Wet Agriculture in the Lowlands: Maize Marceña

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Core Ideas
• The milpa marceña is an ancient maize agrosystem on herbaceous wetlands “popals” in the dry season.
• Three improved maize cultivars and the traditional cultivar mején were evaluated.
• The mején cultivar showed the highest performance.
• The milpa marceña is compatible with the hydrological dynamics of wetlands and without the use of industrial inputs.

ABSTRACT
Although herbaceous wetlands are one of the most productive ecosystems and their functions provide benefits to humankind, they have been subjected to a number of disturbances over the past 65 yr. Wetlands have been drained to convert them into permanent agricultural land and urban areas, or used by the oil industry or for construction of hydroelectric dams. Moreover, little has been done to innovate the milpa marceña, an ancient maize (Zea may L.) agrosystem on herbaceous wetlands dominated by hojilla (Thalia geniculata f. rheamoides) named popals in the dry season (March–June). From an agroecological perspective for improving milpa marceña, in a popal soil (Eutric Molic Gleysol), three improved maize cultivars (CP-560, CP-561, and CP-562) and the traditional cultivar mején were evaluated under three planting densities (50,000, 53,000, and 60,000 plants ha–1) with no use of mineral fertilizers, herbicides, or pesticides. The results show that precipitation during the milpa marceña growth cycle was 50% lower than the amount required for a successful maize crop (>1 Mg ha–1), hence avoiding the risk of flooding. Maize cultivars take groundwater and nutrients from popal soil; however, these results suggest that cultivars were subject to N deficiency and water stress in the flowering stage. We concluded that the mején cultivar showed the highest performance, with 3.3 Mg ha–1, i.e., it has attributes not previously considered (e.g., plant × microbe interactions) in plant breeding programs for drought-tolerant or flood-tolerant cultivars. There is a need for further research and conservation on the use of popals.

Wetlands are global biodiversity hotspots and cover at least 6% of the Earth’s surface (Junk et al., 2013); however, a realistic estimate is that 50% of wetlands have been lost worldwide (Verhoeven and Setter, 2010). In Mexico, wetlands in the states of Veracruz, Tabasco, and Campeche are recognized among the most outstanding systems of their kind (Olmsted, 1993; Mitsch and Hernandez, 2013). Wetlands are transitional fringes between terrestrial and aquatic ecosystems, characterized by the saturation of soil and either temporary or permanent flooding, a condition that favors the development of aquatic vegetation (Neiff et al., 1994; Blumenfeld et al., 2009; Ramsar Convention Secretariat, 2013). Wetland productivity is sustained by the sediments and nutrients deposited when rivers overflow; in addition, the population of different cultures depends on wetlands (Ramsar Convention Secretariat, 2013; Evers et al., 2017; Sabo et al., 2017). Although wetlands are one of the most productive ecosystems, their importance in the carbon cycle and other environmental services has not been considered in regional development (Neiff et al., 1994; Blumenfeld et al., 2009; Ramsar Convention Secretariat, 2013; Evers et al., 2017).

In Tabasco, "popal" herbaceous wetlands are one of the remaining agricultural frontiers (West et al., 1969; Olmsted, 1993; Mitsch and Hernandez, 2013). However, popals have been incorporated into conventional agricultural production through drainage systems, without considering alternative uses that are still practiced today (Neiff et al., 1994; Brown, 2005; Verhoeven and Setter, 2010; Junk et al., 2013; Evers et al., 2017). The results have not been as successful as expected, since the organic and fertile soil horizon has been removed...
along with water, leaving a hard clay layer that hampers internal drainage, mechanization, and agricultural activities (Verhoeven and Setter, 2010). The use of popal in Mexican lowlands is ancient (West et al., 1969; Coe and Diehl, 1980; Pope et al., 2001; Pohl et al., 2007). The various traditional uses of popal wetlands by native peasants while preserving their characteristics consist in maize (Zea mays L.) agroecosystems so-called “milpa marceña” or chamil (Fig. 1; Drucker and Heizer, 1960; Coe and Diehl, 1980; Gliessman, 1998; Brown, 2005). This agriculture modality yields either similar to or higher-than-average summer (“temporal” or rainy season) and winter (“tornamilt”) maize cycles due to the high soil fertility, low incidence of weeds, good residual moisture, and higher illumination associated with the March–June season of the year. However, despite the fact that sustained crops are obtained through time, little research has been conducted on the improvement of this agroecosystem (Neiff et al., 1994; Verhoeven and Setter, 2010). For this reason, the present work aimed at evaluating the planting of marceña maize including four maize cultivars and three planting densities.

**MATERIALS AND METHODS**

**Location and Selection of the Study Area**

The study was conducted in a popal comprising 500 ha at Ejido Santa Teresa (municipality of Cárdenas, Tabasco, Mexico) where marceño maize is traditionally grown. This popal is located between coordinates 93°24′56.21″ W and 17°59′50.05″ N (Fig. 2), at 9 m asl along the margins of 2.5 km of the Cárdenas–Coatzacoalcos segment of the 189 Gulf Circuit federal highway, within the 350,000 ha of the drainage Plan Chontalpa project of 1965. An area of 20 ha was selected for the study, which included the original popal herbaceous vegetation dominated by hojilla (Thalia geniculata f. rheumoides).

The current soil type in the popal is Eutric Molic Gleysol (IUSS-WRB, 2006). The natural soil develops on fine alluvial sediments accumulated by recurrent floods (lasting 6 mo in the rainy season) on low alluvial plains located on the right bank of the Seco River in the Mezcalapa River Delta (West et al., 1969). The texture is clayey (49.1% clay, 32.1% silt, 18.8% sand), with very poor drainage, slightly acid (pH 6.2), and very high concentrations of Mo (25.4%), N (1.3%), P (27.9 mg kg⁻¹), K (1.4 cmolc kg⁻¹), Ca (55.9 cmolc kg⁻¹), Mg (14 cmolc kg⁻¹), Na, (1.1 cmolc kg⁻¹), CEC (34.5 cmolc kg⁻¹), and with no salinity issues (<0.11 dS m⁻¹).

The weather statistics for the study area (1961–2003) indicate a climate characterized by an annual precipitation and evaporation of 2131.1 and 1098.8 mm, respectively (Díaz-Padilla et al., 2006). The mean annual temperature is 26.3°C, with a maximum of 31.9°C (May) and a minimum of 20.7°C (January); the mean relative humidity is 90%. The marceño maize cycle records an average of 5.7 d of rainfall, equivalent to 91.68 mm of precipitation and 116.9 mm of evaporation, resulting in a water deficit of −25.22 mm during the dry season.

**Experimental Site**

This study involved the participation of a cooperating farmer that grows marceño maize since 1965. The experiment was conducted over an area of 3008 m² (47 × 64 m) in his plot of land.

**Experimental Design**

A split-plot design was selected, were the large plots (20 × 10 m) corresponded to three planting densities (6.0, 5.3, and 5.0 plants m⁻²) and small plots (10 × 3 m) to four maize genotypes. Each experimental unit was 10 m long and 3 m wide and consisted of three rows.
The plating method and cultural tasks were performed according to the traditional marceño maize crop system practiced in La Chontalpa region, Tabasco. The cooperating producer performed crop management; the researchers provided the inputs (seeds) and recorded the data.

1. Cultivars. The maize genotypes evaluated were the improved cultivars and the traditional mején cultivar. Three improved open-pollinated tropical cultivars CP-560 (Tuxpeño ground floor), CP-561 (white tropical mix), and CP-562 (La Posta) were developed (alternating combined family selection) at the Colegio de Postgraduados (Mejía-Conteras and Molina, 2002) from CIMMYT populations (family selection of whole sibling); whereas the mején cultivar is a short-cycle (75–90 d) variant derived from the Tuxpeño (Gulf Coast) and Olotillo (Yucatan Peninsula Dzit-Bacal) races, characterized by corn-cobs with thin and flexible rachis (bacal), and large heavy grains.

2. Planting density. The planting densities used were 60,000, 53,000, and 50,000 plants ha⁻¹; five, four and three seeds were sown separated by 0.5, 0.75, and 1.0 m on 1.0-m wide rows, respectively.

3. Popal slashing. Popal plants of the plot were slashed with a machete in the first week of March, when the plot showed a sheet of water of 4.8 ± 6.5 cm above the soil surface.

4. Burning. Twenty days after popal slashing, once the foliage was dry, a 1-m wide guardarraya (strip of land devoid of vegetation to prevent fire from spreading out of the plot) was prepared around the plot. This practice aims to remove the dry foliage, litter, and in general all foreign materials to facilitate seed planting and the labor involved in maize cultivation. It also serves to reduce the populations of some pests (insects, snakes, rodents, and others).

5. Planting. The planting was performed using the planting stick or espeque method. This wooden stick with a sharp tip (5–8 cm thick and 120–160 cm long) was used to drill 5- to 9-cm deep holes and deposit the number of seeds at the corresponding planting density and leave them almost uncovered.

6. Weeding. Manual wedding was performed 30 to 35 d after planting using a “sweeping” machete; weeds and popal shoots with an average height of 350 ± 7.9 cm were cut at ground level. Prior to the harvest, to facilitate the entry of farmers and prevent the access of mice to corncobs, another light manual weeding (chapoleo) was carried during plant bending, whereby the plot was ready for the harvest.

7. Fertilization. No mineral fertilizer of any kind is usually applied in this agroecosystem.

8. Plant bending. When maize plants reach physiological maturity (90 d), individual plants are bent just below cobs, so these remain hanging and thus protected against rain and predator.

9. Pest and disease control. Mice (Rattus sp.), ants, birds (Quiscalus mexicanus), and the fall armyworm (Spodoptera frugiperda Smith) were the most common pests that damaged maize seeds and seedlings.

The response variables recorded in each replicate of the treatments evaluated maize cycle were the following:

1. Planting density was recorded at Day 37 after sowing, by counting the total number of plants of each genotype in each experimental unit.

2. Then, the percentage of damage by fall armyworm, anthesis, plant and cob height, number of leaves, and spontaneous or natural bent percent (acame) were recorded at Days 45, 70, 80, and 92, selecting 10 plants from the central row of each replicate of each of the treatments evaluated.

3. Corncobs were harvested (pizca) on Day 125 of planting and placed in plastic bags (30–50 kg) labeled with the respective treatment. In the laboratory, cobs were threshed and grains were dried (63 ± 3°C for 72 h) and weighed.

4. Records of climatic variables (precipitation, evaporation, and temperature) were obtained from the meteorological station at Colegio de Postgraduados-Campus Tabasco (CEW-75).

5. The water table was recorded every 30 d in a piezometric well located within the experimental plot.

The results were analyzed using a two-way ANOVA to test for differences between treatments in the number of plants, damage by fall armyworm, anthesis, plant and cob height, number of leaves, natural bent, and grain production. In all the ANOVAs, significant differences between means were analyzed with the Tukey’s HSD test. The statistical analysis was performed using the Statistica software.

**RESULTS**

**Weather.** In the 90 d of the marceño maize growth cycle, rainfall only occurred in 9 d (1 d in May, 6 d in June, and 2 d in July), for a total of 223.0 mm of precipitation and 356.2 mm of evaporation, which represent a water deficit of –133.2 mm. Mean temperature during the crop cycle was 31.1°C, with a maximum and a minimum of 38.5 and 23.0°C, respectively.

**Plant Density.** At Day 40 after planting, plant density was lower than sown density (60,000, 53,000, and 50,000 plants ha⁻¹; Table 1). The actual plant population varied significantly across the planting density evaluated ($F = 4.1, P = 0.025$). Low and intermediate plant densities were similar (32,583 ± 5,793 and 35,854 ± 8,470 plants ha⁻¹, respectively), whereas the high plant density was 39,375 ± 6,269 plants ha⁻¹.

**Fall Armyworm.** The variation in the percentage of plants damaged by fall armyworm was similar between maize cultivars.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Plant density</th>
<th>Height Plant</th>
<th>Height Cob</th>
<th>No. of leaves</th>
<th>Flowering</th>
<th>Spontaneous bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mején</td>
<td>39,056 ± 8,229 a</td>
<td>218.3 ± 18.3 c</td>
<td>141.8 ± 18.3 c</td>
<td>18.9 ± 1.2 b</td>
<td>60.6 ± 6.3 a</td>
<td>14.3 ± 12.2 a</td>
</tr>
<tr>
<td>CP-560</td>
<td>35,917 ± 6,880 a</td>
<td>172.5 ± 17.5 a</td>
<td>98.6 ± 13.9 a</td>
<td>17.1 ± 1.5 a</td>
<td>93.3 ± 3.5 b</td>
<td>13.2 ± 5.9 a</td>
</tr>
<tr>
<td>CP-561</td>
<td>36,333 ± 7,259 a</td>
<td>166.4 ± 25.8 a</td>
<td>100.8 ± 13.8 ab</td>
<td>16.7 ± 1.5 a</td>
<td>91.5 ± 8.1 b</td>
<td>9.5 ± 4.8 a</td>
</tr>
<tr>
<td>CP-562</td>
<td>32,444 ± 6,240 a</td>
<td>188.8 ± 23.3 b</td>
<td>110.8 ± 19.0 b</td>
<td>17.6 ± 1.3 a</td>
<td>65.0 ± 4.6 a</td>
<td>8.9 ± 5.7 a</td>
</tr>
</tbody>
</table>

*Table 1. Plant density and morphological parameters of the three improved maize (CP-560, CP-561, CP-562) and the traditional mején maize in the milpa marceña. In each column, different letters indicate significant differences at $P < 0.05$ (Tukey’s HSD).*
At Day 45 after planting, 78.3% of plants of the four maize cultivars evaluated suffered foliar damage by the fall armyworm.

**Plant Height.** Plant height differed significantly between maize cultivars ($F = 35.01, P = 0.0001$). Plant height in the mején cultivar surpassed all the genotypes evaluated (26.6, 31.2, and 15.6%), i.e., the shortest genotypes were CP-560 and CP-561, whereas CP-562 showed an intermediate height, respectively (Table 1).

**Number of Leaves.** Significant differences were observed between maize cultivars in terms of number of leaves ($F = 14.38, P = 0.0001$). The mején maize was the cultivar that had a significantly greater number of leaves (10.4%) relative to the improved cultivars CP-560, CP-561, and CP-562 (Table 1).

**Cob Height.** Cob height differed significantly between maize cultivars ($F = 44.08, P = 0.001$). Cob height in the mején cultivar was significantly taller (43.8, 40.7, and 7.4%) relative to cultivars CP-560, CP-561, and CP-562, respectively (Table 1).

**Number of Senescent Leaves.** The variation in the percentage of senescent leaves was similar between maize cultivars. At Day 65 after planting, the four cultivars showed a similar average number of senescent leaves (>50% of dry leaf area), with an average of 10 leaves below cob height.

**Flowering.** The mean flowering differed significantly between maize cultivars ($F = 25.75, P = 0.0001$). At Day 60 after planting, 92.4% of plants in the improved cultivars CP-560 and CP-561 reached the anthesis stage; in comparison, only 62.8% of plants from cultivar CP-562 and the mején had flowered (Table 1).

**Natural Bending.** The variation in the percentage of bent plants was similar between genotypes. At the end of the experiment (120 d), the average percentage of natural bent plants was similar (range from 8.9 to 14.3%) between the four cultivars evaluated (Table 1).

**Grain Yield.** Genotype significantly influenced maize yield ($F = 3.47, P = 0.025$). The highest average grain production was observed in CP-560 and the mején cultivars, representing a 17 and 10% increase in production, respectively, vs. cultivars CP-561 and CP-562 (Fig. 3).

**DISCUSSION**

The planting density of maize has changed with time, from 3 to 18 plants m$^{-2}$ on average; however, the potential yield per plant has remained unchanged (Hammer et al., 2009; Li et al., 2015; Xue et al., 2016). The results indicate that in areas where fire did not burn the foliage (*T. geniculata*)—or where sown seeds were either damaged and/or consumed by rodents, ants, or birds—there was a 34% reduction in the three densities planted. Also, results showed that when planting at high densities, regardless of the improved cultivars (CP-560, CP-561, and CP-562), manual weeding needs to be done carefully to avoid damaging maize plants. In addition, the improved cultivars planted due to their low foliar coverage at a low planting density are associated with a greater loss of soil moisture through evaporation. Due to their lower height, the improved cultivars tend to lower the risk of natural bending or tilting due to the effect of wind and rain, whereas the native maize is more susceptible to these damages. In contrast, when the improved cultivars are bent, the cobs are exposed (close to the soil surface) to the attack of rodents, whereas the cobs of the native cultivar are less likely to being consumed. In contrast, the four cultivars were susceptible (without applying pesticides) to the attack of the fall armyworm.

The tropical regions of Mexico and the world are continuously exposed to drought and N deficiency (Bodner et al., 2015). In the current popal soil (Eutric Molic Gleysol), high-activity clays accumulate nutrients, and high amounts of organic matter from the popal are deposited in the rainy season (historical and annual flooding). In the dry season, maize plants in the *milpa marceña* take groundwater and nutrients from the soil for plant growth and development. Plants extract more water and nutrients in the upper 70 cm of soil because most of the roots are located in this zone (Bänzinger et al., 2000; Bouffaud et al., 2012; Lynch, 2013). In here, during anthesis and grain filling, the water table was deeper (average of 1.2 m) than the maize root zone, i.e., the four maize cultivars were subjected to water stress and this restrained the use of the available N (an average 238.1 Mg ha$^{-1}$; Tiessen et al., 1982) in the soil.
Our results show that precipitation during the milpa marceña growth cycle was <50% of the lower limit of the seasonal precipitation (400–500 mm) required for a successful maize crop (>1 Mg ha⁻¹) in tropical lowlands (Bänzinger et al., 2000). That is, cultivating milpa marceña in the dry season avoids the risk of flooding, contrary to what has been proposed (Coe and Diehl, 1980; Arnold, 2009). Water deficiency in soil affects the flowering and seed-growth of maize (NeSmith and Ritchie, 1992; Chapman et al., 1997; Sangoi and Salvador, 1998; Daryanto et al., 2016). For example, when drought occurs during these stages, both leaf area and photosynthesis rate decrease, and leaf senescence accelerates (Sangoi and Salvador, 1998; Bänzinger et al., 2000). In this study, the four maize cultivars recorded a 54.4% leaf senescence below cobs in Day 65; however, given its greater number of leaves and leaf area, the mején cultivar showed a higher photosynthesis rate than the improved cultivars. Trachsel et al. (2016) observed that in maize plants established in the summer, anthesis occurred on average at Days 57.6, 60.8, and 60.4 under optimal conditions, N deficiency, and extreme temperature, respectively. Moreover, for each degree of temperature above 30°C, grain yield drops by 40% under water stress and high temperature (Lobell et al., 2011). In this regard, the three improved (82.7%) and the mején (60.6%) cultivars reached the anthesis stage at Day 60 under a water deficit of 133.2 mm and a mean temperature of 31.1°C. Some farmers manage water stress during anthesis through the date of planting; for instance, planting was late in this study, since the normal planting season starts 20 to 30 d earlier (Bodner et al., 2015). Supplementary irrigation is also practiced, by hand drilling wells (1.5- to 2.0-m depth) in parcels to extract water and pour it on each individual plant.

Bänzinger et al. (2000) suggested that maize under drought stress is produced with a N deficiency (adsorption of 20–50 kg ha⁻¹) because of the slow net mineralization rate. That is, N adsorption is associated with grain yield ($r > 0.9$) because of its presence in photosynthetic enzymes. When evaluating elite maize variants in six regions under multiple conditions of abiotic stress, Trachsel et al. (2016) reached an average yield of 6.2 and 2.15 Mg ha⁻¹ under optimal conditions and drought and N deficiency, respectively. The results of this study showed that the traditional mején cultivar yielded 3.3 Mg ha⁻¹, a production that was significantly higher (18.5%) than that of the improved cultivars (CP-560, CP-561, and CP-562, equivalent to 45–60% of yield under no stress conditions; Mejía-Cortesas and Molina, 2002), but similar to the maize–mucuna rotation agroecosystem practiced in southeastern Mexico and Latin America (Ortiz-Ceballos et al., 2012, 2015; Pacheco-Cobos et al., 2015). Also, the traditional mején cultivar reached an average yield higher than the obtained in lowland milpas of the Mexican tropics (Donnet et al., 2017).

All the above suggests that the traditional mején cultivar has attributes that have not been considered in plant breeding programs. More than 11 races have been recorded in the lowlands of southeastern Mexico, which are adapted to the abiotic and biotic constraints and which could be used for cross-breeding with high-productivity elite lines to achieve resistance to drought and N deficiency (Orozco-Ramírez et al., 2017). This suggests that replacing traditional cultivars with improved cultivars is seemingly an inadequate strategy for low-income farmers. Mexico is the center of origin and genetic diversity for maize (Ruiz-Corral et al., 2008; Perales and Goličer, 2014). The comparison of traditional vs. improved cultivars revealed that the beneficial interactions between plant and soil biota may have been lost by the supply of high amounts of easily available nutrients (Bouffaud et al., 2012; Chen et al., 2015; Szoboszlay et al., 2015; Pérez-Jaramillo et al., 2016; Hochholdinger et al., 2018). For this reason, the popal is a suitable agroecosystem to assess the plant root systems potential for adaptation to various stresses (flooding and drying) and nutrient uptake (Lynch, 2013; Ryan et al., 2016; Coskun et al., 2017), and the interactions between plant rhizosphere and soil biota (McCully and Boyer 1997; Sasse et al., 2018; Van Deynze et al., 2018).

In conclusion, the maize cultivars studied were drought-tolerant, with the traditional mején cultivar achieving the highest yield. These results show that the milpa marceña is suitable for conducting tests on plant–soil biota interactions under drought stress and N deficiency. The marceña milpa is a sustainable agricultural system, it does not harm the environment (without the use of industrial inputs), and is compatible with the hydrological dynamics of wetland popal.

ACKNOWLEDGMENTS

The authors thank Mario M. Osorio-Arce, Angel Ramos-Sánchez, and Efrain Hernández-Xolocotzi, promoters of agroecology in southeastern Mexico. We thank Olaf Jaime-Riverón and Nicolás Granados-Álvarez for helpful suggestions. In addition, the authors are grateful to four anonymous reviewers and Diana Pérez-Staples for valuable comments and careful revision of the manuscript. We thank Dinesh Rao and René A. Paléstina-Guerrero for support in the design of figures 1 and 2, respectively.

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