RESEARCH ARTICLE

Morpho-agronomic evaluation of native maize races associated with Mexican tropical climate agroforestry systems

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Abstract

Maize (Zea mays L.) is native to Mexico, in which wide genetic diversity can be found; however, maize is at risk of genetic erosion, and agroforestry systems (ASs) can be a strategy for conservation and sustainable use of this crop. The objective of this study was to evaluate the variation in the morpho-agronomic characteristics of three native maize races, Tuxpeño, Olotillo × Tuxpeño and Ratón × Tepecintle, cultivated in different AS in a tropical climate of Veracruz, Mexico, as well as its association with microclimatic conditions. In 2019, experiments were established in the localities La Gloria and La Luisa, Veracruz, where the three maize races are cultivated, in a randomized complete block design with three replications in a 3 × 4 factorial scheme (three native maize races and three AS arrays, plus monoculture). Ten morpho-agronomic variables were recorded in each experiment and were analyzed by analysis of variance (ANOVA; Tukey’s post-hoc test, all p ≤ 0.05) and principal component analysis (PCA). Six morpho-agronomic characteristics showed significant differences for the race × system interaction. Consistently standing out both in the Myroxylon with 2.8 m × 2.0 arrays and in the monoculture was the Olotillo × Tuxpeño race, as there were no variations (p ≥ 0.05) in 50% of its morpho-agronomic characteristics. The first three PCs explained 87.7% of the cumulative variance, determined by five variables of the ears, three of the grain and plant height, which were associated with temperature; therefore, the microclimatic conditions of the studied ASs are associated with the morpho-agronomic characteristics of the native maize races. The results show that ASs could be a strategy for the conservation and use of native corn germplasm and could allow the diversification of sustainable production for rural farmers.
Introduction

Approximately 7000 species of cultivated plants have been domesticated in Mesoamerica [1], but only 30 contribute approximately 90% of the global food security of the population [2]. Among them are wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*) [3]. In 2050, the world population is expected to reach 9.7 billion, so a major goal is to ensure food security [3]. In addition, it is mandatory to preserve plant genetic resources under a sustainable agricultural system without compromising natural resources and environmental balance [4].

In Mexico, *Z. mays* is a native species that was domesticated and diversified by prehispanic cultures. It has high sociocultural and economic importance. Terán and Rasmussen [5] reported that maize had been cultivated by Mayan culture in milpa systems. Evidence of teosinte derivation has been found [6]. Additionally, 64 native maize races have been identified (17% of the total found on the North American continent). These races are distributed between a wide variety of climate and altitude conditions, from sea level to nearly 3400 m [7].

The wide morpho-agronomic and genetic variation registered in native maize races from Mexico [8, 9] is being lost at rates of approximately 1.22 to 1.43 of native races per producer in 5-year intervals [10]. This implies genetic erosion of germplasm [11]. This can be due to several factors, such as no interest in culture [12], introduction of monocultures with improved varieties, low productivity and culture reconversion of sugar cane (*Saccharum* spp.) and people migration [11, 13, 14].

Faced with this loss of diversity of native maize races, ASs are part of a strategy for the conservation and sustainable use of plant genetic resources [15, 16]; furthermore, the combination of trees, bushes, crops, and animals integrates an economical and sustainable environmental option. This might benefit small producers in tropical regions [17]. However, due to the unknown morpho-agronomic variation of maize races under different AS conditions, the adoption level of this technology by farmers or other actors involved in this field of knowledge is low [16, 18].

Previous empirical evidence [19–24] has documented the viability of intercropping ASs with annual crops such as gramineous sugar cane (*Saccharum* spp.), wheat (*Triticum aestivum* Linn) and maize (*Z. mays*), which have C4 metabolism, and the same researchers have found differences in the morphological, agronomic and physiological characteristics.

Schwerz et al. [25] evaluated the leaf area index, dry matter, yield, juice volume, solar radiation interception, and efficient use of solar radiation in sugar cane (*Saccharum officinarum* L.) in AS arrays and found important differences in productive and physiological variables between the AS system and monoculture. They attributed this behavior to the tree canopy, interactions between plants, plantation spatial arrangement, microclimatic conditions, and competition for resources such as radiation. Caron et al. [22] studied morpho-productive and physiological aspects in *T. aestivum* cv. BRS Tarumá in AS arrays, in addition to incorporating monocultures, and found that a decrease in solar radiation affected the dried matter, kernel yield, leaf area index, phytochrome content, and photosynthetic rate of the cultivar itself. These researchers are in the process of evaluating other variables such as microclimatic conditions, plantation space arrangement, and the morphophysiological plasticity of genotypes.

Artru et al. [24] analyzed the artificial shading effect in wheat plants (*T. aestivum* cv. Edgard) where differences were found in dry matter, yield and its components, and the kernel protein concentration between treatments with and without artificial shading during plant phenological processes.

However, there is limited research on morpho-agronomic variation in *Z. mays* intercropped with ASs. Bertomeu [20] found that in maize hybrids, grain yield was less related to monoculture-grown trees because shading affects this variable. Nardini et al. [23] reported
that the growth of hybrid maize plants (e.g., the leaf index area and net growth rate) was affected by tree shading, but when plants were cultivated under AS conditions, they showed a higher efficiency with respect to solar radiation than when they were grown in monocultures.

In Mexico, ASs have been studied from a conservation approach, particularly native biodiversity, and their relationship with the traditional knowledge of farmers [26, 27]. These researchers have emphasized that these farmers are immersed in a global economic market where conventional agriculture is promoted, as it is essential to incorporate traditional knowledge into public policies on the conservation of plant genetic resources. All of the above-described findings are evidence of the lack of knowledge about the morpho-agronomic variation of the maize races Tuxpeño, Olotillo × Tuxpeño, and Ratón × Tepecintle native to Mexico associated with AS schemes; therefore, generating this knowledge is critical to encourage in situ conservation strategies and the sustainable use of these races through the implementation of appropriate SA arrangements for each of them. In addition, with this information, planned decisions could be made in the transfer of this technology to small producers in rural areas of tropical areas to contribute to the diversification of their products, such as wood, grains and ecosystem services [16–18]. In this sense, the objectives of the present work were 1) to evaluate the variation in the morpho-agronomic characteristics of three races of maize native to Mexico, Tuxpeño, Olotillo × Tuxpeño and Ratón × Tepecintle, cultivated under different AS arrangements in a climate tropical and 2) to relate the morpho-agronomic variables of the three native maize races to the microclimatic conditions recorded in the AS arrangements.

Materials and methods

Collection and classification of genetic material

In April and May 2019, the first botanical exploration was carried out in three locations in Veracruz, Mexico (Table 1), to collect populations of native maize cultivated in the State of Veracruz [28]. Collection was made following Ortega-Paczka [29]. These collections were deposited in the germplasm bank of the Instituto Tecnológico Superior de Zongolica with corresponding passport data, and they were classified racially by the Mexican expert Rafael Ortega Paczka.

Study description

The study was performed in the following locations: La Gloria and la Luisa, municipality of Tezozonapan, Veracruz (18.2425 LN, -96.4136 LW, at 94 m.a.s.l; 18.3420 LN, -96.4310 LW, at 180 m.a.s.l, respectively). Both locations have warm-wet climates (Am), rainy summers and an average annual temperature of 18˚C and mean annual precipitation of 1259.3 mm, with Acrisol and Lixisol soils, respectively [30, 31].

Establishment and management of experimental plots

At La Gloria location, three native maize races were planted in a coffee plantation (Coffea canephora) aged 2 years, with a plantation arrangement of 3.0 × 2.0 m (1666 plants ha-1). In the La

![Table 1. Passport data of native maize races examined in this study.](https://doi.org/10.1371/journal.pone.0269896.t001)
Luisa location, the same races of maize were planted in two balsam ASs (*Myroxylon balsamum* L.) in two plantation arrays of $2.8 \times 2.0$ m (1785 plants ha$^{-1}$) and $2.0 \times 2.0$ m (2500 plants ha$^{-1}$). The trees were 3 years old. Additionally, three maize races were planted in a monoculture system with a population density of 62 500 plants ha$^{-1}$ (Fig 1). Maize requires cross-pollination, and pollination was not controlled in the present study.

Culture management was performed according to conventional maize farmer practices in the location. Sowing was performed on 8 and 10 June 2019 under dry farming conditions.

Fig 1. Representation of an Experimental Unit for Each AS: A) *Myroxylon* $2.0 \times 2.0$, B) *Myroxylon* $2.8 \times 2.0$, C) *Coffea* $3.0 \times 2.0$, D) and Native Maize Monoculture. Black circles represent the trees, and discontinuous lines indicate maize plants.

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During planting with the help of a punch, three seeds were set, i.e., 0.2 m between plants and 0.8 m between ruts. Chemical fertilization was carried out with doses of 46N-00P-00K; one third of the N was applied 25 days after sowing and the remainder during the second weeding. Weeding and cleaning were conducted manually during the crop cycle, and no chemical products were applied to control insects or bushes. For each system, daily temperatures and precipitation were recorded during the whole experiment using a digital thermometer-hygrometer (HTC-2) and a rain gauge with a datalogger (WatchDog 1120) (Fig 2).

Experimental design and unit
A randomized complete block experimental design with three repetitions was used in a 3 × 4 factorial scheme represented by the three maize races (Factor R) and three agroforestry system arrays (3.0 × 2.0) for C. canephora and M. balsamum at spacings of 2.8 × 2.0 and 2.0 × 2.0 m, respectively, plus monoculture (Factor S), i.e., a total of 12 treatments (Table 2). The experimental unit consisted of 15 maize plants. The morphometric characteristics of the perennial C. canephora and M. balsamum plants heights were 2.1 and 3.0 m, respectively, and the stem diameters were 6.0 cm and 7.0 cm, respectively.

Variables evaluated
In each experimental unit, 10 plants with complete competition were chosen at random in each plot and were labeled to obtain their morpho-agronomic data. Complete competition means that those maize plants that had neighboring ones in the four cardinal points were chosen. The plant height (cm) and stem diameter (mm) were quantified. At harvest, five ears were collected from previously labeled plants, and the length and ear diameter (mm), number of
kernels per row, and cob diameter (mm) were recorded. The ears were shelled manually; 10 kernels were collected, the length and width (mm) were determined, and the average weight of 100 kernels was recorded. These seeds were adjusted to 10% humidity. Variables were evaluated according to the maize descriptors of [9, 33, 34].

Statistical analysis

Data obtained from the morpho-agronomic measures were analyzed by the Shapiro–Wilk test to verify a normal distribution, whereas Levene’s test was used for homogeneity of variance [35]. The morpho-agronomic variables of the maize races studied were analyzed by analysis of variance (ANOVA) under a randomized complete block design. When significant differences were detected between races and between ASs, Tukey’s separation (\( p \leq 0.05 \)) post hoc test was applied. To associate the morpho-agronomic variables of the native maize races with the microclimatic variables of the AS arrangements, principal component analysis (PCA) was conducted with a correlation matrix [36] using the PRINCOMP procedure of SAS v. 9.1 [37] to obtain the eigenvalues and eigenvectors. Based on a graph by Gabriel [38], the correlation structure between variables and the magnitude of each of them relative to the global variation

### Table 2. Description of the evaluated factors of the three maize races in different ASs.

| Treatment | Maize race name | System arrangement | Population density (plants ha\(^{-1}\)) |
|-----------|-----------------|--------------------|---------------------------------------|
| 1         | Tuxpeño         | Monoculture        | 62 500                                |
| 2         | Olotillo × Tuxpeño | Monoculture       | 62 500                                |
| 3         | Ratón × Tepecintle | Monoculture       | 62 500                                |
| 4         | Tuxpeño         | Coffea 3.0 × 2.0   | 33 300                                |
| 5         | Olotillo × Tuxpeño | Coffea 3.0 × 2.0  | 33 300                                |
| 6         | Ratón × Tepecintle | Coffea 3.0 × 2.0  | 33 300                                |
| 7         | Tuxpeño         | Myroxylon 2.8 × 2.0 | 35 000                                |
| 8         | Olotillo × Tuxpeño | Myroxylon 2.8 × 2.0 | 35 000                                |
| 9         | Ratón × Tepecintle | Myroxylon 2.8 × 2.0 | 35 000                                |
| 10        | Tuxpeño         | Myroxylon 2.0 × 2.0 | 25 000                                |
| 11        | Olotillo × Tuxpeño | Myroxylon 2.0 × 2.0 | 25 000                                |
| 12        | Ratón × Tepecintle | Myroxylon 2.0 × 2.0 | 25 000                                |

### Table 3. Means, average squares and coefficient of variation of the ANOVA of the morpho-agronomic variables in native maize races of Mexico under different systems.

| Variable (Measurement unit) | Race (R) | System (S) | Race × System (R x S) | Mean | CV (%) |
|-----------------------------|----------|------------|------------------------|------|--------|
| Plant height (cm)           | 6695.43** | 6387.41**  | 9742.86**              | 325.7 | 7.7    |
| Stem diameter (mm)          | 20.02**   | 125.00**   | 28.55**               | 27.4  | 7.7    |
| Ear length (cm)             | 5.02**    | 66.15**    | 5.15**                | 15.1  | 8.0    |
| Ear diameter (mm)           | 15.65**   | 206.73**   | 11.09 ns              | 41.4  | 6.3    |
| Number of kernel rows       | 2.60 ns   | 10.06**    | 1.58 ns               | 11.9  | 7.9    |
| Number of kernels per rows  | 25.40 ns  | 155.00**   | 32.11 ns              | 23.8  | 17.0   |
| Cob diameter (mm)           | 15.35 ns  | 67.17**    | 13.17 ns              | 20.8  | 13.4   |
| Kernel length (mm)          | 0.62 ns   | 8.55**     | 1.08**                | 10.4  | 5.1    |
| Kernel width (mm)           | 4.32**    | 5.13**     | 2.03**                | 9.7   | 5.2    |
| 100-kernel weight (g)       | 0.02*     | 4.95**     | 0.50**                | 30.0  | 9.7    |

* Significance at 0.05
** significance at 0.001; ns: no significant difference CV: coefficient of variation.

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were visualized [39]. Before PCA, the data were standardized to mean 0 (zero) and variance 1. The results are shown in a biplot with the two PCs, as those that presented a minimum cumulative variance of 70% were sought [25] to detect possible association patterns based on similarities-dissimilarities of the morpho-agronomic and microclimatic variables [25, 35]. These analyses were performed with the Statistical Analysis System v. 9.1 [37].

Results
Morpho-agronomic variables
The average squares of the morpho-agronomic variables in the native maize races of Mexico are presented in Table 3. According to the ANOVA, significant differences were observed \( (p \leq 0.05) \) in the plant height, stem diameter, ear length and width kernel characteristics of the native maize races evaluated for the R and R x S factors. However, for the latter, a significant difference existed at \( p \leq 0.001 \) for kernel length and the 100-kernel weight (Table 3). Therefore, there is evidence of a particular adaptation of the races to each of the systems. ANOVA showed a significant difference \( (p \leq 0.001) \) in 100% of the analyzed variables for the S factor (Table 3), which suggests an effect on each characteristic evaluated in the present work.

The Tuxpêno race associated with Coffea bushes had a greater plant height (PH; 343.5 cm; \( p \leq 0.001 \)) compared with Myroxylon 2.8 × 2.0 and 2.0 × 2.0 m, with values of 305.5 and 301.5 cm, respectively (Fig 3A). The PH of the Olotillo × Tuxpêno race in the Coffea 3.0 × 2.0 m, Myroxylon 2.8 × 2.0 and monoculture systems was statistically similar \( (p \geq 0.001) \), with means of 356.3 cm, 362.3 cm and 362.0 cm, respectively, but these systems were different \( (p \leq 0.001) \) from AS Myroxylon 2.0 × 2.0 m, with 306.5 cm PH (Fig 3A). Moreover, the Raton × Tepecintle race grown with Myroxylon 2.8 × 2.0 was taller (383 cm; \( p \leq 0.001 \)) than that in the other systems (Fig 3A).

Monocultured Olotillo × Tuxpeño had better performance in SD, i.e., 31.2 mm, which was significantly different \( (p \leq 0.001) \) from the conditions with Myroxylon 2.0 × 2.0 m, with a value of 23.8 mm and 25.0 mm, corresponding to the Coffea 3.0 × 2.0 m and Myroxylon 2.0 × 2.0 environments, respectively (Fig 3B).

Plants from the maize races evaluated in this present work had the greatest cob diameter (EarD) (46 mm; \( p \leq 0.001 \)) in monoculture, compared with the Coffea system (3.0 × 2.0 m), which had the lowest value (37 mm) (Fig 4A).

The native maize races evaluated in this study had a greater number of rows on the cob (NKeR) (13.00; \( p \leq 0.001 \)) under monoculture conditions compared with the AS Myroxylon (in the two planting arrays) and Coffea 3.0 × 2.0 m, by 11.0, 11.6 and 11.4 rows, respectively (Fig 4B).

The native maize races studied here had 25.0, 26.0 and 24.0 grains per row (NKPR); these values were not significantly different \( (p \geq 0.001) \) between the monoculture systems Myroxylon 2.8 × 2.0 and Myroxylon 2.0 × 2.0 m, but were higher \( (p \leq 0.001) \) than the 19.0 value recorded in the culture system with Coffea (Fig 4C).

The 23.7 mm cob diameter value (COBD) for the native maize races, evaluated in the monoculture environment, was higher \( (p \leq 0.001) \) than those in the arrays of Coffea 3.0 × 2.0 m, Myroxylon 2.8 × 2.0 m and Myroxylon 2.0 × 2.0 m, with means of 18.7, 20.3 and 20.4 mm, respectively (Fig 4D).
The monoculture and *Myroxylon* 2.8 × 2.0 m with the Tuxpeño race did not differ statistically (p ≥ 0.05) as they presented means of 18.2 and 16.1 cm for EL, but these were different (p ≤ 0.05) from the *Coffea* environment, with a value of 13.5 cm (Fig 5A). The monoculture and *Myroxylon* 2.8 × 2.0 m systems with the Olotillo × Tuxpeño race did not present statistically significant differences (p ≥ 0.05), with means of 16.8 and 14.7 cm, respectively. The
Ratón × Tepecintle monoculture had the highest EL (18.0 cm; $p \leq 0.001$) compared with intercropping with AS Coffea and Myroxylon (Fig 5A).

With respect to the Tuxpeño race in terms of KeWi, no statistically significant differences ($p \geq 0.05$) were found between the AS Myroxylon 2.8 × 2.0 m and Myroxylon with 2.0 × 2.0 m arrangement, showing values of 10.7 and 11.1 mm. However, the Coffea system had the lowest value (9.8 mm; Fig 5B). The Olotillo × Tuxpeño race did not show significant changes ($p \leq 0.001$) in the KeWi characteristic among the four systems, Coffea 3.0 × 2.0 m, conventional, Myroxylon 2.8 m × 2.0 and Myroxylon 2.0 × 2.0 m, with values of 8.8, 9.6, 9.5 and 9.0 mm, respectively (Fig 5B). The Ratón × Tepecintle monoculture presented ears with higher KeWi (9.9 mm; $p \leq 0.05$) than in the Coffea arrangement 3.0 × 2.0 m, i.e., 8.8 mm (Fig 5B).

The Tuxpeño collection had greater grain length (KeLe) (11.4 mm; $p \leq 0.001$) in the monoculture system compared with the means of 9.2, 9.4 and 9.9 mm for AS Coffea, Myroxylon 2.8 × 2.0 m and Myroxylon 2.0 × 2.0 m, respectively (Fig 5C). The Olotillo × Tuxpeño race did not show significant differences ($p \geq 0.001$) in KeLe when it grew under monoculture, Myroxylon 2.8 × 2.0 m and Myroxylon 2.0 × 2.0 m, with values of 10.8, 10.8 and 10.2 mm in each culture system (Fig 5C). The monoculture in which the Ratón × Tepecintle race was established presented the best KeLe values (11.6 mm; $p \leq 0.001$), while smaller means were measured in the maize plants with the Coffea 3.0 × 2.0 m, Myroxylon 2.8 × 2.0 m and Myroxylon 2.0 × 2.0 m arrays (9.3, 10.2 and 10.0 mm, respectively) (Fig 5C).
The *Tuxpeño* race had a higher value for the weight of 100 kernels (100KW) (38.0 g; $p \leq 0.001$) under monoculture conditions compared with the ASs *Coffea* (3.0 × 2.0 m), *Myroxylon* (2.8 × 2.0 m) and *Myroxylon* (2.0 × 2.0 m) (25.2, 28.4 and 30.8 g, respectively) (Fig 5D). On the other hand, there are no statistically significant differences in Olotillo × *Tuxpeño* between the conventional system and *Myroxylon* 2.8 × 2.0 m and *Myroxylon* 2.0 × 2.0 m, which presented means of 33.4, 31.4 and 30.4 g for 100KW (Fig 5D). Between the monoculture systems and *Myroxylon* 2.0 × 2.0 m, no significant differences were detected ($p \geq 0.05$), in the Ratón × Tepecintle race, with means of 39.8 and 33.9 g for 100KW in each system. However, these values in the monoculture and *Myroxylon* 2.0 × 2.0 m were higher ($p \leq 0.05$) than the 19.0 g for *Coffea* 3.0 × 2.0 m (Fig 5D).

**Associations between the morpho-agronomic variables of the native maize races and the microclimatic conditions of the agroforestry systems**

According to the PCA results, there was a positive correlation between the morpho-agronomic variables of the native maize races and the microclimatic conditions that fluctuated depending on the AS and monoculture (Fig 6). The first 11 principal components (PCs) explained 100% of total variance (data not shown). However, the first three PCs explained 87.7% of the total variance.

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**Fig 5.** Ear Length (A), Kernel Width (B), Kernel Length (C) and 100-Kernel Weight (D) of Three Native Maize Races (*Tuxpeño*, Olotillo × *Tuxpeño* and Ratón × Tepecintle) Associated with AS and Cultivated in Monoculture. The values for each maize race followed by the same lowercase letter do not differ significantly, while the means for each system marked with the same uppercase letter do not differ significantly according to Tukey’s test, $p \leq 0.05$). The bars represent the standard error of the mean.

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The spatial distribution of the association of the different AS arrangements with respect to the morpho-agronomic and microclimatic characteristics was concentrated in quadrants I and IV (Fig 6). PC1 placed treatments 1, 2, 3 and 8 in quadrants I and IV because the three maize races under monoculture conditions and in *Myroxylon* 2.8 × 2.0 m had the highest values for ear length, ear diameter, cob diameter, kernel length, weight of 100 kernels, maximum temperature and average temperature, while kernel width, number of kernels per row and minimum temperature were related to PC2 (value of 3.3). With respect to PC3, only plant height contributed, with a value of 1.2 (Table 4).

The spatial distribution of the association of the different AS arrangements with respect to the morpho-agronomic and microclimatic characteristics was concentrated in quadrants I and IV (Fig 6). PC1 placed treatments 1, 2, 3 and 8 in quadrants I and IV because the three maize races under monoculture conditions and in *Myroxylon* 2.8 × 2.0 m had the highest values for ear length, ear diameter, cob diameter, kernel length, weight of 100 kernels, maximum temperature and average temperature in contrast to the other arrangements of quadrants II and III (Fig 6). In contrast, in PC2, treatments 1, 2, 3, 4, 5 and 6 belonging to the monoculture schemes and *Coffea* 3.0 × 2.0, respectively, were associated with quadrants I and II, and the maize races that had the lowest kernel width values, number of kernels per row and minimum temperature with respect to the *Myroxylon* (2.8 × 2.0 and 2.0 × 2.0 m) treatments were concentrated in quadrants III and IV (Fig 6).

**Discussion**

**Morpho-agronomic variables**

The objective of this study was to evaluate the variation in the morpho-agronomic characteristics of three maize races, Tuxpeño, Olotillo × Tuxpeño, and Ratón × Tepecintle, native to
Mexico cultivated under different AS schemes. The significant differences found among the ASs indicate that the morpho-agronomic characteristics of the native maize races evaluated were affected by the AS arrangement and therefore by the tree canopy, with an impact on biomass production, as shade negatively affects plants with C4 metabolism, such as maize, as it requires more solar radiation for physiological and photosynthetic processes [21]. Although tree shade was not directly evaluated in the present study, it induces a heterogeneous light environment for the crops beneath the canopy [24]. In this sense, it has been documented that 70% shade positively affected the height of two grass species (Brachiaria decumbens and Brachiaria brizantha), with stem elongation and a greater leaf area with less weight adopted as strategies to intercept as much light as possible, although this did not manifest in an increase in productivity [40].

The native maize races analyzed in this study had particularities in the morpho-agronomic characteristics in each AS even when there were differences between the microclimatic conditions of the AS, particularly temperature (Fig 2). For instance, in general, the plant height and stem diameter of the Tuxpeño race did not present significant differences between the AS Myr-oxylon 2.8 × 2.0 m, Coffea 3.0 × 2.0 m and monoculture (Fig 3). In this sense, the planting arrangements of each AS and the plasticity of the characteristics of the maize plants are determined by the variety of environmental conditions that prevail in the AS [22]. For example, Caron et al. [41] found that the high growth rate of Eucalyptus reduced the stem weight of S. officinarum by 50%, attributing this discrepancy to interspecific competition, particularly due to the interception of solar radiation by the crop.

Some variables that are correlated with plant height and stem diameter are the total dry matter and leaf area index [42]. In this regard, Schwerz et al. [21], when intercropping S. officinarum with Aleurites fordii trees, recorded greater dry matter and leaf area index in the 12 × 12 m planting arrangement than in the 6 × 6 m arrangement, so they concluded that the canopy, biology (perennial or deciduous) and age of the tree play an important role in the

| Variable (Measurement unit) | Acronym | PC1       | PC2       | PC3       |
|-----------------------------|---------|-----------|-----------|-----------|
| Plant height (cm)           | PH      | 0.11 (0.30) | -0.23 (0.38) | 0.74 (0.82) |
| Stem diameter (mm)          | SD      | 0.27 (0.77) | -0.25 (0.41) | 0.30 (0.32) |
| Ear length (cm)             | EL      | 0.31 (0.88) | 0.03 (-0.05) | -0.33 (-0.36) |
| Ear diameter (mm)           | Ed      | 0.34 (0.97) | 0.02 (-0.03) | 0.06 (0.06)  |
| Number of kernel rows       | NKeR    | 0.28 (0.80) | -0.24 (0.39) | -0.10 (-0.12) |
| Number of kernels per rows  | NKPR    | 0.20 (0.56) | 0.41 (-0.68) | -0.11 (-0.01) |
| Cob diameter (mm)           | COBD    | 0.30 (0.85) | -0.17 (0.28) | 0.16 (0.17)  |
| Kernel length (mm)          | KeLe    | 0.32 (0.91) | -0.06 (0.09) | -0.02 (-0.01) |
| Kernel width (mm)           | KeWi    | 0.14 (0.40) | 0.42 (-0.70) | -0.12 (-0.01) |
| 100-kernel weight (g)       | 100KW   | 0.32 (0.91) | 0.09 (-0.16) | 0.01 (0.02)  |
| Maximum Temperature         | MaxTemp | 0.30 (0.87) | -0.21 (0.34) | -0.26 (-0.28) |
| Minimum Temperature         | MinTemp | -0.29 (-0.56) | 0.41 (-0.68) | 0.34 (0.37)  |
| Average Temperature         | AverTemp| 0.29 (0.83) | 0.30 (-0.50) | 0.08 (0.08)  |
| Precipitation               | Prec    | 0.25 (0.72) | 0.37 (-0.62) | 0.13 (0.15)  |
| Eigenvalue                  |         | 8.2       | 2.8       | 1.2        |
| Variation explained (%)     |         | 58.9      | 20.0      | 8.7        |
| Cumulative variation (%)    |         | 58.9      | 78.9      | 87.7       |

Variable correlation coefficients with the PC are in parentheses. Bold numbers indicate the contribution of the variables to each PC.

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vegetative stage of the species studied. In addition to planting density, tree species influence the growth of maize hybrids. In this sense, Nardini et al. [23] measured a higher relative growth rate in maize under *Eucalyptus* than under *Peltophorum dubium*.

The ear diameter, number of kernel rows, and cob diameter of the native maize and the Tuxpeño, Olotillo × Tuxpeño, and Ratón × Tepecintle races presented higher values (*p* ≤ 0.05) in monoculture than when intercropped with *Coffea* and *Myroxylon* (Fig 4). The number of kernel rows is a variable considered stable [43]; however, in the present work in agroforestry systems, stability was not maintained because in these environments, the number of kernel rows of the three races of *Z. mays* decreased compared to the monoculture system (Fig 4B). This may be due to the microclimatic conditions of each system, since in the monoculture, the average temperature exceeded 28˚C (Fig 2). Scherwerz et al. [21] noted that the canopy of the forest species influenced the microclimatic conditions in each system and affected the growth rate of *S. officinarum*. Similar results were found by Rocandio-Rodrı ´ guez et al. [9], who reported significant differences in the number of kernel rows, ear diameter, and cob diameter in seven native maize races from Mexico. Such differences were attributed to climatic and edaphic contrasts among the three environments. Additionally, these researchers noted that crop management influenced the characteristics of *Z. mays*.

The number of kernels per row did not differ significantly (*p* ≥ 0.05) among the three maize races analyzed in the present study in monoculture or *Myroxylon* AS (Fig 4C). Data for this variable are important because grain yield values depend on this variable, as indicated by Pecina-Martı ´ nez et al. [43]. Rincón-Tuexí et al. [44] showed that the higher the number of rows, the more kernels there are per ear, which is reflected in the grain yield. In the AS *Myroxylon* 2.8 × 2.0 m and 2.0 × 2.0 m systems, the number of kernels per row was statistically similar to that in the monoculture (Fig 4C), which suggests that adequate yield may be obtained with these plantation densities; however, in future studies it would be desirable to take this variable into account to rule out hypotheses. Purroy-Vasquez et al. [45] reported that the yield of native maize from the State of Veracruz, Mexico, was 0.919 t ha⁻¹ under rainfed agricultural conditions. In addition, it can be inferred that the biological characteristics of the *Myroxylon* tree favor this characteristic of the maize races studied in this work.

Generally, the greatest cob diameter and ear length values were measured in the monoculture system, while the lowest values were measured in the AS *Coffea* 3.0 × 2.0 m system, independent of the maize race. These variables may be associated with the different microclimatic conditions of the ASs (Fig 2). By contrast, in a study with seven races of native maize from Mexico, Rocandio-Rodrı ´ guez et al. [9] found a significant genotype × environment effect for cob diameter but not ear length.

Pecina-Martı ´ nez et al. [43] found significant differences between environments and groups of populations in the total number of grains, number of kernel rows, kernels per row and individual grain weight, suggesting that there is variability and specificity within and between different population groups. It should be noted that the values recorded for the number of rows per ear in our study are within the range of 10 to 14 rows reported by Sierra-Maci ´ as et al. [28].

The length and width of the kernel differed significantly among the systems (Fig 5B and 5C), with greater kernel length in the monoculture of the Tuxpeño and Ratón × Tepecintle races, whereas the lowest values were measured in the AS *Coffea* 3.0 × 2.0 m with Olotillo × Tuxpeño. With respect to the kernel width, higher values were found in the *Myroxylon* 2.0 × 2.0 m system with the Tuxpeño race, with a mean of 11.1 mm, while in the monoculture with Ratón × Tepecintle, a high value of 9.9 mm was measured compared with the *Coffea* 3.0 × 2.0 m system. However, Olotillo × Tuxpeño did not show changes in this characteristic among the four systems. These two characteristics of the kernel, among others, have allowed the racial classification of maize from the Highlands of Mexico, as they are the most stable
with respect to the environment [9]. However, our findings allow us to report that both the length and width of the kernel are influenced by the prevailing conditions in each AS, although the genotype may play a determining role in the stability of the grain width, as evidenced by the Olotillo × Tuxpeño race.

The weight of 100 kernels of the three native maize races presented higher values ($p \leq 0.05$) in the monoculture system than in the three established planting schemes. These results show that the grain yield could possibly be affected by the conditions of each system. Although some authors [44] consider that the individual weight of the kernel is a variable little affected by temperature stress, findings from our work reveal that kernel weight was influenced by the planting arrangement differentially between races, possibly due to the microclimatic conditions of each AS. For example, the average temperature in the monoculture was higher than that of the other systems (Fig 2).

Other characteristics, such as yield, of maize hybrids, are affected by the spacing of the plantation and the tree species, so the grain yield was statistically equal for the 1 × 10 m treatment (1000 stalks ha$^{-1}$ of Gmelina arborea) in the first two cultivation cycles [20]. The same author emphasized that from the third cycle of cultivation, the control yield exceeded that of treatment 1 since the crown of the tree was closed, leading to both a reduction in available solar radiation and photosynthesis of C4 plants, which are shade intolerant [46].

Finally, in general, it can be summarized that the lowest values of most of the morpho-agronomic variables of the native maize races were measured in the AS Coffea system, as they could possibly be affected by secondary metabolites such as alkaloids (caffeine) that are present in the fruits and leaves of coffee bushes, which naturally serve as herbivore repellants [47], and these secondary metabolites may affect the growth of maize plants. In this sense, although the study by Sarvade and Singh [17] did not evaluate the interactions of secondary metabolites between maize and coffee, these researchers documented that the different organs (for example, leaves) of agroforestry plants produce allelochemicals (toxic metabolites) that also affect the growth, germination, development, metabolism, and reproduction of other living organisms, such as weeds, pathogens, insects, and nematodes.

**Associations between the morpho-agronomic traits of the native maize races and the microclimatic conditions of the agroforestry systems**

The objective of this study was to associate the morpho-agronomic variables of the three native maize races with the microclimatic conditions recorded in the AS arrays. Gepts [48] points out that the important climatic variables in the development and physiological processes of plants are solar radiation, average air temperature, and average annual rainfall. However, the results obtained in this study show that the morphological and agronomic characteristics of the native maize races were largely related to temperature rather than precipitation, which was demonstrated by PCA (Fig 6), possibly because C4 metabolism requires high amounts of solar radiation for photosynthesis. The results obtained in this study are consistent with those reported by [44] in the sense that temperature significantly influenced the agronomic characteristics of four populations of *Z. mays*.

Similar to *Z. mays* studied in this work, research related to AS intercropped with annual crops such as *Glycine max* L. Merr. and *Zea mays* L. [46], *Triticum aestivum* L. [19, 22], *Zea mays* L. [20, 23] and *Sacharum officinarum* [21] reported morpho-agronomic and physiological differences in these crops and attributed such important differences to planting density, tree canopy, tree species, tree age, biology (perennial or deciduous), microclimatic conditions, tolerance of shade genotypes, species plasticity and crop management.
Based on the above results, knowledge of the response of the morpho-agronomic variables of native maize races to different planting arrangements with different tree species has increased, and this information will serve public policy decision-makers through the promotion of ASs since they promote sustainable and resilient agriculture in the face of certain biotic or abiotic factors, such as climate change [16].

In addition, rural farmers, by integrating ASs with native annual crops such as maize, will not only continue to conserve a wide diversity of plant genetic resources [27] but will also obtain other products such as wood, grains and ecosystem services, which will contribute to the food security of their families [16, 17]. For this reason, it is advisable to continue with this line of research, since other variables not analyzed in this study must be considered, such as the yield, chemical and physiological characteristics and genetic quality of the native Mexican maize races based on the physical quality (soil chemistry), solar radiation and position of the arrangements (for example, cardinal points) of the agroforestry systems, without excluding aspects of economic profitability [20, 24, 35].

Conclusions

The morpho-agronomic characteristics of the three described native maize races showed important differences associated with the ASs. The Olotillo × Tuxpeño race stands out, as it did not show significant differences in 50% of the variables analyzed in the monoculture and the Myroxylon system with the 2.8 m × 2.0 m arrangement. Therefore, we suggest that wider planting arrangements benefit the morpho-agronomic growth of this maize race. Certain morpho-agronomic characteristics of the maize races studied were influenced by the maximum, average and minimum temperatures, which allowed the differentiation between the different arrangements of AS and monoculture. ASs could be a tool that reduces genetic erosion in the face of the loss of native maize races and in turn contributes to the conservation and sustainable use of germplasm. In addition, they allow diversification, such as grains, wood and ecosystem services.

Supporting information

S1 Table. (DOCX)

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References
1. Harlan JR. Crops & man. Madison, Wisconsin, USA: American Society of Agronomy: Crop Science Society of America. 1992 [cited 17 September 2021]. Available from: https://dl.sciencesocieties.org/publications/books/tocs/ accesspublicati/cropsandman.
2. SCDB (Secretaría del Convenio sobre la Diversidad Biológica). La biodiversidad y la agricultura: salvaguardando la biodiversidad y asegurando alimentación para el mundo. Montreal, Quebec, Canada: SCDB; 2008.
3. FAOSTAT (Organización de las Naciones Unidas Para la Alimentación y la Agricultura). El futuro de la alimentación y la agricultura: tendencias y desafíos. Rome: Organización de las Naciones Unidas Para la Alimentación y la Agricultura; 2017.
4. González-Valdivia NA, Casanova-Lugo F, Cetzal-Ix W. Sistemas agroforestales y biodiversidad. AGROProductividad. 2016; 9: 56–60.
5. Terán S, Rasmussen CH. Genetic diversity and agricultural strategy in 16th century and present-day Yucatecan milpa agriculture. Biodivers Conserv. 1995; 4: 363–381.
6. Caballero-García MA, Córdova-Téllez L, De López-Herrera AJ. Validación empírica de la teoría multicéntrica del origen y diversidad del maíz en México. Rev Fitotec Mex. 2019; 42: 357–366.
7. CONABIO. Proyecto global de maíces nativos. Biodiversidad Mexicana. 2021 [cited 17 September 2021]. Available from: https://biodiversidad.gob.mx/diversidad/proyectoMaíces.
8. Sanchez JJ, Goodman MM, Stuber CW. Isozymatic and morphological diversity in the races of maize of Mexico. 2000 [cited 17 September 2021]. Available from: https://riudg.udg.mx/handle/20.500.12104/65788.
9. Rocandio-Rodríguez M, Santacruz-Varéla A, Córdova-Téllez L, López-Sánchez H, Castillo-González F, Lobato-Ortiz R, et al. Caracterización morfológica y agronómica de siete razas de maíz de los Valles Altos de México. Rev Fitotec Mex. 2014; 37: 351–361.
10. Dyer GA, López-Feldman A, Yúñez-Naude A, Taylor JE. Genetic erosion in maize’s center of origin. Proc Natl Acad Sci USA. 2014; 111: 14094–14099. https://doi.org/10.1073/pnas.1407033111 PMID: 25197088
11. Guzzon F, Arandia Rios LW, Caviedes Cepeda GM, Céspedes Polo M, Chavez Cabrera A, Muriel Figueroa J, et al. Conservation and use of Latin American maize diversity: pillar of nutrition security and cultural heritage of humanity. Agronomy. 2021; 11: 172.
12. Turrent Fernández A, Cortés Flores JI, Espinosa Calderón A, Mejía Andrade H, Serratos Hernández JA. ¿Es ventajosa para México la tecnología actual de maíz trangénico? Rev Mex Cienc Agríc. 2010; 1: 631–646.
13. Jaramillo Albuja JG, Peña Olvera BV, Hernández Salgado JH, Díaz Ruiz R, Espinosa Calderón A. Caracterización de productores de maíz de temporal en Tierra Blanca, Veracruz. Rev Mex Cienc Agríc. 2018; 9: 911–923.
14. Donnet ML, López-Becerril ID, Domínguez C, Arista-Cortés J. Análisis de la estructura del sector y la asociación público-privada de semillas de maíz en México. Agron Mesoam. 2020; 31: 367–383.
15. Moreno-Calles AI, Toledo VM, Casas A. Los sistemas agroforestales tradicionales de México: una aproximación biocultural. Bol Sci. 2013; 91: 375–398.
16. Liu W, Yao S, Wang J, Liu M. Trends and features of agroforestry research based on bibliometric analysis. Sustainability. 2019; 11: 3473.
17. Sarvade S, Singh R. Role of agroforestry in food security. Pop Kheti. 2014; 2: 25–29.
18. Cessa-Reyes V, Ruiz-Rosado O, Liliana AA. The coffee agroforestry system in Mexico. AGRO Productividad. 2020; 13: 45–52.

19. Li F, Meng P, Fu D, Wang B. Light distribution, photosynthetic rate and yield in a Paulownia-wheat intercropping system in China. Agrofor Syst. 2008; 74: 163–172.

20. Bertomeu M. Growth and yield of maize and timber trees in smallholder agroforestry systems in Claveria, northern Mindanao, Philippines. Agrofor Syst. 2012; 84: 73–87.

21. Schwerz F, Medeiros SLP, Elli EF, Eloy E, Sgarbossa J, Caron BO. Plant growth, radiation use efficiency and yield of sugarcane cultivated in agroforestry systems: an alternative for threatened ecosystems. An Acad Bras Ciênc. 2018; 90: 3265–3283. https://doi.org/10.1590/0001-3765201820160806 PMID: 30517214

22. Caron BO, Pinheiro MVM, Korcelski C, Schwerz F, Elli EF, Sgarbossa J, et al. Agroforestry systems and understory harvest management: the impact on growth and productivity of dual-purpose wheat. An Acad Bras Ciênc. 2019; 91: e20180667. https://doi.org/10.1590/0001-3765201920180667 PMID: 31778451

23. Nardini C, Sgarbossa J, Schwerz F, Elli EF, Medeiros SLP, Caron BO. Growth and solar radiation use efficiency of corn cultivated in agroforestry systems. Emir J Food Agric. 2019: 535–543.

24. Artru S, Garré S, Dupraz C, Hiel MP, Blitz-Frayret C, Lassois L. Impact of spatio-temporal shade dynamics on wheat growth and yield, perspectives for temperate agroforestry. Eur J Agron. 2017; 82: 60–70.

25. Schwerz F, Caron BO, Nardino M, Elli EF, Stolzle JR, De Carvalho LG, et al. Assessing yield, growth and climate traits in agroforestry systems in Southern Brazil. J Sustain For. 2021; 40: 169–187.

26. Pascual-Mendoza S, Manzano-Medina GI, Saynes-Vásquez A, Vásquez-Dávila MA. Agroforestry systems of a Zapotec community in the Northern Sierra of Oaxaca, Mexico. Bot Sci. 2020; 98: 128–144.

27. Vallejo M, Casas A, Blancas J, Moreno-Calles AI, Solis L, Rangel-Landa S, et al. Agroforestry systems in the highlands of the Tehuacán Valley, Mexico: indigenous cultures and biodiversity conservation. Agrofor Syst. 2014; 88: 125–140.

28. Sierra-Macías M, Andrés-Meza P, Palafoux-Caballero A, Menezes-Márquez I, Francisco-Nicolás N, Zambrada-Martínez A, et al. Variación morfológica de maíces nativos (Zea mays L.) en el estado de Veracruz, México. AGROProductividad. 2014; 7: 58–66.

29. Ortega-Paczka R. Exploraciones etnobotánicas para conocer la diversidad de maíces nativos de México. In: Ortega-Paczka R, editor. Exploraciones etnobotánicas para conocer la diversidad de maíces nativos de México. Chapingo, Estado de México: Universidad Autónoma Chapingo; 2021. pp. 39–54.

30. García E. Clasificación de climas. In: Climas de la república Mexicana (clasificación de Köppen, modificado por García) Escala 1:000 000 México. México: CONABIO Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad; 1998. p. ANEXO A.

31. INEGI. Censo nacional de transparencia, acceso a la información pública y protección de datos personales estatal 2019. 2019 [cited 17 September 2021]. Available from: https://www.inegi.org.mx/programas/cntaippdppe/2019/.

32. Martínez AD. Ecofisiología del cultivo de maíz. In: Alberto GJ, Cruz CJ, editors. El cultivo de maíz en San Luis. Argentina: INTA Ediciones; 2015. pp. 7–31.

33. Descriptors for Maize. CIMMYT/IPBGR. 1991 [cited 17 September 2021]. Available from: https://scholar.google.com/scholar_lookup?q=Descriptors+for+maize.

34. Ángeles-Gaspar E, Ortiz-Torres E, López PA, López-Romero G. Caracterización y rendimiento de poblaciones de maíz nativas de Molcazac, Puebla. Rev Fitotec Mex. 2010; 33: 287–296.

35. Mantino A, Volpi I, Micci M, Pecchioni G, Bosco S, Dragoni F, et al. Effect of tree presence and soil characteristics on soybean yield and quality in an innovative alley-cropping system. Agronomy. 2020; 10: 52.

36. Rawlings JO. Applied regression analysis: a research tool. Pacific Grove, California: Advanced Books & Software; 1988.

37. SAS (Statiscal Analysis System). SAS user’s guide: statistics. Cary, NC: SAS Institute; 2004.

38. Gabriel KR. The biplot graphic display of matrices with application to principal component analysis. Biometrika. 1971; 58: 453–467.

39. Pla LE. Análisis multivariado: método de componentes principales. Washington, DC: Secretaria General de la Organización de los Estados Americanos; 1986.
40. Martuscello JA, Jank L, Gontijo Neto MM, Laura VA, De Noronha Figueiredo Vieira Da Cunha D. Produção de gramíneas do gênero Brachiaria sob níveis de sombreamento. Rev Bras Zootec. 2009; 38: 1183–1190.

41. Caron BO, Elli EF, Behling A, Eloy E, Schmidt D, Stolzle J. Growth of tree species and sugarcane production in agroforestry systems. An Acad Bras Ciênc. 2018; 90: 2425–2436. https://doi.org/10.1590/0001-3765201820170313 PMID: 30066745

42. Pérez-Vázquez A, Hernández-Salinas G, Ávila-Reséndiz C, Valdés-Rodríguez O, Gallardo-López F, García-Pérez E, et al. Effect of the soil water content on Jatropha seedlings in a tropical climate. Int Agrophysics. 2013; 27: 351–357.

43. Pecina-Martínez JA, Mendoza-Castillo MC, López-Santillán JA, Castillo-González F, Mendoza-Rodríguez M. Respuesta morfológica y fenológica de maíces nativos de Tamaulipas a ambientes contrastantes de México. Agrociencia. 2009; 43: 681–694.

44. Rincón-Tuexi, Castro-Nava S, López-Santillán JA, Huerta AJ, Trejo-López C, Briones-Encinia F. High temperature and water stress during flowering in tropical corn populations. Phyton. 2006; 75: 31–40.

45. Purroy-Vásquez R, Ortega-Vargas E, Hernández-Santiago Q, Ángel-Piña OD, Meza-Hernández J, Reyes-Santiago B, et al. Maize small-scale agroecosystems in the high Huasteca region of Veracruz: economic-energetic efficiency and poverty. Agric Soc Desarro. 2019; 16: 105–121.

46. Reynolds PE, Simpson JA, Thevathasan NV, Gordon AM. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecol Eng. 2007; 29: 362–371.

47. Simon-Gruita A, Pojoga MD, Constantin N, Duta-Cornescu G. 14—genetic engineering in coffee. In: Grumezescu AM, Holban AM, editors. Caffeinated and cocoa based beverages. Sawston, United Kingdom: Woodhead Publishing; 2019. pp. 447–488.

48. Gepts P. Tropical environments, biodiversity, and the origin of crops. In: Moore PH, Ming R, editors. Genomics of tropical crop plants. New York, NY: Springer; 2008. pp. 1–20.