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Agronomic Performance Evaluation of Intercropping Two Common Bean Breeding Lines with a Maize Variety under Two Types of Fertilizer Applications in the Colombian Amazon Region

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Citation: Suárez, J.C.; Anzola, J.A.; Contreras, A.T.; Salas, D.L.; Vanegas, J.I.; Urban, M.O.; Beebe, S.E.; Rao, I.M. Agronomic Performance Evaluation of Intercropping Two Common Bean Breeding Lines with a Maize Variety under Two Types of Fertilizer Applications in the Colombian Amazon Region. *Agronomy* **2022**, *12*, 307. <https://doi.org/10.3390/agronomy12020307>

Academic Editor: Jiaen Zhang

Received: 25 December 2021

Accepted: 21 January 2022

Published: 25 January 2022

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Abstract: Intercropping the common bean (*Phaseolus vulgaris* L.) with maize (*Zea mays* L.) is a widely used agronomic practice in smallholder farms in different regions of the world. Although it is a common practice in the Colombian Amazon region, crop yields are low due to the degradation of low fertility, acidic soil and high-temperature stress. Studies are needed on how the integration of genetically adapted common bean breeding lines into an intercropping system can benefit smallholders. The objective of this study was to: (i) evaluate differences in agronomic performance of two common bean lines when intercropped with maize in two different patterns under two types of fertilizer applications; and (ii) identify which intercropping pattern is better to maximize productivity and land use in the Colombian Amazon region. To achieve these aims, 2 field experiments (October 2018 to January 2019, season 1; April to June 2019, season 2) were conducted in the Colombian Amazon region. A randomized complete block design (RCBD) with three replications in a nested trifactorial arrangement in a split-plot scheme was used. The experimental design consisted of 2 advanced bean breeding lines of BFS 10 and ALB 121 (main plots); 3 cropping system patterns, including a monoculture, intercropping pattern 1, and intercropping pattern 2 (subplots); and 2 types of fertilizer, inorganic and organic (sub-subplots), for a total of 12 treatments. The experiment was conducted in two growing seasons in low fertility, acidic soil. Different competition indices and monetary advantage index values were estimated depending on the yield and cost of production from maize and bean intercropping patterns (land equivalent ratio, LER; relative crowding coefficient, RCC; aggressiveness index, AI; competitive ratio, CR). A significant effect on grain yield was observed with both intercropping patterns compared to monocropping of beans and maize. Grain yields obtained for maize were similar under monoculture with both types of fertilizer application, while both bean lines yielded better in monoculture under the application of inorganic fertilizer. Under intercropping patterns, the yield reductions were from 8 to 30% for maize and from 43 to 72% for the 2 bean lines. LER values increased with intercropping patterns under both types of fertilization, which was supported by positive values in the actual yield loss index. The interaction indices between the two crop components showed a greater dominance of maize over beans (RCC, AI, CR). However, the intercropping systems increased the economic advantage (the monetary advantage index) over monocropping. Smallholders in the Amazon region can profit through increased grain yield as well as land-use efficiency by integrating a genetically adapted bean breeding line, BFS 10, as an intercrop with maize under the application of organic fertilizer.

Keywords: aggressiveness; bean-maize intercrop; grain yield; land equivalent ratio (LER); plant competition

1. Introduction

The management, production and land-use efficiency of intercropping (mixed intercropping with simultaneous sowing, intercropping in single and double rows, intercropping with temporal variation in sowing, intercropping in relay) compared to monocropping have been researched in different parts of the world [1–4]. Several studies have demonstrated that intercropping can be used as an effective strategy for sustainable and efficient crop production to improve food security for smallholders in areas with high climatic variation and resource-poor farming conditions [5–7]. Intercropping also contributed to increasing the yield and quality of crops and improved efficiency in the use of resources such as land, light, soil, water and nutrients [7–9], particularly in regions that are confronted with soil and environmental degradation problems [10].

Among the food crops available for human consumption, the common bean (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) have been produced and managed using intercropping in many regions of the world [9–11]. For example, 60% of bean producers in Latin America intercrop beans with maize [7], and this is also a common practice for bean producers in Colombia [7,12]. However, it has been observed that in bean-maize intercropping, there are reductions in bean yields [13–15], where the magnitude of production efficiency of this management depends largely on the growth habit of the bean cultivar used [7].

Among the decisions to be made by farmers in practicing the intercropping of a cereal with a legume include planting density [16], the time of planting of both components [4], as well as the application of inorganic and organic fertilizer [17]. Higher planting density can lead to plant stress in intercropped crops and increase competition among the two crop components for water, light and nutrients [18,19], leading to decreased yields of both crops [11,20]. The sowing of common beans with maize simultaneously gave a more stable total yield compared to either alternate or paired sowing patterns [21] due to differences in phenological behavior (days to flowering, maturity and plant height) [4]. Regarding the effect of fertilizer application, it has been reported that this practice stabilizes yield compared to unfertilized treatment [22] and increases system yield due to higher nutrient availability [17], demonstrating a 6 to 28% increase over monocropped maize yield [23]. However, the substitution of mineral fertilizers with green manures has also been shown to lead to more stable yields due to improved C input and N recovery efficiency [9], a practice that can also improve intercropping productivity in the Colombian Amazon region. Thus, the biggest challenge for researchers and farmers is to find the right combination of intercropping patterns that will improve the growth and yield of both maize and beans [20]. Therefore, the selection of crop components that differ in their competitive capacity in time and/or space is essential for a more resource-efficient and productive intercrop [4,19].

To measure and explain the competition generated in intercropping, different indices have been formulated, including the land equivalence ratio (LER) [24]. LER is defined as the total area of land required to produce a certain amount of intercropped grain in reference to the monoculture [3], and LER is commonly used to evaluate the yield of intercropped components [25]. There are also other indices developed to quantify competition, aggressiveness and economic advantage, and these include: (i) the competition coefficient or competition ratio (CR) [26–28], which describes the characteristics of the effect, intensity and result of competition between the two crop components [29]; (ii) aggressiveness index (AI), which is defined among the partial values of the LER and indicates which is the dominant or dominated crop [30]; and (iii) others such as the relative agglomeration coefficient (K), the actual yield loss (AYL), the monetary advantage index (MAI) and the

intercropping advantage index (IAI). These parameters/indices all describe the competition and economic advantage of intercropping systems over monocropping systems [27,30–33].

In the Colombian Amazon region, crops such as bananas (*Musa x paradisiaca*), rice (*Oryza sativa*), maize (*Zea mays*) and beans (*Phaseolus vulgaris*) have been produced by smallholders as part of improving household food security and income generation. These crops have been produced in areas where the process of soil degradation is aggravated due to livestock farming [34], and the use of these degraded pasture lands for cropping results in lower crop yields. Recent studies identified a number of common bean lines that are genetically adapted to aluminum-toxic acid soil and high-temperature stress conditions [35,36]. Among the most promising common bean lines, Suárez et al. [37] used two common bean breeding lines (ALB 121, BFS 10) to determine the photosynthetic and grain yield responses of these lines to intercropping with maize under two types of fertilizer application in the Colombian Amazon region. They found that the photosynthetic response of BFS 10 was superior to ALB 121 under both monoculture and intercropping patterns with either inorganic or organic fertilizer applications. Further studies are needed to determine how the integration of the above two genetically adapted common bean lines into an intercropping system can benefit smallholders in terms of improving crop productivity as well as land-use efficiency. The objective of this study was to: (i) evaluate differences in the performance of two common bean breeding lines when intercropped with maize in two different patterns under two types of fertilizer applications; and (ii) identify which intercropping pattern is better to maximize productivity and land use in the Colombian Amazon region. We tested the hypothesis that acid soil and high-temperature-stress-adapted bean lines, with their indeterminate growth habit, can compete with maize when grown as an intercrop and produce economically viable grain yield with either inorganic or organic sources of fertilizer application.

2. Materials and Methods

2.1. Experimental Site and Meteorological Conditions

In this study, two field experiments (October 2018 to January 2019, season 1; April to June 2019, season 2) were conducted at the Macagual Research Center of the University of the Amazon, Colombia (1°37' N and 75°36' W) located in Florencia, Caquetá (Colombia) within a tropical rainforest ecosystem. The location has an average annual precipitation of 3800 mm with 1700 h of sunshine year⁻¹, an average temperature of 25.5 °C, and an average relative humidity of 84%. During the growing season (season 1, season 2), maximum and minimum average temperatures were 32 °C and 23 °C, respectively [37]. The total rainfall in the 2 seasons (season 1, season 2) during the flowering growth stage was 148.6 and 271 mm with a daily average of 3.7 and 6.0 mm, respectively; in the pod filling growth stage, the average was 171.5 and 63.8 mm with a daily average of 7.7 and 2.7 mm, respectively [37]. The soil is a clay loam Oxisol with bulk density values that ranged between 1 and 1.3 g cm⁻³ and pH values that ranged from 4.1 to 5.2, with mean values of organic carbon content of 1.35%, available phosphorous (P) content (Bray-II) of 2.58 mg kg⁻¹, saturation of total bases of 7.1% (calcium, Ca: 0.38 cmol kg⁻¹, magnesium, Mg: 0.1 cmol kg⁻¹, potassium, K: 0.14 cmol kg⁻¹, sodium, Na: 0.1 cmol kg⁻¹, total bases: 0.8 cmol kg⁻¹), cation exchange capacity (CEC) of 11.3 cmol kg⁻¹, and an exchangeable aluminum (Al) content of 6.3 cmol kg⁻¹ with 73.4% Al saturation [37].

2.2. Field Layout and Experimentation

As reported before, the experiment was conducted under the same design of treatments at the same location in two seasons, and we used a randomized complete block design (RCBD) with 3 replications in a nested trifactorial arrangement in a split-plot scheme. The experiment consisted of two advanced bean breeding lines, BFS 10 and ALB 121 (main plots); three cropping system patterns, including a monoculture pattern (with maize sown at 5 plants m⁻² and beans sown at 6.5 plants m⁻²), intercropping pattern 1 (with maize sown at 3 plants m⁻² and beans sown at 3 plants m⁻²), and intercropping pattern 2 (with

maize sown at 5 plants m^{-2} and beans sown at 2.5 plants m^{-2}] (subplots); and two types of fertilizer, inorganic and organic (sub-subplots) for a total of 12 ($2 \times 3 \times 2$) treatments [38]. The maize variety (ICA V109) with yellow grain color was used. This variety is known to perform well under a monoculture system due to its adaptation to the hot climate. It is cultivated by Amazonian farmers. Soil preparation and planting were done manually. In each planting season (season 1, season 2), a dose of 1000 kg ha^{-1} of dolomitic lime ($\text{CaMg}(\text{CO}_3)_2$) was applied at 20 days after planting in order to improve the efficiency in the availability and absorption of nutrients from the fertilizers applied to the crop. The experimental field used for the study was under common bean cultivation for the past five years, and it had not received any type of inorganic or organic fertilizer application. The details on the two common bean lines and the planting patterns of monocropping, intercropping pattern 1 and intercropping pattern 2 were described before [37]. Briefly, there were 4 rows in the monoculture plot with 60 plants in a row. This came to a total of 240 plants in each plot, which is equivalent to 50,000 plants of maize ha^{-1} . This is a normal density of sowing in the Amazon region. Four rows were planted in the monoculture plot for each bean line (ALB 121, BFS 10) at a distance of 1 m between rows. In each row, 80 bean seeds were sown at a distance of 0.15 m between plants, for a total of 320 plants per plot, which is equivalent to 66,600 bean plants ha^{-1} .

In both intercropping patterns (intercropping 1, intercropping 2), bean and maize lines were planted simultaneously. Seeding patterns were selected with the aim of minimizing the impact of the shading effect of maize on beans and generating better complementarity and efficiency in the use of resources of both crops (6). The crops were planted on the same row, conserving the distance between the bean and maize in the intercropping (0.15 m) pattern [37]. The seeding ratio when the lines of beans and maize were sown simultaneously was 1:1 (intercropping pattern 1): in each row, 40 plants of beans and maize were sown for a total of 80 plants per row; between plants of beans and maize, the distance was 0.15 m, and between plants of the same crop, the distance was 0.30 m. This comes to a total per plot of 320 plants (160 plants per each crop), which is equivalent to 66,600 plants ha^{-1} . For the 2:1 seeding ratio (intercropping pattern 2), 30 bean plants and 60 maize plants were sown in each row for a total of 90 plants per row. Two maize seeds were sown at a distance of 0.1 m and a bean seed was sown at a distance of 0.15 m for a total per plot of 360 plants (120 plants for beans and 240 plants for maize). This is equivalent to 75,000 plants ha^{-1} (25,000 bean plants ha^{-1} and 50,000 maize plants ha^{-1}) [37].

During soil preparation, dolomitic lime was applied at a dose of 1 t ha^{-1} at 20 days before planting to raise soil pH and minimize the effect of aluminum (Al) and manganese (Mn) toxicity, as well as to improve the efficiency of nutrient availability and absorption from the soil [39]. The foliar fertilizer application (both inorganic or organic) was made via fertigation using a manual back-held sprayer (Royal Condor Classic, volume of 20 L (Progen S.A., Soacha, Colombia)). According to the Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) scale of growth for bean [40] and maize [41], the fertilizer applications were made at different times of plant development. The first application was made at 15 days after planting for maize, when the first pair of leaves unfolded (BBCH 12), and at 30 days for beans, when the first lateral bud is visible (BBCH 21). The second application was made at 35 days after planting for maize, when it had three detectable nodes (BBCH 33), while the second lateral bud was visible for beans (BBCH 22). Foliar application of inorganic fertilizer was in the form of Nutrimins (Colinagro S.A., Bogotá, Colombia). The foliar application of organic fertilizer was in the form of mineral-enriched and cow-manure-based Super-Magro Biofertilizer. Three manual weedings were carried out from ten days after sowing with an interval of two weeks each. The preventive management of pests and diseases was done by spraying the plants with Manzate 200 WP (DuPont, Wilmington, NC, USA) and a broad-spectrum pesticide, Lorsban 480 EM (Dow AgroSciences, Indianapolis, IN, USA). The cost of each fertilizer was USD 3.85 per liter for Nutrimins fertilizer and USD 1.37 per 8 L for Super-Magro biofertilizer. These amounts are equivalent to fertilizing an equal number of plants. The cost of organic fertilizer applied was only 64% of the cost

of the inorganic fertilizer applied. At physiological maturity, which corresponds to 50% of the mature pods (BBCH 85), sampling was carried out to determine the grain yield. This consisted of taking the central row of each plot, threshing the pods of the harvested plants and cleaning and drying the grains until a constant weight was reached.

2.3. Competition Indices and Monetary Advantages

Different competition indices and monetary advantage index values were estimated depending on the yield and cost of production through maize and bean intercropping patterns (see Table 1). The advantage of intercropping common bean lines with maize was evaluated using the land equivalent ratio (LER) [32]. The total LER for a bean-maize intercrop is the sum of the partial LER values for bean (LER_B) and maize (LER_M) (Table 1). To better illustrate the results on competition, such as yield advantages of intercropping, Bedoussac and Justes [32] suggested plotting the partial LER values of each species, LER_B , as a function of LER_M . We considered the sowing rate of each species in the intercrop in relation to the monoculture in order to draw the reference lines that would allow the grain yield per plant to be compared (i.e., reference lines were drawn showing both the sowing rate and the yield that each crop species has in monoculture), and this allowed us to distinguish areas of interest to perform a better analysis (Figure 1 for more details).

The relative dominance of one crop species over another in a mixture can be estimated using the relative crowding coefficient (RCC or K) [42]. When the product of the two coefficients ($K_{\text{Bean}}; K_{\text{Maize}}$) is greater than one, there is a yield advantage; when K is equal to one, there is no yield advantage; and when it is less than one, there is a disadvantage. The relative yield increase of a crop in an intercropping system can also be measured using the aggressiveness index [31]. The competitive ratio (CR) estimates the competitive capacity of the crops compared to the crowding coefficient and aggressiveness index [33]. The CR represents simply the ratio of the individual LERs of the two component crops [43].

Actual yield loss (AYL) [44] can be estimated, and it is the proportional yield loss or gain of intercropping of crops compared to monoculture. The intercropping advantage index (IAI) [27] and the monetary advantage index (MAI) [28] can be estimated. The MAI value provides information on the economic advantage of the intercropping pattern over the monocropping pattern.

2.4. Data Analysis

A mixed linear model (MLM) was adjusted to analyze the effect of fixed factors (crop component, cropping system pattern, fertilizer type). Plots associated with crop components within season (temporal repetition) were considered as random effects. The assumptions of normality and homogeneity of variance were evaluated using an exploratory residual analysis. Differences between crop components were analyzed by Fisher's post-hoc LSD test with a significance of $\alpha = 0.05$. The MLM was made using the lme function in the nlme package in the R language software, version 3.4.4 [45], by the interface in InfoStat [46].

Table 1. Name, symbol, source, formula and meaning of the various indices used in the study. Abbreviations used to describe the formula of the indices include: B (common bean lines), M (maize variety), MC (monocrop), IC (intercrop), Y (grain yield), Z (ratio of actual density of intercropped bean and maize crops to monoculture), and P (commercial price of the crop species in USD per kg).

Full Name	Symbol	Source	Formula	Meaning
Land equivalent ratio	LER	[32]	$\text{LER}_B = (Y_{B-IC}/Y_{B-MC}) \quad (1)$ $\text{LER}_M = (Y_{M-IC}/Y_{M-MC}) \quad (2)$ $\text{LER} = (\text{LER}_B + \text{LER}_M) \quad (3)$	See Figure 1 for details.
Relative crowding coefficient	K	[42]	$K_B = (Y_{B-IC} \times Z_{M-IC}) / (Y_{B-MC} - Y_{B-IC}) \times Z_{M-IC} \quad (4)$ $K_M = (Y_{M-IC} \times Z_{B-IC}) / (Y_{M-MC} - Y_{M-IC}) \times Z_{B-IC} \quad (5)$ $K = (K_B \times K_M) \quad (6)$	When the coefficient $K > 1$, there is a performance advantage; for $K = 1$, there is no performance advantage; for $K < 1$, there is a disadvantage.
Aggressiveness index	AI	[31]	$A_B = [(Y_{B-IC}) / (Y_{B-MC} \times Z_{B-IC})] - [(Y_{M-IC}) / (Y_{M-MC} \times Z_{M-IC})] \quad (7)$ $A_M = [(Y_{M-IC}) / (Y_{M-MC} \times Z_{M-IC})] - [(Y_{B-IC}) / (Y_{B-MC} \times Z_{B-IC})] \quad (8)$	When $A = 0$, both crops are equally competitive; if $AM > AB$, maize is the dominant crop. Similarly, when $AB > AM$, beans are the dominant crop.
Competitive ratio	CR	[33]	$\text{CR}_B = (\text{LER}_B / \text{LER}_M) \times (Z_{M-MC} / Z_{B-MC}) \quad (9)$ $\text{CR}_M = (\text{LER}_M / \text{LER}_B) \times (Z_{B-MC} / Z_{M-MC}) \quad (10)$	When $\text{CR} = 1$, it indicates situations where both species have equal grain yield. $K > 1$ reflects yield dominance and vice versa when $K < 1$.
Actual yield loss	AYL	[44]	$\text{AYL}_B = \{[(Y_{B-IC} / Z_{B-IC}) / (Y_{B-MN} / Z_{B-MN})] - 1\} \quad (11)$ $\text{AYL}_M = \{[(Y_{M-IC} / Z_{M-IC}) / (Y_{M-MN} / Z_{M-MN})] - 1\} \quad (12)$ $\text{AYL} = \text{AYL}_B + \text{AYL}_{\text{Maize}} \quad (13)$	The AYL can have + or – values that indicate an accumulated advantage or disadvantage in intercropping in relation to the monocultures; the main objective is to compare the yield per plant.
Intercropping advantage index	IAI	[27]	$\text{IA}_B = \text{AYL}_B \times P_B \quad (14)$ $\text{IA}_M = \text{AYL}_M \times P_M \quad (15)$ $\text{IA} = \text{IA}_B + \text{IA}_M \quad (16)$	The IA shows the economic losses (– values) or gains (+ values) for each species and crop.
Monetary advantage index	MAI	[28]	$\text{MAI} = [(\text{value of combined intercropping}) \times (\text{LER} - 1)] / \text{LER} \quad (17)$	High MAI values indicate higher economic benefit in intercropping systems.

Figure 1. Land equivalent ratio (LER) values from intercropping two bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) in two intercropping patterns (1:1, 2:1) under the application of inorganic or organic fertilizer. In intercropping pattern 1 (1:1), beans correspond to 50% and maize to 67% of the monocropping planting density, and for intercropping pattern 2 (2:1), beans correspond to 37% and maize to 100% of the monocropping planting density. The diagonal (corresponding to the values of $LER_{Bean} = LER_{Maize}$) separates the areas of the graph where the bean lines have a competitive advantage over maize in grain production for intercropping pattern 1 (a) and for intercropping pattern 2 (b) and vice versa (b, c). The other diagonal (corresponding to $LER_{Maize} + LER_{Bean} = 1$) separates the areas of the graph where monocultures are more efficient than intercropping in grain production (d) and vice versa (e). The areas corresponding to partial values of LER_{Bean} below 0.5 (g) and LER_{Bean} below 0.37 (i) for bean lines on the Y-axis, and values of LER_{Maize} below 0.67 (j) and LER_{Maize} below 1 (k) for maize on the X-axis; indicate that the grain yield per plant is lower for each crop species in intercropping than in monocrops. Text as line (red and blue) in each crop species represent the intersection of intercropping patterns 1 and 2, respectively. Conversely, areas corresponding to values greater than 0.5 (f) and 0.37 (h) for the bean line and values greater than 0.67 (k) and 1 for maize represent situations where the yield of grains per plant for each crop species is greater in intercropping patterns 1 and 2 than monocropping. The area (l) corresponds to situations where bean lines suppress the maize; the opposite occurs on the surface (p). Finally, in the area (o), both crop species are suppressed in intercropping due to competition, while in area (m), both species grow better in intercropping than in monocrops, indicating the so-called “facilitation”. The neutral points (n) in the intercropping of $LER_{Bean} = 0.5$ with $LER_{Maize} = 0.67$, and $LER_{Bean} = 0.37$ with $LER_{Maize} = 1$ indicate situations where the grain yield per plant in the two crop species is similar in intercropping patterns 1 and 2 and also in monocrops.

3. Results

3.1. Performance of Two Bean Lines and One Maize Variety under Three Different Planting Patterns and Two Types of Fertilizer Applications

Significant ($p < 0.05$) differences in grain yield were observed under different intercropping planting patterns of both maize and beans. Yields obtained for maize were not different in monocultures (4943 ± 174 and $4929 \pm 226 \text{ kg ha}^{-1}$ under the application of inorganic or organic fertilizer, respectively) (Figure 2). For both bean lines in monoculture under the application of inorganic fertilizer, the yield obtained for BFS 10 and ALB 121 was 2426 ± 93 and $2150 \pm 34 \text{ kg ha}^{-1}$, respectively, while for these same bean lines under the application of organic fertilizer, the yields were 2053 ± 52 and $1742 \pm 62 \text{ kg ha}^{-1}$, respectively (Figure 2). The results in Figure 2 show the yield response of each crop under each fertilizer application and cropping system model. For example, in intercropping model 1, maize, regardless of the bean line, produced 74% and 70% of the observed yield in the monoculture under the application of inorganic and organic fertilizer, respectively. Similarly, for bean lines, BFS 10 produced 57 and 52% of the yield, and ALB 121 produced 46 and 45% of the yield observed in monoculture under the application of inorganic and organic fertilizer, respectively (Figure 2). However, in intercropping model 2, maize, regardless of the bean line used, produced 98 and 106.5% of what was produced in the maize monoculture under the application of inorganic and organic fertilizer, respectively. In the case of BFS 10, it produced 34% and 39% of the yield, and ALB 121 produced 28% and 32% of the yield observed in the monoculture under the application of inorganic and organic fertilizer, respectively (Figure 2).

3.2. Intercropping Induced Changes in Competition Indices and Their Effects on Yield Benefit under the Application of Inorganic or Organic Fertilizer

In general, LER values with both intercropping patterns were greater than 1, indicating a higher efficiency due to intercropping patterns on the production of grain compared with the monoculture system. The LER values obtained with intercropping pattern 1 for BFS 10/ICA V109 were 1.35 and 1.20, while for ICA V109/ALB 121, the values were 1.17 and 1.19 under the application of inorganic and organic fertilizer, respectively. Similarly, LER values with intercropping pattern 2 for ICA V109/BFS 10 were 1.36 and 1.46, and for ICA V109/ALB 121, these values were 1.19 and 1.40 under inorganic and organic fertilization, respectively. In addition, it was found that LER_{Maize} was dominant over LER_{Bean} for both intercropping patterns (values below the $LER_{\text{Bean}} = LER_{\text{Maize}}$ diagonal), evidencing the competitive advantage of maize over beans in grain production, as shown in Figure 3. It was found that in intercropping pattern 1 (circle in Figure 3), under the application of inorganic fertilizer, for ICA V109/BFS 10, the values for both crop species were above the reference line (red line), indicating a yield increase of 7% for bean and 11% for maize compared to monoculture, respectively. This indicates that both crop species grow better with intercropping than with monocropping patterns. However, for ICA V109/ALB 121 intercropping patterns, we observed that under the same intercropping pattern, the yield of both crops was similar to that obtained with the monoculture pattern (Figure 3). The situation was similar for the ICA V 109/BFS 10 intercropping patterns under the application of organic fertilizer. In the case of ICA V109/ALB 121 with intercropping pattern 2 (triangle in Figure 3), the yield per plant was lower than that obtained in the monoculture pattern under the application of inorganic fertilizer. Both crops were below the reference line (blue line), which indicated that the grain yield per plant is lower for each crop species with the intercropping patterns. For the case of intercropping pattern 2 of ICA V109/BFS 10, the bean value was above the reference line, which shows a yield per plant value similar to that presented in monoculture. However, in the case of maize, it was above the reference line, and this behavior was statistically similar for both crop species under the application of inorganic as well as organic fertilizer.

Figure 2. Grain yield in monocropping compared to intercropping of 2 bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) in 2 intercropping patterns (1:1, 2:1) under the application of inorganic or organic fertilizer. Maize:Bean 1:1 and 2:1 ratios correspond to 67%:50% and 100%:37% of the sowing density in relation to the monocropping. The percentage values in the bars of each panel indicate the relative yield with reference to the yield of the monocultures of each crop species. The values shown are averages over two growing seasons. a, b, c, d, e, f, g: Different letters within the same crop in different systems (bars and letters of the same color) indicate statistical differences using Fisher's LSD half test ($p < 0.05$).

The relative agglomeration coefficient (K) did not show significant differences ($p < 0.05$) between the factors evaluated or the cropping patterns under each type of fertilizer application and for each crop species. Maize was found to have higher K_{Maize} values relative to the K_{Bean} values of beans in all three cropping patterns under each type of fertilizer application, except for the BFS 10:ICA V109 intercropping pattern 2 under the application of inorganic fertilizer, which showed a negative value (-2.92 ; Table 2). This resulted from a maize yield that was higher than that presented in monoculture. On the other hand, the values of K_{Bean} (>1) indicated that the bean yield was not affected by intercropping patterns compared to monoculture.

Figure 3. Estimated land equivalent ratio (LER) values for intercropped bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) based on the grain yield obtained in monoculture. (i) Solid line diagonal means intercropping LER in reference to the monoculture; values of 1.2 and 1.4 mean an increase of 20% and 40% in the yield of grain production with reference to the monoculture, respectively. (ii) Dotted diagonal means the dominance of a crop. $LER_{\text{Bean}} = LER_{\text{Maize}}$. Lines and text (red and blue) mean intercropping patterns 1 and 2, respectively. If points are below this line, it means the dominance of maize over bean and vice versa for the above-located points. (iii) The red line drawn on the Y-axis corresponds to the LER_{Bean} point, and it is equal to 0.5. The red line on the X-axis LER_{Maize} is equal to 0.66, and this represents the production ratio under intercropping 1 pattern compared to monoculture. The blue line attached to the Y-axis corresponds to the LER_{Bean} point, and it is equal to 0.33; the blue line attached to the X-axis LER_{Maize} is equal to 1.0, and it indicates the production ratio under intercropping pattern 2 compared to monoculture. If the values obtained are located above the interception, it means that the yield obtained in intercropping was higher than the yield obtained in the monocropping pattern. a, b: Different letters within the same crop in different cropping patterns indicate statistical differences using the LSD test ($p < 0.05$).

In general, maize has a greater advantage in grain yield per plant ($114.18 \pm 5.10 \text{ g plant}^{-1}$) in relation to beans, which only present $34.26 \pm 3.81 \text{ g plant}^{-1}$ for BFS 10 and $26.36 \pm 3.81 \text{ g plant}^{-1}$ for ALB 121, respectively. This information is reflected in the results of the previous indicators and the positive values of aggressiveness index that maize showed (A_{Maize}) over the two lines of beans (A_{Bean}). Similarly, maize presented the highest values in the competitive ratio (CR_{Maize}) for both intercropping patterns under both types of fertilizer application. The CR_{Bean} values were similar to those of maize for the BFS 10 line with intercropping pattern 1 under both types of fertilizer application, showing an equal level of competition and benefit for both crop species. The estimated actual yield loss (AYL) value reflects that the most benefited crop was maize (AYL_{Maize}) with intercropping, since its positive values indicate a higher yield per plant compared to the monoculture (except under inorganic fertilizer application to ICA V109/ALB 121 intercropping patterns 1 and 2, which presented a yield reduction). The bean crop was the least benefited, but it is important to note that the BFS 10 line yielded better with intercropping pattern 1 under both inorganic and organic fertilizer application treatments in comparison to monoculture. The AI, CR and AYL indices did not present statistical differences between the evaluated factors (Table 3). Interestingly, no statistical differences, especially in

the AYL index, reveal that per plant yield of both crop components with both intercropping patterns is not reduced in relation to the monoculture, as shown in Figure 3.

Table 2. Estimated relative crowding coefficient values for intercropping 2 bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) in 2 intercropping patterns (1:1, 2:1) under the application of inorganic or organic fertilizer.

Crops (Maize:Bean)	Intercropping Pattern	Relative Crowding Coefficient		
		K _{Maize}	K _{Bean}	K
Inorganic fertilizer				
ICA V109/ALB 121	1:1	1.70 ^a	1.31 ^a	2.36 ^a
ICA V109/BFS 10	1:1	4.85 ^a	1.84 ^a	6.28 ^a
ICA V109/ALB 121	2:1	3.33 ^a	0.13 ^a	3.71 ^a
ICA V109/BFS 10	2:1	−2.92 ^a	1.32 ^a	−4.59 ^a
Organic fertilizer				
ICA V109/ALB 121	1:1	2.04 ^a	1.13 ^a	2.29 ^a
ICA V109/BFS 10	1:1	2.02 ^a	1.41 ^a	2.80 ^a
ICA V109/ALB 121	2:1	11.22 ^a	1.36 ^a	15.73 ^a
ICA V109/BFS 10	2:1	7.39 ^a	1.57 ^a	12.65 ^a
LSD _{0.05}		6.01	0.27	8.73

^a: Differences within the same index for each crop species are not statistically significant based on the Fisher's LSD means test ($p < 0.05$).

Table 3. Estimated values of aggressiveness index (AI), competitive ratio (CR) and actual yield loss (AYL) for intercropping 2 bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) in 2 intercropping patterns (1:1, 2:1) under the application of inorganic or organic fertilizer.

Crops (Maize:Bean)	Intercropping Pattern	Aggressiveness Index		Competitive Ratio		Actual Yield Loss		
		AI _{Maize}	AI _{Bean}	CR _{Maize}	CR _{Bean}	AYL _{Maize}	AYL _{Bean}	AYL Total
Inorganic fertilizer								
ICA V109/ALB 121	1:1	0.04 ^a	−0.04 ^a	1.04 ^a	0.97 ^a	−0.02 ^a	−0.02 ^a	0.01 ^a
ICA V109/BFS 10	1:1	0.13 ^a	−0.13 ^a	1.24 ^a	0.92 ^a	0.22 ^a	0.08 ^a	0.3 ^a
ICA V109/ALB 121	2:1	0.10 ^a	−0.10 ^a	1.13 ^a	0.89 ^a	−0.11 ^a	−0.21 ^a	−0.32 ^a
ICA V109/BFS 10	2:1	0.16 ^a	−0.16 ^a	1.25 ^a	0.87 ^a	0.04 ^a	−0.13 ^a	−0.09 ^a
Organic fertilizer								
ICA V109/ALB 121	1:1	0.18 ^a	−0.18 ^a	1.20 ^a	0.84 ^a	0.09 ^a	−0.08 ^a	0.01 ^a
ICA V109/BFS 10	1:1	0.01 ^a	−0.01 ^a	1.01 ^a	1.02 ^a	0.03 ^a	0.02 ^a	0.05 ^a
ICA V109/ALB 121	2:1	0.16 ^a	−0.16 ^a	1.18 ^a	0.85 ^a	0.06 ^a	−0.10 ^a	−0.04 ^a
ICA V109/BFS 10	2:1	0.13 ^a	−0.13 ^a	1.16 ^a	0.90 ^a	0.09 ^a	−0.03 ^a	0.04 ^a
Fisher LSD _{0.05}		0.14	0.14	0.17	0.12	0.08	0.09	0.11

^a: Differences within the same index for each crop species are not statistically significant based on the LSD means test ($p < 0.05$).

The values of the intercropping advantage index (IAI) indicated the economic viability of intercropping patterns when compared to monoculture. This viability was reflected by the positive and different values of AYL for each crop (AYL_{Maize} and AYL_{Bean}). The most advantageous maize-bean mixture was ICA V109/BFS 10 intercropping pattern 1 with a ratio of 1:1 seeding under inorganic fertilizer application; it showed the highest value. The monetary advantage index (MAI) values showed that the intercrop presents a greater economic advantage. The highest values for the intercropping pattern 2 under both types of fertilizer application resulted mainly due to the greater production of maize. This intercropping system could be beneficial to a smallholder producer who wishes to mainly produce maize. In the same way, the intercropping pattern 1 for ICA V109/BFS 10 under the application of inorganic fertilizer indicated a greater economic advantage, mainly due to the higher production of both bean and maize. This system is profitable and therefore recommended for a resource-poor producer who wishes to mainly produce beans, and this intercropping pattern does take into account the advantage due to the higher market price of beans (4.5 times higher than for maize) (Table 4).

Table 4. Estimated intercropping advantage index (IAI) and monetary advantage index (MAI) values for intercropping 2 bean lines (ALB 121, BFS 10) with a maize variety (ICA V109) in 2 intercropping patterns (1:1, 2:1) under the application of inorganic or organic fertilization.

Crops (Maize:Bean)	Intercropping Pattern	Intercropping Advantage Index			Monetary Advantage Index (MAI)
		IAI _{Maize}	IAI _{Bean}	IAI Total	
Inorganic fertilizer					
ICA V109/ALB 121	1:1	31.53 ^a	−22.61 ^a	8.93 ^b	333.91 ^a
ICA V109/BFS 10	1:1	306.52 ^a	301.51 ^a	608.03 ^a	682.60 ^a
ICA V109/ALB 121	2:1	−170.90 ^a	−221.04 ^a	−391.95 ^b	360.18 ^a
ICA V109/BFS 10	2:1	92.25 ^a	−120.48 ^a	−28.23 ^b	656.45 ^a
Organic fertilizer					
ICA V109/ALB 121	1:1	118.62 ^a	−107.05 ^a	11.56 ^b	334.36 ^a
ICA V109/BFS 10	1:1	38.71 ^a	55.00 ^a	93.71 ^b	345.75 ^a
ICA V109/ALB 121	2:1	106.75 ^a	−95.27 ^a	21.47 ^b	706.17 ^a
ICA V109/BFS 10	2:1	177.79 ^a	21.68 ^a	199.48 ^b	777.69 ^a
Fisher LSD _{0.05}		132.49	150.58	171.53	117.95

^{a, b}: Different letters within the same index for each crop indicate statistically significant differences based on the LSD means test ($p < 0.05$). Current purchase price per ton in USD for common beans = 1385 and for maize = 302 (exchange rate: COP 3970 per USD as of December 2021).

4. Discussion

4.1. Association of Bean Lines with Maize Improves Agronomic Performance of Maize Plants under Two Intercropping Patterns

Under the Amazonian weather and soil conditions, we found that the intercropping planting pattern significantly reduced the grain yield per unit area of both beans and maize compared to the monoculture system. At the level of bean genotypes, grain yield in monocropping compared to intercropping was higher only for the bean line BFS 10, contrary to what was observed with ALB 121. When we compared the yield per plant under intercropping pattern 1, BFS 10 presented better plasticity in agronomic behavior, presenting an improvement in yield of 7% and 2% with the application of inorganic and organic fertilizers, respectively. However, under intercropping pattern 2, only a 2% yield increase was observed under organic fertilizer application. Additionally, this greater adaptation of BFS 10 to local soil and weather conditions could have contributed to the greater acquisition of both aerial and belowground resources, possibly resulting in higher yields under the intercropping pattern, as observed by Gebeyehu et al. [13]. Previous studies [35] indicated that BFS 10 line has high adaptability in tropical conditions such as those of the Colombian Amazon (acid soils and high temperatures), which allows it to perform better, as revealed by a higher yield per unit area.

Similarly, we found that the maize variety benefited under intercropping compared to monocropping. When analyzing intercropping pattern 1, yield per area in this treatment decreased compared to monoculture, but when comparing in terms of yield per plant, irrespective of the associated bean line, maize variety improved its yield by 8% and 3% under the application of inorganic and organic fertilizer, respectively. Similarly, as expected with intercropping pattern 2, maize variety yielded higher per area than with monoculture, mainly due to its equal planting density compared to monoculture. The extent of increase in yield with maize under the application of organic fertilizer was 6.5%. The yield response of maize observed with intercropping patterns 1 and 2 could be attributed to suitable agronomic conditions for resource acquisition in association with the bean line. This positive response could be due to the rapid growth of both the root and shoot systems, one of the main characteristics attributed to C_4 cereal crops such as maize [4,47]. It is known that with an adequate seeding density of plants and the supply of nutrients, the maize crop has the potential to produce a maximum yield [48,49]. Similarly, the partial contribution of N by the associated bean crop in the post-anthesis period could be complementary to the grain-filling process of maize [30,50,51], which could result in a higher grain yield with intercropping patterns [4,49]. Yilmaz et al. [50] reported that growing maize in an intercrop system increases its yields, while Addo-Quaye et al. [52] reported an increase in bean yields

when grown as an intercrop with a 1:1 pattern. Results from this study are consistent with these previous reports.

4.2. Competition Ratio and Monetary Advantage Index Values Indicate Superior Performance of Maize under Intercropping

When analyzing yield as a function of land use, we found that maize presented a higher LER value with intercropping patterns. In the case of bean lines, there were differences between the two intercropping patterns for both bean lines tested and the two types of fertilizer application. These results indicate the dependence of LER values on agronomic management factors. For example, when analyzing the performance of two bean lines (BFS 10 and ALB 121) with intercropping, we found a better performance of the BFS 10 line, which, under both fertilizer application treatments, presented a better utilization of resources as revealed by the higher LER_{Bean} values. Likewise, intercropping pattern 2 resulted in the better performance of both bean lines under both types of fertilizer application. Thus, one of the main causes for the superior performance of maize with both intercropping patterns may be due to the reduced competition offered by both bean lines for belowground resource acquisition. This is attributed to both sowing patterns under fertilizer application that generated a favorable environment for the development of both crops (maize and beans). In addition, the physical support provided by maize as a stake allowed beans to have a better canopy development to intercept photosynthetically active radiation [52] for assimilation of photosynthates, leading to better grain development and yield [53,54].

As expected, LER_{Total} values were found to be higher with both intercropping patterns, indicating a greater advantage in land-use efficiency compared to monoculture [3,50,55]. Specifically, with intercropping pattern 2, LER_{Total} increased for ICA V 109/BFS 10 (46%) and ICA V 109/ALB 121 (40%), with maize (dominant crop) being the main contributor to the total yield under the intercropping pattern [51,56]. However, a possible small contribution of N supply to the soil by the two bean genotypes [30,50] could also influence the observed higher value of the yield per area under intercropping pattern 2 [4,55,57]. These results indicate that the land-use efficiency of the maize and bean intercropping is greater compared to maize and bean monocultures [55]. Furthermore, this study indicates that more area is needed for planting monocultures (maize and beans) in order to obtain the same yields that were obtained with intercropping pattern 2. These results are consistent with previous studies [4,55,57].

The high values of the relative agglomeration coefficient (K) indicated an advantage in the yield of maize over beans with both intercropping patterns. This result was to be expected if we accepted the fact that cereal crops are more competitive than grain legumes [27,50]. Furthermore, the trend found in intercropping pattern 2 with ICA V 109/BFS 10 showed a negative K value when maize production is higher than in monoculture. This may not be attributed as a yield disadvantage, but it may be inappropriate to indicate the advantage of the intercropping pattern 2, as observed by Yilmaz et al. [50].

Considering the relationship in the planted seed densities of each of the intercropping patterns and type of fertilizer application, AI_{Maize} was always positive, while AI_{Bean} was negative, demonstrating the dominance of maize over beans, a situation that has also been reported from different studies [16,20,28,43]. Similarly, the competitive ratio (CR) for maize under the intercropping patterns was higher compared to that obtained for beans [50]. Specifically, with intercropping pattern 1 (ICA V 109/BFS 10) under the application of inorganic or organic fertilizer, the values of CR_{Bean} were similar to those of CR_{Maize} , a situation that favored land-use efficiency for both crops, increasing their complementarity and competitiveness [56], which translated into higher grain yield [58,59].

This was also confirmed by the AYL values. For the AYL_{Bean} value using yield per plant with intercropping patterns, if this value is reduced compared to monoculture, it indicates that genotype BFS 10 was the most benefited. This was seen mainly with intercropping pattern 1, which demonstrated an increased yield by 8% and 2% under the application

of inorganic and organic fertilizer, respectively. On the other hand, the negative values presented for the AYL_{Maize} were only evidenced in the case of ALB 121 with intercropping patterns 1 and 2 under inorganic fertilizer application (-0.02 and -0.11), with a yield loss of 2% and 11%, respectively. A possible explanation was that this result was probably due to the fact that a small amount of N supply from bean line (ALB 121) did not compensate for the vigorous growth of maize in a certain proportion, as well as a greater vegetative vigor of the maize variety, which resulted in greater intra- and interspecific competition between the two crops [27,43,50,60]. Values of intercropping advantage index (IAI) showed that the most advantageous association was observed with intercropping pattern 1 for ICA V 109/BFS 10 under the application of inorganic fertilizer and intercropping pattern 2 for ICA V 109/BFS 10 under the application of organic fertilizer. Higher MAI values were observed with intercropping pattern 2 under the application of organic fertilizer for ICA V 109/BFS 1 and ICA V 109/ALB 121 with values of 777.69 and 706.17, respectively. Therefore, the intercropping pattern of beans with maize in a 2:1 seeding ratio gives higher land-use efficiency and higher profitability, especially if maize is the main cereal crop of interest, for obtaining an additional economic gain by the inclusion of beans as an associated crop [19]. With respect to intercropping pattern 1 of beans with maize using a 1:1 seeding ratio, ICA V 109/BFS 10 association under the application of inorganic fertilizer resulted in an MAI value of 682.60, which indicates a balanced combination of two crop components, where this intercropping pattern not only improves crop productivity and land-use efficiency compared to the monoculture pattern, but it also generates a higher profit for farmers growing both beans and maize [50].

5. Conclusions

Based on results obtained from the agronomic performance evaluation (grain yield, competition indices and monetary benefits to the resource-poor farmer) of two intercropping patterns compared to the monocropping of two bean lines (BFS 10 and ALB 121) and one maize variety (ICA V 109), we recommend the following two options to farmers. First, the use of intercropping pattern 1 (1:1 seeding ratio of bean with maize) is more beneficial in terms of grain yield and the economic viability of using bean lines. Second, the use of intercropping pattern 2 (2:1 ratio of maize with bean) is of greater benefit to maize production. More specifically, in both intercropping patterns (seeding ratios of 1:1 and 2:1) managed under the application of organic fertilizer, the grain yield of BFS 10 and ICA V 109 were improved in comparison to the monoculture. This was achieved through an increase in the values of LER and MAI while decreasing the value of CR, resulting in better economic viability and efficient use of land and other resources under the application of organic fertilizer compared to inorganic fertilizer, owing to its lower cost and greater suitability to growing conditions. Therefore, we recommend the use of the bean line BFS 10 as an intercrop with maize under the application of organic fertilizer. This system is suitable to smallholder agricultural conditions of the Amazon region (acid soils, high temperatures) for improving crop productivity and land-use efficiency.

Author Contributions: Conceptualization, J.C.S., M.O.U., S.E.B. and I.M.R.; data curation, J.C.S., J.A.A., D.L.S., J.I.V. and I.M.R.; formal analysis, J.C.S., J.A.A. and I.M.R.; investigation, J.C.S., J.A.A., D.L.S. and J.I.V.; methodology, J.C.S., J.A.A., A.T.C., M.O.U., S.E.B. and I.M.R.; funding acquisition, J.C.S.; project administration, J.C.S. and J.A.A.; resources, J.C.S. and S.E.B.; supervision, J.C.S., A.T.C., M.O.U., S.E.B. and I.M.R.; writing—original draft, J.C.S., J.A.A., A.T.C., D.L.S., J.I.V., M.O.U. and I.M.R.; writing—review & editing, J.C.S., A.T.C., D.L.S., J.I.V., M.O.U. and I.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and the APC was funded by AVISA project OPP 1198373 funded by Bill & Melinda Gates Foundation.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the authors upon request.

Acknowledgments: We acknowledge the financial support from the CGIAR Research Program on Grain Legumes and Dryland Cereals for the development of breeding lines of common bean. We would also like to thank all donors who supported this work through their contributions to the CGIAR Fund. MOU is grateful for the support of Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and Centre for International Migration and Development (CIM).

Conflicts of Interest: The authors have declared that no competing interest exist.

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