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Influence of Simultaneous Intercropping of Maize-Bean with Input of Inorganic or Organic Fertilizer on Growth, Development, and Dry Matter Partitioning to Yield Components of Two Lines of Common Bean

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Abstract: Intercropping is a common practice among smallholder farmers cultivating common bean (Phaseolus vulgaris L.) and maize (Zea mays L.). It affects agronomic performance, dry matter partitioning, and grain yield. Simultaneous intercropping of common bean with maize can influence growth, development, and dry matter partitioning of grain of common bean. The main objectives of this study are to: (i) evaluate the dynamics of growth and development of the different vegetative organs, and (ii) determine the efficiency in dry matter partitioning to yield components of two common bean lines grown under monoculture compared with two simultaneous intercropping patterns (pattern 1, pattern 2) with maize and managed with two types of fertilizer application. A randomized complete block design (RCBD) with 3 replications was used in a nested trifactorial arrangement in split-plot scheme. The field experiment was conducted in two seasons under conditions of acid soils and high temperatures in the western Amazon region of Colombia. Simultaneous intercropping patterns 1 and 2 had a negative effect on growth dynamics of maize compared to maize monoculture. But the two bean lines when associated with maize showed no significant differences on growth dynamics under both types of fertilizer application. Under both intercropping patterns, the maize cobs were larger, a condition that increased the number of grains, but with smaller size of grains compared to monoculture. In the case of two bean lines, the growth and development responses were different: under monoculture the number of pods and seeds per plant was higher while the number of grains per pod increased under intercropping patterns. Among the two bean lines, 100-seed weight was significantly higher in BFS 10 compared to ALB 121. At the grain yield level of common bean, the simultaneous intercropping pattern increased 516 kg ha\(^{-1}\) and 993 kg ha\(^{-1}\) more than that obtained in monoculture (4936 kg ha\(^{-1}\)) with inorganic and organic fertilizer, respectively. Results from this study indicated that smallholders in the Amazon region of Colombia can achieve higher grain yield through the implementation of simultaneous intercropping of maize with common bean line (BFS 10) under organic fertilizer application.

Keywords: maize; common bean; intercropping pattern; monoculture; cob growth; pod growth; response to fertilizer; agronomic performance

1. Introduction

An increase in food production is required in the next 30 years to feed the growing world population [1]. Radical measures are needed to sustainably feed approximately
9 to 10 billion people by 2050, amidst climate change and diminishing land and water resources for agriculture [2,3]. There is a need to adopt sustainable technologies to make better use of resources for increasing productivity per unit land area [4]. Over the years, the practice of achieving greater plant diversity, such as intercropping within agricultural systems, is increasingly recognized as an important pillar for sustainable development [5,6]. Intercropping contributes to not only a broad range of food crop supply in developing countries [7,8], but also to provision of a wide range of ecosystem services [9] including increased land-use efficiency, food security, and income generation by smallholders in the tropics [10].

Among the combinations most commonly used in intercropping are cereals and legumes, with the association of maize (Zea mays L.) and beans (Phaseolus vulgaris L.) being common practice by farmers in Latin America [11,12]. These two food crops not only provide major nutrients for the human diet [13–15], they also contribute to controlling weeds [9], reducing soil erosion [16], and improving soil organic matter [17]. These two crops are also able to recycle large amounts of nutrients within a cropping system to improve nutrient efficiency [18]. However, the association between these two crops generates interspecific competition processes between the crops, causing a reduction in bean and maize yields of more than 40 and 22%, respectively [10].

In maize-bean intercropping, it is key to take into account the planting density [19] and the planting time of both components [20]. Higher seeding density can lead to intercropping stress and increased competition between the two components for water, light, and nutrients [21,22]. Specifically, growth and development among individual plants can be affected by plant density, causing shading over leaves [23], resulting in a decrease in stem diameter, canopy biomass, and root biomass of both crops [24]. In the case of maize, there is a reduction in photosynthetic capacity and the electron transport chain, generating changes in plant morphology and affecting the concentrations of enzymes related to plant carbon assimilation, processes that are key to seed formation and filling [24–26]. Likewise, beans modify their morphology and specific leaf area to be more efficient in absorption of radiation and diffusion of CO₂ under shading, as it has been reported that this type of management affects leaf gas exchange characteristics [24,27], mainly affecting the pod formation and development, which is the yield component that is mostly affected by competition [10,28].

On the other hand, among the advantages of introducing intercropping of maize-bean is the possibility of increasing nitrogen (N) use efficiency by the cereal [29] due to its association with the N-fixing legume [30]. The change in the microclimatic condition within the intercrop [20,31] could improve and stabilize the yield of the associated crops [32]. Likewise, under different planting patterns, fertilizer application has been reported to stabilize yields [33], and improve nutrient availability, thereby increasing grain yield from 6 to 28% under intercropping compared to monocropping [34]. In addition, mineral fertilizers have been observed to lead to more stable yields due to improved carbon input and N recovery efficiency [35]. Organic fertilizers could improve soil fertility without significant residual effects on the soil, and are also of lower cost as an input [36].

In this context, the major challenge for researchers and farmers is to find the right combination of intercropping patterns that improve growth and yield of both maize and beans [37], even under low fertility soil and high temperature stress conditions such as the conditions normally found in the Colombian Amazonia. Therefore, the selection of crops that differ in their competitive ability in time and/or space is essential for a more resource-efficient intercropping and its productivity [20,38]. In the Colombian Amazon region, specifically in the department of Caquetá, intercropping system in the past was one of the main agronomic approaches used by different settler families [39]. However, at present, many of the lowlands are dedicated to the practice of extensive cattle ranching, while family farming tends to be located on nutrient depleted soils on hillsides which pose challenges for economic sustainability of cropping [40]. Thus, intercropping beans with maize can be a type of sustainable productive management to improve the food security of
local communities [41], even more so when legume crop lines that are better adapted to the edaphoclimatic conditions of the region have been identified and tested with application of either inorganic or organic fertilizer application [42,43]. The main objectives of this study are to: (i) Evaluate the dynamics of growth and development of the different vegetative organs, and (ii) determine the efficiency in dry matter partitioning to yield components of two common bean lines grown under monoculture compared with two simultaneous intercropping patterns (pattern 1, pattern 2) with maize and managed with two types of fertilizer application under conditions of acid soils and high temperatures in the Colombian Amazon. We tested the hypothesis that the growth dynamics and dry matter partitioning responses of two bean lines grown under two different but simultaneous intercropping patterns can be similar to those presented with monocropping with the application of either inorganic or organic fertilizer.

2. Materials and Methods

2.1. Experimental Site and Meteorological Conditions

The agronomic evaluation of simultaneous intercropping was conducted during October 2018 to January 2019 (season 1) and April to June 2019 (season 2) at the Macagual Research Center of the University of Amazonia, Colombia (1°37’ N and 75°36’ W), located in Florencia, Caquetá (Colombia) within the tropical rainforest ecosystem [39]. The study area is characterized by an average temperature of 25.5 °C, and an average relative humidity of 84%, with 1700 h of sunshine year−1 and with an average annual rainfall of 3800 mm. During the evaluation in two seasons, the average daily maximum and minimum temperatures were 32 °C and 23 °C, respectively. The area used in the experiment is characterized by an acid soil (pH between 4.1 and 5.2) with an exchangeable aluminum content of 6.3 cmol kg−1 and an aluminum (Al) saturation of 73.4%. The bulk density values ranged between 1.0 and 1.3 g cm−3, with a soil available phosphorus (P) content of 2.58 mg kg−1, organic carbon content of 1.35%, with a cation exchange capacity of 11.3 cmol kg−1, and a total base saturation of 7.1% (Ca: 0.38 cmol kg−1, Mg: 0.1 cmol kg−1, K: 0.14 cmol kg−1, Na: 0.1 cmol kg−1, total bases: 0.8 cmol kg−1). During 2014 to 2018, the study area was under cultivation with bean crops and it did not receive any application of inorganic or organic fertilizers.

2.2. Field Layout and Experimentation

A randomized complete block design (RCBD) with three replications was used in a trifactorial arrangement nested in a split-plot scheme. The experiment consisted of three cropping system patterns (Figure 1), 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 (main plots), and two advanced bean breeding lines, BFS 10 and ALB 121 (subplots) and two types of fertilizer, inorganic and organic (sub-subplots) for a total of 12 (2 × 3 × 2) treatments as described before by Suárez et al. [43]. The BFS 10 (Red) was described by Suárez et al. [42,44] as tolerant to acid soils and high temperatures, and ALB 121 (Brown) an interspecific line of P. vulgaris and P. coccineus, generated from a cross [(ALB 74 × INB 841) F1 × RCB 593] was described by Butare et al. [45] as resistant to the combined stress conditions of aluminum (Al) and drought.

To implement different planting patterns, the soil was prepared manually and a dose of 1.0 t ha−1 of dolomitic lime [CaMg(CO3)2] was applied at 20 days before planting to minimize the effect of aluminum (Al) toxicity and to increase soil pH [39]. Details on the common bean and maize variety materials used, as well as plot characteristics and planting pattern were described before [43].
In order to have a better effect of the applied fertilizers (both inorganic and organic), applications were made via fertigation using a manual back-held sprayer (Royal Condor Classic, volume of 20 L). Foliar applications were made at different times of crop development [39]. We used the Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) growth scale for beans [46] and maize [47]. At 15 days after sowing when maize had the first pair of leaves unfolded (BBCH 12) and beans had the first lateral bud (BBCH 21), the first foliar application of fertilizer was made. The second foliar application was made at 35 days after planting in the case of maize, when it had three detectable nodes (BBCH 33); in the case of beans, it was when the second lateral bud was visible (BBCH 22). The characteristics and chemical composition of the inorganic and organic fertilizer used were described in detail by Suárez et al. [43].

2.3. Growth and Development Dynamics of the Different Vegetative Organs

Different plant samplings were carried out with the objective of determining the effect of the simultaneous intercropping system on dry matter distribution, a process that was carried out starting at 23 days after planting (DAP) for both crops, with a frequency of seven days between samplings until reaching at 93 and 72 DAP for maize and beans, respectively. Each sampling time corresponded to the BBCH scale.

Vegetative growth and development: Sampling 1 was at 23 DAP; maize had 4 to 6 leaves unfolded (BBCH = 14 to 16) and beans 3 to 5 trifoliate leaves (BBCH = 13 to 15). Sampling 2 was at 30 DAP; 7 to 9 leaves are fully unfolded on maize plants (BBCH = 17 to 19) and for beans the formation of 1 to 2 visible lateral shoots (BBCH = 21 to 22). Sampling 3 was at 37 DAP; stem elongation with 1 to 2 nodes detectable for maize (BBCH = 31 to 32) and for beans the emergence of the inflorescence, first flower buds visible up to the first petals visible with flowers still closed for beans (BBCH = 51 to 59).

Reproductive growth and development: Sampling 4 was at 44 DAP; stem elongation from 7 to 9 nodes detectable for maize (BBCH = 37 to 39) and for beans, 50% of flowers open until first pods are visible for beans (BBCH = 65 to 69). Sampling 5 was at 51 DAP; inflorescence emergence, half tassel emergence for maize (BBCH = 55) and for bean, 60% of pods have reached typical length to pods with individual grains visible (BBCH = 76 to 79). Sampling 6 was at 58 DAP; flowering (anthesis), beginning of pollen release and visible stigma tips for maize (BBCH = 63 to 64) and for bean, 10 to 30% of mature pods (hard beans, BBCH = 81 to 83). Sampling 7 was at 65 DAP; in blister stage for maize (BBCH = 71) and for bean, 50 to 70% of mature pods (hard beans, BBCH = 85 to 87).

Physiological maturity: Sampling 8 was at 72 DAP; the grain has milky content, about 40% dry matter for maize (BBCH = 75) and for beans it corresponds to the time when
the pods are fully mature (BBCH = 89). Sampling 9 was at 79 DAP; time of maturation, early mass where the content of soft grains of the maize cob was about 45% of dry matter (BBCH = 83). Sampling 10 was at 86 DAP; maize grains have yellowish color, containing approximately 55% of dry matter (BBCH = 85). Sampling 11 was at 93 DAP; time of physiological maturity where there is a black spot/visible layer at the base of the grains, about 60% of dry matter for maize (BBCH = 87).

At each sampling time, four plants were taken at random (n = 144 plants monitored per sampling per crop for a total of 2592 plants sampled in each season) per treatment in each block. From each maize and bean plant, the dry matter weights (g) of the stem (WSt: weight of stem), leaf (LeW: leaf weight), cob (CobW: total cob weight), or pod and canopy biomass (CB) were determined. At the time of harvesting the maize plants, the dimensions of the cob were measured (CobL: cob length, DC: diameter of the cob), the number of rows per cob (RC: number of rows per cob and NSR: number of seeds per row) were counted as well as the number of grains per row and total grains per cob (WSC: weight of seeds per cob), and the weight of 100 grains and total grains per cob were determined (SW: 100-seed weight). For bean plants, at physiological maturity, the number of pods (NPP: number of pods per plant) and seeds (NSP: number of seeds per plant) per plant were counted, as well as the number of grains per pod (NSPod: number of seeds per pod) and the total weight of pods per plant (WPP: weight of pods per plant) and canopy biomass (CB). For each homogenized bean treatment, 100 seeds were obtained randomly to determine the seed weight (SW: 100-seed weight).

2.4. Dry Matter, Grain Yield, Yield Components, and Indices of Partitioning of Dry Matter

During the pod filling phase (BBCH 75) and at harvest (BBCH 89) time of beans, four plants were sampled and the dry weights of leaves, stems, pods, and bean seeds were recorded. From these dry weights, different indices related to dry matter partitioning were determined [48] such as canopy biomass (CB); pod partitioning index (PPI): \( \frac{\text{dry weight of pod biomass at harvest}}{\text{dry weight of total canopy biomass at mid-pod filling}} \times 100 \); pod harvest index (PHI): \( \frac{\text{dry weight of seed biomass at harvest}}{\text{dry weight of pod walls biomass at mid-pod filling}} \times 100 \); and harvest index (HI): \( \frac{\text{dry weight of seed at harvest}}{\text{dry weight of total canopy biomass at mid-pod filling}} \times 100 \).

2.5. Data Analysis

A linear mixed model (MLM) was fitted to analyze the data, the factors (crop component, cropping system pattern, fertilizer type) and their interactions were included in the fixed part of the model and the plots associated to the crop components within the season (temporal repetition) were considered random effects in the model. Using an exploratory residual analysis obtained in the MLM analysis, the assumptions of normality and homogeneity of variance were evaluated. Box plots were prepared for measured variables using the results of analysis of variance using Fisher’s post-hoc LSD test with a significance of \( \alpha = 0.05 \). To determine the relationship between grain yield and the other agronomic variables, a Pearson correlation analysis was performed and the results were presented graphically using a heat map at the general level and a chord diagram for each factor was used using the packages of corplot [49] and circlize [50]. The LMMs were performed with the lme function of the nlme package and the graphical outputs were performed in the packages “ade4”, “ggplot2”, “factoextra” and “corplot” in the R language software, version 3.4.4 [51], using the interface in InfoStat [52].

3. Results

3.1. Growth Dynamics and Vegetative Development of Maize and Beans under Three Different Cropping Patterns

Vegetative development response of both maize (Supplementary Figure S1) and beans (Supplementary Figure S2) was contrasting due to the effect of the cropping patterns (monocropping vs intercropping) as well as the type of fertilizer applied (inorganic or
organic). For example, in the case of maize, plant height (Supplementary Figure S1a) and number of leaves (Supplementary Figure S1b) increased with days after planting (DAP) as opposed to stem diameter (Supplementary Figure S1c). Plant height in intercropping 2 (2:1 pattern) and the number of leaves of maize in the monocropping were affected differently from 51 DAP with the type of fertilizer applied. In the case of beans, a marked difference was found between the two bean lines, for example ALB 121 presented higher values of plant height compared to BFS 10 with different cropping patterns (Supplementary Figure S2a). In the case of the number of leaves, the value decreased when associated with maize, reducing from 61 leaves in monocropping to 48 leaves with the intercropping patterns. Among the two bean genotypes there was no marked difference with different cropping patterns, but only with intercropping 2 (2:1 pattern) under the organic fertilization application a small difference was observed during reproductive growth period (Supplementary Figure S2b). As for the number of pods, a significant effect was found between cropping patterns, with a reduction of 13 pods per plant with intercropping patterns compared to the value obtained under monocropping (43 pods per plant, Supplementary Figure S2d).

3.2. Dry Matter Content of Different Plant Parts, Cob and Pod Growth, and Grain Filling

Dry matter content of different plant parts of maize under different cropping patterns was similar with inorganic or organic fertilizer application (Figure 2), but only at 79 DAP there were some significant differences for stem dry matter ($p < 0.05$, Figure 2c) under intercropping 2 (2:1 pattern). Leaf dry matter at 79 DAP in maize monocropping was 36.2 g while with intercropping 1 the average value for the two fertilizer types was 38.2 g. However, with intercropping 2, leaf dry matter was 33.2 g per plant ($p < 0.05$, Figure 2a), and this trend was also similar for the stem dry matter with an average value of 114.6 g per plant under both monocropping and intercropping 1 pattern. This was contrary to what was presented under intercropping 2 pattern where the value was reduced to 74.1 g per plant ($p < 0.05$, Figure 2b). Maximum cob weight was 210.1 g per plant and 205.6 g per plant and it was reached at 93 DAP with intercropping 1 under inorganic and organic fertilizer application, respectively (Figure 2c). In the case of canopy biomass (g per plant) of maize, at 86 DAP it was found that this was higher under intercropping 1 with 352.3 g and 350.2 g with the application of inorganic and organic fertilizer, respectively. However, under the other two cropping patterns (monocropping and intercropping 2), an average value of 305.1 g per plant was observed (Figure 2d).

For beans, cropping pattern rather than genotype had a negative effect on dry matter content of different plant parts and total canopy biomass (CB) per plant and these values were inversely proportional to the increase in maize planting density under intercropping (Figure 3). Leaf dry matter at 65 DAP in the bean plant for both ALB 121 and BFS 10 under monocropping averaged 19.7 g per plant, compared to 16 g per plant and 14 g per plant under intercropping 1 and 2, respectively (Figure 3a). In the case of stem dry matter, while it was higher compared to leaf dry matter, it decreased as maize plant density increased with intercropping 2 (Figure 3b). Under monocropping with inorganic fertilizer application, the highest value of stem dry matter per plant was presented for ALB 121 with 41.6 g per plant and for pod dry matter 36.5 g per plant while for BFS 10 the value observed for stem dry matter was 39.3 g per plant and for pod dry matter, 38.3 g per plant (Figure 3b,c). Finally, the total canopy biomass per plant was reduced under both intercropping patterns compared to monocropping (Figure 3d).
Figure 2. Dry matter content in different plant parts including (a). cobs; (b). leaves; (c). stem; and (d). canopy biomass of the maize variety (ICA V109) grown in monocropping or in two intercropping patterns (1:1 and 2:1) with inorganic or organic fertilizer application during crop development (DAP, days after planting). Each data point of the curve represents the mean and standard deviation of 12 plants for each type of fertilizer application at each sampling time.

Figure 3. Dry matter content of different plant parts including (a). leaves; (b). stem; (c). pods; and (d). canopy biomass of two bean lines (ALB 121, BFS 10) grown in monocropping or associated with a maize variety (ICA V109) under two intercropping patterns (1:1; 2:1) with inorganic or organic fertilizer application during crop development (DAP, days after planting). Each data point of the curve represents the mean and standard deviation of 12 plants for each type of fertilizer application at each sampling time.

As for the yield component variables, a positive effect of the association of maize with beans was found compared to that found under monocropping in relation to the
dimensions of the maize cob (length and diameter), the number of grain rows per cob, the number of grains per row, as well as in the number and weight of grains per cob. However, under monocropping the grains were larger compared to those found under intercropping patterns (Figure 4). Under intercropping 1 (1:1 pattern), 480 and 434 grains per ear and a weight per ear of 138.4 g and 129.6 g were found with the inorganic and organic fertilizer application, respectively; and these values were higher compared to the other treatments ($p < 0.05$, Figure 4e,d).

In beans, a reduction in the number of pods and seeds per plant was found when the density of maize plants under intercropping was increased (Figure 5a,b). Among the two genotypes, no differences were found in these variables. With the number of seeds per pod, there were significant differences between the two types of fertilizers applied (inorganic and organic) for both ALB 121 and BFS 10 (Figure 5c). However, BFS 10 with its larger grain size compared to ALB 121, showed differences in the weight of 100 seeds as well as in the weight of pods and grains per plant (Figure 5d–f), and these values being greater with the application of inorganic fertilizer.
was more efficient compared to ALB 121. BFS 10 reached pod partition index (PPI) values with inorganic fertilizer application were 41.2% and 40.4% of those that were observed were significantly reduced under the intercropping patterns compared to that found in monoculture. For example, the CB values of ALB 121 and BFS 10 under intercropping 2 with the application of organic and inorganic fertilizer, respectively (Figure 6a). When analyzing the mobilization of photosynthates from the pod wall to seed filling (PHI), a trend similar to PPI was found (Figure 6b), where in the harvest index (HI) value was higher than 50% when BFS 10 was grown under intercropping pattern. This is contrary to what was observed with ALB 121 where the HI value was significantly reduced under intercropping patterns compared to monocropping for both bean lines (Figure 6). However, BFS 10 was more efficient compared to ALB 121. BFS 10 reached pod partition index (PPI) values of 73.5 and 69.3% under intercropping 2 with the application of organic and inorganic fertilizer, respectively (Figure 6a). When analyzing the mobilization of photosynthates from the pod wall to seed filling (PHI), a trend similar to PPI was found (Figure 6b), where in the harvest index (HI) value was higher than 50% when BFS 10 was grown under intercropping pattern. This is contrary to what was observed with ALB 121 where the HI value was around 40% for all three cropping systems and two types of fertilizers applied (Figure 6c).

Figure 5. Yield components including (a). pods per plant; (b). seeds per plant; (c). seeds per pod; (d). pods weight per plant; (e). seeds weight per plant; and (f). 100 seeds weight of two bean lines (ALB 121, BFS 10) in monocropping and associated with a maize variety (ICA V109) under two intercropping patterns (1:1, 2:1) with the application of inorganic or organic fertilizers. The dashed black line corresponds to the mean of each variable. a,b,c: Different letters within the same index for each intercropping pattern indicate statistically significant differences based on the LSD means test (p < 0.05). The results include mean ± SE (n = 12). Red dot denotes the mean and black dots are outliers.

3.3. Efficiency in the Mobilization of Photosynthates: Changes in Canopy Biomass, Dry Matter Partitioning and Grain Yield

Canopy biomass (CB) values ranged from 1187 to 11,061 kg ha$^{-1}$ with an average value of 6801 kg ha$^{-1}$ (Supplementary Figure S3). Under monocropping, independent of fertilizer application, bean lines averaged 4827 kg ha$^{-1}$ of CB, while maize averaged 10,546 kg ha$^{-1}$ of CB (Supplementary Figure S3). It was found that CB values for both beans and maize were significantly reduced under the intercropping patterns compared to that found in monoculture. For example, the CB values of ALB 121 and BFS 10 under intercropping 1 with inorganic fertilizer application were 41.2% and 40.4% of those that were observed under monocropping (ALB 121: 4957 kg ha$^{-1}$; BFS 10: 4935 kg ha$^{-1}$), respectively. This trend was accentuated under intercropping 2 (Supplementary Figure S3). For maize, it was found that the CB value under intercropping 1 was higher while with the intercropping 2, it was similar to that observed with monocropping (p < 0.05, Supplementary Figure S3).

In terms of photosynthetic mobilization, a positive effect was found under the intercropping patterns compared to monocropping for both bean lines (Figure 6). However, BFS 10 was more efficient compared to ALB 121. BFS 10 reached pod partition index (PPI) values of 73.5 and 69.3% under intercropping 2 with the application of organic and inorganic fertilizer, respectively (Figure 6a). When analyzing the mobilization of photosynthates from the pod wall to seed filling (PHI), a trend similar to PPI was found (Figure 6b), where in the harvest index (HI) value was higher than 50% when BFS 10 was grown under intercropping pattern. This is contrary to what was observed with ALB 121 where the HI value was around 40% for all three cropping systems and two types of fertilizers applied (Figure 6c).
Grain yield (GY) of beans and maize under monoculture with inorganic and organic fertilizer application averaged 2288 kg ha$^{-1}$ and 1897 kg ha$^{-1}$ for beans and 4943 kg ha$^{-1}$ and 4929 kg ha$^{-1}$ for maize, respectively (Figure 7). Between the two bean lines, un-
under monoculture and under two different intercropping patterns, with both inorganic and organic fertilizer application, grain yield of BFS 10 was higher compared to ALB 121 with variability ranging from 218 to 392 kg ha\(^{-1}\) \((p < 0.05)\). When comparing intercropping, under intercropping 1 (1:1 pattern) the bean produced a higher value of GY compared to intercropping 2 (2:1 pattern), and the opposite was observed with the maize crop (Figure 7). When analyzing in general the different planting patterns, we found that the GY in the maize and bean association was greater than that obtained under the monoculture \((4936 \text{ kg ha}^{-1} p < 0.05)\), with an increase in production of 516 kg ha\(^{-1}\) and 993 kg ha\(^{-1}\) with inorganic and organic fertilizer application, respectively (Figure 7).

**Figure 7.** Grain yield of two bean lines (ALB 121, BFS 10) under either monoculture or associated with a maize variety (ICA V109) under two intercropping patterns (1:1, 2:1) with inorganic or organic fertilizer application. The percentage values in the bars of each graph indicate the relative yield with reference to the monoculture yield of each crop. \(a,b,c\): Different letters within the same crop in different systems (bars of the same color) indicate statistical differences by Fisher LSD means test \((p < 0.05)\), the darker colored bar under intercropping indicates the cumulative yield of associated crops (maize and beans). Results include the mean ± SE \((n = 12)\).

### 3.4. Correlation Coefficients between Grain Yield and Dry Matter Contents of Different Plant Parts under Different Cropping Patterns

When analyzing the relationship of weight of seed per cob (WSC) of maize, we found a high correlation \((r \geq 0.8, p < 0.05)\) with different variables (CB: canopy biomass; WSt: weight...
of stem; LeW: weight of leaf; CobW: cob weight; NLe: number of leaves per plant; SD: stem diameter; CobL: cob length; NSR: number of seeds per row; NSC: number of seeds per cob) for all the factors analyzed (general, planting patterns and fertilizer, Figure 8a). However, for maize weight of seeds per cob (WSC) showed correlation with PH (plant height) under intercropping 1 and 2, while only under the latter system, WSC showed correlation with SW (100-seed weight, Figure 8a). When analyzing the correlations independently for each factor, we found that in general, SW correlated negatively with NSR and NSC (Figure 8b), a situation that is also present with the factors such as organic fertilizer application (Figure 8d) and under the monoculture planting pattern (Figure 8e). Likewise, in the general factor (Figure 8a), with the inorganic fertilizer application (Figure 8b), under the monoculture pattern (Figure 8e) and under the intercropping 2 pattern (2:1 pattern, Figure 8g), a negative correlation was found between RC (number of rows per cob) and NSR.

**Figure 8.** Correlation coefficients between agronomic variables of the maize crop. (a) Heat map of Pearson correlation coefficients between grain yield per plant and other variables was presented. Color gradient from green to red signifies the magnitude of positive to negative correlation. *, ** and *** represent significance probability levels of 0.05, 0.01, and 0.001, respectively. Circles correspond to chord diagram of the correlation coefficients between agronomic variables, the ribbons within the circle correspond to significant correlations with a p-value < 0.05, the green ribbons indicate positive coefficients and the red ribbons indicate negative coefficients. (b) general, (c) inorganic fertilizer application, (d) organic fertilizer application, (e) monoculture planting pattern, (f) intercropping 1 (1:1 pattern), and (g) intercropping 2 (2:1 pattern). WSC: weight of seeds per cob; CB: canopy biomass; WSt: weight of stem; LeW: leaf weight; CobW: cob weight; SW: 100-seed weight; PH: plant height; NLe: number of leaves per plant; SD: stem diameter; CobL: cob length; DC: diameter of the cob; RC: number of rows per cob; NSR: number of seeds per row; NSC: number of seeds per cob.
Correlations coefficients for the bean crop were mostly positive for all factors with different variables (CB: canopy biomass; WPP: weight of pods per plant; SW: 100-seed weight; NSP: number of seeds per plant; NPP: number of pods per plant; PPI: pod partitioning index; PHI: pod harvest index; HI: harvest index), and only the number of seeds per pod (NSPod) presented negative correlation (Figure 9a). When analyzing specifically by each factor, we found that the variable with the highest amount of negative correlation was with NSPod, a situation that occurred with the application of inorganic (Figure 9c) and organic fertilizer (Figure 9d), under the monoculture pattern (Figure 8e) and with the ALB 121 bean line (Figure 9h). At the bean line level (Figure 9h,i) there were negative correlations between SW with NSP, NPP and CB.

**Figure 9.** Correlation coefficients between agronomic variables of the bean crop. (a) Heat map of Pearson correlation coefficients between seed yield per plant and other variables was presented. Color gradient from green to red signifies the magnitude of positive to negative correlation. *, ** and *** represent significance probability levels of 0.05, 0.01, and 0.001, respectively. Circles correspond to chord diagram of the correlation coefficients between agronomic variables, the ribbons within the circle correspond to significant correlations with a p-value < 0.05, the green ribbons indicate positive coefficients and the red ribbons indicate negative coefficients. (b) General, (c) inorganic fertilizer application, (d) organic fertilizer application, (e) monoculture planting pattern, (f) intercropping 1 (1:1 pattern), (g) intercropping 2 (2:1 pattern), (h) ALB 121, and (i) BFS 10. CB: canopy biomass; WPP: weight of pods per plant; SW: 100-seed weight; NSP: number of seeds per plant; NPP: number of pods per plant; NSPod: number of seeds per pod; PPI: pod partitioning index; PHI: pod harvest index; HI: harvest index.
4. Discussion

4.1. Positive Effects of Intercropping on Vegetative Development of Maize and Beans

It was found that the intercropping pattern had a positive effect on vegetative development of both maize and beans. Specifically, this type of management had an impact on the height of the maize plants as well as on the mobilization of photosynthates for the formation of vegetative organs (number of leaves and stem diameter) [53,54], compared to what was found in the monoculture. The above mentioned is due to the planting system, the arrangement, and spacing of rows and plants between intercropping crops which can either reduce or increase the effects of crop shade [24], generating variations in the amount of incident radiation, which affects the morphological responses of crops [35]. Likewise, it has been observed that significant genotype x cropping system interactions occur in the dominated crop (beans), being less pronounced in the dominant crop (maize) [56], due to changes in competitive ability between cultivars [57,58].

On the other hand, it has been observed that the behavior of beans under intercropping is directed toward an increase in plant height and a reduction in stem diameter [59,60]. However, the results of our study showed an opposite behavior. When observing the responses of the two bean lines (BFS 10 and ALB 121) under intercropping patterns with respect to monoculture, the bean plants responded to the light reduction created by the maize plants, thus developing shade avoidance/adaptation responses [61,62]. Thus, the influence of intercropping of bean with maize, showed a positive relationship between bean plant height and maize plant density [63]. At higher maize plant density, the height of both bean genotypes decreased under intercropping 1 and 2, while stem diameter increased under intercropping compared to monocropping. This condition could be due to competition from maize with beans, or as reported by Carruthers et al. [64] as a compensation mechanism that decreases the amount of photosynthates allocated to vegetative growth (number of leaves), due to interspecific competition between both crops for available resources (light, water, nutrients) in the early growth phase when these crops are planted simultaneously [20].

4.2. Positive Effects of Intercropping on Maize Cob and Bean Pod Formation

Increased planting densities had an effect on both maize and beans in relation to the efficiency of assimilate mobilization. For example, under intercropping 1 (1:1 pattern), which has 66% of the maize plant population compared to monoculture (33,000 plants ha$^{-1}$), the dry matter of plant organs (leaves, stem, cob and total plant weight) increased. However, with intercropping 2 (2:1 pattern), an opposite behavior was found where dry matter was reduced by 10% and 7% with the inorganic and organic fertilizer application, respectively, under the monoculture planting pattern. At the level of maize cob variables, a positive effect on shape and size was found under intercropping 1 (1:1 pattern), since under this planting pattern the length, diameter, as well as the number of rows and grains increased; however, the weight of 100 seeds decreased compared to monoculture [30,65,66]. Therefore, densities between 20,000 and 40,000 plants ha$^{-1}$ of maize under simultaneous intercropping planting pattern increase dry matter per plant, which is in agreement with what has been found from different studies [19,37,67,68]. These previous studies suggested the implementation of this type of planting patterns in tropical areas of high rainfall and humidity, similar to the present study, which can increase not only radiation interception but also soil cover to maintain soil moisture and benefit from the contribution of N by the bean crop [19,65].

With beans, a reduction in dry matter of 10% and 12% was found under both intercropping 1 and 2 compared to monoculture for both bean genotypes [10], and consequently in the accumulation of dry matter in the pods. Variables such as the number and weight of pods per plant and the number and weight of seeds per plant decreased due to the maize-bean interaction with both inorganic and organic fertilizer application [30,66]. This effect was more pronounced with bean line ALB 121 since BFS 10 tends to develop larger grains than ALB 121 [42] which significantly impacted 100-seed weight and consequently the values of the harvest index (HI). BFS 10 is an elite bean line that uses avoidance/adaptation
mechanisms when grown under a type of abiotic stress that affects its growth and development [42]. The BFS 10 responds with higher production of leaves and pods compared to ALB 121 to maintain its physiological function under combined acid soil and heat stress, and this strategy also contributes to mobilize greater proportion of assimilates from vegetative structures to grain (HI) and from the pod wall to grain development (PHI) [42,67].

4.3. Intercropping Improves Agronomic Efficiency of Both Maize and Bean

Maize grain yield increased under intercropping 2 in association with ALB 121 or BFS 10 compared to that obtained under monoculture with both inorganic and organic fertilizer application. The conditions that made this type of response possible are mainly due to the interspecific competition between the associated crops that accelerated growth as well as the additional N input generated by the bean [68,69] that likely impacted on greater photosynthetic activity and C gain by maize [70] which translated into increases in grain production [71]. At the level of planting pattern design, the double-furrow arrangement of maize had an impact on weed reduction and therefore facilitated better maize growth [20]. Results from this study are in agreement with previous studies [8,31] in which the increased maize grain yield was attributed to increased maize plant density in maize/soybean and maize/beans intercropping in addition to the contribution from application of fertilizer. With beans, the intercropping planting pattern penalized grain yield due to competition with maize for aboveground radiation and belowground nutrients for resources [10,20].

Regarding the analysis at the intercropping system level, a positive agronomic effect was found for the vegetative development and stability of maize as revealed by rapid vegetative growth characteristics and grain yield under adequate plant density [20,72], allowing the crop to develop its maximum yield potential [73,74]. Similarly, partial N input by the associated bean crop generates a complementary contribution to the grain filling of maize [61], which translates into higher grain yield under intercropping and increases productivity per unit area [20,74]. Therefore, our results are consistent with these previous reports, where Yilmaz et al. [75] reported that growing maize in an intercropping system increased yields while Addo-Quaye et al. [76] reported higher bean yields when grown under an intercropping system (1:1 pattern). The positive responses observed in this study under simultaneous intercropping conditions in the Colombian Amazon region indicate that these two crop components (maize variety and two bean lines) are well adapted to local abiotic stress conditions [40]. Improved understanding intra- and interspecific competition within and between crop components allows to ensure an adequate and sustainable supply of resources both above- and belowground using different planting patterns so that there is less competition between the two crop components and a more positive coexistence is resulted [77].

4.4. Intercropping Improves Efficiency in the Mobilization of Photosynthates to Grain in Maize and Bean

Correlation analyses between the different plant attributes indicated that certain traits change due to planting patterns. In maize, different plant traits such as canopy biomass, stem weight, leaf weight, cob weight, and stem diameter remained the same under intercropping compared to that presented in monoculture, a situation that was also described by Bitew et al. [66]. However, the plant traits related to the mobilization of photosynthates toward the formation of grains (number of grains and rows per cob, weight of grains and yield) were indeed affected by both intercropping patterns tested in this study. This is possibly due to the spatial arrangement and density of maize plants, as well as the competition generated by simultaneous sowing with another crop [65,76]. In the case of beans, the mechanism of grain filling and grain formation was improved to cope with the decrease in the availability of radiation and nutrients when associated with a cereal [77]. ALB 121 increased the number of seeds per pod and BFS 10 increased the number of pods per plant, thus maintaining higher HI and PHI values. This emphasizes the importance of photosynthetic remobilization for grain filling. Several studies [48,75]
pointed out the importance of maintaining a high PHI value to improve common bean yield under different abiotic stress conditions. The results from this study support the use of this adaptive strategy by common bean not only when it is grown as a monocrop but also under simultaneous intercropping pattern [20].

5. Conclusions
   We evaluated the growth, development, and yield components of two bean lines (BFS 10 and ALB 121) and one maize variety (ICA V 109) grown under two simultaneous intercropping patterns compared to monocropping with inorganic or organic fertilizer application. We found positive effects of the intercropping pattern on the growth and development of corn and beans through changes in the dry matter partitioning indices which indicated a greater mobilization of photosynthates toward the grain production. In addition to the above, the yield components of both crops were also improved under intercropping through the number of rows and the number of grains in the ear of corn and the number of seeds per pod of beans. At the overall grain yield level, the intercropping pattern increased grain yield of 516 kg ha\(^{-1}\) and 993 kg ha\(^{-1}\) more with both inorganic and organic fertilizer application, respectively than that obtained under monocropping (4936 kg ha\(^{-1}\)). Thus, the use of simultaneous intercropping under the acid soil and high temperature stress conditions of the Colombian Amazon can improve grain production per unit area. We recommend the use of the BFS 10 bean line for simultaneous intercropping with maize variety (ICA V 109) together with the application of organic fertilizer.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12051216/s1. Figure S1. Development dynamics in the different components of the maize plant (ICA V109) in monoculture and in two intercropping patterns of 1:1 and 2:1 under application of inorganic or organic fertilizers during the days after planting (DAP). (a) Height, (b) number leaves, (c) stem diameter. Each data of the curve represents the mean and standard deviation of 12 plants for each type of fertilizer at each sampling time. Figure S2. Development dynamics in the different plant components in two bean lines (ALB 121, BFS10) in monoculture and associated with a maize variety (ICA V109) in two intercropping patterns (1:1, 2:1) under application of inorganic or organic fertilizers during the days after planting (DAP). (a) Height, (b) number leaves, (c) stem diameter, (d) number pods. Each data of the curve represents the mean and standard deviation of 12 plants for each type of fertilizer at each sampling time. Figure S3. Canopy biomass of two bean lines (ALB 121, BFS 10) grown in monoculture or associated with a maize variety (ICA V109) in two intercropping patterns (1:1, 2:1) under inorganic or organic fertilizer application. The percentages in the bars of each graph indicate the relative yield in reference to the monoculture yield of each crop. \(^{a,b,c}\): Different letters within the same crop in different systems (bars of the same color) indicate statistical differences by Fisher LSD means test (\(p < 0.05\)), the darker colored bar in intercropping indicates the cumulative yield of associated crops (maize and beans). Results include the mean ± SE \((n = 12)\).


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