consistent with the present findings, where increased production can be viewed as an alternative solution to the adverse effects of climate change and recurrent drought events—characteristic of the region—thus offering evidence for the potential of regenerative agriculture to mitigate these impacts.

In this study, the principles of regenerative agriculture were applied, resulting in higher average forage yields. Rowntree *et al*. (2020) argued that regenerative agriculture in modern livestock systems can be redesigned to better exploit the ecological niche of animals as biological recyclers, thereby regenerating landscapes from an ecological perspective while accounting for numerous symbiotic complexities—an alternative model of livestock production. The adoption of regenerative practices and models should be promoted on a larger scale. Moreover, it is essential to continue advancing research on technologies and approaches aimed at improving the efficiency of pasture and forage production while actively engaging stakeholders in the ongoing development of regenerative agriculture.

The economic analysis revealed high yields per unit area, with potential positive impacts on low-income populations. The lowest cost was recorded for the fertilization treatment combined with organic amendments and biofertilizers, making these models promising for implementation in the region and potentially contributing to improved livelihoods for farmers. These findings underscore the importance of fostering the production of organic inputs as a means to increase soil fertility (Lone *et al*., 2013).

Climate variability, expressed through abrupt temperature shifts and less frequent but more intense rainfall events, can lead to productivity losses (Dibala, 2019). In this context, emerging trends in regenerative agriculture and livestock production—particularly those involving holistic land management practices that increase the photosynthetic capacity of plants to increase yields and improve soil health—are forthcoming.

These approaches foster and sustain both soil fertility and biodiversity (Schreefel *et al*., 2020; Villach, 2023). This study revealed significant yield increases, underscoring the potential of such practices to be integrated into meat and dairy production systems in semiarid regions. This integration is grounded in the fundamental principles of resource management and conservation, which are not merely key components but rather the very essence of regenerative agriculture (Newton *et al*., 2020).

CONCLUSIONS

The results of incorporating regenerative practices in the production of the "AGROSAVIA V-117" variety of forage maize are viable and sustainable in the study area, with yields above the national average in all the treatments evaluated.

The development of systems for forage maize production that incorporate regenerative agricultural practices such as soil cover, green manures, soil organic matter, plant growth-promoting microorganisms, efficient irrigation systems, and a fertilization plan has proven to be an economically viable alternative. This model can be implemented in the area as a productive solution to the shortage of livestock feed during dry seasons.

The enhancement of forage production for cattle feed through regenerative practices has the potential to boost livestock activity and the sustainability of the agricultural system. This is particularly relevant in regions with agroecological characteristics similar to those studied, where the adoption of these practices could lead to significant improvements.

Studies that evaluate regenerative forage maize production systems during different monitoring periods (short, medium, and long term) are necessary to determine the temporal variability and cumulative effects of different treatments on soil fertility and yield components. To support the evidence base for scaling, it is recommended integrating multivariate analyses (e.g., principal component analysis or structural equation modeling) to elucidate interactions between soil properties, microbial activity, and forage productivity. Additionally, participatory on-farm trials across diverse semiarid regions would help validate the replicability and socio-economic acceptability of these practices.

AUTHOR CONTRIBUTIONS

Conducting research and investigation process, data collection, Rodrigo Tofiño and Nelson Piraneque; Preparation of the published work, data analysis, Writing-Reviewing and Editing, Writing Original draft preparation, Visualization, Nelson Piraneque and Sonia Aguirre Forero.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

REFERENCES

Aguirre Forero, S. E., Piraneque Gambasica, N. V., & Fernández, T. (2022). *Suelo y cambio climático: Incluye estudio de casos* (1st ed.). Editorial Unimagdalena. http://doi.org/10.21676/9789587464993

Buchelt, A. C., de Mello Prado, R., Caione, G., de Almeida Carneiro, M., & Litter, F. A. (2021). Effects of silicon fertigation on dry matter production and crude protein contents of a pasture. *Journal of Soil Science and Plant Nutrition*, *21*, 3402-3413. https://doi.org/10.1007/s42729-021-00615-9

Bueno, G. A., Pardo, O., & Mojica, J. E. (2003). *Ensilaje de cultivos forrajeros para la alimentación de bovinos en el Piedemonte Llanero*. Corporación Colombiana de Investigación Agropecuaria – Agrosavia. http://hdl.handle.net/20.500.12324/16992

Cañet-Prades, F., Guie-Wong, J. S., Rodríguez, J. D., Muller-Castro, E., Chassot, O., & Arango-Berrocal, A. (2022). Aplicación de los principios de la agricultura regenerativa para aumentar los niveles de nutrientes en el suelo y enfrentar una emergencia de seguridad alimentaria y nutricional local en Guanacaste, Costa Rica. *Regeneratio*, *1*(2), 17-28. https://doi.org/10.55924/ucireg.v1i2.12

Castellanos-Navarrete, A., Chocobar-Guerra, A., Cox, R., Fonteyne, S., Govaert, B., Jespers, N., Kienle, F., Sayre, K. D., Enyanche, F., Martínez, B., & Verhulst, N. (2017). *Protocolos para mediciones de plantas en las plataformas de investigación*. Centro Internacional de Mejoramiento de Maíz y Trigo. https://repositorioslatinoamericanos.uchile.cl/handle/2250/7510959

Coral Eraso, D. M., Lemos, G., & Jaramillo Velasteguí, R. E. (2021). Opciones de fertilización orgánico mineral y biocontrol en maíz, fríjol y soya (accessed 13 March 2025). https://www.youtube.com/watch?v=u9aocJ7dvNw

Cuenca, N. J., Chavarro, F., & Díaz, O. H. (2008). El sector de ganadería bovina en Colombia. Aplicación de modelos de series de tiempo al inventario ganadero. *Revista Facultad de Ciencias Económicas, 16*(1), 165-177.

Cusworth, G., Lorimer, J., Brice, J., Garnett, T. (2022). Green rebranding: Regenerative agriculture, future-pasts, and the naturalisation of livestock. *Transactions of the Institute of British Geographers*, *47*(4), 1009-1027. https://doi.org/10.1111/tran.12555

Dibala, R. H. (2019). Forage production and diversification for climate-smart tropical and temperate silvopastures. University of Missouri-Columbia. https://hdl.handle.net/10355/75004

Faji, M., Kebede, G., Tsegahun, A., Mohammed, K., Minta, M., Feyissa, F., Mengistu, S. (2021). Evaluation of maize (Zea mays L.) genotypes for forage biomass yield and nutritional quality. *Ethiopian Journal of Agricultural Sciences*, *31*(1), 65-81.

Fan, H., Miao, R., Guo, C., Bao, X., He, W., Sun, Y., & Zhao, C. (2025). Research on the effect of diversified cropping on crop quality: A review. *Agriculture*, *15*(5), 456. https://doi.org/10.3390/agriculture15050456

Gantner, R., Steiner, Z., & Herman, G. (2021). Forages production. https://urn.nsk.hr/urn:nbn:hr:151:906608

García Botina, M. J. (2021). *Cadenas sostenibles ante un clima cambiante*. El maíz en Colombia. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). https://hdl.handle.net/10568/114766

Gómez-Ramírez, L. F., Sierra-Baquero, P. V., Fuentes-Cassiani, D., & Rubiano-Rodríguez, J. A. (2023). Quimigación y bio-irrigación con pivote central para el control de *Spodoptera frugiperda* (J E Smith, 1797) (Lepidoptera: Noctuidae) en maíz en el Caribe seco colombiano. *Revista Chilena de Entomología, 49*(1), 197-212.

González-Álvarez, Á., Viloria-Marimón, O. M., Coronado-Hernández, Ó. E., Vélez-Pereira, A. M., Tesfagiorgis, K., Coronado-Hernández, J. R. (2019). Isohyetal maps of daily maximum rainfall for different return periods for the Colombian Caribbean Region. *Water*, *11*(2), 358. https://doi.org/10.3390/w11020358

Govaerts, B.; Vega, D.; Chávez, X.; Narro, L.; San Vicente, F.; Palacios, N.; Pérez, M.; González, G.; Ortega, P.; Carvajal, A.; Arcos, A. L.; Bolaños, J.; Romero, N.; Bolaños, J., Vanegas, Y. F., Echeverría, R., Jarvis, A.; Jiménez, D.; Ramírez-Villegas, J.; Kropff, W.; Gonzáñez, C.; Navarro-Racines, C.; Ordoñez, L.; Prager, S.; & Tapasco, J. (2019). *Maíz para Colombia Visión 2030*. CIMMYT. https://hdl.handle.net/10883/20218

Gutiérrez-León, F. A., Alvarado-Ochoa, S. P., Reascos-Castillo, J. F., Ortiz-Flores, E. N., Portilla-Narvaez, A. R., & Rivera-Montesdeoca, M. A. (2023). Efecto sinérgico de la aplicación de biofertilizante y fertilizante nitrogenado en pasturas. *Pastos y Forrajes*, *46*, e14.

Jayasinghe, S. L., Thomas, D. T., Anderson, J. P., Chen, C., & Macdonald, B. C. T. (2023). Aplicación global de la agricultura regenerativa: una revisión de definiciones y enfoques de evaluación. *Sustainability*, *15*(22), 15941. https://doi.org/10.3390/su152215941

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability*, *15*(3), 2338. https://doi.org/10.3390/su15032338

Khatun, M., Shuvo, M. A. R., Salam, M. T. B., & Rahman, S. M. H. (2019). Effect of organic amendments on soil salinity and the growth of maize (*Zea mays* L.). *Plant Science Today*, *6*(2), 106-111.

Kumar, S., Sieverding, H., Lai, L., Thandiwe, N., Wienhold, B., Redfearn, D., Archer, D., Ussiri, D., Faust, D., Landblom, D., Grings, E., Stone, J., Jacquet, J., Pokharel, K., Liebig, M., Schemer, M., Sexton, P., Mitchel, R., Smalley, S., Osborne, S., Ali, S., Şentürklü, S., Sehgal, S., Owens, V., & Jin, V. (2019). Facilitating crop–livestock reintegration in the Northern Great Plains. *Agronomy Journal*, *111*(5), 2141–2156. https://doi.org/10.2134/agronj2018.07.0441

Liu, Y., Liang, F., Yan, S., Tu, T., Shi, Z., Pezzuolo, A., & Feng, Q. (2025). Optimizing fertilization strategies for low-carbon agriculture: Balancing greenhouse gas mitigation, soil health, and productivity. *Results in Engineering*, *27*, 107094. https://doi.org/10.1016/j.rineng.2025.107094

Lone, A. A., Allai, B. A., & Nehvi, F. A. (2013). Growth, yield and economics of baby maize (*Zea mays* L.) as influenced by Integrated Nutrient Management (INM) practices. *African journal of agricultural research*, *8*(36), 4537-4540. https://doi.org/10.5897/AJAR08.335

Mahapatra, S., Kumar, D., Singh, B., & Sachan, P. K. (2021). Biofuels and their sources of production: A review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus. *Energy Nexus*, *4*, 100036. https://doi.org/10.1016/j.nexus.2021.100036

Mkomwa, S., & Kassam, A. (2022). *Conservation agriculture in Africa: climate-smart agricultural development*. CABI. https://doi.org/10.1079/9781789245745.0000

Naranjo, J. F., & Ruiz-Buitrago, J. D. (2020). Sobre algunos mitos y realidades de la ganadería. bovina. *Revista Ciencia and Tecnología Agropecuaria*, *21*(3), 1-13. https://doi.org/10.21930/rcta.vol21_num3_art:1524

Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., & Johns, C. (2020). What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. *Frontiers in Sustainable Food Systems*, *4*, 577723. https://doi.org/10.3389/fsufs.2020.577723

OCDE/FAO (2020). *Perspectivas Agrícolas 2020-2029*. OECDC publishing. https://doi.org/10.1787/a0848ac0-es

Ogunleye, A. M. (2022). Semiarid Land Sustainable Agricultural Practices: The Evaluation of Annual Cover Cropping Systems Influence on Forage Productivity and Short-Term Soil Health Impact. University of Nevada. https://www.proquest.com/docview/2773849735/

Paul, B. K., Mutegi, J. K., Wironen, M. B., Wood, S. A., Peters, M., Nyawira, S. S., Misiko, M. T., Dutta, S. K., Zingore, S., Oberthür, T., Notenbaert, A. M. O., & Cook, S. (2023). Livestock solutions to regenerate soils and landscapes for sustainable agri-food systems transformation in Africa. *Outlook on agriculture*, *52*(2), 103-115. https://doi.org/10.1177/00307270231179747

Peng, W.; Wang, Z. K.; Sun, X. C.; Mu, X. H.; Huan, C.; Chen, F. J.; Lixing, Y.; Mi, G. H. (2019). Interaction effect of nitrogen form and planting density on plant growth and nutrient uptake in maize seedlings. *Journal of Integrative Agriculture*. 18(5): 1120-1129. https://doi.org/10.1016/S2095-3119(18)61977-X

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, *362*(6417), eaav0294. https://doi.org/10.1126/science.aav0294

Pulleman, M. M., Rahn, E., & Valle Pilia, J. F. (2024). *Agricultura regenerativa para sistemas cafeteros resilientes y con bajas emisiones de carbono-Una guía práctica*. Centro Internacional de Agricultura Tropical (CIAT). https://hdl.handle.net/10568/141572

R Core Team. (2016). R: A language and environment for statistical computing. Version 4.0.0. https://www.r-project.org/

Rao, I. M., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., Miles, J., Lascano Aguilar, C., Blümmel, M., Bungenstab, D., Tapasco, J., Hyman, G., Bolliger, A., Paul, B., van der Hoek, R., Maass, B., Tiemann, T., Cuchillo, M., Douxchamps, S., Villanueva, C., Rincón, Á., Ayarza, M., Rosenstock, T., Subbarao, G., Arango, J., Cardoso, J. A., Worthington, M., Chirinda, N., Notenbaert, A., Jenet, A., Schmidt, A., Vivas, N., Lefroy, R., Fahrney, K., Guimarães, E., Tohme, J., Cook, S., Herrero, M., Chacón, M., Searchinger, T., & Rudel, T. K. (2015). *LivestockPlus- The sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics*. Centro Internacional de Agricultura Tropical (CIAT). https://hdl.handle.net/10568/68840

Rehberger, E., West, P. C., Spillane, C., & McKeown, P. C. (2023). What climate and environmental benefits of regenerative agriculture practices? an evidence review. *Environmental Research Communications*, *5*, 052001. https://doi.org/10.1088/2515-7620/acd6dc

Rowntree, J. E., Stanley, P. L., Maciel, I. C., Thorbecke, M., Rosenzweig, S. T., Hancock, D. W., Guzman, A.; Raven, M. R. (2020). Ecosystem impacts and productive capacity of a multi-species pastured livestock system. *Frontiers in Sustainable Food Systems*, *4*, 544984. https://doi.org/10.3389/fsufs.2020.544984

Salazar-Sosa, E., Trejo-Escareño, H. I., López-Martínez, J. D., Vázquez-Vázquez, C., Serrato-Corona, J. S., Orona-Castillo, I., Flores-Márgez, J. P. (2010). Efecto residual de estiércol bovino sobre el rendimiento de maíz forrajero y propiedades del suelo. *Terra Latinoamericana*, *28*(4), 381-390

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Science*, *114*(36), 9575–9580. https://doi.org/10.1073/pnas.1706103114

Schreefel, L., Schulte, R. P., De Boer, I. J. M., Schrijver, A. P., & Van Zanten, H. H. E. (2020). Regenerative agriculture–the soil is the base. *Global Food Security*, *26*, 100404. https://doi.org/10.1016/j.gfs.2020.100404

Singh, S., Devi, N. B., Divya, D., Kumar, A., Singh, S., Tyagi, G. & Kumar, A. (2024). Soil fertility management: Role of organic amendments and bio-fertilizers: A review. *International Journal of Research in Agronomy*, *7*(12), 766-772. https://doi.org/10.33545/2618060X.2024.v7.i12j.2253

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (2023). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219-241. https://doi.org/10.1111/gcb.14815

Soro, D., Ayolié, K., Zro, F. G. B., Yéboua, F. Y., Kouadio, H. K. K., Bakayoko, S., Angui, P. T., & Kouadio, J. Y. (2015). Impact of organic fertilization on maize (*Zea mays* L.) production in a ferralitic soil of centre-west Côte d'Ivoire. *Journal of experimental biology and Agricultural Sciences*, *3*(6), 556-565. http://dx.doi.org/10.18006/2015.3(6).556.565

Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in Agriculture*, *4*, 2. https://doi.org/10.1186/s40538-016-0085-1

Tapia, J. J., Atencio, L. M., Ramírez, J., Osorio, K. V., Castillo, J., & Mejía, S. (2020). Situación actual y avances tecnológicos para mejorar la productividad del cultivo de maíz (*Zea mays* L.) en Colombia. *ACI Avances en Ciencias e Ingenierías*, *14*(1), 1-12. https://doi.org/10.18272/aci.v14i1.2585

Terán-Chaves, C. A., Duarte-Carvajalino, J. M., Ipaz-Cuastumal, C., Vega-Amante, A., & Polo-Murcia, S. M. (2023). Assessing the vulnerability of maize crop productivity to precipitation anomalies: A case study in the semiarid region of Cesar, Colombia. *Water*, *15*(11), 2108. https://doi.org/10.3390/w15112108

Thierfelder, C., Baudron, F., Setimela, P., Nyagumbo, I., Mupangwa, W., Mhlanga, B., Lee, N., & Gerard, B. (2018). Complementary practices supporting conservation agriculture in southern Africa: A review. *Agronomy for Sustainable Development*, *38*, 16. https://doi.org/10.1007/s13593-018-0492-8

Verhulst, N., Sayre, K., & Govaerts, B. (2012). *Manual de Determinación de Rendimiento* (1st ed.). SAGARPA, CIMMYT. https://repository.cimmyt.org/server/api/core/bitstreams/3c50e668-ebe9-42d2-b6ca-651ba-7ca492e/content

Villach, Q. G. (2023). La agricultura regenerativa: Regeneración del suelo. Sostenible o Sustentable. (accessed 28 June 2023). https://sostenibleosustentable.com/es/medioambiente/la-agricultura-regenerativa-regeneracion-del-suelo/#origen-de-laagricultura-regenerativa

White, C. (2020). Why regenerative agriculture?. *American Journal of Economics and Sociology*, *79*(3), 799-812. https://doi.org/10.1111/ajes.12334

Yitbarek, M. B. (2019). Livestock and livestock product trends by 2050. *International Journal of Animal Research*, *4*, 30.