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Effect of Maize–Legume Intercropping on Maize Physio-Agronomic Parameters and Beneficial Insect Abundance

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Abstract: In developing countries, intercropping is commonly used to boost land productivity and agricultural benefits. However, in the Yucatan region of Mexico, maize (*Zea mays* L.) yields remain low, despite consistent fertilizer and pesticide inputs in traditional intercropping systems. Furthermore, little is known about the photosynthetic mechanisms that occur when maize plants interact with legumes, and there is a lack of understanding of how intercropping systems affect other organisms in the system, such as beneficial and insect pest population dynamics. A field experiment was carried out on the Yucatan Peninsula in 2021 to assess the impact of maize–legume intercropping systems on maize yield, physiological characteristics as evaluated by gas exchange measurements, and the abundance of beneficial insects in traditional and novel maize intercropping systems. The experiment was carried out with a randomized complete block design with three replicates. Treatments included maize intercropped with a novel legume, crotalaria (*Crotalaria juncea* L.), maize intercropped with a traditional legume, cowpea (*Vigna unguiculata* (L.) Walp.), and sole maize as a control. Significant differences in plant height were shown at growth stages V12 (45 days after sowing) and VT (60 days after sowing). No differences were observed in stem diameter, leaf area index, or chlorophyll content. The maize/cowpea intercrop increased the photosynthesis rate by 12.9% and 9.84% in the maize/crotalaria and sole maize, respectively ($p < 0.001$), and transpiration rate by 6.5% and 8.5% in the maize intercropped with crotalaria and sole maize treatments, respectively ($p < 0.001$), of maize plants. No significant effects on stomatal conductance or water use efficiency were observed, but the carbon intercellular rate was reduced by 9.74% and 9.15 when compared to the maize/crotalaria and the sole maize treatments, respectively. Overall, intercropping treatments attracted more beneficial insects than sole maize. For predators, the families that stood out were Coccinelidae, Formicidae, Araneidae, Thomisidae, Syrphidae, Chrysomelidae, Oxypidae, Vespidae, Reduviidae, Carabidae, Asilidae, Salthicidae, Dolichopodidae, while among parasitoids, the most frequent families were Eurytomydae, Braconidae, Tachinidae, Pteromalidae, Scelionidae, and Figitidae. In comparison to the maize/cowpea and maize/crotalaria treatments, the sole maize treatment resulted in a grain yield increase of 24.5% and 32%, respectively. However, sole maize was not statistically different to that of maize/cowpea intercropping. In conclusion, our findings suggest that maize/cowpea intercropping could be a viable alternative to sole maize cropping systems for enhancing maize yield and the abundance of beneficial insects, without increasing interspecific competition with the maize crop. Therefore, the maize/cowpea intercropping system represents a sustainable planting alternative for promoting maize grain yield and also promoting edible legume production within the system. Furthermore, the outcomes of this study can serve as a theoretical framework for increasing maize–legume intercropping profitability under growing conditions on the Yucatan Peninsula.

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1. Introduction

Intercropping is the practice of planting two or more crops in the same field during the same growing season. The primary goal of intercropping is to increase production on a specific piece of land by utilizing resources that would otherwise go unused by a single crop [1]. In developing countries, intercropping has historically been the most common type of cropping system. In particular, the cereal–legume intercropping system is the most widely used cropping system in the world [2]. Since traditional intercropping systems promote crop diversity, yield stability, and risk reduction, they are still estimated to contribute up to 15–20 percent of the world's food supply [3]. In Latin America, maize-based intercropping systems are common [4] and account for approximately 60% of maize production [5]. On the Yucatan Peninsula, most farmers intercrop maize with lima bean (*Phaseolus lunatus* L.) or cowpea (*Vigna unguiculata* (L.) Walp.)] due to the ability of these legumes to provide the Mayan people's basic food supply [6].

In general, cereal–legume intercropping has several major advantages in cropping systems, including increasing yield [7], improving soil properties [8], controlling weeds [9,10], and increasing the number of nitrogen-fixing bacteria [11,12]. Furthermore, when properly structured, intercropping systems can more fully utilize light, heat, water, and nutrient resources in agroecosystems, resulting in higher yields and crop composite group stability [13,14]. However, interspecific competition between legumes and primary crops may be limited, thus the choice of legume species, seeding ratio, and row spacing must be taken into account to avoid a negative impact on crop growth [15,16].

In addition to crop yield increases and stability, intercrops have also been shown to improve the diversity of beneficial entomofauna in agricultural production systems. Four major hypotheses have been found in the literature to explain why intercropping systems attract more beneficial insects than monocropping systems. For example, intercropping attracts more predators and parasitoids than monocropping, which is one of the mechanisms used by intercropping to reduce pest infestation [17]. Second, monocropping makes it easier for herbivores to find hosts, increase feeding rates, and reproduce at higher rates than herbivores with narrow host ranges [18]. Third, plants closer to the host may interfere with the herbivore's ability to recognize and locate the host [19]. Fourth, compared to monocultures, the intercropping system may have a negative impact on the quality and chemical suitability of herbivore host plants [20]. Several authors have reported on the ability of intercropping to attract beneficial insects when compared to monocropping systems. For example, in a field experiment conducted in India, Kennedy et al. [21] recorded a significant increase in predators (*Coccinella* sp. and *Menochilus sexmaculatus*) and parasitoids (*Chelonus* sp.) when groundnuts were intercropped with pearl millet [*Pennisetum americanum*]. The addition of cropped plants may result in a more diverse ecosystem, which in turn attracts more beneficial insects, including parasitoids and predators [22,23]. Furthermore, the increase in abundance of parasitoids in intercropped systems has shown a significant increase in parasitism of pest insects [23]. These advantages can be found in mass-flowering plants [24], as well as aromatic herbs [25,26]. High crop diversity creates a mosaic of habitats that provide continuous and complementary resources throughout the season [27], providing food and shelter for natural enemies [28,29], and releasing volatile chemicals that attract parasitoids [30].

Due to the low crop productivity of the traditional intercropping system of the region, Pierre et al. [6] suggested that there is a need to conduct more field trials with the aim of improving the current management practices in this system (e.g., seeding ratio, row spacing, temporal niche difference). Despite the fact that the potential benefits of maize–legume intercropping systems are well documented, there are numerous management complications and other agronomic challenges [16]. Furthermore, the majority of recent intercropping research on the Yucatan Peninsula has focused on the relationships between vegetative and reproductive growth traits and grain yield [31]. However, a few studies have focused on evaluating maize–legume in strip intercropping systems. In addition, despite its importance, little is known about the photosynthetic mechanisms that occur during interactions between maize plants and legumes in various maize–legume intercropping systems. Furthermore, little research has been conducted in the following two key areas of study: understanding how plants interact in intercropping systems, as well as how intercropping systems affect other organisms in the system, such as beneficial and insect pest population dynamics. In this sense, it has been proposed that physiological characteristics associated with crop growth and competition in intercropping systems be investigated to address the issue of site-specific competition with the primary crop [32]. In addition, despite its importance, the impacts of intercropping on the abundance of beneficial insects in legume-based intercropping systems are largely understudied.

In this work, we hypothesize that cereal–legume intercropping systems can maintain maize grain productivity while boosting the quantity of beneficial insects (parasitoids, predators, and pollinators) in comparison to the region's maize monocropping system. Therefore, to advance our understanding of photosynthetic mechanisms during interactions between maize plants and legumes, as well as its impact on maize yield and the quantity of beneficial entomofauna, the goals of this research were: (1) to evaluate the effects of maize–legume intercropping systems on maize's physiological characteristics based on gas exchange measures, as well as their impact on maize's productivity; (2) to assess the influence of maize–legume intercropping systems on the abundance of beneficial insects in maize. The results of this study could be used by scientists and farmers to reduce interspecific competition between crop species, while also improving the region's crop production system. Furthermore, the outcomes of this study can serve as a theoretical framework for increasing maize–legume intercropping profitability under growing conditions on the Yucatan Peninsula.

2. Materials and Methods

2.1. Experimental Site

In this study, a hybrid maize Pioneer4082w obtained from a local seed supplier was used. This hybrid maize is commonly used by farmers of the region. Crops grown in the region's intercropping systems are utilized primarily for human consumption and, secondarily, as green manure. The experiment was conducted from July 2021 to December 2021 as an on-farm trial on the land of a small-scale maize farm within a small area in Becal, Campeche, Mexico (20°26′55″ N, 90°2′6″ W) (Figure 1). The weather conditions during the growth stage of the intercrops in 2021 was as followed: the maximum, minimum, and mean temperature were 34.5, 18.8, and 26.6 °C, respectively; the precipitation was 516.02 mm. Soil samples were taken to a depth of 0 to 30 cm one week prior to the experimental establishment. The available N was measured using the alkaline permanganate method [33], the available P was measured using the Olsen method [34], and the available K was measured using a flame photometer [34]. The soil texture was clay. The soil bulk density of the plough layer (0–30 cm) was 1.25 g/cm^3, the total nitrogen was 2500 ppm, the available phosphorus was 14.40 ppm, and the available potassium was 720 ppm. The soil's high K content is very common in Mexico, where most soils (77%) exceed 200 ppm of potassium, so adding K is not recommended [35]. The organic matter was 3.89%, and the pH was 7.84.

Figure 1. Map of Mexico showing the Yucatan Peninsula (left) and Campeche State with Becal municipality (right).

2.2. Experimental Design

The experiment was conducted in the summer and fall of 2021. The experiment was set in a randomized complete block design with three replications. The three cropping systems were: (1) Maize/Crotalaria intercropping, (2) Maize/Cowpea intercropping, and (3) Maize monocropping (Figure 2). An additive intercropping was used in this experiment. For the intercropping of maize and legumes, one row of legumes was planted in each row of maize; the planting was carried out with a punch stroke and two maize seeds per hole, with a distance of 100 cm between rows and 40 cm between plants (50,000 plants ha^{-1}); the total area planted was 3456 m^2. Plots had a dimension of 8 × 6 m. Maize was sown first on 17 July 2021, and legume crops were sown on 30 July 2021. The formula 80-60-00 (NPK) kg ha^{-1} was applied only to maize as a side dressing. The fertilizer application was divided into two applications: half of the N and all the P was applied one week after the emergence of the seedlings; the rest of the fertilizer was applied four weeks after the first application (growth stage). Weed control was performed manually; no insecticides were applied.

2.3. Data Collection and Processing

2.3.1. Growth and Biomass Production

For maize, data on growth, such as plant height, stem diameter, leaf dry biomass, and root biomass, were measured following the guide for maize [36]. Maize biomass was harvested in the last week of September and first week of October at 65 days after sowing (DAS) and 85 days after sowing (DAS).

Three plants were harvested at random from the central 6 m of two rows of maize and the central 6 m of three rows of legumes in each plot. After cutting plants from the central row, plants were separated into roots, stems, and aerial biomass and oven-dried at 70 °C for 48 h to estimate the total dry matter (DM) content. Knowing the fresh and dry matter of the harvested plants, the dry matter content of maize plants was determined per unit area [37]. The grain yield was calculated by multiplying the average grain yield of a plant as measured by taking six central plants of each plot and multiplying by the number of plants in a hectare (50,000 plants ha^{-1}). This plant density was calculated based on the plant and row spacing as previously described.

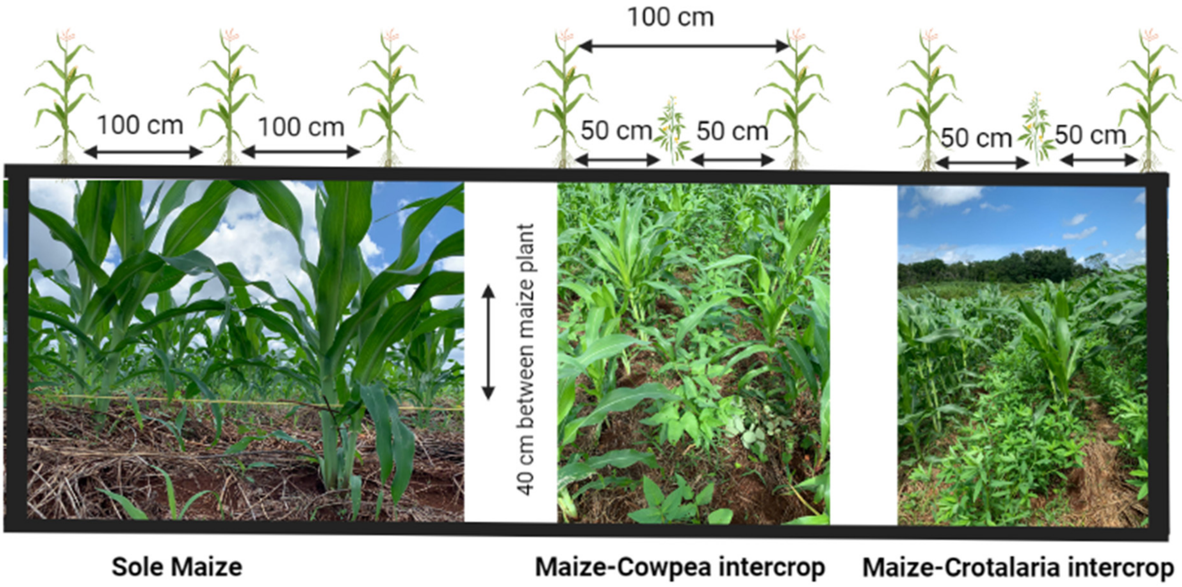

Figure 2. Schematic diagram indicating the different planting patterns. In the intercropping systems, 15 days following the maize planting dates, a legume was planted at 50 cm between the 100 cm interrow maize spacing. Created in BioRender.com, [38].

2.3.2. Leaf Area Index (LAI)

Maize leaf area index was estimated at the R1 maize growth stage when maize plants reach their greatest height during the silking stage of development. The Leaf Area Index (LAI) is used as an indication of leafiness per unit ground area and determines the rate of dry matter production. This was measured at 10 AM on 22 September 2021, by using the LI-2200C Plant Canopy Analyzer-Cap (LI-COR Biosciences, Lincoln, NE, USA) for measurements: 180°. All data were corrected in order of 3 K. K is a parameter used to correct the dispersion of the detected radiation from B (below canopy) and is calculated based on the calibration values when the values of A (Above canopy, Sequence 4A or 3A) are measured under clear sky. Then, data were processed by using the following formula: Leaf Area Index (LAI) = L/A (L = Leaf Area, A = Ground Area).

2.3.3. Gas Exchange Measurements and Total Chlorophyll Concentration

Measurements were made throughout the day on an hourly basis, and it was determined that at noon (12 h) the plants reached their maximum photosynthetic rate. An infrared gas analyzer (IRGA; LICOR, LI-6400, Lincoln, NE, USA) was used to evaluate gas exchange parameters. A CO_2 reference was set at 400 μmol mol^{-1} and a light source was connected to the IRGA and was set at 2000 μmol m^{-2} s^{-1} to avoid heterogeneity due to cloudiness. CO_2 assimilation rate (A_N), stomatal conductance (g_s), and intercellular carbon and transpiration (E) were measured at 12 pm [39]. Water Use Efficiency (WUE) was calculated as A_N/E [40]. The measurements were made in the central part of the second mature leaf (considering the flag leaf as the first). Five plants were evaluated per treatment, one leaf per plant, and three measurements were taken per leaf. Measurements were performed in the same leaves used in chlorophyll measurement. A total of three plants were measured per treatment.

Total chlorophyll concentration was measured by a SPAD-502 portable chlorophyll meter (Minolta, Osaka, Japan) on the same leaves used previously. The SPAD-502 meter was calibrated before each measurement by pressing the probe without a sample until the screen displayed ‘N = 0’.

2.4. Diversity and Abundance of Predators and Parasitoids

In both intercropping treatment plots (maize with crotalaria and maize with cowpea) and control plots, the diversity and abundance of predators and parasitoids were recorded in maize plants (sole maize). Data were collected every week between 07:30–11 AM until the maize plants reached the VT growth stages.

The predators and parasitoid insects were sampled using a sweep net (35 cm diameter). A total of 40 sweeps were performed per plot (6 × 8 m). Insect samples were stored in 300 mL plastic jars of 95% ethanol until processing. Insects were collected on a weekly basis from the beginning of August to the beginning of September 2021 for a total of five sampling events. Insects from all sampling events were pooled and presented for analysis as a total of five sampling events. For the majority of the insects sampled, identification to family was followed by a quick ID to genus or species level to determine whether an insect was actually a phytophagous, predator, or parasitoid [41].

2.5. Statistical Analyses

All statistical analyses were conducted using Minitab 20.3 (Minitab, LLC, State College, PA, USA, 2021). The results were analyzed with an ANOVA and then a comparison of means was compared using Tukey's test at $p \leq 0.05$.

3. Results

3.1. Plant Height and Stem Diameter of Maize

In the field experiment, there was a significant difference ($p < 0.001$) in maize height between treatments. Maize plant height showed no significant differences between the maize–legume intercropping systems compared to sole maize during both V5 and V8 growth stages (Figure 3A). However, maize plants in the maize–legume intercropping systems were shorter (V12: 171.3, 183.8; VT: 217.6 cm, 196.9 cm for maize/crotalaria and maize/cowpea, respectively) than maize plants in the sole maize system (198.3 cm, 232.3 cm) during the V12 (45 DAS) and VT (60 DAS) growth stages (Figure 3A). In relation to maize stem diameter, there were no significant differences ($p = 0.250$) among treatments in any evaluated period (Figure 3B).

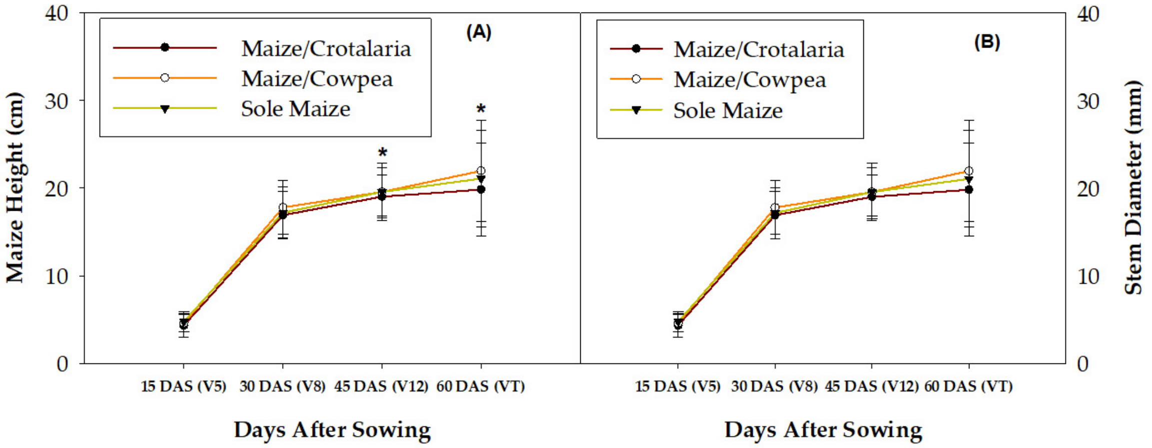

Figure 3. Maize height (**A**) and stem diameter (**B**) of maize in maize–legume intercropping, and sole maize systems grown under rainfed conditions of Becal, Campeche, 2021. * indicates treatments are significantly different from each other at $p < 0.05$.

3.2. Photosynthetic Parameters and Chlorophyll Content

Maize–legume intercropping had a significant effect on maize photosynthetic characteristics (Table 1). The maize/cowpea intercropping improved the maize photosynthetic rate (48.83 μmol m^{-2} s^{-1}), stomatal conductance (0.49 mol m^{-2} s^{-1}), and transpiration rate (10.33 mmol m^{-2} s^{-1}) when compared to sole maize. In contrast, intercellular carbon

(139 µmol mol^{-1}) and water use efficiency were significantly lower in maize/crotalaria (µmol CO_2/mmol H_2O) than in sole maize (Table 1). No difference was found in chlorophyl content (53.4, 52.7, and 54.8) in the maize/crotalaria, maize/cowpea, and control treatments, respectively.

Table 1. Physiological characteristics of maize in the maize monocrop and in two intercropping systems (maize/crotalaria and maize/cowpea) under rainfed conditions. Becal, Campeche, 2021.

Treatment	A_N (µmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	C_i (µmol mol^{-1})	E (mmol m^{-2} s^{-1})	WUE (µmol CO_2/mmol H_2O)
Maize/Crotalaria	42.53 ± 6.61 ^{b}	0.44 ± 0.1 ^{b}	154 ± 29 ^{a}	9.35 ± 1.48 ^{b}	4.56 ± 0.47 ^{b}
Maize/Cowpea	48.83 ± 5.68 ^{a}	0.49 ± 0.1 ^{a}	139 ± 24 ^{b}	10 ± 1.57 ^{a}	4.76 ± 0.29 ^{a}
Sole Maize	44.03 ± 5.53 ^{b}	0.45 ± 0.01 ^{ab}	153 ± 24 ^{a}	9.15 ±1.39 ^{b}	4.84 ± 0.31 ^{a}
Significance	$p < 0.001$	$p = 0.014$	$p < 0.002$	$p < 0.001$	$p < 0.001$

A_N (CO_2 assimilation rate or photosynthesis); g_s (stomatal conductance); C_i (intercellular carbon); E (transpiration rate); and WUE (water use efficiency). Means ± standard deviation with different letters are significantly different, $p < 0.05$, Tukey's test.

3.3. Dry Matter Productivity, Grain Yield, and Leaf Area Index (LAI) (m^2 m^{-2}) of Maize

The findings indicate that there were no differences in dry matter accumulation of maize in maize–legume and sole maize intercropping systems, as evaluated at 65 DAS (2450, 2349, 2499 kg/ha) and at 85 DAS (2108, 2382, 2479 kg/ha^{-1}) (Table 2). Plant growth was not significantly influenced by the intercropping system ($p = 0.924$) (Table 2). The LAI of maize in maize–legume and sole maize intercropping systems was not significantly different (1.5, 1.3, 1.36 m^2/m^{-2}).

Table 2. Grain yield (kg ha^{-1}), dry matter accumulation (kg plant^{-1}), Leaf Area Index (mean ± SD) for maize in both monoculture and intercropping systems (maize/crotalaria and maize/cowpea) under rainfed conditions of Becal, Campeche, 2021.

Treatment	TDM (50,000 Plants ha^{-1})		Grain Yield (kg ha^{-1})	LAI (m^2/m^{-2})
	(65 DAS)	(85 DAS)		
Maize/Crotalaria	2450 ± 450 a	2108 ± 65 a	4187 ± 54.6 b	1.5 ± 0.21 a
Maize/Cowpea	2349.4 ± 246 a	2382 ± 86 a	4641 ± 25 ab	1.3 ± 0.75 a
Sole Maize	2499 ± 45 a	2479 ± 46 a	6146 ± 11 a	1.36 ± 0.74 a
Significance	$p = 0.346$	$p = 0.481$	$p = 0.025$	$p = 0.924$

TDM Total Dry Matter Accumulation of maize (leaf, stem, and root). Means ± standard deviation with different letters are significantly different, $p < 0.05$, Tukey's test.

There were significant differences ($p = 0.025$) in the grain yield of maize between the maize–legume intercropping and sole maize systems (Table 2). Maize grain yield (4187, 4641, 6146 kg ha^{-1}) was significantly higher in sole maize relative to that of maize/crotalaria intercropping, but no difference was observed in maize grain yield between sole maize and maize/cowpea intercropping systems.

3.4. Beneficial Insect (Predators and Parasitoids) Abundance per Cropping System

The inclusion of legumes in the cropping systems did not influence the abundance of predators compared to the sole maize system (Figure 4). With respect to parasitoids, the inclusion of legumes in the intercropping systems caused a significant increase in the abundance of these beneficial insects compared to the sole maize system ($p = 0.061$).

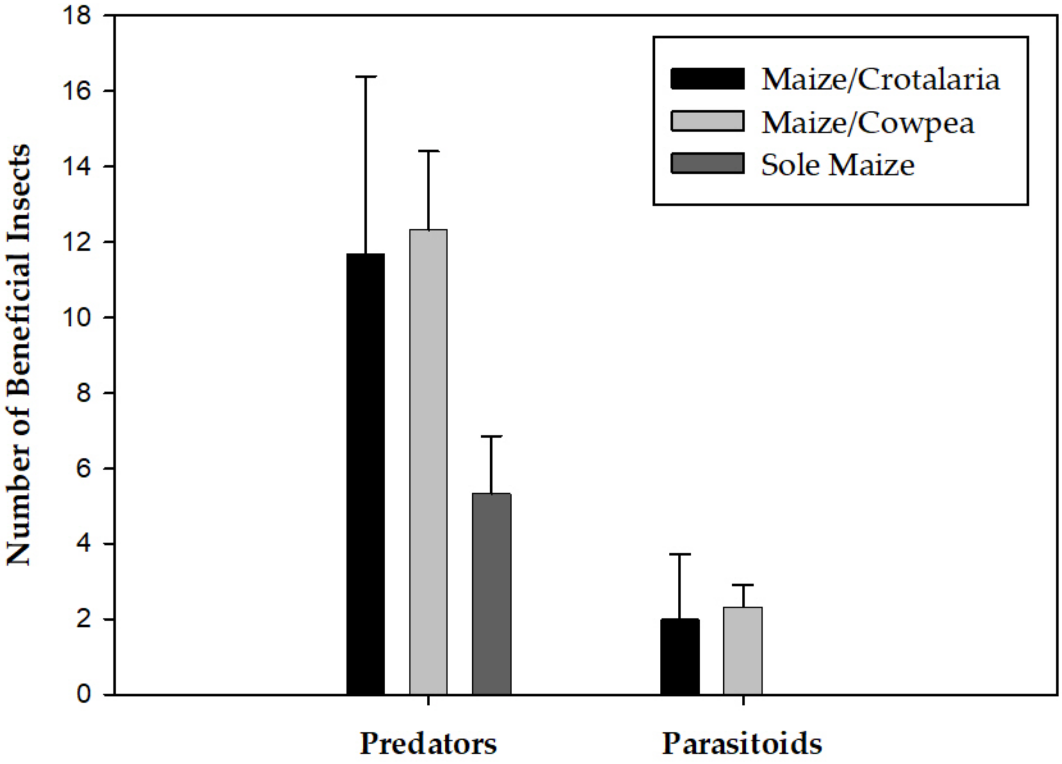

Figure 4. Diversity of beneficial insects (predators and parasitoids) observed in both monoculture and intercropping systems under rainfed conditions. Becal, Campeche, 2021. Means ± standard deviation with different letters are significantly different, $p < 0.05$, Tukey's test.

The analysis of the composition of the beneficial insect community showed that the most frequent families for predators (57%) in all cropping systems were Coccinelidae, Formicidae, Araneidae, Thomisidae, Syrphidae, Chrysomelidae, Oxypidae, Vespidae, Reduviidae, Carabidae, Asilidae, Salthicidae, and Dolichopodidae (Table 3). Among parasitoids, the most frequent families (28.6%) in the maize–legume intercropping systems were Eurytomydae, Braconidae, Tachinidae, Pteromalidae, Scelionidae, and Figitidae (Table 3). No parasitoids were observed in the maize monocrop system (Figure 3).

Table 3. Diversity of beneficial insects (predators and parasitoids) observed in both monoculture and intercropping systems (**+**: Presence of Beneficial Insect; **-**: Absence of Beneficial Insect) under rainfed conditions. Becal, Campeche, 2021.

Family	Maize/Crotalaria	Maize/Cowpea	Sole Maize
Predators			
Coccinelidae	-	-	+
Formicidae	+	+	+
Araneidae	+	+	+
Thomisidae	+	+	+
Syrphidae	+	+	+
Chrysomelidae	+	+	+
Oxypidae	+	+	+
Vespidae	+	+	+
Reduviidae	+	+	+

Table 3. *Cont.*

Family	Maize/Crotalaria	Maize/Cowpea	Sole Maize
Carabidae	-	+	-
Asilidae	-	+	-
Salthicidae	+	-	-
Dolichopodidae	+	-	-
Parasitoids			
Eurytomydae	-	+	-
Braconidae	+	-	-
Tachinidae	-	+	-
Pteromalidae	-	+	-
Scelionidae	+	+	-
Figitidae	+	-	-

3.5. Analysis of the Relationship between Photosynthetic Parameters, Chlorophyll Content, Grain Yield, and Leaf Area Index

A Pearson correlation analysis was performed to determine the relationship between the photosynthetic parameters, chlorophyll content, grain yield, and LAI traits in maize plants. The number of spad units was found to be highly negatively correlated with the level of photosynthesis rate and stomatal conductance ($r = -0.99$, $p = 0.035$; $r = -1$, $p = 0.009$), respectively. In addition, the level of photosynthesis rate had a strong positive correlation with the level of stomatal conductance ($r = 0.99$, $p = 0.025$) (Appendix A).

4. Discussion

4.1. Effect on Growth Parameters of Crops

The fundamental benefit of intercropping practice is the optimal use of available natural resources, such as water, nutrients, and light [42–45]. In this study, maize–legume intercropping systems did not affect maize growth compared to maize when established as a monocrop. Even though maize plants in the maize monocrop system were slightly higher than in intercropping, this did not reflect on dry matter accumulation. The slight difference in plant height was primarily related to resource competition, as previously documented [46], but the inclusion of legumes two weeks after maize plants improves maize crop performance in terms of biomass production. It is important to note that, in our study, to avoid competition, legumes were planted 15 days following maize sowing. This strategy allowed maize to grow enough at the beginning of the crop cycle. Other studies have pointed out that in a maize–legume intercropping system, legumes should be planted 2–4 weeks after maize sowing to help in the prevention of interspecific competition among crop species [47]. In this study, the improvement in growth metrics of intercrops was attributable to a variation in temporal niche. According to other studies, the temporal niche divergence between maize and cowpea or crotalaria was mostly due to seeding and harvesting both species at different periods [48]. In an intercropping system, changes in the growth characteristics of maize and legumes have been well documented [49]. In the present study, the intercropping systems and monocropping were not different in terms of the Leaf Area Index (LAI). This again was most likely due to the delay in planting the legumes between the maize lines, which allows maize to develop before competition among crop species begins, even though maize has an excellent capacity to compete for resources when established with legumes. In this regard, Mburu et al. [50] showed that, in intercrops, maize has a competitive advantage for light and water over legumes because it is taller and has a larger root system, resulting in less competition. On the other hand, it is important to note that, in some cases, the intercropping system may affect the LAI, as seen by Ünay et al. [51], who observed that the LAI of sole soybean and sole maize systems outperformed the maize–soybean intercropping system. Even though there was no difference in the LAI between treatments, grain yield was significantly lower in the maize/crotalaria treatment than in the sole maize. Since the Leaf Area Index was measured during the R1 maize growth stage, and crotalaria plants had just begun to grow taller than maize plants, we infer that there was greater competition for light interception, which may have impacted the biomass partitioning process in maize crops and, consequently, maize grain yield in the maize/crotalaria intercrops. Many studies have found that more efficient solar radiation capture and utilization is a major reason for the yield advantage in intercropping systems [52].

4.2. Photosynthetic Parameters and Leaf Chlorophyll

This study found that intercropping with legumes had a significant effect on maize photosynthetic parameters. In our study, maize/cowpea intercropping improved the maize photosynthetic rate, stomatal conductance, and transpiration rate. This may be attributed to the complementarity effect between cowpea and the cereal. However, more studies should be conducted to better understand the reasons why maize increased the photosynthetic parameters when intercropped with cowpea. Our result is consistent with the findings of Zhang et al. [53], who found that maize–soybean intercropping increased the maize crop's photosynthetic rate (μmol m^{-2} s^{-1}), stomatal conductance (mol m^{-2} s^{-1}), and transpiration rate (mmol m^{-2} s^{-1}). Plants with the highest photosynthetic rate also had the largest stomatal conductance, with a high degree of correlation ($r = 0.99$, $p = 0.025$; Appendix A). Overall, the photosynthetic rate of maize in maize/cowpea intercropping was significantly higher than that of sole maize, indicating that intercropping can significantly improve the photosynthetic rate of maize plants. Increasing the leaf photosynthetic performance is one of the most important measures for obtaining high yields in maize [54,55]. Therefore, we infer that the intercropped cowpea may have created better conditions for water and nutrient uptake by maize. Intercropped legumes probably facilitated the growth of maize by transferring the N fixed [56–58]. Furthermore, the present study found that intercropping with cowpea increases water use efficiency (4.76 μmol CO_2/mmol H_2O), equivalent to the maize monocropping system (4.84 μmol CO_2/mmol H_2O). When compared to the other cropping systems, maize crops in the maize/crotalaria system had the greatest loss of water through the stomata during gas exchange. Based on our results, we infer that cereal/legume intercrops with high water use efficiency could boost maize yield by sharing the available water between both crops in an efficient way. This can also be related to the architecture of both crops in competing for fewer resources. The existing study also clearly revealed that maize–legume intercropping had no effect on the chlorophyll content of maize. This contrasts with the findings of Ewansiha et al. [59], who documented that maize intercropped with cowpea performed better in terms of light interception, energy use efficiency, and chlorophyll content than sole maize. Similarly, in maize/peanut intercropping, the maize's chlorophyll content increased significantly [60]. Therefore, the chlorophyll content in maize plays a significant role in the plant's photosynthetic activity [61], which can influence the plant's growth and yield [61].

4.3. Effects of Intercropping on Maize Grain Yield

Despite the fact that the sole maize had a higher grain yield, the maize/cowpea intercropping system (4420 kg ha^{-1}) was statistically on par with the grain yield observed with sole maize (6146 kg ha^{-1}) ($p > 0.05$). This is in line with the review published by Pierre et al. [62], who reported that the advantages of monocropping yield benefit over the maize/legume intercropping system are mostly due to the interspecific competition that exists among the cereal/legume species for space, nutrients, water, and light. Our findings show, however, that the maize/cowpea intercropping system may maintain similar yield production to a maize monocropping system (Table 2). Our findings are consistent with those of Saudy [63], who found that a maize/cowpea alternating intercrop provides the highest maize grain yield per hectare. The increase in grain yield may be attributed to the improvements in photosynthetic activity which were observed in the maize/cowpea intercropping system. Other studies have shown that intercropping maize/mung bean (*Vigna radiata* L.) or maize/mash bean (*Vigna mungo* L.) considerably ($p < 0.05$) enhanced maize grain yield [41]. Although maize/cowpea was planted in a 1:1 row arrangement in this study, there is still a lack of evidence that a different row arrangement ratio would be helpful for the traditional intercropping system of the region. In this regard, Iderawumi [64] observed that cowpea intercropped with maize at a 1:1 row arrangement produced the maximum grain yield when compared to 1:2 and 2:1 row arrangements. Additionally, it has been documented that maize–legume intercropping enhances maize biomass production due to higher maize crop growth indices or better resource utilization [65]. Such resources include nutrients, water, and light [66–68]. In our study, we found no effect of the intercropping system on biomass accumulation. However, based on the grain yield, the traditional maize/cowpea intercropping is recommended rather than the novel maize/crotalaria intercropping, as cowpea is a good source of edible legume for the rural population on the Yucatan Peninsula. However, if more on-farm demonstrations are not conducted to enhance the acceptance rate of this approach, maize/cowpea grown as a strip intercrop may have certain negatives among growers in the region. This is consistent with the findings of Pierre et al. [6], who found that the majority of farmers surveyed suggest that field trials should be conducted on their farms before incorporating any novel legumes into their traditional cropping system.

Overall, we can observe that for the maize–legume intercropping system, the best candidate is cowpea over crotalaria. The maize/crotalaria intercropping system had the lowest dry grain yield and photosynthesis rate, as well as the lowest water use efficiency rate, indicating that they fix less carbon. If the yield of irrigation maize in southeast Mexico is assumed to be 4.5 t ha^{-1} [54], all of the cropping systems tested in our field experiment achieved or exceeded the region's average maize grain yield.

4.4. The Abundance of Natural Enemies

In this study, the inclusion of legumes in cropping systems had a pattern of an increase in the abundance of beneficial insects. In terms of predators, there was no significant difference between the cropping systems ($p > 0.05$). This is consistent with the findings of other studies that found that predatory coccinellid density did not differ among intercropping systems [23]. In terms of parasitoids, we observed that the addition of legumes to intercropping systems enhanced the number of parasitoids in the cropping systems. In the maize monocropping system, no parasitoids were found. Overall, this may be due to the low level of damage by insects (e.g., *Spodoptera frugiperda*) observed in the overall experiment (data not reported). According to the natural enemy hypothesis, intercropping attracts more predators and parasitoids than monocropping, which is one of the mechanisms used by intercropping to reduce pest infestation [17]. Tiroesele et al. [23] recorded considerably more parasitoids in intercropping, when compared to the monocropping system. Several studies have found that intercropping boosts insect diversity dramatically, as this system provides a more diverse field habitat for parasitoids and predators [69]. Having a high diversity and abundance of predators and parasitoids in the intercropping systems guarantees natural enemies for the suppression of agricultural pests in the agroecosystems (Table 3). Therefore, we infer that crop diversification may create a favorable environment that attracts more insects and, consequently, can attract a considerable number of beneficial insects to suppress phytophagous insects. This is in line with other studies. For example, in maize, two of the main pests in tropical areas, the fall armyworm (*Spodoptera frugiperda*) and corn earworm (*Helicoverpa zea*), may be effectively suppressed by parasitoids or predators [70,71]. Related studies have also reported the role of intercrops in the suppression of the population of phytophagous insects by enhancing the abundance of natural enemies [72,73].

5. Conclusions

The current study shows that intercropping systems slightly affected plant height but not stem diameter. Even though the Leaf Area Index and chlorophyll content in maize were similar regardless of the cropping system, intercropping with cowpea significantly increased the physiological parameters of maize and grain yield. These findings show that under the rainfed circumstances of the Yucatan Peninsula, a maize/cowpea intercropping system may maintain similar yield production to a maize monocrop. Additionally, intercropping systems boost the quantity of beneficial insects. Based on our results, the maize/cowpea intercropping system represents a sustainable planting alternative for promoting maize grain yield and also promoting edible legume production within the system. However, in order for intercropping to be appealing to the region's smallholder farmers, more information about the overall economic benefits of this technique in comparison to the region's maize monocropping system is needed. Furthermore, future research is needed to investigate and assess the effects of different planting ratios, row spacing, and temporal niche differences (TND) in different seasons and contrasting habitats across a number of years.

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Appendix A

Table A1. Correlation analysis of chlorophyll, photosynthetic activity, and leaf area and correlation among grain yield, water use efficiency, and biomass accumulation.

	Correlations							
	lai	**spad**	**an**	**gs**	**Ci**	**E**	**wue**	**yield**
lai	1	0.839	−0.868	−0.847	0.771	−0.559	−0.838	−0.435
spad	0.839	1	−0.999 *	−1.000 **	0.993	−0.920	−0.406	0.124
an	−0.868	−0.999 *	1	0.999 *	−0.986	0.897	0.455	−0.070
gs	−0.847	−1.000 **	0.999 *	1	−0.992	0.914	0.419	−0.110
Ci	0.771	0.993	−0.986	−0.992	1	−0.959	−0.298	0.238
E	−0.559	−0.920	0.897	0.914	−0.959	1	0.016	−0.503
wue	−0.838	−0.406	0.455	0.419	−0.298	0.016	1	0.856
yield	−0.435	0.124	−0.070	−0.110	0.238	−0.503	0.856	1

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

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