
# VARIABLE SEEDING RATE TO MANAGE WITHIN-FIELD VARIABILITY

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***Abstract.***

*We investigated whether varying soybean seeding density and cultivar can contribute in managing within-field variability in Southern Brazil. We tested the hypotheses that optimal agronomic seeding density is higher in low yield environment and that high-yielding cultivars outperform stable ones in high yield environment. We set up a factorial experiment on a 124 ha commercial field where 3 cultivars x 4 seed densities x 3 yield zones were tested in 50x50 m plots that was repeated for two seasons (2021-22,2022-23), the experiment was conducted on a single replicate.*

*Our results agrees with the hypothesis that low yield environment have a higher optimal agronomic seeding rate, however the interaction between density and zone did not have a significant effect on yield. In our study we observed that in low yield environment a higher seed density boosted canopy growth compared to medium-high zones, and a stronger —despite not significant — correlation between the number of pods in high and medium zones than in low ones, suggesting that the yield environment where a plant is grown influence its plasticity. We did not find a genotype x yield environment effect. We also observed that beginning maturity stage (R7) was reached about 140 degrees days earlier in low than in medium and high zones, and that the air at canopy level was warmer in low zones.*

***Keywords.***

*soybean, precision agriculture, yield environment, within-field variability.*

## Introduction

Within-field variability can greatly influence final yield and the effectiveness of the crop inputs, like seeds and fertilizer. For example, Maestrini and Basso (2018) found that in US-Midwest soybean crops within-field variability amounted to 60% of the variability occurring among the years, i.e. the one that is attributable to weather. Therefore, managing such variability through precision agriculture is key to the efficient usage of inputs like, water, fertilizer, liming, seeds, agrochemicals. Although many studies have investigated the influence of seed density on yield, less research has been conducted on how seeding and genotype technologies can help manage within-field variability. Here we explore how variable seeding rates and multi-variety soybean planting can help to optimize yield. The use of variable seeding rate is more common in corn, whereas this technology is less widespread for soybean both because corn is generally more profitable and because soybean is assumed as being a more plastic crop than corn (Tokatlidis 2013) since the number of pods per soybean plant can vary with seeding rate. The major effect of increasing seeding density is a faster canopy closure (Holshouser and Whittaker 2002; Xu et al. 2021). Thus a higher sowing density has been recommended for late planting (Siler and Singh 2023, for North America Environments), early maturity group (Walker et al. 2010), or low yield environment (Carciochi et al. 2019 in North America, and Corassa et al. 2018 in Brazil). The following studies suggested that the optimal seeding rate of soybean should be higher in low yielding zones than in high zones: Corassa et al. (2018) based their conclusions on observations from Brazil, whereas Gaspar et al. (2020) and Carciochi et al. (2019) used observations from North America. The results from Carciochi et al. (2019) have been used to inform a decision support system (Correndo et al. 2022) for determining optimal soybean seeding rate taking account the historical yield in the field.

These three studies on the interaction of yield environment x sowing density used large datasets coming from various different fields within large ecological regions, however no study — to the best of our knowledge — investigated the effect of the interaction variable seeding rate x zone at within-field level. This scale is however relevant as farmers can vary the seeding rate at within-field scale using variable rate seeders.

The finding that soybeans have a higher agronomic optimal seeding rate in low zones than in high zones is opposite what has been observed for corn. A decade ago, Hörbe et al. (2013) conducted an experiment in the same study area as the present study and found that corn yield is negatively correlated to sowing density in low yield environment and positively in high ones. Our study also aims at investigating the agronomic reasons for the different behavior of soybean and corn.

Smart seeding technology can be used to manage within-field variability also through multi-variety planting, i.e. planting different varieties of a similar maturity group in the different management zones of a field. Currently multi-variety planting has a low adoption rate in Brazil due to the lack of multi-seeders present in the market. However, Corassa et al. (2019) showed that soybean may benefit from planting robust and stress-tolerant varieties in low yielding classes, and lodging-tolerant varieties in high yielding classes. In a similar study on corn Assefa et al. (2016) found that early maturity cultivars are a better fit for low yield environments – despite yield environments were clustered not at within-field scale – and late cultivar for high yield environment. Here we hypothesized that high-yielding cultivars — because of their higher requirements and low plant plasticity — perform better in a high yield environment that has low crop limiting factors while stable cultivars perform better in low yielding zones that are more prone to have some sort of limiting factor.

In this study, we aim to answer the following questions:

1. Can we extend the findings on high optimal seeding rates in low zones clustered at regional level (Gaspar et al. 2020; Carciochi et al. 2019; Corassa et al. 2019) to yield zones delineated at within-field scale?

2. If yes, why does soybean in low zones have a higher optimal rate? We hypothesized three possible non-mutually exclusive mechanisms that we are testing in this study:
    a. The canopy growth in low environment needs to be compensated with more seeds to quickly establish a good within-row canopy cover
    b. Soybean exhibits lower plasticity in low zones as hypothesized by Carciochi et al. (2019)
    c. Soybean in low zones have a lower emergence rate and thus benefit more from higher seeding rate?
3. Do high-yield cultivars perform better in high environment zones and stable cultivar perform better in low ones?

We answered these questions by conducting a field experiment in the Aquarius Project located in Nao-me-toque (Rio Grande do Sul, Brazil) for two growing seasons, 2021-2022 and 2022-2023.

## Materials and methods

The study site is a 124 ha field located in Não-Me-Toque in the state of Rio Grande do Sul (Brazil). The coordinates are 28° 280 S, 52° 470 W, 500 m a.s.l., the climate is humid subtropical and average annual and precipitation are 18.7 ° and 1680 mm, while the soil type is clayey, kaolinitic and classified as a Rhodic Hapludox (Soil Survey Staff). The soil has been managed under a no-tillage system since 2002. The field has been split into management zones defined by applying k-means to a stack of maps of soybean and corn yield, and apparent electrical conductivity (EC). Further information on the site and the generation of the management zone map can be found in Pott et al. (2019). We conducted a full factorial experiment where 3 cultivars x 4 seed densities x 3 yield environments were tested (Figure 1). The plots size was 50 x 50 m, the experiment was conducted on a single replicate in the crop seasons 2021-2022, and 2022-2023. Medium and high environments were irrigated as they fell within the area of the irrigation pivot, whereas the low yielding zones were not irrigated. The field was sown on October 20 in 2021 and October 17 in 2022, the field was cultivated following standard practices, the field received in June the following fertilization: 200 kg ha$^{-1}$ monoammonium phosphate, 200 kg ha$^{-1}$ potassium chloride (KCl) and 50 kg ha$^{-1}$ elemental sulfur (S) at sowing . Row spacing was 45 cm. The weather in the two seasons was drier than the normal average of the past 30 years (600 mm rain between 15 Oct-31 March vs an average of 800 mm in the last 30 years) and January-March of 2022 was exceptionally hot.

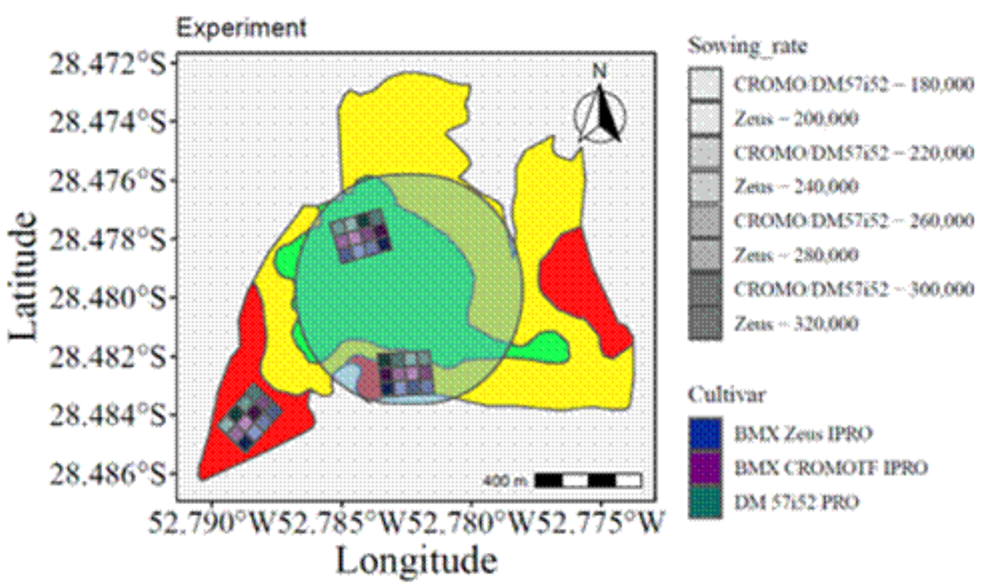


*Figure 2: Management zones and plots of the experiment. The parts of the field in red indicate*

*low yield zones, the parts in yellow the medium yield zones and the parts in green the high zones. The circle indicates the portion of the field that was irrigated.*

The cultivars used in this study were Brasmax Zeus IPRO, Brasmax Cromo TF IPRO and DMDM 57i52 IPRO and are commercialized by GDM. The cultivar Brasmax Zeus IPRO was previously used in this same field, giving excellent yield results. We considered the cultivar Brasmax Zeus IPRO as the high-yielding cultivar and Brasmax Cromo TF IPRO and DMDM 57i52 IPRO as the stable cultivars. Based on previous experience from the seed producers and the field managers we regarded Brasmax Zeus IPRO as the high potential whereas Brasmax Cromo TF IPRO and DMDM 57i52 IPRO were considered stable cultivars. The cultivars have similar maturity group (Brasmax Zeus IPRO 5.5, Brasmax Cromo TF IPRO and DMi5752 5.7),

### Measurements and Data Collection

Yield components were assessed at crop maturity by destructively sampling a 0.5 m² area. Five replications were collected per plot, and the number of pods per plant, grains per pod, final stand population density, thousand-grain weight, and soybean moisture content were recorded. Grain yield was reported on a 13% moisture basis. Measurements were taken at 158 days after sowing (DAS) in the 2021–22 season and at 147 DAS in the 2022–23 season.

Crop canopy development was monitored using the Normalized Difference Vegetation Index (NDVI), which was estimated from satellite imagery obtained through the Planet Scope surface reflectance product. The satellite imagery had a spatial resolution of 3 m, and a negative buffer of 10 m was applied to plot boundaries to minimize border effects. Only cloud-free images were used for analysis.

Crop phenology was monitored weekly in 2021–22 and twice per week in 2022–23 using the Fehr growth stage scale.

Air temperature and relative humidity within the canopy were monitored during the 2022–23 season at 24–31, 35–45, 52–59, 70–78, 83–91, 104–119, and 120–147 DAS. Measurements were recorded using ZB-TB04 air temperature and humidity loggers (Tzone, Shenzhen, China) housed within an AcuRite 06054M temperature and humidity solar radiation shield (AcuRite, Lake Geneva, USA). Sensors were positioned 0.5 m above the ground. Canopy-level temperature and humidity were not measured during the 2021–22 season.

Air temperature at a height of 2 m was obtained from Naspower gridded hourly weather data. Sensors were installed in plots sown with the Brasmax Zeus IPRO soybean cultivar at a planting density of 260,000 seeds $ha^{-1}$. Final plant population was determined by counting three replications of 10 m row sections per plot. Measurements were conducted at 15 DAS in the 2021–22 season and at 45 DAS in the 2022–23 season.

### Statistics

To test for the interaction zone by density on final yield the following model was fit to the data:

$$Yield = \alpha_{year} + \beta_{cultivar} + \delta_{zone} + \vartheta * density + \varphi_{zone} * density \quad (1)$$

An anova test was performed to test for significant factors in the model.

To test for the interaction zone by density in early stage canopy development the following model was fit to the data:

$$NDVI = \alpha_{year} + \beta_{cultivar} + \delta_{zone} + \gamma_{year,zone} * DAS +$$

$$+\gamma_{year,zone} * DAS^2 + +\vartheta * density + \rho_{zone} * density \quad (2)$$

To test for the interaction zone by density in the different yield components the following model was tested

$$Y = \alpha_{year} + \beta_{cultivar} + \vartheta * density + \delta_{zone} + \rho_{zone} * density \quad (3)$$

Where Y represent at turns the yield components: pods per plant, the grain per pod, the grain weight, and the plants per m2 at harvest time.

The tests were performed in R4.3.1 extended by the package *emmeans* (Lenth 2023) for post-hoc comparisons using marginal means.

## Results

### Descriptive statistics

The average yield was 4270 (st.dev. 1325) kg $ha^{-1}$ in 2021-2022 and 4163 (st.dev. 1488) kg $ha^{-1}$ in 2022-2023. In line with previous yield environment map, the average yield was 3017 (st.dev. 757) kg $ha^{-1}$ in low, 4383 (st.dev. 1218) kg $ha^{-1}$ in medium, and 5249 (st.dev. 1170) kg $ha^{-1}$ in high. On average there were 63.9 pods per plant, 2.4 grains per pod, and grain weight was 0.2 g / grain.

We observed that the phenology of crops in low yield environment tend to achieve the end of cycle faster. On average crops in low yield environments reached the R7 stage (beginning maturity) 166 degree days (base temperature 2 degrees) earlier than high yield environments (Figure 2). We observed a positive relationship between grain yield and thermal time to reach R7 (beginning maturity).

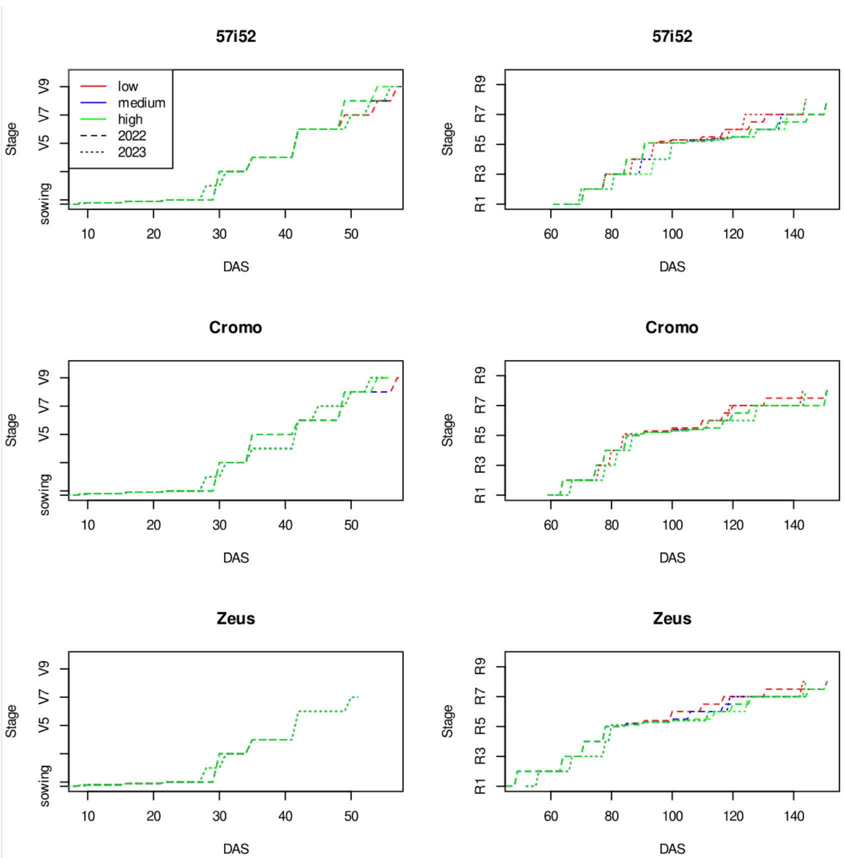


*Figure 2: Phenological stages averaged by cultivar, zone and year. On the left are the vegetative stages and to the right the reproductive stages following (Fehr and Caviness 1977). The figure shows that in low zones beginning maturity (R7) is reached earlier than in high zones.*

The air temperature between 11 and 3 pm at the canopy height (50 cm, measured using temperature loggers on site) was generally 11% hotter than at 2 m height (gridded data values from Nasapower) already at sowing time suggesting that the shield may have not completely insulated the sensor from radiation heat. We observed that in February (the month of max growth rate) the air temperature at canopy level was hotter in the low environment than in mid and high ones, this may result from a lower evaporation from the crop, as well as from a lower canopy density and thus from a higher influence of solar radiation not completely insulated by the shield. Air humidity at canopy height was on average 20% lower than air humidity from Nasapower gridded data at sowing, which agrees with the expected air humidity profiles of bare soils, and in February was 20% higher than 2m height air in low zones and 50% higher in high zones, as a result of higher crop transpiration.

### Effect of the interaction zone by density on yield

The data collected agrees with our hypothesis that low yield environment benefit from higher sowing density, in fact the slope of the yield response to seeding density is positive in low yield environment and flat or negative in medium-high environments (Figure 3). However the difference between the treatments is not a significant factor in the model (ANOVA test on model eq. 1). A seeding rate of 320k seeds ha$^{-1}$ instead of 180k seeds ha$^{-1}$ produced an increment of 11.4 % (SE. 7.9) in low environment, a decrement of -3.1 % (SE. 7.1) in medium, and an increment of 1.0 % (SE. 7.3) in high one.

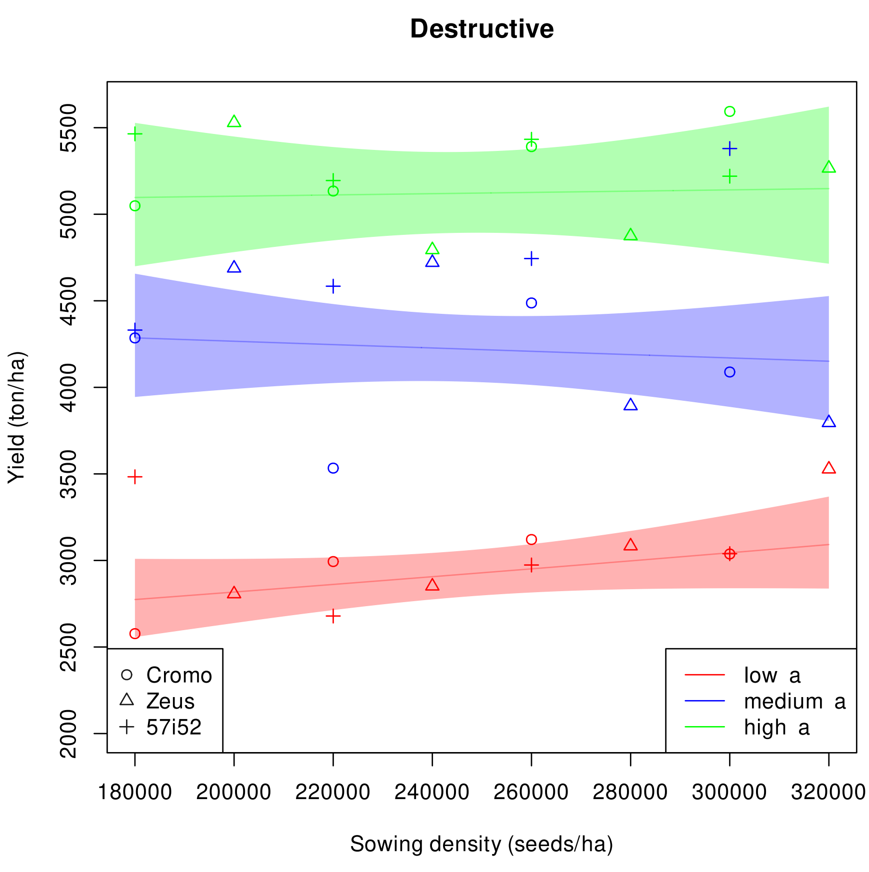


*Figure 3: HP1: Effect of increased sowing density on yield by zone. The predicted values are marginalized over year and cultivar; the shaded area is the standard error of the prediction. The letters indicate differences between slopes among zones. Each symbol represents a plot (average of 5 pseudo-replicates).*

**Effect of the interaction zone by density on early-stage canopy growth**

The data collected supports our hypothesis that in the earlier stages a higher seed density helps establish a canopy faster in a low environment (Figure 4*)*. The analysis of the model parameters showed a significant interaction between seed density and zone on NDVI. In low zones a higher NDVI is reached with high sending density than with low sowing densities compared to high densities, whereas no difference were observed for medium and high environments.

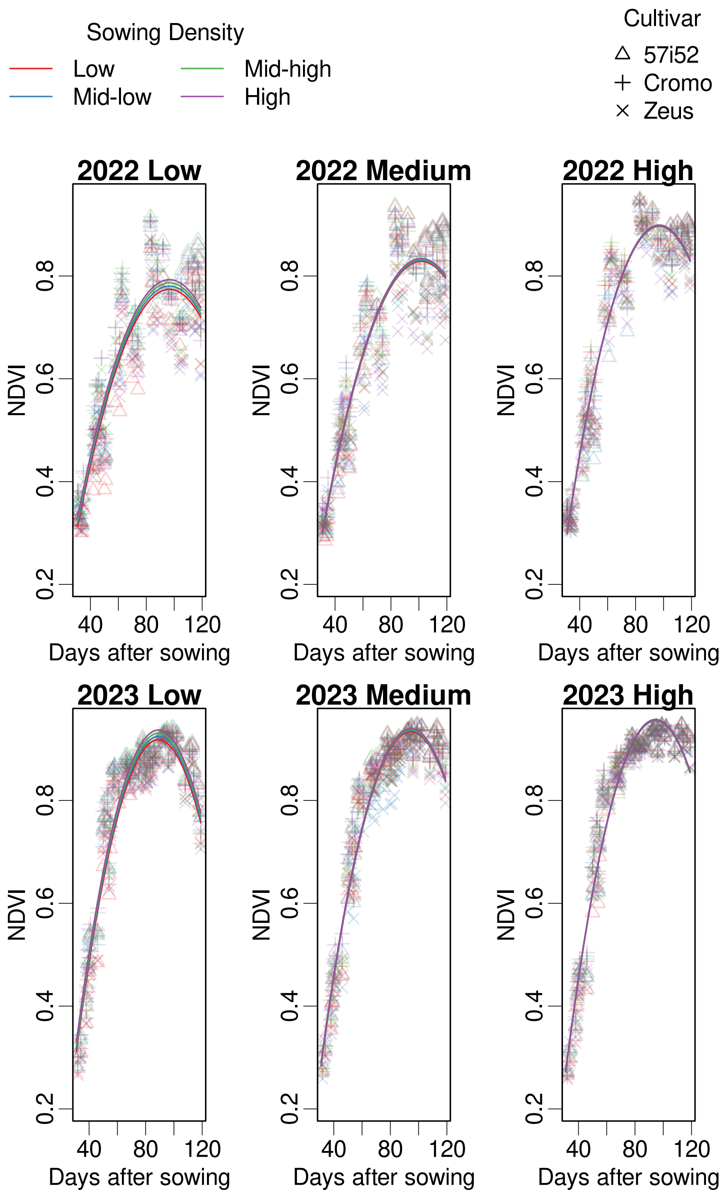


*Figure 4: HP1.1 Effect of sowing density over NDVI time series, marginalized by zone and year. In each plot, we are highlighting the impact of the density on NDVI.*

## Effect of the interaction zone by density on yield components and emergence (HP2b,2c)

The data support our hypothesis that the association between number of pods and grain yield is weaker in low yield environment than in high ones (HP2a), in fact we found that the regression slope between number of pods and seed density is more flat (despite not significantly different) in low environment than in high ones (Figure 5), and that the coefficient of determination between pods and seed density is lower in low yield environment. This implies that the compensation mechanism (in lower seed density each plant occupy more space and compensate with higher pods production) is more efficient in high zones than in low zones. The main plasticity mechanism that we observed in this study was the decrease of the number of pods per plant in response to increasing densities, whereas we did not see an effect of density on number of grain per pod, nor on grain weight. Our data do not support HP 2c on reduced emergence of seeds/ death of young plants in low environments, as we did not observe significant interactions between zone and emergence.

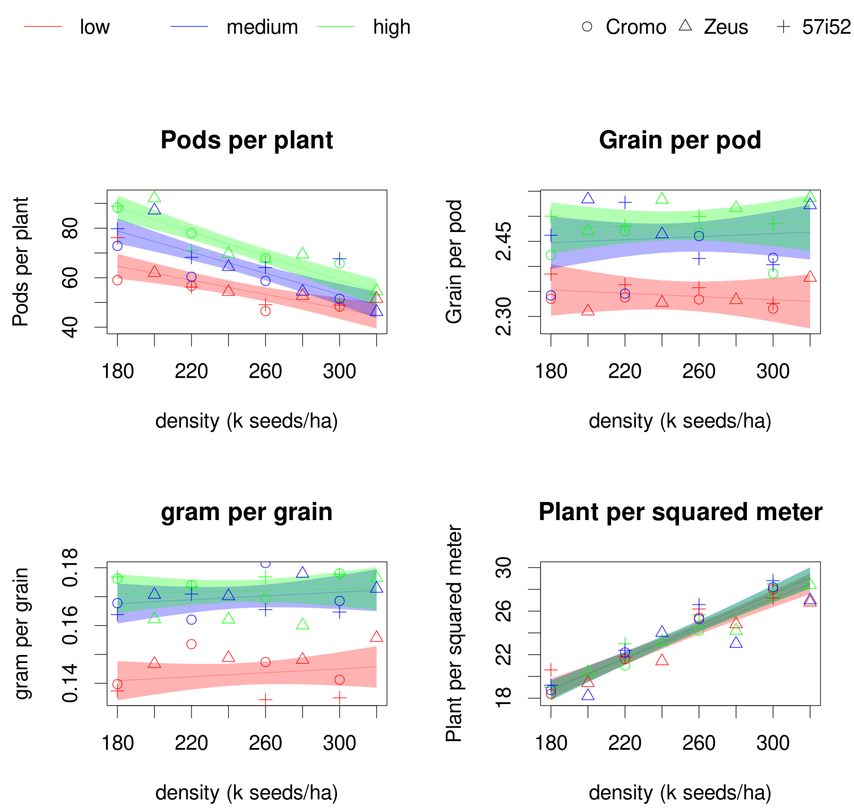


*Figure 5: Estimate mean number of pods per plant by zone and density marginalized over cultivar and year. The slopes of the curve are not significantly different among them.*

## Effect of interaction zone by cultivar stability on Yield (HP3)

Our data do not support HP3 on high yielding cultivars outperforming stable cultivars in high yield environments, in fact we saw that stable cultivars (Brasmax Cromo TF IPRO and DMDM 57i52 IPRO) performed equally (in medium and high zones) or better (between 0.5 and 1 Mg $ha^{-1}$ more) than the high-yielding cultivar Brasmax Zeus IPRO.

## Discussion

### Hypothesis 1 - Low yielding zones benefit from higher seeding rate

The results partially confirmed our hypothesis that low yield environment could benefit from an increased seeding rate (HP1). This finding extends at within-field scale similar observations developed at a regional scale by Carciochi et al. (2019) and Corassa et al. (2019). This study and the works of Carciochi and Corassa reach similar implications (high optimal agronomic seeding rate in a low environment), though the analysis that brought us to this conclusion differs from theirs. Carciochi and Corassa found that yield response to sowing density plateaued later in low zones than in high yield environment, whereas we observed a correlation between yield and seed density in low yield environment whereas we did not find such correlations in medium and high ones. Nonetheless if a simple linear model – instead of a linear regression with plateau – was fit to the North American data of Carciochi et al. (2019, Figure 4), the result would be reconciled as low yield environment would show a stronger correlation between yield and density than medium and high ones. The existence of an interaction environment x seed density both at regional and within-field level induces us to think that in both cases a low environment is more prone to water crop shortage. However, at regional scale the major driver of water limitation is the amount of precipitation, and the soil-type, whereas at field scale topography, main runoff pathways, drainage and soil texture, organic matter content and depth — that are often correlated with topography components as elevation, slope and shape — are a major driving factors (Feria and Basso 2019). This agrees with findings from Krause et al. (2020) who showed that planting rate was a marginal predictor for yield (4.1% explained variation, farmer-centric data from the state of New York, US), whereas its predictive importance increased when considered in interaction with other within-field variables like topography. The testing of our sub hypotheses attempts to shed a light on why low yield environments benefit from higher seeding rates. The first hypothesis is that the initial growth in low zones is limited and thus a higher seeding density results in a faster establishment of a full canopy coverage, as observed previously by Schmitz and Kandel (2021) in an experiment in Northern United States, and by Sampaio et al. (2021) using a crop growth model (CROGRO) for Brazilian sites. A plurality of factors may limit the initial growth of seeds in a low environment, primarily water shortage, but soil compaction, and a higher pressure of soil diseases could also contribute. In this study, the water shortage is the most likely factor contributing to reducing growth in low zones because they are located are not irrigated and have a lower clay content and higher altitude compared to mid and high zones. The quick establishment of a canopy cover is also beneficial in limiting weeds growth; however, this aspect was not investigated in the present study, and the field was regularly sprayed to prevent weeds growth.

The second sub hypothesis that we formulated to understand the interaction environment x seed density is that soybean expresses a lower plasticity in low environment than in medium and high zones, thus a lower plant density in low environment is not sufficiently compensated by more pods per plant. Our results support this hypothesis as we found a stronger correlation between seed density and number of pods per plant in a low yield environment than in medium and high ones (Figure 5). Similarly, Ferreira et al. (2020) in a field in Southern Brazil observed that the increase in number of pods per plant compensated the lower number of plants at seeding rates above the 60% of recommended seeding rate. However, they also observed a negative relationship between the number of grains per pod and seed density, and an increase of thousand grain weight with seed density that we did not observe. This could be due to the fact that high yielding zones — that in our study were irrigated — have more resources to establish a higher number of pods. Moreover, low yielding environments have a higher canopy temperature that also limits pods addition rate, as modeled in CROGRO bean model (Boote et al. 1998). The third and last of our hypothesis to explain the interaction environment x seed density is that low yield environment have a more hostile bed to the seed causing a nonuniform emergence rate that is linked to many factors as soil crusting, diseases, poor seed-to-soil contact and dry soil conditions (Anderson 2023) that reduce the shoot growth rate. This hypothesis was proposed by Corassa et al. (2018) but rejected by Carciochi et al. (2019) as their findings were based on final population (i.e. the density of emerged plants). Our data do not support this hypothesis as we do not observe differences in emergence rates between the environments. Despite the emergence rate does not differ it is still possible that low yield environment emerges later than medium and high ones causing nonuniform plant growth through this zone. Later emergence in a low yield environment would be linked to slow shoot growth that contributes to a slower canopy establishment, as we observe in this study (Figure 4). We did not observe large differences in emergence time in our study, however observing small differences in emergence time would require tools with at least daily or couple of days logging rate —e.g. camera-traps — that were not used in this study.

The three possible explanation for the higher optimal seeding rate in high yielding zones (early canopy establishment, weaker compensation mechanism in low yield environment and lower emergence rate) are non-mutually exclusive and which would prevail would depend on the timing of the stress, for example the early canopy establishment mechanism may prevail if the water stress occurs early in the season whereas (vegetative stages) whereas the weaker compensation mechanism will likely prevail if the water stress occurs around flowering time.

### Hypothesis 2 – Genotype x yield-environment at within-field scale

The results from two years of experiment did not confirm the initial hypothesis that stable cultivars (Brasmax Cromo TF IPRO and DM52i57 in our study) perform better in low yield environment and that high yielding cultivar (Brasmax Zeus IPRO) do better in high yield environment. While this may still be true in the long run, the two seasons of this study were dry — specially the 2021-2022 season — and this may have favored stable cultivars over the high-yielding cultivars regardless of the environment investigated. In this case, the wheater induces a large-scale effect on the cultivars that was dominant in relation to within-field variability scale effect. Moreover it should be noted that the three cultivars of this study are categorized as high yielding cultivars, so the higher yield potential of Brasmax Zeus IPRO compared to the other two cultivars may be little.

### Drivers of within-field differences

In the present study we also investigated the processes that are behind soybean yield variability, the major limiting factor in low yield environment was water availability as they are located at a relatively higher altitude, they are rainfed and have a lower clay content and soil organic matter. The lower soil water availability in low zones caused lower growth and evapotranspiration rates, that resulted in a warmer and drier air temperature at canopy height, as observed also by Maestrini and Basso (2018) who found a negative correlation between crop yield and canopy temperature at within-field scale. This likely generated an undesirable increase in crop phenological development rate that contributed to shortening the grain filling period. The higher temperature could impair some mechanisms of plant plasticity like reducing the number of pods per plant, as reported in our study, or grains weight. Despite a rich literature on the influence of canopy growth, water balance and weather on microclimate and crop phenology — these interactions are even included in some crop models (Brisson et al. 2003) — few studies investigated the variability of crop phenology at within-field scale. For example, Verdugo-Vásquez et al. (2016) investigated the grapevine phenology variability at within-field level, but studies on this phenomenon in annual crops are lacking. Nonetheless, the variability in crop phenology between within-field zones may be high, especially in large, non-uniform and undulated fields like our study area. Such large differences may be evened out by sowing cultivars with slightly higher maturity groups (i.e. cultivar with a longer growing period) to attainment of a homogeneous ripening within the field, however, this was not investigated in the present study.

### Beyond seeding technology to manage within-field variability

In this study we explore seed technologies to limit the stress of plants growing in low environments, however complementary technologies can also be used for example for liming (Pott et al. 2019, Bossolani et al. 2021) or biological inputs that help the crop to tolerate the abiotic stress. We did not find an interaction cultivar x environment, however addition, some innovative farmers are reporting that mix of varieties pertaining to similar maturity groups in the same field increase the crop sanity through the field, mainly to decrease soybean rusty (main crop disease in Brazil). To overcome the lack of multi-variety seeders, the farms mix the cultivars in the same seed tank. Overall large field variability calls for a differentiated treatment in low zones, for example input in low zones can be reduced given the lower economic return and high environmental risk and products like carbon credit derived from less intensive cultivation could be considered in these zones.

## Conclusion

This study investigated how seeding technology (varying seeding rate and genotype according environment) can be used to manage within-field spatial variability. We added a piece of evidence in support to the theory that a low yield environment has a higher optimal agronomic seeding rate for soybean. We extend previous findings on the interaction seeding rate x environment from yield zones clustered at regional scale to yield zones at within-field scale. We provide evidence that the causes for higher agronomical optimal seeding rate in low yield environment are: a slow row canopy cover and a weaker soybean plastic response to missing plants/slow early shoot growth, however the plant physiological reasons that are associate to the lower plastic response demands deeper investigation in future studies. There can be more causes for a lower optimal rate in low zones, for example emergence rate, but we did not find evidence for that, in our use case. We also did not find evidence supporting multi-cultivar seeding (i.e. seeding various cultivar in various zones of a field), however it is possible that the drought of the two seasons examined favored the stable cultivars over high-yielding one irrespective of the within-field spatial yield environment variability. These findings represent a step forward toward a better understanding of the influence of smart seed technologies in soybean at different scale (large-regional and small-within field) taking account the weather conditions prevalent which is the foundation for a wider adoption of variable seeding technologies in precision agriculture.

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