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SCIENTIFIC ARTICLE

Effect of summer green manures on the yield and profitability of off-season maize

Efecto de abonos verdes de verano sobre el rendimiento y la rentabilidad del maíz de entrezafra

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ABSTRACT

Green manures can improve the productivity and profitability of off-season maize. The objective of this study was to evaluate the effect of different summer legume sequences on maize yield, yield components, and economic performance. The experiment was conducted from 2018 to 2019 at the experimental field of FCA-UNA, Caazapá Branch Campus, Paraguay, using a randomized complete block design with five treatments and four replications. The treatments were fallow followed by maize (F+M), *Cajanus cajan* followed by maize (Cc+M), *Mucuna pruriens* followed by maize (Mp+M), *Crotalaria juncea* followed by maize (Cj+M), and *Canavalia ensiformis* followed by maize (Ce+M). Grain yield, number of rows per ear, number of kernels per row, 100-kernel weight, production costs, net income, and profitability were evaluated. Green manure treatments significantly increased yield compared with F+M, which produced 2.74 t ha-¹. Yields were 3.94, 4.79, 4.29, and 4.18 t ha-¹ for Cc+M, Mp+M, Cj+M, and Ce+M, respectively. Yield components did not differ significantly among treatments. Mp+M showed the highest net income, at PYG 1,237,500 ha-¹, and the highest profitability, at 34.86%. Under the evaluated conditions, Mp+M was the most efficient sequence for increasing yield and the immediate economic return of off-season maize.

Keywords: *Zea mays* L., family farming, cover crops, legumes, yield.

RESUMEN

Los abonos verdes pueden mejorar la productividad y la rentabilidad del maíz de entrezafra. El objetivo de este estudio fue evaluar el efecto de diferentes secuencias con leguminosas estivales sobre el rendimiento, sus componentes y el desempeño económico del maíz. El experimento se realizó entre 2018 y 2019 en el campo experimental de la FCA-UNA, Filial Caazapá, Paraguay, mediante un diseño de bloques completos al azar con cinco tratamientos y cuatro repeticiones. Los tratamientos fueron barbecho seguido de maíz (B+M), *Cajanus cajan* seguido de maíz (Cc+M), *Mucuna pruriens* seguido de maíz (Mp+M), *Crotalaria juncea* seguido de maíz (Cj+M) y *Canavalia ensiformis* seguido de maíz (Ce+M). Se evaluaron el rendimiento de granos, el número de hileras por mazorca, el número de granos por hilera, el peso de 100 granos, los costos de producción, el ingreso neto y la rentabilidad. Los tratamientos con abonos verdes incrementaron significativamente el rendimiento respecto a B+M, que produjo 2,74 t ha-¹. Los rendimientos fueron de 3,94, 4,79, 4,29 y 4,18 t ha-¹ en Cc+M, Mp+M, Cj+M y Ce+M, respectivamente. Los componentes del rendimiento no difirieron significativamente entre los tratamientos. Mp+M presentó el mayor ingreso neto, con G 1.237.500 ha-¹, y la mayor rentabilidad, con 34,86%. En las condiciones evaluadas, Mp+M fue la secuencia más eficiente para aumentar el rendimiento y el retorno económico inmediato del maíz de entrezafra.

Palabras clave: *Zea mays* L., agricultura familiar, plantas de cobertura, leguminosas, rendimiento.

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INTRODUCTION

Sustainable crop production in the Eastern Region of Paraguay faces major constraints associated with soil degradation, acidity, and low fertility. In the department of Caazapá, 75% of the soils evaluated showed low overall fertility, with pH values close to 5.5 and organic matter contents of approximately 1.2% (Arce Barrios, 2017). These conditions can restrict the availability of essential nutrients, such as nitrogen, phosphorus, potassium, calcium, and magnesium, and limit agricultural productivity, particularly in systems with low nutrient replenishment and limited crop residue inputs (Fullaondo Navarro, 2014; Arce Barrios, 2017). The decline in organic matter also compromises soil functions related to nutrient cycling, water regulation, and sustained productivity, reducing the capacity of agroecosystems to respond to adverse environmental conditions (Villalba Algarin, 2025).

Crop diversification and the retention of plant residues on the soil surface are important strategies for conserving soil and improving the sustainability of agricultural systems (Villalba Algarin et al., 2025). However, their adoption remains limited in Paraguay. According to the 2022 VI National Agricultural Census, of the 291,497 farms with land registered in the country, 145,228 practiced crop rotation and only 23,666 used green manure crops, equivalent to 49.8 and 8.1% of farms, respectively (Ministerio de Agricultura y Ganadería, 2023). These figures show that approximately half of all farm units do not incorporate rotations and that the use of green manures remains uncommon. This situation is particularly relevant on family farms, where seed availability, establishment costs, labor demand, and uncertainty about productive and economic benefits can limit the adoption of conservation practices (Derpsch, Lange, Birbaumer, and Moriya, 2016).

Green manures represent an alternative for diversifying crop sequences, keeping the soil covered, and increasing organic residue inputs to the system (Souza et al., 2025). Their use can reduce soil exposure to the direct impact of rainfall, conserve moisture, recycle nutrients, and contribute to maintaining organic carbon and the functions associated with soil quality (Villalba Algarin, González, Szostak, and Sanabria Franco, 2024; Villalba Algarin, 2025). In addition, legumes are distinguished by their ability to fix atmospheric nitrogen through symbiotic associations with rhizobial bacteria and incorporate it into their biomass. After cover crop termination, residue decomposition and mineralization can increase nitrogen availability for the subsequent crop, although the magnitude of this contribution depends on the species, the biomass produced, and the chemical quality of the residues. A recent meta-analysis showed that legume cover crops increased maize nitrogen content and generated the greatest yield benefits when nitrogen fertilizer availability was low (Juneja et al., 2026). Summer legumes used as green manures in tropical and subtropical environments include gray velvet bean (*Mucuna pruriens*), sunn hemp (*Crotalaria juncea*), pigeon pea (*Cajanus cajan*), and jack bean (*Canavalia ensiformis*), species that can differ widely in biomass production and nutrient accumulation (Carvalho, Galera, Scholten, Canisares, and Cherubin, 2026).

The incorporation of green manures on family farms must also be evaluated from an economic perspective. Their establishment involves costs related to seed purchase, sowing, cutting, and biomass distribution (Roberts et al., 2025; Smee, Girkin, Simmons, and Falagán, 2026). However, abundant and persistent cover can reduce weed emergence and growth, decrease the need for hand weeding, and generate labor savings (Kumar et al., 2025; Imorou et al., 2026). Consequently, an increase in the yield of the subsequent crop does not necessarily guarantee greater profitability, because the economic outcome depends on the balance between establishment costs, the productivity achieved, and the reduction of other operating costs (Bergtold, Ramsey, Maddy, and Williams, 2019). Jointly evaluating these components is especially important in family farming, where the availability and cost of labor can determine the viability of management technologies.

Studies conducted in Paraguay have shown that diversifying cropping systems and retaining plant residues can promote nutrient conservation, soil quality, and agricultural productivity, although the magnitude of the benefits depends on soil and climatic conditions, the species used, and the management adopted (Villalba Algarin et al., 2025; Villalba Algarin, Sanabria Franco, González, and Lavres, 2026). Recent experimental evidence obtained in family farming systems in Caazapá also demonstrated that including cover crops can improve soil attributes and favor crop yields (Ortigoza Guerreño et al., 2026). Nevertheless, information comparing different summer legume species while simultaneously considering their effects on maize yield, yield components, and the economic profitability of the system is still limited.

In this context, the objective of this study was to evaluate the effect of four legume species used as summer green manures on the yield components and economic profitability of off-season maize grown on a sandy loam soil in Caazapá, Paraguay. We hypothesized that growing maize on green manure residues would increase yield and profitability compared with fallow, although the magnitude of the agronomic and economic benefits would vary among the species evaluated.

MATERIALS AND METHODS

Experimental site

The research was conducted from August 2018 to July 2019 at the experimental field of the Facultad de Ciencias Agrarias of the Universidad Nacional

de Asunción (FCA-UNA), Caazapá Branch Campus, located in Compañía 20 de Julio, Caazapá district, department of Caazapá, Eastern Region of Paraguay, approximately 225 km from the city of Asunción. The site is located at 26°11′ S latitude and 56°22′ W longitude, at an altitude of 143 m a.s.l. The regional climate is humid and mesothermal, with a mean annual precipitation of 1,640 mm and a mean annual temperature of 22.9 °C. The maximum, minimum, and mean temperatures, as well as the rainfall recorded during the 2019 maize growing period, are presented in Table 1. The soil of the experimental area was classified as a Rhodic Paleudult and is characterized by a sandy loam texture, a deep profile, and reddish color (López Gorostiaga, 2024).

Experimental design and treatments

The experiment was established in a randomized complete block design with five treatments and four replications, totaling 20 experimental units. Each experimental unit consisted of seven 5-m-long maize rows, with a spacing of 0.70 m between rows and 0.25 m between plants. Blocks were separated by 1-m alleys, while a distance of 1.5 m was maintained between experimental units. The total area of the experiment was 713 m². To reduce border effects, the harvest plot consisted of the five central rows, excluding the two outer rows and the plants located at the plot ends. The harvest plot had an area of 14 m² and comprised 80 plants.

The treatments evaluated corresponded to five management sequences: fallow followed by maize (F+M), *Cajanus cajan* followed by maize (Cc+M), *Mucuna pruriens* followed by maize (Mp+M), *Crotalaria juncea* followed by maize (Cj+M), and *Canavalia ensiformis* followed by maize (Ce+M). The temporal sequence of the treatments is presented in Figure 1.

Crop management

Before the experiment was established, the area had been managed under a conventional production system with subsistence crops, mainly beans, cassava, maize, and peanut. Initial soil preparation consisted of deep plowing followed by manual leveling with a hoe. The green manures were sown manually on August 30, 2018, using a hand-operated jab planter. *Mucuna pruriens*, *Canavalia ensiformis*, and *Cajanus cajan* were established at a spacing of 0.50 m between rows and 0.30 m between plants, while *Crotalaria juncea* was sown by continuous drilling in furrows spaced 0.50 m apart. In the F+M treatment, the soil remained fallow during the same period.

The green manures were terminated five months after sowing, during the last week of January 2019. Plants were cut manually with a machete, and the residues were evenly distributed over the surface of the respective experimental units. After green manure termination, a single glyphosate application was made in all treatments at a rate of 250 mL of commercial product per 20-L tank of water.

The subsequent crop was the single-cross maize hybrid Status Viptera 3, a short-cycle hybrid with yellow semi-flint grain, glyphosate tolerance, and protection against lepidopteran pests (Syngenta Paraguay, 2026). Maize was sown in February 2019 directly over the green manure residues and the fallow, without further soil preparation.

After the initial herbicide application, weed control was performed by hand weeding, according to the needs of each experimental unit. To determine the timing of intervention, plots were monitored every ten days using a 25 × 25 cm quadrat placed randomly at three points in each experimental unit. Hand weeding was performed when weed leaf cover reached or exceeded 50% of the evaluated area and weeds had an average height of approximately 10 cm. The number of labor days required for this task was recorded for each treatment and subsequently included in the economic analysis.

Data collection

Maize was harvested from all plants within the harvest plot of each experimental unit. Grain yield, number of kernel rows per ear, number of kernels per row, 100-kernel weight, and labor demand for manual weed control were evaluated.

Grain yield was determined by harvesting all ears in the harvest plot. The ears were then shelled, and the grain was cleaned and weighed on a precision

Table 1. Monthly climate data recorded during the experimental period. Caazapá, Paraguay, 2019.

Month	Maximum temperature (°C)	Minimum temperature (°C)	Mean temperature (°C)	Precipitation (mm)
February	34	22	28	122.1
March	32	19	25	114.4
April	29	17	23	103.0
May	26	15	20	69.6
June	24	13	19	103.7

*Source: compilation of meteorological data recorded by timeanddate.com (2019).

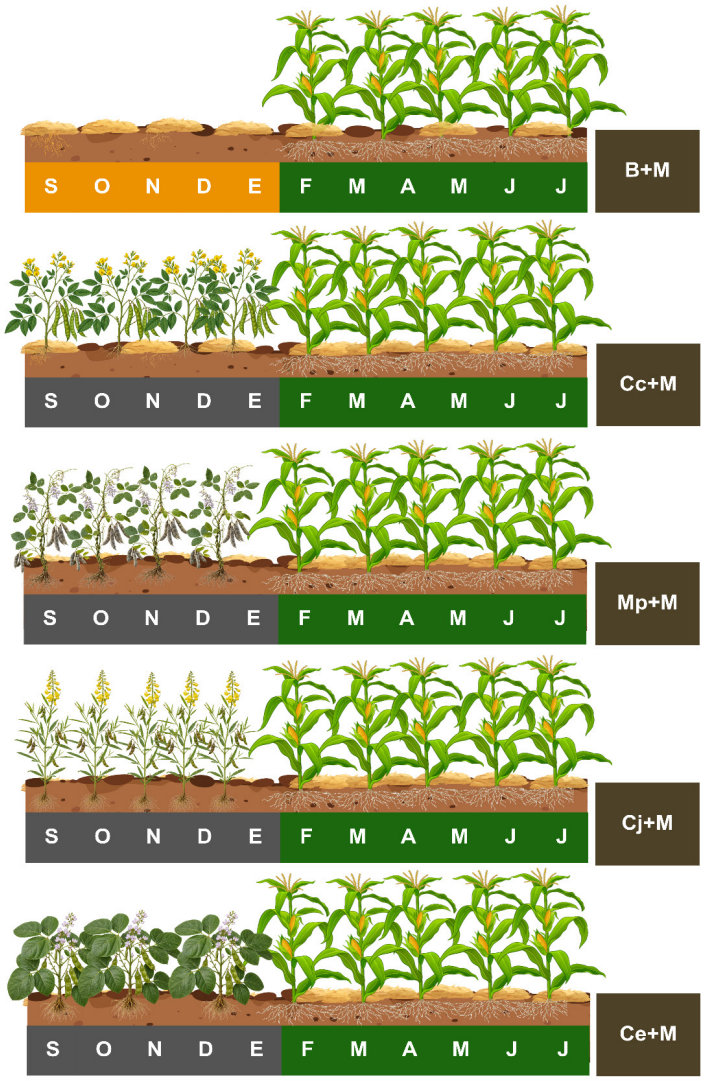


Figure 1. Temporal sequence of the summer green manure and off-season maize treatments. Caazapá, Paraguay, 2018–2019. F+M: fallow followed by maize; Cc+M: *Cajanus cajan* followed by maize; Mp+M: *Mucuna pruriens* followed by maize; Cj+M: *Crotalaria juncea* followed by maize; Ce+M: *Canavalia ensiformis* followed by maize.

balance. The weight obtained was adjusted to 14% moisture content and converted to kg ha-¹.

To determine the number of kernel rows per ear, ten ears were randomly selected from each experimental unit, and the number of longitudinal kernel rows was counted. The result was expressed as the mean of the ten ears evaluated.

The number of kernels per row was determined on the same ten ears used to evaluate the number of rows. On each ear, the kernels in one complete row were counted, excluding the imperfect kernels located at the ear tip. The results were expressed as the mean per experimental unit.

The 100-kernel weight was determined from a representative sample of the grain obtained from the ten ears evaluated in each experimental unit. One hundred kernels were randomly separated and weighed on a precision balance, and the results were expressed in grams.

Financial analysis and economic profitability

Production costs, gross income, net income, and economic profitability were determined for each treatment. A common baseline cost of PYG 2,180,000 ha-¹ was established and applied uniformly to all treatments. This cost included maize seed, soil preparation, herbicide and its application, insecticide and its application, maize sowing, harvesting, threshing, and bagging. The components, quantities, and values used are presented in Table 2.

Treatment-specific costs were added to the common baseline cost, including the purchase of green manure seeds, labor days for sowing, cutting, and distributing the biomass, and the labor used for hand weeding. For the F+M treatment, no costs for green manure seed, sowing, or management were considered, but labor days for manual weed control were included. All costs and income were expressed in guaraníes per hectare and corresponded to 2019 values.

Table 2. Common baseline production cost of off-season maize, expressed in guaraníes per hectare. Caazapá, Paraguay, 2019.

Item	Quantity	Unit cost (PYG)	Total (PYG)
Seed (kg)	14	20,000	280,000
Insecticide (L)	1	80,000	80,000
Harrowing (ha)	1	400,000	400,000
Herbicide (L)	3	30,000	90,000
Herbicide application (tank)	8	20,000	160,000
Maize sowing (labor day)	3	70,000	210,000
Insecticide application (tank)	6	20,000	120,000
Harvesting (labor day)	6	70,000	420,000
Threshing and bagging (labor day)	6	70,000	420,000
Common baseline cost			**2,180,000**

The gross income was calculated by multiplying the grain yield of each treatment by the maize selling price:

$$GI = Y \times P$$

where GI is the gross income (PYG ha-¹), Y is the grain yield (kg ha-¹), and P is the maize selling price (PYG kg-¹).

The net income was calculated as the difference between the gross income and the total cost:

$$NI = GI - TC$$

where NI is the net income (PYG ha-¹) and TC is the total production cost (PYG ha-¹).

The economic profitability was calculated using the following expression:

$$\text{Profitability (\%)} = \frac{GI - TC}{TC} \times 100$$

Positive values indicated gains relative to the capital invested, whereas negative values represented economic losses.

Statistical analysis

Data on grain yield, number of kernel rows per ear, number of kernels per row, and 100-kernel weight were subjected to analysis of variance according to the randomized complete block design. Beforehand, the normality of residuals was verified using the Shapiro–Wilk test, and the homogeneity of variances using Levene's test. When significant differences among treatments were detected ($p \leq 0.05$), means were compared using Tukey's test at a 5% significance level. Analyses were performed using InfoStat software, version 2015 (Di Rienzo et al., 2015).

Production costs, income, and economic profitability were not subjected to statistical analysis because they were calculated from prices, input quantities, labor used, and the mean yield obtained in each treatment.

RESULTS AND DISCUSSION

Yield

Maize grain yield differed significantly among treatments ($p \leq 0.05$; Figure 2). All green manure treatments outperformed fallow followed by maize (F+M), which yielded 2.74 t ha-¹. The highest mean value was recorded in Mp+M, at 4.79 t ha-¹, representing a 75% increase over F+M. Mp+M was significantly higher than Cc+M, while Cj+M and Ce+M showed intermediate values of 4.29 and 4.18 t ha-¹, respectively, not differing statistically from either Mp+M or Cc+M. Cc+M, in turn, reached 3.94 t ha-¹ and significantly outperformed the fallow.

The yield increase following all four legumes indicates that replacing fallow with green manures created more favorable conditions for the subsequent crop. Because the maize received no mineral fertilization, this response may have been related to nitrogen incorporated through biological fixation and subsequently released during residue decomposition and mineralization. A recent meta-analysis showed that legume cover crops increased unfertilized maize yield by more than 50% and its nitrogen content by 34% relative to fallow. Therefore, the increases of up to 75% observed in this study are consistent with the magnitude of response reported in systems without nitrogen fertilization (Juneja et al., 2026).

In addition to the nitrogen incorporated through biological fixation, the cover crops may have contributed to the recycling of other nutrients accumulated in their shoot and root tissues (Villalba

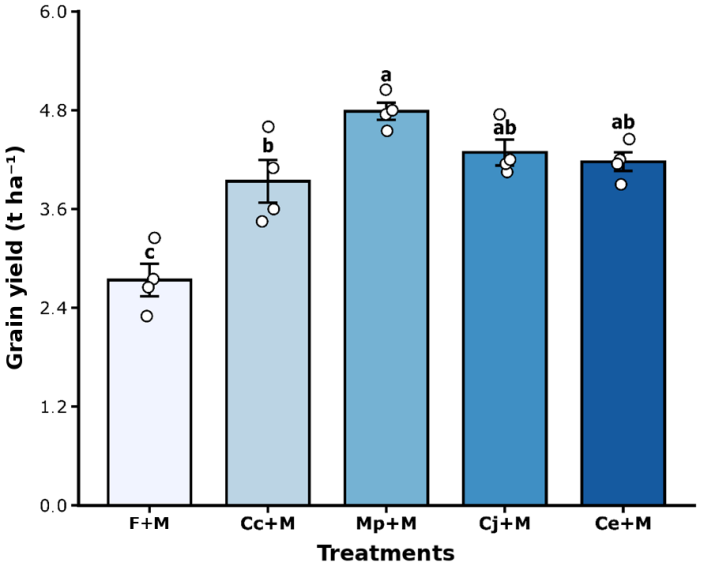


Figure 2. Grain yield (t ha-¹) of maize grown after different summer green manures. F+M: fallow followed by maize; Cc+M: *Cajanus cajan* followed by maize; Mp+M: *Mucuna pruriens* followed by maize; Cj+M: *Crotalaria juncea* followed by maize; Ce+M: *Canavalia ensiformis* followed by maize. Values are means ± standard error (n = 4). White circles represent individual replicates. Means followed by different letters differ significantly according to Tukey's test ($p \leq 0.05$).

systems in Caazapá, reinforcing the consistency of the response obtained under regional conditions (Ortigoza Guerreño et al., 2026).

Yield components

The number of rows per ear did not differ significantly among treatments ($p > 0.05$; Figure 3). Mean values ranged from 13.15 rows in F+M to 15.25 rows in Mp+M. The Cc+M, Cj+M, and Ce+M treatments had 14.63, 14.88, and 15.10 rows per ear, respectively.

The number of kernels per row also did not differ significantly among treatments ($p > 0.05$; Figure 4). The lowest mean value was recorded in F+M, with 17.9 kernels per row, whereas Mp+M had the highest mean, with 23.5 kernels. The Cc+M, Cj+M, and Ce+M treatments reached 20.5, 21.9, and 22.3 kernels per row, respectively.

The 100-kernel weight showed no significant differences among treatments ($p > 0.05$; Figure 5). Values ranged from 22.56 g in F+M to 26.52 g in Mp+M. The Cc+M, Cj+M, and Ce+M treatments recorded mean values of 25.83, 26.47, and 24.53 g, respectively.

Algarin et al., 2026). By exploring different soil depths, their roots can capture nutrients present in subsurface layers and, after residue termination and decomposition, return a fraction of these elements to the surface, where they may become available to the maize. This process is known as vertical nutrient redistribution or biological nutrient pumping (Madrid et al., 2026). Differences among species in biomass production and composition, root architecture, and nutrient accumulation could partly explain the yield variations observed among treatments (Carvalho et al., 2026).

The retention of residues on the soil surface may also have favored yield by modifying the soil environment. Plant cover reduces direct soil exposure, promotes infiltration, and helps conserve moisture, processes that are especially relevant in sandy loam soils with limited water-holding capacity (Souza et al., 2025). A recent global synthesis also showed that cover cropping can increase porosity, aggregate stability, and infiltration, as well as reduce soil bulk density and penetration resistance (Yan and Arthur, 2025). However, because biomass production, nutrient accumulation, soil moisture, and soil physical properties were not quantified in this study, these processes should be interpreted as plausible mechanisms rather than directly demonstrated effects. Increased maize productivity under cover crops has also been observed in family farming

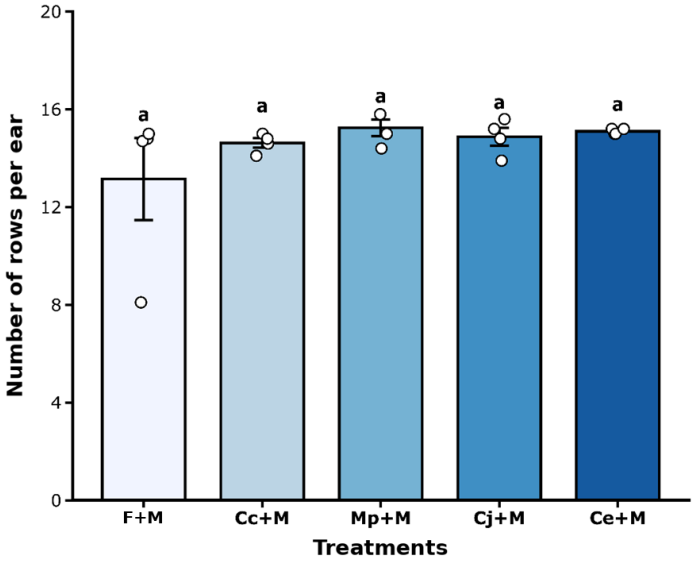


Figure 3. Number of rows per ear of maize grown after different summer green manures. F+M: fallow followed by maize; Cc+M: *Cajanus cajan* followed by maize; Mp+M: *Mucuna pruriens* followed by maize; Cj+M: *Crotalaria juncea* followed by maize; Ce+M: *Canavalia ensiformis* followed by maize. Values are means ± standard error (n = 4). White circles represent individual replicates. Means followed by the same letter do not differ significantly according to Tukey's test ($p > 0.05$).

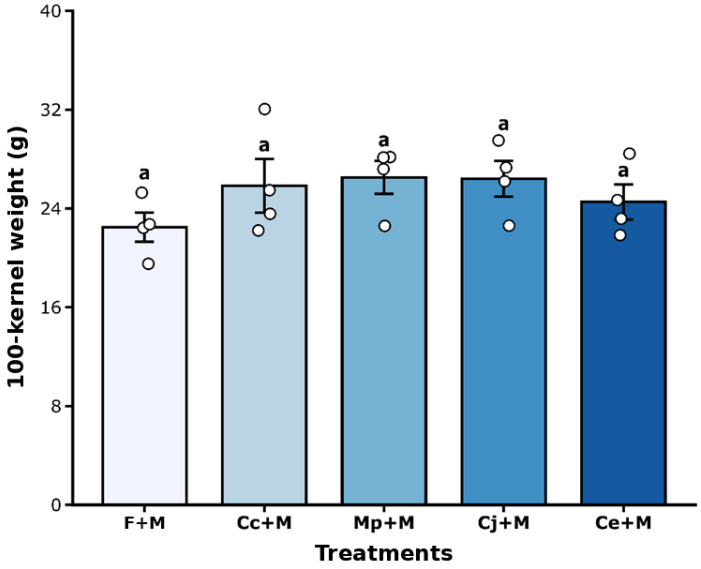


Figure 4. Number of kernels per row of maize grown after different summer green manures. F+M: fallow followed by maize; Cc+M: *Cajanus cajan* followed by maize; Mp+M: *Mucuna pruriens* followed by maize; Cj+M: *Crotalaria juncea* followed by maize; Ce+M: *Canavalia ensiformis* followed by maize. Values are means ± standard error (n = 4). White circles represent individual replicates. Means followed by the same letter do not differ significantly according to Tukey's test ($p > 0.05$).

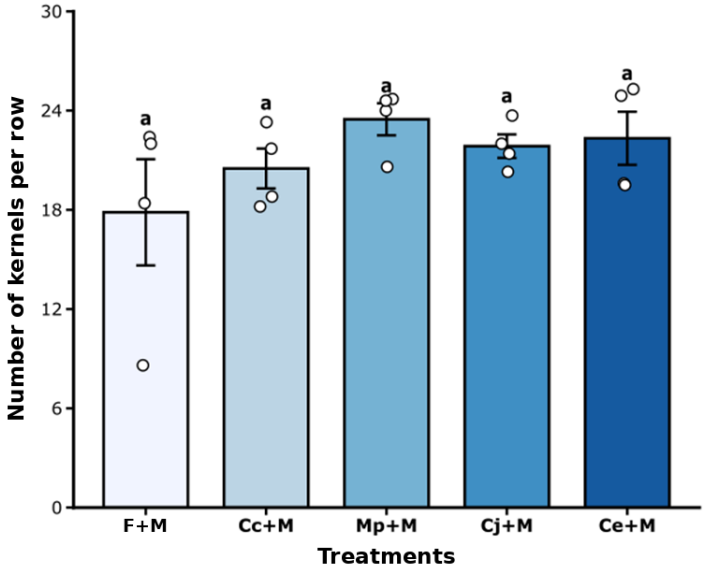


Figure 5. 100-kernel weight of maize grown after different summer green manures. F+M: fallow followed by maize; Cc+M: *Cajanus cajan* followed by maize; Mp+M: *Mucuna pruriens* followed by maize; Cj+M: *Crotalaria juncea* followed by maize; Ce+M: *Canavalia ensiformis* followed by maize. Values are means ± standard error (n = 4). White circles represent individual replicates. Means followed by the same letter do not differ significantly according to Tukey's test ($p > 0.05$).

The absence of significant differences in the number of rows per ear, number of kernels per row, and 100-kernel weight indicates that none of these components responded individually and consistently to the treatments. However, all three showed a favorable numerical trend under Mp+M compared with F+M. The number of rows was 16.0% higher, the number of kernels per row increased by 31.3%, and the 100-kernel weight was 17.6% greater. The concurrence of these responses in the same direction may have jointly contributed to the 74.9% yield increase observed, even though variability among replicates prevented the detection of statistical differences for each component separately.

Maize yield results from the integration of the number of ears per unit area, the number of kernels formed, and their final weight. Within the ear, the number of rows and kernels per row partly determine the kernel-setting potential (Long, Zeng, Liu, and Yang, 2024), whereas final kernel weight depends on the availability and translocation of photoassimilates, as well as on the rate and duration of the grain-filling period (Cao, Yu, Shi, Zhang, Z., and Zhang, Y., 2026). These traits are positively associated with productivity but differ in their degree of genetic control and environmental sensitivity. The number of rows is largely genetically determined, whereas kernel set and filling respond with greater plasticity to water, nutrient, and radiation availability during the reproductive stages (Zhang et al., 2025). Recent studies further show that the number of kernels per ear and kernel weight jointly contribute to yield, although kernel number usually accounts for a larger proportion of its variation (Wu et al., 2024).

In this regard, the conditions created by the legume residues may have moderately favored different processes, from ovule differentiation and fertilization to dry matter accumulation during grain filling (Wu et al., 2024). A recent study of maize grown after different cover crops also found that legumes simultaneously increased ear size, kernel proportion, and yield, whereas the no-cover treatment had the lowest productive values (Kale, K., Kale, H., Bingöl, and Işık, 2026). Therefore, the higher yield obtained with green manures in the present study appears to reflect the integration of small advantages across several components rather than a marked change in a single trait.

This interpretation should be treated with caution, because the total number of kernels per ear and the relative contribution of each component to yield were not determined. In addition, the evaluation of only ten ears per experimental unit and the variability observed, mainly in F+M, may have limited the statistical power to detect individual differences. Consequently, the results allow an agronomically consistent trend to be recognized but do not

definitively identify which component was primarily responsible for the yield increase.

Financial analysis and economic profitability of the system

Economic performance was determined by the combination of maize yield, green manure establishment and management costs, and labor demand for weed control (Table 3). Mp+M had the highest net income, at PYG 1,237,500 ha-¹, and the highest profitability, at 34.86%. Cj+M and Cc+M also generated positive results, with profitabilities of 8.82 and 1.35%, respectively. In contrast, Ce+M and F+M recorded profitabilities of −7.63 and −36.04%, respectively.

The economic superiority of Mp+M was associated with the highest grain yield and the lowest hand-weeding demand. This treatment yielded 4.79 t ha-¹ and required eight labor days for weed control, whereas F+M yielded 2.74 t ha-¹ and required 30 labor days. The reduction of 22 labor days represented a saving of PYG 1,540,000 ha-¹. This lower labor requirement may have been related to the creeping and climbing growth habit, rapid vegetative growth, and canopy expansion of *Mucuna pruriens*, traits that favor soil cover and weed shading. After termination, its residues may also have acted as a physical barrier to the emergence of new weeds. The ability of *M. pruriens* to reduce weed biomass through competition during its growth and through the cover provided by its residues has been highlighted in studies on summer legumes (Zannopoulos et al., 2024).

Cj+M showed a positive profitability of 8.82%, whereas Cc+M remained close to the break-even point. Ce+M recorded a profitability of −7.63%, mainly due to the combination of a demand of 23 labor days for hand weeding and a gross income insufficient to recover the total cost during the evaluated cycle. F+M had the poorest economic performance owing to its lower yield and the high cost of the 30 labor days used for weed control. These results show that a yield increase alone does not guarantee greater profitability, since the costs of seed, establishment, biomass management, and weed control must also be considered.

The negative profitability of Ce+M should not be interpreted as definitive evidence of the economic unviability of *Canavalia ensiformis*. The analysis covered only one off-season maize harvest and attributed all green manure establishment and management costs to it. The economic benefits of cover crops may not fully materialize in the first subsequent crop, because they depend on the period analyzed, the initial costs, and potential savings or productivity gains in later harvests (Bergtold et al., 2019). Therefore, the values in Table 3 represent short-term immediate profitability rather than the full economic return of the production system.

Future studies should maintain the treatments over several cycles and evaluate their effects on off-season maize, the main-season crop, and other subsequent crops. The analysis should integrate the costs and income of the entire annual cycle and estimate the cumulative profitability of the system, rather than considering a single harvest. Long-term evaluations show that the productive effects of cover crops can vary among seasons and that diversified rotations can achieve greater cumulative profitability when all crops in the sequence are considered together (Piva et al., 2021; Garbelini et al., 2022). Under

Table 3. Production costs, income, and economic profitability of off-season maize grown after different summer green manures. Caazapá, Paraguay, 2019.

Item	Unit cost (PYG)	F+M	Cc+M	Mp+M	Cj+M	Ce+M
Hand weeding (labor day)	70,000	30	15	8	15	23
Green manure sowing (labor day)	70.000		3	3	3	3
Cajanus cajan seed (kg)	7.000		35			
M. pruriens seed (kg)	4.000			100		
C. juncea seed (kg)	6.000				50	
C. ensiformis seed (kg)	4.000					80
Rolling (ha)	200.000		1	1	1	1
Common baseline cost (PYG)*		2.180.000	2.180.000	2.180.000	2.180.000	2.180.000
TOTAL COST (PYG) (TC)		4,280,000	3,885,000	3.550.000	3.940.000	4.520.000
Yield (t ha-¹) (Y)		2.7375	3.9375	4.7875	4.2875	4.175
Gross income (PYG) (Y × P		2,737,500	3,937,500	4,787,500	4,287,500	4,175,000
Net income (PYG) (NI)		−1,542,500	52,500	1,237,500	347,500	-345,000
Profitability (NI/TC) × 100		-36.04	1.35	34.86	8.82	-7.63

*The common baseline cost included maize seed, soil preparation, herbicide and its application, insecticide and its application, maize sowing, harvesting, threshing, and bagging. These costs were considered equally across all treatments.

2019 conditions and prices, Mp+M was the most economically favorable alternative, but the definitive viability of the other green manures will require a multi-year, system-scale evaluation.

CONCLUSIONS

Summer green manures increased off-season maize yield compared with fallow, with Mp+M standing out for the highest productivity. Although the number of rows per ear, number of kernels per row, and 100-kernel weight did not differ significantly among treatments, their combined numerical variations may have contributed to the observed yield differences.

Mp+M also had the lowest labor demand for weed control and the highest economic return, with a profitability of 34.86%. However, this result represents the immediate performance of a single off-season maize harvest. The overall economic viability of green manures should be confirmed through multi-cycle evaluations that consider their residual effects on subsequent crops and the annual and cumulative profitability of the production system.

REFERENCES

Arce Barrios, A. C. (2017). *Diagnóstico de la fertilidad de los suelos de la Región Oriental del Paraguay* (Tesis de grado, Carrera de Ingeniería Agronómica, Área de Suelos y Ordenamiento Territorial). San Lorenzo: Facultad de Ciencias Agrarias, Universidad Nacional de Asunción. https://repositorio.conacyt.gov.py/handle/20.500.14066/4127

Bergtold, J. S., Ramsey, S. M., Maddy, L., & Williams, J. R. (2019). A review of economic considerations for cover crops as a conservation practice. *Renewable Agriculture and Food Systems, 34*(1), 62–76. https://doi.org/10.1017/S1742170517000278

Cao, W., Yu, Z., Shi, Y., Zhang, Z., & Zhang, Y. (2026). Photosynthetic performance of spring maize leaves and the development and formation of superior and inferior grains. *Frontiers in Plant Science, 16*, 1732666. https://doi.org/10.3389/fpls.2025.1732666

Carvalho, M. L., Galera, L. de A., Scholten, R. S., Canisares, L. P., & Cherubin, M. R. (2026). Dry matter production and nutrient uptake by cover crops in Brazilian agriculture. *Nutrient Cycling in Agroecosystems, 132*, 28. https://doi.org/10.1007/s10705-026-10470-8

Derpsch, R., Lange, D., Birbaumer, G., & Moriya, K. (2016). Why do medium- and large-scale farmers succeed practicing CA and small-scale farmers often do not? Experiences from Paraguay. *International Journal of Agricultural Sustainability, 14*(3), 269–281. https://doi.org/10.1080/14735903.2015.1095974

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., González, L., Tablada, M., & Robledo, C. W. (2015). *InfoStat, versión 2015* [Software estadístico]. Córdoba: Grupo InfoStat, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba. http://www.infostat.com.ar/

Fullaondo Navarro, E. F. (2014). *Clasificación del nivel de materia orgánica de los suelos de la Región Oriental del Paraguay* (Tesis de grado, Carrera de Ingeniería Agronómica). San Lorenzo: Facultad de Ciencias Agrarias, Universidad Nacional de Asunción. https://informacionpublica.paraguay.gov.py/public/964942-ErichFullaondopdf-ErichFullaondo.pdf

Garbelini, L. G., Debiasi, H., Balbinot Junior, A. A., Franchini, J. C., Coelho, A. E., & Telles, T. S. (2022). Diversified crop rotations increase the yield and economic efficiency of grain production systems. *European Journal of Agronomy, 137*, 126528. https://doi.org/10.1016/j.eja.2022.126528

Imorou, L., Yemadje, P. L., Ranaivoson, L., Christina, M., Tovihoudji, P. G., N'Douro, M. Z. S., … Tittonell, P. (2026). Conservation agriculture systems reduce weed emergence and alter weed community structure in a cotton-based cropping system in Benin. *Agriculture, Ecosystems & Environment, 401*, 110262. https://doi.org/10.1016/j.agee.2026.110262

Juneja, P., Baath, G. S., Brar, J. S., Flynn, K. C., Yost, J. L., & Rajan, N. (2026). Corn responses to nitrogen fertilization as influenced by cover cropping: A meta-analysis. *Agronomy for Sustainable Development, 46*, 3. https://doi.org/10.1007/s13593-025-01067-6

Kale, K., Kale, H., Bingöl, S., & Işık, D. (2026). An approach to increasing sustainability in agricultural systems: Evaluating the effects of different cover crops on yield components in maize (*Zea mays* L.). *International Journal of Plant Production, 20*, 54. https://doi.org/10.1007/s42106-026-00438-7

Kumar, V., Singh, V., Flessner, M. L., Reiter, M. S., Kumari, A., Price, A., … Mirsky, S. B. (2025). Impact of cover crops and termination timing on weed management in corn. *Weed Technology, 39*, e69. https://doi.org/10.1017/wet.2025.39

Long, Y., Zeng, Y., Liu, X., & Yang, Y. (2024). Multivariate analysis of grain yield and main agronomic traits in different maize hybrids grown in mountainous areas. *Agriculture, 14*(10), 1703. https://doi.org/10.3390/agriculture14101703

López Gorostiaga, O. E. (2024). *Grandes grupos de*

suelos de la región oriental del Paraguay (J. Á. Lesme Brun, Comp.). José Ángel Lesme Brun. https://isbn.bibliotecanacional.gov.py/catalogo.php?mode=detalle&nt=17284

Madrid, L. B., Sehgal, A., Ye, R., Siddique, K. H. M., Hein, K., Topp, C., & Narayanan, S. (2026). Cover crop root attributes and their contribution to soil processes and agroecosystem sustainability. *Agriculture, Ecosystems & Environment, 407*, 110468. https://doi.org/10.1016/j.agee.2026.110468

Ministerio de Agricultura y Ganadería. (2023). *VI Censo Agropecuario Nacional 2022* (Vol. 1). Dirección de Censos y Estadísticas Agropecuarias. https://can2022.mag.gov.py/geoportal/VI_CENSO_AGROPECUARIO_NACIONAL_Volumen_1.pdf

Ortigoza Guerreño, J., Torres Ferreira, A. M., Alonso Giménez, B. B., Báez Arzamendia, M. E., Villalba Algarin, C. A., & Sanabria Franco, M. F. (2026). Plantas de cobertura en sistemas de agricultura familiar: Evidencias experimentales iniciales sobre las propiedades del suelo y los rendimientos de los cultivos en Paraguay. *Revista de la Sociedad Científica del Paraguay, 31*, e3108. https://doi.org/10.32480/rscp.2026.e3108

Piva, J. T., Bratti, F., Locatelli, J. L., Ribeiro, R. H., Besen, M. R., Brancaleoni, E., & Schmitt, D. E. (2021). Use of winter cover crops improves maize productivity under reduced nitrogen fertilization: A long-term study. *Bragantia, 80*, e0621. https://doi.org/10.1590/1678-4499.20200165

Roberts, C., Gholson, D., Quintana-Ashwell, N., Locke, M. A., Pieralisi, B. K., Spencer, G. D., … Krutz, L. J. (2025). Economic implications of reduced tillage and cover crops in the irrigated mid-South. *Agronomy Journal, 117*(2), e70034. https://doi.org/10.1002/agj2.70034

Smee, M., Girkin, N. T., Simmons, R. W., & Falagán, N. (2026). Uncovering the potential of cover cropping for regenerative horticulture. *European Journal of Agronomy, 180*, 128243. https://doi.org/10.1016/j.eja.2026.128243

Souza, V. S., Canisares, L. P., Schiebelbein, B. E., de Castro Santos, D., Menillo, R. B., Pinheiro Junior, C. R., & Cherubin, M. R. (2025). Cover crops enhance soil health, crop yield and resilience of tropical agroecosystem. *Field Crops Research, 322*, 109755. https://doi.org/10.1016/j.fcr.2025.109755

Syngenta Paraguay. (2026). *Agrisure Viptera3*. Recuperado el 22 de julio de 2026, de https://www.syngenta.com.py/agrisure-viptera3

Villalba Algarin, C. A. (2025). Avanzando hacia una agricultura climáticamente inteligente: El papel del carbono orgánico en las funciones del suelo, los servicios ecosistémicos y la sostenibilidad de agroecosistemas. *Investigación Agraria, 27*(1), e2701825. https://doi.org/10.18004/investig.agrar.2025.2701825

Villalba Algarin, C. A., González, A. C., Szostak, J. E., & Sanabria Franco, M. F. (2024). Explorando el estado del arte de la labranza y su impacto en la calidad del suelo y la productividad agrícola: Una revisión crítica de los últimos 20 años. *Investigación Agraria, 26*(2), 111–124. https://doi.org/10.18004/investig.agrar.2024.diciembre.2602806

Villalba Algarin, C. A., Sanabria Franco, M. F., González, A. C., & Lavres, J. (2026). Legacy effects of 32 years of tillage and crop diversification on soil biological activity in Paraguay. *Soil Systems, 10*(6). https://doi.org/10.3390/soilsystems10060066

Villalba Algarin, C. A., Thiengo, C. C., Cherubin, M. R., Bieluczyk, W., Mariano, E., Amorim, D. J., … Lavres, J. (2025). Can no-tillage and crop diversification sustain nutrient stocks in acidic and poorly-fertilized soils? Evidence from 32 years of real-world agricultural management in Paraguay. *Soil Advances, 4*, 100084. https://doi.org/10.1016/j.soilad.2025.100084

Wu, W., Yue, W., Bi, J., Zhang, L., Xu, D., Peng, C., … Wang, S. (2024). Influence of climatic variables on maize grain yield and its components by adjusting the sowing date. *Frontiers in Plant Science, 15*, 1411009. https://doi.org/10.3389/fpls.2024.1411009

Yan, F., & Arthur, E. (2025). Cover crops alter soil physicochemical properties: A global meta-analysis. *Geoderma, 460*, 117436. https://doi.org/10.1016/j.geoderma.2025.117436

Zannopoulos, S., Gazoulis, I., Kokkini, M., Antonopoulos, N., Kanatas, P., Kanetsi, M., & Travlos, I. (2024). The potential of three summer legume cover crops to suppress weeds and provide ecosystem services: A review. *Agronomy, 14*(6), 1192. https://doi.org/10.3390/agronomy14061192

Zhang, H., Li, T., Zhang, Z., Wang, J., Yang, H., Liu, J., … Xu, S. (2025). Dissecting the genetic architecture of yield-related traits by QTL mapping in maize. *Frontiers in Plant Science, 16*, 1624954. https://doi.org/10.3389/fpls.2025.1624954