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Revisiting plant density by environment interaction in maize across contrasting sowing dates

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ABSTRACT

Context: The definition of the agronomic optimum plant density (AOPD) in maize is a critical management practice due to seed cost and impact on final yield. Farmers often reduce plant density when planting later in the season because of the lower expected yield compared to earlier plantings. However, this practice may lead to lost yield opportunities that need to be quantified.

Objectives: Our objectives were i) to understand how farmers define maize plant density for different planting dates and, ii) to explore the yield response to plant density in early and late plantings across a range of yield environments (YE).

Methods: We explored maize on-farm records (2017–2021; n = 25,143 fields) and field experiments (n = 491 paired comparisons) across Argentina under early (ESM) and late (LSM) plantings to characterize plant density used by farmers and attainable yields at contrasting sowing dates. Then, we conducted field experiments across different YEs, where several commercial genotypes were tested at different plant densities under both ESM (n = 39 location-years) and LSM (n = 54 location-years).

Results and conclusion: The proportion of area with ESM and LSM varied across regions and YEs in Argentina. Farmers usually chose higher plant densities at ESM than LSM, but not necessarily ESM always out-yielded LSM in the study region. Maize response to plant density varied depending on the YE, with no apparent difference between sowing dates.

Implications: Although practical reasons often justify reducing plant density in later planting, farmers should base their decisions about the AOPD based on the expected YE regardless of the planting date. Accurately predicting the YE should therefore be a key priority to optimize yields and resource allocation. The expected yield in later planting seems to be currently underestimated by farmers.

1. Introduction

Argentina ranks as the fourth largest global producer of maize (*Zea mays* L.) and the second largest exporter. In recent years, the country's maize production systems have undergone significant transformations (Satorre and Andrade, 2021). A key agronomic shift has been the diversification of maize planting dates, with traditional early spring planting (late September to early October) being extended into late

Abbreviations: ESM, early-sown maize; LSM, late-sown maize; AOPD, agronomic optimum plant density; YE, yield environment.

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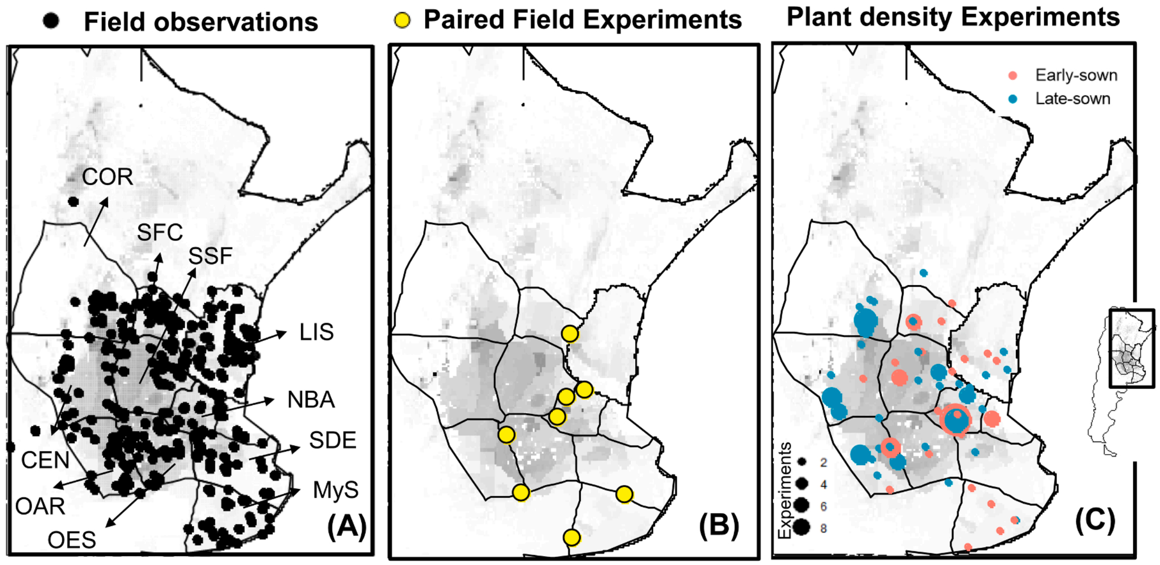

Fig. 1. Geographical distribution of the different databases involved in this study. (A) Maize on-farm records across 2017–2021; (B) Paired early and late-sown maize field experiments and, (C) Locations and number of experiments per location of genotype x plant density x sowing date maize experiments. The grey area represents the sown area of maize derived from https://mapspam.info/data/. The letters inside each region represent the acronym used to name each region (MyS: Mar y Sierras; SDE: Sudeste; OES: Oeste; OAR: Oeste Arenoso; NBA: Norte de Buenos Aires; SSF: Sur de Santa Fe; CEN: Centro; COR: Córdoba Norte; SFC: Santa Fe Centro; LIS: Litoral Sur).

spring (late November to early December). These distinct planting systems are commonly referred to as early-sown maize (ESM) and late-sown maize (LSM), respectively (Otegui et al., 2021). The Central region of Argentina currently accounts for a significant portion of the country's maize production (Otegui et al., 2021). In this region, ESM maximizes yield potential and reduces the risk of frost during the grain-filling stage (Otegui et al., 1996, 1995). Meanwhile, LSM often benefits from more favorable water conditions during grain number determination (Maddonni, 2012), mitigating the effects of soil limitations and interannual climate variability (Florio et al., 2014; Otegui et al., 2021). These advantages have allowed LSM to expand maize production into more restrictive environments across Argentina (Rotili et al., 2019). However, LSM adoption is not confined to low-yield areas; it is also a common choice in high-yield environments as part of current crop rotation schemes (Vitantonio-Mazzini et al., 2020).

Actual farm-level yields can still be improved by adjusting the agronomic management for an expected target environment for ESM and LSM (Vitantonio-Mazzini et al., 2020). It is well documented that yields can be increased by managing key agronomic factors such as genotype choice (Baum et al., 2019), plant density and nitrogen fertilization (Schwalbert et al., 2018), among others. However, these practices interact with environmental conditions and/or sowing dates (Baum et al., 2019; King et al., 2024), adding complexity to farmers' decision-making processes (Vitantonio-Mazzini et al., 2020). Farmers are aware of this, which has become increasingly relevant due to the recent extension of the maize sowing window in Argentina. As a result, understanding the differential effects of management options in ESM and LSM has garnered significant interest (Vitantonio-Mazzini et al., 2020).

Plant density management is a key strategy for managing maize yield variability and reducing yield gaps (Winans et al., 2021). Maize grain yield typically follows a quadratic response to variations in plant density, with an agronomic optimum plant density (AOPD) that maximizes yield (Assefa et al., 2018; Lacasa et al., 2020). The existence of an AOPD is tied to maize's reproductive plasticity in response to resource availability (Sarlangue et al., 2007; Vega et al., 2001), and incorrect plant density selection can lead to both yield and economic losses (Lacasa et al., 2020). Additionally, AOPD varies with other management practices such as genotype selection (De Bruin et al., 2023; Hernández et al., 2014) and sowing date (Vitantonio-Mazzini et al., 2020). Moreover, the AOPD increases in environments with higher resource supply for the crop, either radiation (Muchow et al., 1990), water (Echarte et al., 2023) or nitrogen (Boomsma et al., 2009), which can be termed as yield environment (YE), where higher environmental resource offer determines higher YEs (Assefa et al., 2018; Lacasa et al., 2020). Understanding the variability in AOPD is particularly important for maize management due to high seed costs and the different quadratic yield response to plant density across YEs (Hernández et al., 2014; Lacasa et al., 2020; Sarlangue et al., 2007).

Farmers often select a higher AOPD for a given genotype in ESM compared to LSM, as LSM is generally expected to yield less than ESM (Otegui et al., 1995). However, some regions in Argentina report similar (Vitantonio-Mazzini et al., 2020) or even higher (Rotili et al., 2019) yields in later plantings. This situation complicates farmers' decisions regarding the AOPD for different sowing dates, and previous studies did not resolve this plant density × sowing date × environment interaction (Gambin et al., 2016; Vitantonio-Mazzini et al., 2020). This is a critical question for farmers, but it remains partially addressed in previous research.

More information is needed to reduce uncertainty in selecting the optimal AOPD across environmental conditions in regions with a wide sowing window. It remains unclear whether farmers should adjust maize plant density based on sowing dates, the expected YE, or both. We hypothesized that AOPD is primarily influenced by the expected YE, irrespective of the sowing date. The objectives of this study were: i) to understand how farmers define the plant density for different planting dates and, ii) to explore the yield response to plant density in early and late plantings across a range of YE.

2. Materials and methods

Three different datasets were used for the analysis (Fig. 1): (i) farmers' field observations, (ii) paired field experiments and (iii) stand density experiments. The studied area covered most of the Central Argentina, from 30° to 39° S and from 58° to 65° W (Fig. 1). Soils, weather and maize agronomic management vary across regions (Andrade and Satorre, 2015; Aramburu Merlos et al., 2015). Details of each data set are provided in the following sections.

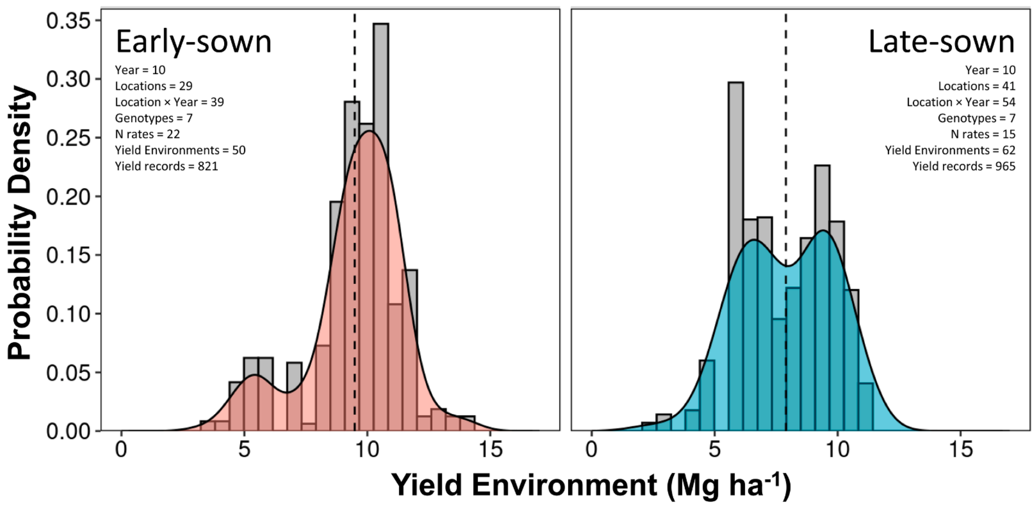

Fig. 2. Probability density of yield environment for early and late-sown maize for plant density field experiments in Argentina. An environment was defined as the combination of location x year x nitrogen rate separately for each sowing date. Dashed line represents the mean of each sowing date.

2.1. Farmers' field observations

Farmers' maize production records were provided by DAT-CREA (https://www.crea.org.ar/dat-crea/), the agricultural traceability database belonging to the Regional Consortiums for Agricultural Experimentation (CREA), a non-governmental organization. Their members meet monthly in regional groups to share experiences and information, while also generating technology and knowledge for the sustainable development of companies (https://www.crea.org.ar/). Thus, farming systems within each region share not only edaphoclimatic conditions but also the guidelines for crop management. The database consisted of observations of maize management records of five years (2017–2021) from ten CREA regions (Fig. 1A). Each observation corresponded to an individual paddock managed independently for a particular year (hereinafter called field).

The database involved 13,923 (722,819 ha) and 11,850 (819,247 ha) individual fields for ESM and LSM, respectively. The variables extracted from this database were region, sowing date, YE class (i.e. high, intermediate and low yield potential), individual field area (ha), sown plant density (pl. m^{-2}) and grain yield at 14.5 % moisture (Mg ha^{-1}). Fields were further classified into ESM and LSM according to sowing date (i.e. before and after the 20th of November, respectively). Likewise, maize fields with water table influence were classified into a different YE class, due to their differential effects on ESM and LSM yield (Vitantonio-Mazzini et al., 2020). A very high proportion of the area corresponding to ESM was sown between September 20th and October 10th, as well as between November 20th and December 10th for LSM (data not shown). Also, the YE of each field was defined by CREA farmers supported by hired agronomists based on soil toposequence and the historic yield. High-yield potential fields are expected to yield more than medium and low-potential fields. The environmental potential assessment is intrinsic to each region or to the same climatic regime. This classification was also used in previous agronomic studies (Leguizamón et al., 2023).

For each region and YE class, the average annual share of the area (%), average plant density used by farmers and average yield across years were separately calculated for ESM and LSM. Also, for a better understanding of the current plant density choices according to the YE by farmers, a linear regression model was fitted between sown plant density and average yield for ESM and LSM. Regression models for ESM and LSM were compared to evaluate if farmers change their sowing density-YE decision based on sowing date. Additionally, a 90th percentile quantile regression was fitted considering both sowing dates.

2.2. Paired field-experiments with contrasting sowing dates

We retrieved publicly available data of multi-environmental trials that evaluated grain yield of both ESM and LSM for different commercial genotypes under the same location × year, hereafter called paired field-experiments (Fig. 1B). Those experiments were conducted at the "Mar y Sierras" region (from 2010 to 2016), the "Oeste Arenoso" and "Oeste" regions (from 2004 to 2020), the "Norte de Buenos Aires" region (from 2009 to 2021) and the "Sudeste" region (from 2014 and 2015) by public or private organizations that promote research projects and agronomic innovations in the region, like the National Institute of Agricultural Research (INTA) and private consultants. Depending on the region, the experiments had three or two replicates per genotype in each sowing date. Grain yield (Mg ha^{-1}) was reported at 14.5 % moisture.

Genotypes at each site-year were not always the same, but they were representative of maize commercial germplasm sown by farmers. Only a proportion of them appeared on both sowing dates. This dataset involved 491 genotype-site-year combinations of ESM *versus* LSM in paired field experiments. In those experiments, biotic adversities were effectively controlled, no reporting major effects on crop productivity neither frost damage nor major lodging events. Other management practices (e.g. nitrogen fertilization) followed similar ones used by farmers near the experimental site. We compared the yield difference between ESM and LSM using the paired field experiments. Positive values resulting from that relationship show specific site × year where ESM presents a higher yield than LSM and the opposite occurs with negative values.

2.3. Plant density experiments

Yield response to plant density experiments were conducted by the seed company GDM under rainfed conditions from the 2010 to the 2021 growing seasons, both for ESM and LSM in Argentina (Fig. 1C). At each experiment, several genotypes belonging to GDM's commercial portfolio were grown at different plant density treatments. In each field experiment, farmers performed all field operations, including planting, fertilizer applications, herbicide spraying, and harvesting. The plots had 200–300 m^{-2} each.

The range of plant density treatments was from 3 to 11 pl. m^{-2} for both planting dates. We evaluated 39 and 54 location-year combinations for ESM and LSM, respectively (Fig. 2). Additionally, several experiments included nitrogen rates as an extra treatment. In those cases, as nitrogen availability can be considered as a modifier of the environmental resource offer, each nitrogen rate was considered as a different

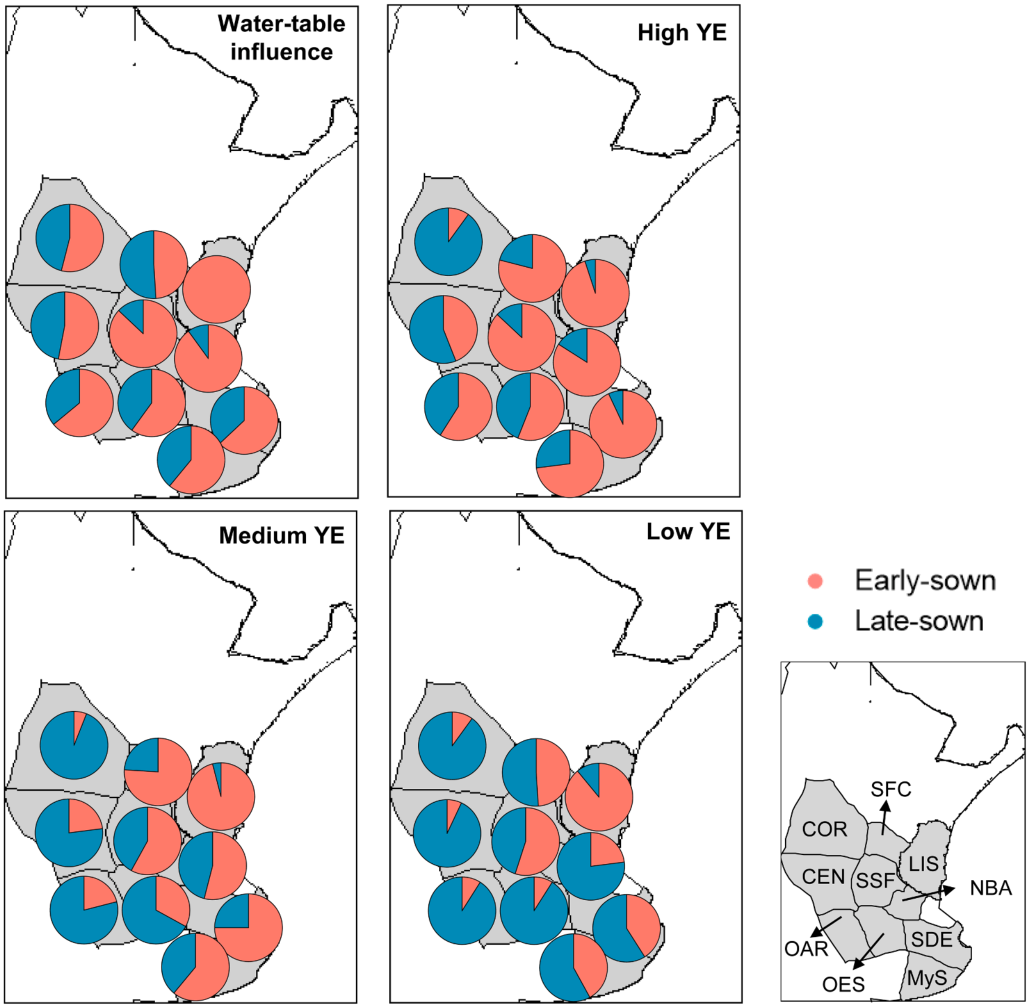

Fig. 3. Average annual proportional share of maize area between 2017 and 2021 for early and late-sown at on-farm scale across different environments. Environments were grouped based on farmers' expertise supported by the recommendation of agronomists. YE, yield environment. The letters inside each region represent the acronym used to name each region (MyS: Mar y Sierras; SDE: Sudeste; OES: Oeste; OAR: Oeste Arenoso; NBA: Norte de Buenos Aires; SSF: Sur de Santa Fe; CEN: Centro; COR: Córdoba Norte; SFC: Santa Fe Centro; LIS: Litoral Sur).

environment within the location. The combination of year, location, genotypes and nitrogen rates provided 50 and 62 environments for ESM and LSM, respectively (Fig. 2). The YE ranged from 2 to 14 Mg ha^{-1} (Fig. 2). However, not all genotypes were necessarily tested in ESM and LSM. Therefore, we structured the analysis within a hierarchical model framework and balanced the dataset to include only experiments that evaluated genotypes with the same sowing date, similar plant density, and YE range at ESM and LSM (Supplementary Fig. S1). The final dataset involved YEs between 6 and 13 Mg ha^{-1} testing four genotypes at different stand densities.

Since one of our main objectives was to evaluate how sowing date affects the YE × plant density maize yield response, each location-year combination was initially converted to YE (expressed in Mg ha^{-1}). The YE was extracted from the following model (Eq. 1):

$$Y_{ij} = G_i + E_j + e_{ij} \quad (1)$$

where Y is the of the genotype i in the environment j, G is the genotype effect, E is the effect associated to the environment j, and e is the model residual (Supplementary Fig. S1).

As an input for this model, we used the average yield at the AOPD extracted from quadratic regression models adjusted for each genotype in each environment as a proxy of YE (Supplementary Fig. S1). The reason for using the yield at the AOPD as YE and not directly the average yield of each experiment was to avoid underestimating the YE due to supra/super optimal plant densities within experiments.

We adjusted statistical models to the entire data set to explore the maize yield response to plant density across YE and planting dates (Supplementary Fig. S1). For this purpose, we used a Bayesian approach to account for parameter uncertainty. This type of analysis has been previously used for modelling yield response to stand density (King et al., 2024; Lacasa et al., 2020). We assumed the yield response to plant density × YE to follow a quadratic curve according to the following model (Eq. 2):

$$Y = \beta_1 \times (PD) + \beta_1 : YE \times (PD) + \beta_2 \times (PD^2) + \beta_2 : YE \times (PD^2) \quad (2)$$

where Y is the adjusted yield, PD is plant density, β_1 and β_2 are the linear and angular density-level coefficients and β_1:YE and β_2:YE are their corresponding interaction with YE. The model was constraint to have a zero Y-intercept at $x = 0$. The genotype, sowing date, and the genotype × sowing date interaction effects we added as group-level effects within the *brms* specification in R environment, allowing the abovementioned parameters to vary across the different levels within each group. From the fitted model, the expected estimates of the coefficients were retrieved as the median (50th percentile) of the posterior distributions.

The width of the posterior distribution indicates the uncertainty in the parameter value. To summarize this uncertainty, we used the 95 %

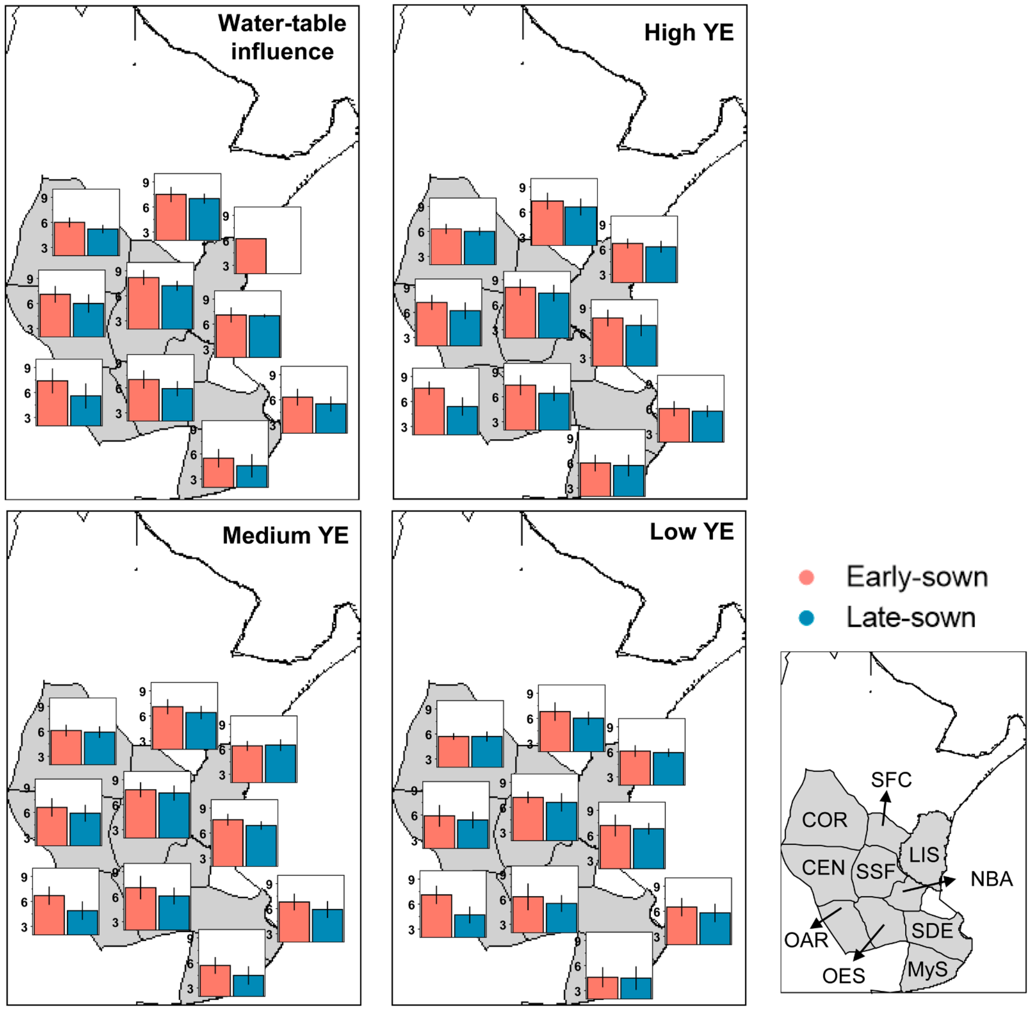

Fig. 4. Average sown plant density (pl. m^{-2}) between 2017 and 2021 for early and late-sown maize at on-farm scale across different environments. Environments were grouped based on farmers' expertise supported by the recommendation of agronomists. YE, yield environment. The letters inside each region represent the acronym used to name each region (MyS: Mar y Sierras; SDE: Sudeste; OES: Oeste; OAR: Oeste Arenoso; NBA: Norte de Buenos Aires; SSF: Sur de Santa Fe; CEN: Centro; COR: Córdoba Norte; SFC: Santa Fe Centro; LIS: Litoral Sur). Vertical bars represent the standard deviation.

highest density interval (HDI, Supplementary Fig. S1). Any parameter value inside the HDI has higher probability density than any value outside the HDI. There are different options of decision rules available for rejecting or accepting parameter values in Bayesian estimations (Kruschke, 2018). In this study, we were interested in exploring if the most credible parameter values are sufficiently far away from the null value. This means that if the null value is within the HDI the parameter values will be rejected, indicating that there is considerable probability that this parameter could be removed from the model. This rationale was also used for comparing quantities extracted from the models, as the adjusted yield and the AOPD, among the different YE, genotypes and sowing dates.

3. Results

3.1. Share of area, sown plant density and grain yield for different sowing dates across environments at farmer fields

Farmers in Argentina managed differently their maize crops depending on the region, YE and the sowing date (Figs. 3, 4, 5). The proportion of area under LSM increased as the environmental quality decreased. The area under LSM was 37 % (0–47 %) and 39 % (5–90 %) for environments with water-table and high YE, respectively. These values increased to 54 % (4–94 %) and 72 % (11–93 %) under medium and low YE (Fig. 3). The share of the area between ESM and LSM also varied among regions (Fig. 3). For example, farmers in LIS and SSF regions always had higher proportion of early plantings, while COR and CEN regions only planted early in the season in fields with water-table influence.

Plant density choice by farmers varied depending on the YE and the sowing date (Fig. 4). Across regions and YE, the average sown plant density was always higher for ESM than for LSM (average 1.1 pl. m^{-2} difference). Average sown density from ESM to LSM changed from 7.3 to 5.9 pl. m^{-2} and from 7.2 to 6.1 pl. m^{-2} in environments with water table and high YE, respectively. Plant density from ESM to LSM changed from 6.7 to 5.8 pl. m^{-2} and from 6.4 to 5.5 pl. m^{-2} in medium and low YE, respectively. For both sowing dates, farmers in the central regions (NBA, SSF, CEN) consistently planted higher densities than those in the more limited peripheral regions (MyS, OAR, COR, LIS).

Average grain yield was higher for ESM (8.7 Mg ha^{-1}) than for LSM (7.4 Mg ha^{-1}), but its magnitude varied according to the YE in both sowing dates (Fig. 5). Fields with water-table influence showed an average yield of 10.0 Mg ha^{-1} for ESM and 7.6 Mg ha^{-1} for LSM. These values varied from 9.2 to 8.2 Mg ha^{-1} for high YE. For medium YE, grain yield differences between showing dates were lower (7.2 and 7.3 Mg ha^{-1} for ESM and LSM, respectively). The same was observed in low YE (6.4 and 6.1 Mg ha^{-1} for ESM and LSM, respectively).

While the difference in favor of ESM was consistently higher for most

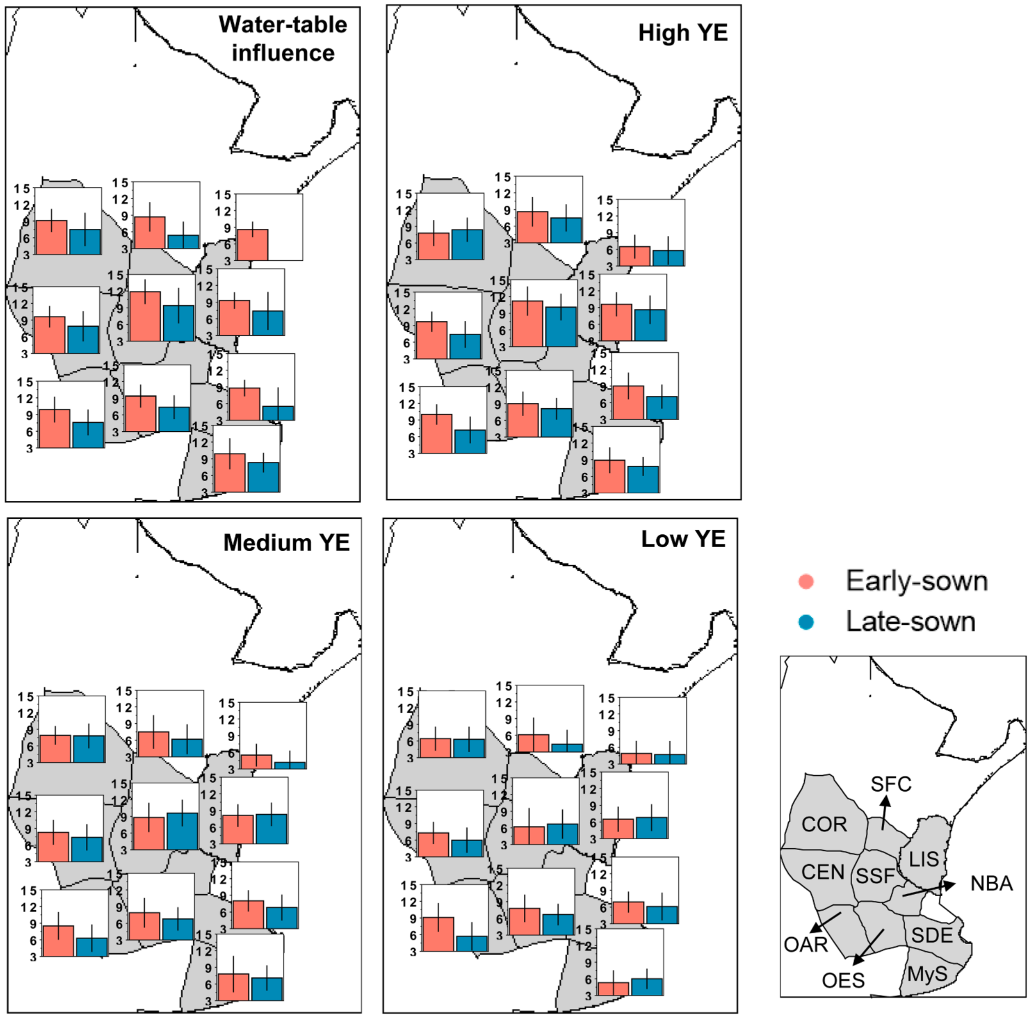

Fig. 5. Average grain yield (Mg ha^{-1}) between 2017 and 2021 for early and late-sown maize at on-farm scale across different environments. Environments were grouped based on farmers' expertise supported by the recommendation of agronomists. YE, yield environment. The letters inside each region represent the acronym used to name each region (MyS: Mar y Sierras; SDE: Sudeste; OES: Oeste; OAR: Oeste Arenoso; NBA: Norte de Buenos Aires; SSF: Sur de Santa Fe; CEN: Centro; COR: Córdoba Norte; SFC: Santa Fe Centro; LIS: Litoral Sur). Vertical bars represent the standard deviation.

regions in high YE and water table influence environments, this was not the case for medium and low YE (Fig. 5). In medium YE, two central regions had higher yield for LSM than for ESM (NBA 8.3 and 8.1 Mg ha^{-1}, and SSF 9.6 and 8.8 Mg ha^{-1}, for LSM and ESM, respectively). Finally, in the low YE fields, LSM had higher yields than ESM in three regions (MyS, NBA and SSF; Fig. 5).

In summary, farmers accommodated the plant density according to expected yield variations, but they adjusted it differentially depending on the sowing date (Fig. 6). For every 1 Mg ha^{-1} increase in average yield, plant density should increase in a similar magnitude ($p = 0.18$) in both sowing dates (0.26 and 0.22 pl m^{-2} for ESM and LSM, respectively). However, the actual plant density used by farmers was approximately 0.5 pl m^{-2} higher for early than late plantings across explored environments ($p = 0.017$). Considering the 90^{pth} percentile for the whole data, farmers sown 0.18 pl. m^{-2} extra plants for every increase of 1 Mg ha^{-1}. Thus, for example, for an average yield of 6 Mg ha^{-1}, farmers chose to sow 5.8 and 6.2 pl. m^{-2} for LSM and ESM, respectively, but, 7.1 pl. m^{-2} at the top 10 % of the distribution (Fig. 6).

3.2. *Yield difference between early and late sowing dates in paired field experiments*

Paired field experiments showed a clear relationship between the yield difference between ESM and LSM and the ESM yield ($R^2 = 0.75$; $p < 0.001$, Fig. 7). Comparatively, higher yield levels were obtained at later planting when yield level at early planting dates were lower than ~10.2 Mg ha^{-1}. There was a clear advantage in favor of early planting dates at higher yield levels. Therefore, the expected grain yield at the same location × year combination differed between ESM and LSM. On average, yields were higher for LSM than for ESM in these paired field experiments. However, yields were less variable for LSM than for ESM (18 and 36 % CV, respectively).

3.3. *Yield response to plant density by yield-environment across sowing dates*

Significant yield responses to plant density occurred in the different YEs, as drawn from the $\beta_1 \times$ YE and $\beta_2 \times$ YE distributions (Fig. 8). More important, model coefficient samples drawn from the posterior distribution suggested that maize yield response to plant density was similar in ESM and LSM (Fig. 8). This suggests that for a given YE, the adjusted yield-plant density relationship from the posterior distribution for ESM and LSM overlap the HDI for AOPD for both sowing dates (Fig. 9). Therefore, the AOPD for a particular YE is similar for ESM and LSM (Fig. 9).

The AOPD increased with the YE, irrespective of the sowing date

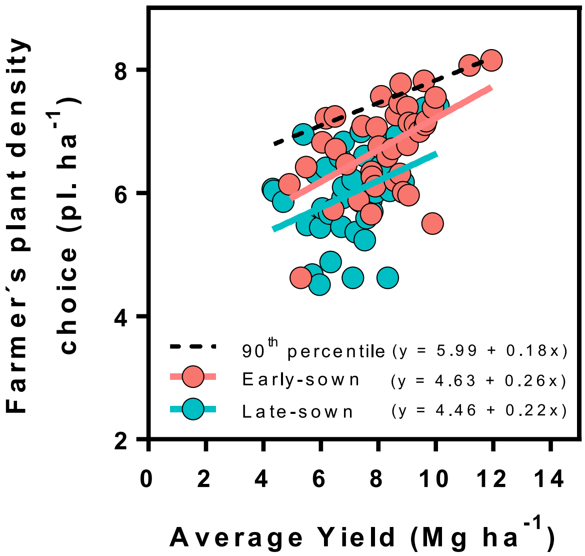

Fig. 6. Average sown plant density by farmers as a function of average yield for early and late-sown maize across regions and yield environments in Argentina between 2017 and 2021. Each point represents the average value of the five years for the fields in a particular region and yield environment combination. A different model was adjusted for each sowing date (Different model for each sowing date, $p = 0.017$). The dashed line represents a fitted model to the 90th percentile for whole data.

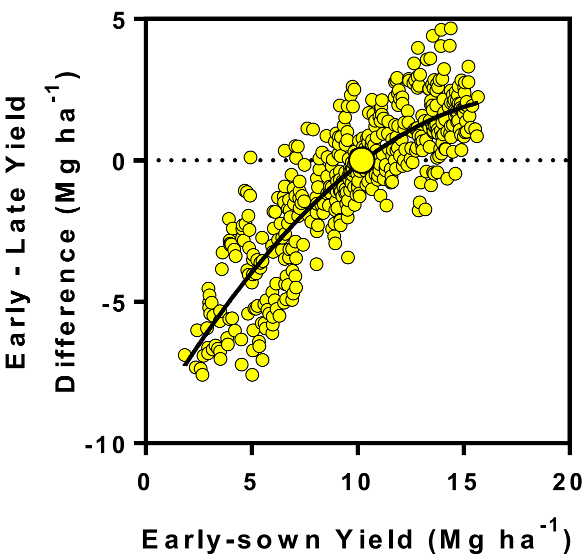

Fig. 7. Early sown maize - late sown maize grain yield difference as a function of early-sown maize grain yield for paired field experiments across Argentina ($n = 487$; $R^2 = 0.75$; $p < 0.001$). Each point represents the result from an experiment where early and late sown maize were sown in the same location × year. The big point represents the expected early maize yield where no difference of grain yield can be expected between sowing dates according to the adjusted model.

(Fig. 10). For example, both for ESM and LSM, for a YE of 6 Mg ha^{-1} the most probable AOPD was 6.6 pl. m^{-2}, increasing to 8.0 pl. m^{-2} for a YE of 13 Mg ha^{-1} (Fig. 10). This represented an average increase in AOPD of 21 % between the lowest and highest YE explored.

4. Discussion

Our approach combining farmer survey records and field experiments enabled a comprehensive diagnosis about how farmers currently choose maize plant density for different productive conditions across central Argentina. Moreover, this analysis provided information for reducing the uncertainty behind the decision on plant density across YE and sowing dates. This is particularly relevant when facing the recent diversification of maize planting dates in Argentina and the required information for guiding farmers' decision for contrasting sowing dates (Vitantonio-Mazzini et al., 2020). Our research fills this gap in terms of AOPD choice, suggesting that farmers usually choose higher plant densities at ESM than LSM, but not necessarily ESM always out-yields LSM in the study region. Our main finding is that there was an interaction between maize plant density and YE, but this yield response did not differ between ESM or LSM conditions. Therefore, the hypothesis of the existence of an AOPD that maximizes maize grain yield at each YE, regardless of the sowing date, is supported by our results, at least with the genotypes and management conditions we explored in the present study.

Analysis of farmers' data can help evaluate performance of different crop management practices, contextualize their adoption, and explore potential discrepancies with experimental results (Andrade et al., 2019). We explored a large farmer survey database covering the main core region of maize production in Argentina, which has experienced a shift in the sowing date window during the last decades, and consequently, in the land assignment to maize crops. Our analysis reinforced the idea that farmers tend to sow proportionally more area of LSM *versus* ESM under restrictive conditions (Otegui et al., 2021). Farmers are highly risk-averse (Gonzalez-Ramirez et al., 2018), and the annual allocation of area to maize is a complex process that follows expected weather conditions and yield levels (Bert et al., 2006). Under fixed crop rotation schemes, farmers delay maize sowings from mid-September to December facing restrictive soil conditions, inadequate soil water availability in September (sowing of ESM), and/or expected dry conditions during December (critical yield period of ESM; Bert et al., 2006). Thus, LSM constitutes a defensive strategy facing weather uncertainty and/or restrictive edaphic conditions (Rotili et al., 2019). However, despite ESM still being the main choice under less restrictive environments, the farmers under analysis also allocated some area to LSM under environments with water-table influence. Paradoxically, under this type of environment, it is expected that LSM yields would be lower than that of ESM (Vitantonio-Mazzini et al., 2020). We speculate that the underpinning causes of the maintenance of LSM area under non-water limited environments is not related to a higher-expected productivity but mainly to socio-economic factors like farmer risk-aversion and/or the option of differing grain production to stabilize productivity and market entrance timing (Bert et al., 2006). Additionally, operational constraints like the unavailability of machinery to plant early may increase the possibilities of delaying maize plantings under high-yielding environments or with water-table influence (Bert et al., 2006).

Our study also provided observational evidence related to the plant density choice by the farmers in ESM and LSM fields. Maize AOPD varies with the YE (Assefa et al., 2016) which can involve different soil (Woli et al., 2014), weather (Lacasa et al., 2023) and crop management conditions (Vitantonio-Mazzini et al., 2020). At a regional scale, the surveyed farmers of this study followed that general agronomic premise, but the increase of plant density to adapt to the resource offer given a better expected YE was different between ESM and LSM. Plant density choice was approximately 0.5 pl. m^{-2} higher for ESM than for LSM across similar YEs. Thus, the selection of a lower plant density for LSM could explain at least partially the lower grain yield obtained at LSM for a similar expected YE. Apart from a lower expected YE, the reduction in plant density in late plantings can be attributed to several practical reasons. For instance, the late-fall to early-winter harvest period in the study region (Maddonni, 2012) is often accompanied by increasing rainfall, winds, and high relative humidity, which enhance the risk of yield losses before harvest. To mitigate these risks, farmers may reduce plant density to decrease the likelihood of lodging or stalk breakage. This strategy addresses the altered source-sink relationship during the

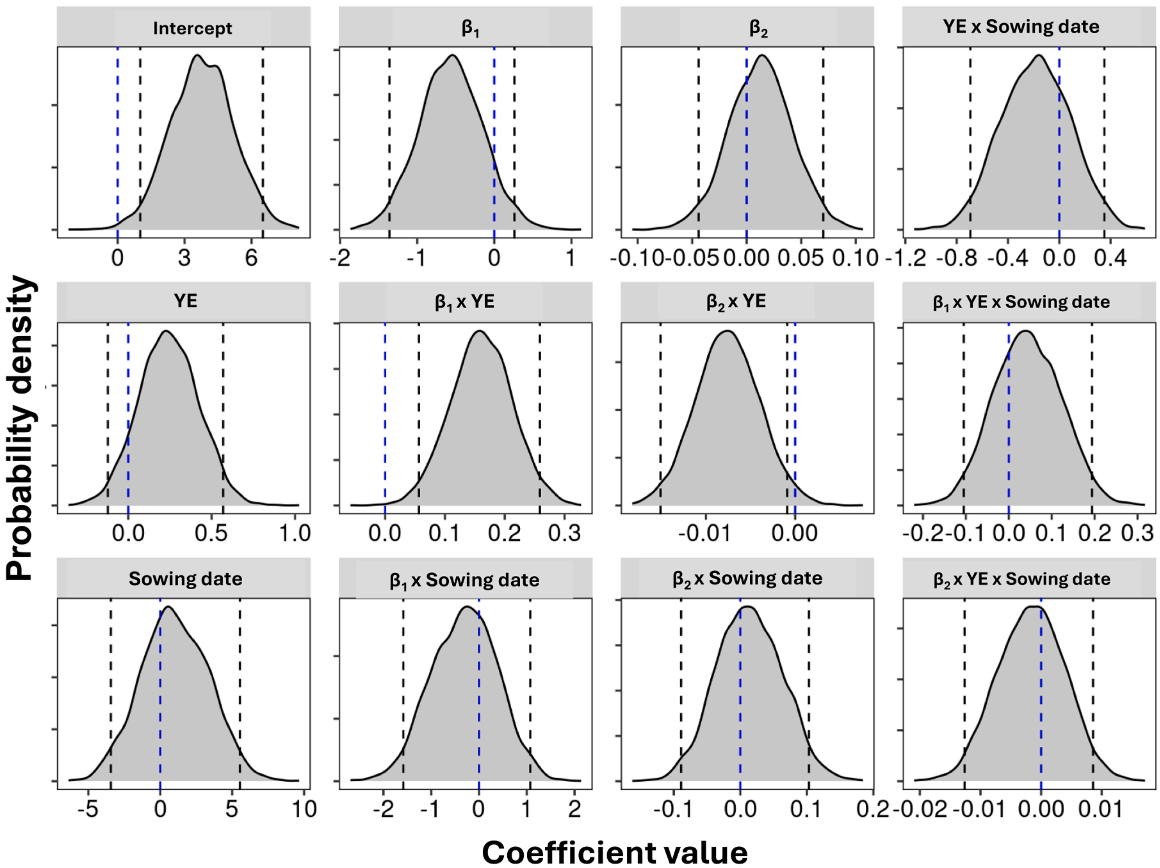

Fig. 8. Model coefficients samples drawn from the posterior distribution. Black dashed lines represent the lower and upper limits of the 95 % high density interval (HDI). When the zero (blue dashed line) is within of the HDI there is a high probability that this coefficient is zero, which indicates that there is a considerable probability that this coefficient could be removed from the model (no effect). β_1 and β_2 correspond to the linear and quadratic coefficients for the relationship between yield and plant density. YE, yield environment.

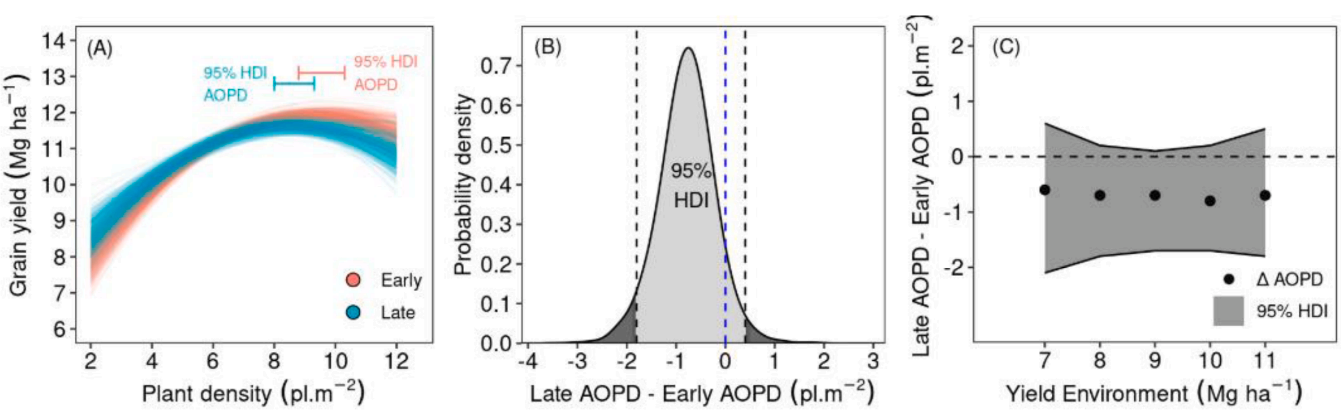

Fig. 9. (A) Grain yield - plant density curves drawn from the posterior distribution from early and late plant density at an environment of 11 Mg ha^{-1}. Horizontal bars at the top of the curves represent the 95 % high density interval (HDI) for the agronomical optimal plant density (AOPD) for early and late planting date. (B) Posterior distribution of differences between AOPD from late and early planting date at 11 Mg ha^{-1}. When the zero (blue dashed line) is within of the HDI there is a high probability that this coefficient is zero, which indicates that there is a considerable probability that this coefficient could be removed from the model (no effect). (C) Differences between AOPD from late and early planting date across yield environments. The grey shadow area represents the 95 % HDI. When zero was within the HDI we assumed no differences between the tested effects.

grain-filling stage (Bonelli et al., 2016) and accounts for the extended time LSM plants remain in the field to reach commercial moisture levels (Chazarreta et al., 2021). Also, socio–economic factors such as farmer risk-aversion in face of varying hybrid seed / grain price ratios in interaction with low predictability of weather conditions during the coming season could be causes of lower-than-optimum density choices in LSM (Lacasa et al., 2020; Bert et al., 2006).

Adapting crop growth duration and the occurrence of the main phenological events to the dynamics of the environmental resource offer, both linked to sowing date selection, are key variables to be managed for maximizing maize yields (Baum et al., 2019; Massigoge et al., 2023). In rainfed maize systems, the main yield difference due to the sowing delay is associated with the modification of the radiation regime, evaporative demand, and the probability of water deficit during

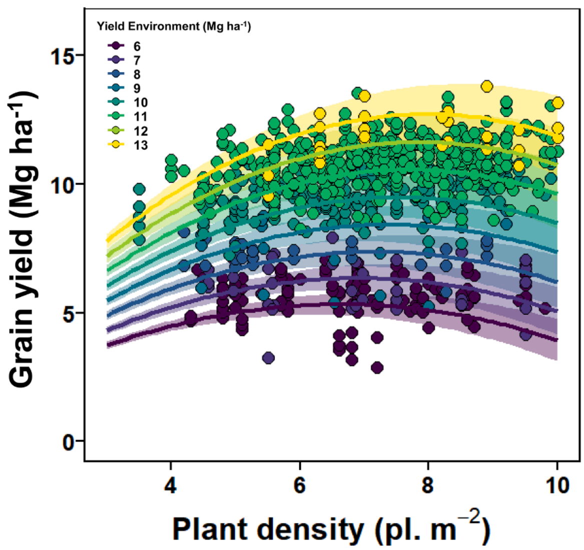

Fig. 10. Relationship between grain yield and plant density for yield environments from 6 to 13 Mg ha^{-1} (colors). Models were fitted across sowing dates using hierarchical Bayesian models.

the critical period for yield determination (Otegui et al., 2021). In our study region, while ESM maximizes yield potential due to higher incident radiation and temperature during the reproductive period (Otegui et al., 1996, 1995), the LSM strategy faces better water conditions when determining grain number (Maddonni, 2012). Therefore, although the farmer field survey consistently showed that ESM outperformed LSM, the yield differences associated with changes in sowing dates observed in paired field experiments revealed more comparable results. When ESM yields were high (e.g., under low water stress conditions), ESM outperformed LSM. Conversely, in more restricted environments where ESM yields fell below 10.2 Mg ha^{-1}, LSM demonstrated higher yields than ESM. Results from this study reveal that late plantings can achieve competitive yields in certain conditions, and that farmers may currently be underestimating the potential of these planting dates. However, nitrogen fertilization can be managed differently between ESM and LSM which within our conceptual framework can modify YE (Vitantonio-Mazzini et al., 2020). A comprehensive plant density × sowing date × YE × nitrogen availability analysis was not totally explored in the present study and deserves attention in future research.

The results of this work regarding plant density management shed light on the above-mentioned issues. Recently, Vitantonio-Mazzini et al. (2020) suggested that management optimization in Central Argentina could increase ESM and LSM yields around 3.4 and 1.6 Mg ha^{-1}, respectively, and approximately 90 and 10 % of observed yield responses were associated with changes in plant density for ESM and LSM, respectively. Still, it was not clear if ESM and LSM responded differentially to plant density for a given YE or if it was that the LSM comprised lower YEs or a narrower range of plant densities than ESM crops, hindering their comparison in previous studies. This is even more relevant when considering that, using a different database from the same region, Gambin et al. (2016) found an overall strong positive response to plant density across environments for LSM, suggesting that farmers could still explore higher plant densities with positive yield results. We addressed these unresolved issues through ESM and LSM experiments that combined for both sowing dates a wide range of YE × plant densities. As it has been documented, we found that there was an interaction between maize plant density and YE (Assefa et al., 2016; Lacasa et al., 2020; Schwalbert et al., 2018), however, and as we hypothesized, the yield responses did not differ between contrasting sowing dates.

Thus, this work showed that for a given site and season, the sowing date indirectly determines the YE (Otegui et al., 1996), and the AOPD should be selected upon that expected YE without considering a further direct effect of the sowing date on that response. The underestimation of AOPD by farmers reported by Gambin et al. (2016) and suggested by the results of our farmers' survey could be related to a corresponding underestimation in the expected YE under LSM. Following this premise, we believe that the reduced range of plant densities used by farmers in Argentina for LSM is a resultant of extrapolating agronomic recommendations generated in other regions with yield-limiting conditions, and therefore, a reduced YE (Rotili et al., 2019). Currently, LSM is a common crop choice and part of the typical agricultural rotation under high-yielding environments, and possibly, its rapid adoption in this region was not initially accompanied by specific agronomic information for their management, particularly that related to plant density as opposed to what occurred with other practices (Coyos et al., 2018; Madias et al., 2023). Our research fills this gap, but further research is required to guide AOPD choice in maize production regions that we did not explore in this study, both in Argentina, and also in countries where maize can be produced in a wide sowing window (Massigoge et al., 2023; Nóia Júnior and Sentelhas, 2019). Also, although the genotypes used in the experiments were representative of commercial germplasm, different genotypes available in the market could still respond differently either to plant density (Hernández et al., 2014), plant density × YE (Assefa et al., 2016; Edwards, 2016) or sowing date (Otegui et al., 1995; Tsimba et al., 2013). Recently, seed companies in Argentina have started to adjust recommendations of plant density for different genotypes in response to sowing date; therefore, exploring the plant density × sowing date × YE × genotype interaction in a comprehensive manner would be desirable.

5. Conclusions

Contrasting planting dates expose the crop to different growing environments, which in turn increases uncertainties related to other management decisions like AOPD. It is currently not clear if farmers should manage AOPD based on sowing dates, the expected YE or both. Our approach combining farmer survey records and field experiments suggested that farmers usually choose higher plant densities at ESM than LSM, but not necessarily ESM always out-yields LSM in the study region. Our main finding is that there was an interaction between maize plant density and YE, but these yield responses did not differ between ESM or LSM conditions. Consequently, for a given YE farmers should choose the same AOPD, irrespective of the sowing date. This study provides information to reduce the uncertainty to handle plant density for maize production across different environmental conditions.

CRediT authorship contribution statement

Rotili Diego H.: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Di Mauro Guido:** Writing – original draft, Visualization, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Gambin Brenda L.:** Writing – review & editing, Conceptualization. **Parra Gonzalo:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Micheloud José:** Writing – review & editing, Validation, Data curation. **Costanzi Jerónimo:** Validation, Resources, Conceptualization. **Paolini María:** Data curation. **Martini Gustavo:** Writing – review & editing, Validation, Data curation. **Schwalbert Raí:** Writing – review & editing, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109917.

Data availability

Data will be available upon reasonable request

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