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Can an increase in plant population benefit or impede soybean crop productivity in Petric Plinthosols?

O aumento da população de plantas pode trazer ganhos ou perdas para a cultura da soja em Plintossolos Pétricos?

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Highlights

Soybean production in Petric Plinthosol of Tocantins;
Population responses of two soybean cultivars in Ferralsols and Petric Plinthosols;
Adaptation of soybean cultivation to environments with risk of productivity loss.

Abstract

The rising global demand for soybeans has resulted in using land with soils that are poorly suited for agriculture, such as Petric Plinthosols. However, most annual crops cultivated in these soils lack an adequate and sustainable technological framework to maintain stable productivity under the challenges posed by climate change. One of the primary challenges of soybean cultivation in these environments is achieving optimal crop establishment to ensure considerable productivity gains. In this context, examining whether soybean plants respond proportionally or more intensively to stand changes in Petric Plinthosols than to those in Ferralsols is pertinent. The influence of the plant growth environment on intraspecific competition among soybean plants in Plinthosols, characterized by limited environmental resources (particularly water availability), warrants examination. If one soil exhibits lower water availability than another, such as a Petric Plinthosol, can larger populations adversely impact productivity by extracting water from the soil at a faster rate? Therefore, this study aimed to compare different populations of two legume varieties exhibiting distinct drought tolerances in Petric Plinthosols and Ferralsols, to identify optimal management practices for cultivation in gravelly soils. The results

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indicated differences in the responses of the two varieties to the two soil types. Higher population densities led to increased productivity in Ferralsols. Although productivity did not correlate directly with the plant population increase in the Petric Plinthosols, this increase resulted in a greater leaf area and plant height, thereby increasing the risk of soybean lodging.
Key words: Tocantins. MATOPIBA. Gravel. Drought.

Resumo

A crescente demanda mundial por soja tem impulsionado a incorporação de áreas com solos de baixa aptidão agrícola, como os Plintossolos Pétricos. Entretanto, a grande maioria dos cultivos anuais nestes solos não dispõe de um portfólio tecnológico adequado e sustentável, que mantenha a estabilidade da produtividade frente às mudanças climáticas. Um dos principais desafios para o cultivo de soja nestes ambientes é a formação de um estande adequado, o que pode trazer ganhos expressivos em produtividade. Neste contexto, questiona-se se as respostas da soja às variações de estande no Plintossolo Pétrico seriam proporcionais ou mais intensas que as respostas às variações de estande no Latossolo. Questiona-se ainda como a competição intraespecífica das plantas de soja em Plintossolos Pétricos (com menor oferta ambiental, principalmente disponibilidade de água) poderia ser influenciada pelo tipo de ambiente em que a cultura se desenvolve. E ainda, se um solo apresentar menor disponibilidade de água que outro, como um Plintossolo Pétrico, maiores populações poderiam ser mais prejudiciais à produtividade, pois poderiam retirar com maior rapidez a água dos solos? Assim, este trabalho propõe a comparação de populações diferentes, de dois cultivares com tolerância diferencial à seca, em ambientes com Plintossolo Pétrico e Latossolo, na busca de um manejo mais adequado do cultivo desta leguminosa em Plintossolo Pétrico. De acordo com os resultados observados, há variação de resposta das duas cultivares aos dois solos. Maiores densidades populacionais só trouxeram ganhos de produtividade no Latossolo. Embora a produtividade não seja proporcional ao aumento do estande de plantas em Plintossolos Pétrico, esse aumento assegurou a maior área foliar e altura de plantas.
Palavras-chave: Tocantins. MATOPIBA. Cascalho. Seca. Estande.

Introduction

Soy has emerged as the main agricultural crop developed in Central Brazil. It is widely used as a source of oil and vegetable protein and commonly exported as grains (Hirakuri et al., 2018). In response to rising global demand, many agricultural enterprises have increasingly incorporated land that was previously excluded from production because of physical and chemical limitations. In this context, soils with low agricultural suitability, such as Petric Plinthosols (Lumbreras et al., 2015), have been cultivated in different regions of Brazil, especially in Tocantins (Campos et al., 2019, 2022). Most annual crops in Plinthosols are cultivated without the support of an adequate and sustainable technological framework for this condition (Almeida et al., 2023), leading to production instabilities and reduced resilience during droughts or dry spells (Evangelista et al., 2022). Despite these difficulties, soybean cultivation in Petric Plinthosols has gained prominence in Central Brazil, yielding productivity levels ranging from 2,700 to 4,200 kg ha^{-1} (Campos et al., 2022).

Petric Plinthosols are characterized by low natural fertility and the marked presence of ironstone gravel. The large particle size of gravel restricts mechanization and the water-retaining capacity in the surface horizons. However, the formation of superficial physical barriers (horizons with low permeability) can lead to flooding in certain areas (Lumbreras et al., 2015; Santos et al., 2018). Producers have also reported a decrease in the stand of soybean plants cultivated in Petric Plinthosols relative to Ferralsols. This phenomenon may be associated with the lower water retention capacity of Petric Plinthosol and smaller seed contact with the soil due to its coarser texture (Lumbreras et al., 2015; Santos et al., 2018). Consequently, these factors may limit the intensive cultivation of grains, fibers, and oilseeds (Ramalho & Pereira, 1999).

Forming an adequate stand is a primary challenge in soybean cultivation within these environments, as it can substantially increase productivity. However, information regarding populations that fall below or above the recommended levels in Petric Plinthosols remains limited. The question is whether soybean responses to stand variations in Petric Plinthosols are proportional or more intense than those in Ferralsols.

Increasing plant density typically increases intraspecific competition, which may pose challenges in environments with limited natural resources (e.g., water and nutrients). Producers and technicians use soybean sowing density to increase productivity and efficiency in natural resource utilization at cultivation sites (Balbinot et al., 2018; Ferreira et al., 2020). However, these studies focused on environments characterized by abundant environmental resources and cultivars lacking differential drought tolerance.

Research indicates that higher soybean population densities in soils other than Petric Plinthosols may enhance productivity (Xu et al., 2021a,b). Conversely, other studies (Board, 2000; Tourino et al., 2002) have not reported any substantial differences in the effects of variations in the soybean population on productivity. Watanabe et al. (2005) reported that soybean productivity was higher at lower densities (a population of 200 thousand plants ha^{-1} than at a density of 400 thousand plants ha^{-1}). Carciochi et al. (2019) found that in environments with greater environmental supplies (productivity >4,300 kg ha^{-1}), the optimal agronomic density of soybean plants was 24% lower than that in environments with lower environmental supplies (productivity < 4,000 kg ha^{-1}).

In this context, several questions arise. Firstly, how can intraspecific competition among soybean plants in Petric Plinthosols (with a lower environmental supply, mainly water availability) be affected by the type of environment in which the crop grows? These environmental variations may alter the responses associated with soybean plant density. Therefore, if a Petric Plinthosol exhibits a lower potential or environmental supply, by what proportion should the optimal density be greater than that of a Ferralsol? Furthermore, if one soil type exhibits lower water availability than another, such as a Petric Plinthosol, can larger populations adversely impact productivity by removing water from the soil more rapidly?

Therefore, this study compared different populations of two cultivars exhibiting different tolerances to drought in Petric Plinthosol and Ferralsol environments to establish a more appropriate management strategy for cultivating this legume in gravelly soils.

Materials and Methods

The experiment was conducted at Fazenda Invernadinha do Tocantins (10°11'16.1'' S, 48°40'55.9'' W, 386 m elevation) in the municipality of Paraíso do Tocantins/TO during the 2019/20 growing season. The local climate is characterized as Aw, tropical with a dry winter season, according to the Köppen–Geiger classification, featuring an average temperature of 26.6 °C and annual precipitation of 1,909 mm. The two soils were cultivated on the same property, located 360 m apart, and classified as Plinthic Ferralsol dystric soil and Petric Plinthosol dystric soil (Mantel at al., 2023) or Latossolo Vermelho Amarelo distrófico plintossólico and Plintossolo Pétrico concrecionário típico (Santos et al., 2018). The precipitation and minimum and maximum temperatures were measured throughout the experiment (Figure 1). The experiment utilized a randomized block experimental design using a double factorial scheme for each soil type, aimed at a joint analysis of a factorial experiment (cultivar and population factors), with four replicates.

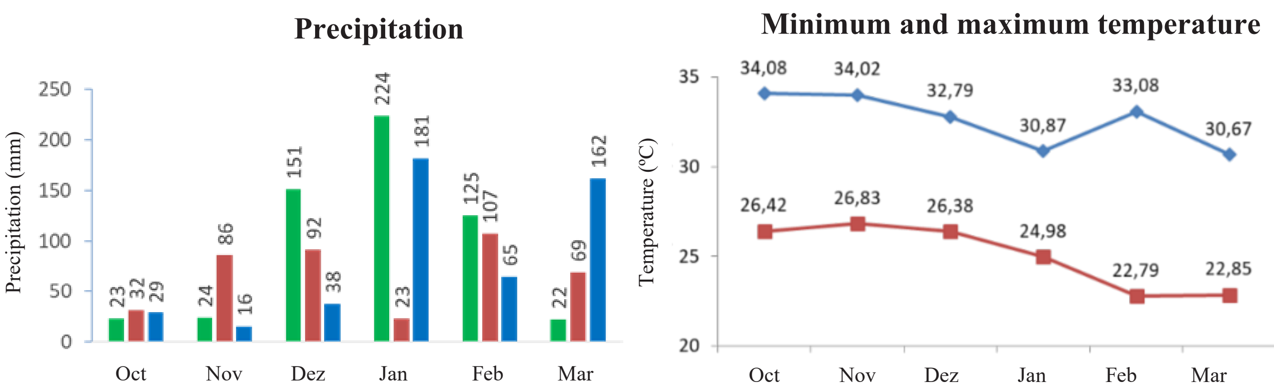

Figure 1. Accumulated precipitation recorded every 10 d (with green, red, and blue bars representing the first, second, and third ten-day periods, respectively) alongside the average minimum and maximum temperatures (in °C) obtained from meteorological stations at Fazenda Invernadinha do Tocantins, covering the period from October 1, 2019, to March 31, 2020.

Chemical analyses of the soils revealed the following values for the Ferralsol and Petric Plinthosol, respectively: pH, 6.21/6.87; potential acidity, 3.2/2.8 cmolc dm^{-3}; aluminum, 0/0 cmolc dm^{-3}; Ca^{+2}, 2.55/2.95 cmolc dm^{-3}; Mg^{+2}, 1.33/2.02 cmolc dm^{-3}; K^{+}, 0.08/0.09 cmolc dm^{-3}; P, 5.99/5.43 mg dm^{-3}; Cu^{+2}, 0.83/0.8 mg dm^{-3}; Fe^{+2}, 49.8/41.5 mg dm^{-3}; Mn, 8.22/6.91 mg dm^{-3}; and Zn, 1.49/1.35 mg dm^{-3}. The textural analysis of the soils revealed proportions of 98, 492, and 410 g kg^{-1} of sand, silt, and clay, for the Ferralsol, respectively, and 280, 315, and 405 g kg^{-1} of sand, silt, and clay for the Petric Plinthosol, respectively. The percentage of gravel (> 2 mm) per soil mass (in the 0–20 cm layer) was 0% for the Ferralsol and 49% for the Petric Plinthosol.

The sowing fertilization method used 20 kg ha^{-1} N, 100 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O in both soils according to the technical recommendations of the culture and chemical analysis of the soil. Seeds were treated with fipronil and cobalt/molybdenum at the recommended commercial dosages (5 and 25 g ha^{-1} of cobalt and molybdenum, respectively). A peat inoculant comprising *Bradyrhizobium japonicum* and *Bradyrhizobium diazoefficiens* (strains SEMIA 5079 and SEMIA 5080, respectively) was applied to the seeds (five doses per hectare), followed by the addition of a 10% sugar solution. The seeds were treated on the day of sowing.

The BRASMAX BÔNUS IPRO 8579 RSF (Bônus), GMR 7.9 and RK 7518 IPRO, GMR 7.5 cultivars, characterized by indeterminate growth and purple flowers, were extensively cultivated in Tocantins and sown on November 21, 2019. BMX Bônus IPRO is characterized by medium branching, whereas RK 7518 IPRO exhibits a lower branching potential. The recommended plant population for BMX Bônus IPRO cultivation ranges from 240 to 280 thousand plants ha^{-1}, whereas that for RK 7518 IPRO ranges from 380 to 400 thousand plants ha^{-1}. The BMX Bônus IPRO and RK 7518 IPRO cultivars are classified as moderately sensitive and moderately tolerant to drought, respectively (Cabral et al., 2020, 2021).

The seeding rates used in the two soil types were 6, 11, 15, and 19 plants m^{-1}, which, at a spacing of 0.5 m, corresponded to populations of 120, 220, 300, and 380 thousand plants ha^{-1}, respectively (Figure 2; Supplementary Material). To ensure a minimum number of plots (four rows of 5 m) with a uniform distribution and planned population, eight experimental plots were sown per population; therefore, those that did not meet this criterion were discarded. Finally, each treatment had four replicates in a randomized block design for each soil type.

Cultural treatments (weed, pest, and disease management) were performed according to the specific needs identified at each location. The harvest occurred when the cultivars reached full maturity, characterized by yellow pods and over 80% defoliation on the plant, scale R8 (Fehr & Caviniess, 1977), between March 17–20, 2020.

The following characteristics were measured: leaf area index (Lai), diffuse light not intercepted by the canopy (Difn), plant height, and grain yield. Lai and Difn plants were collected at the onset of flowering (R1, approximately 40 d post-germination) using a leaf canopy analyzer (model LI-COR LAI-2200) at four locations within each plot. This analyzer has a five-angle light capture sensor that integrates light capture both above and below the canopy to estimate the leaf area index.

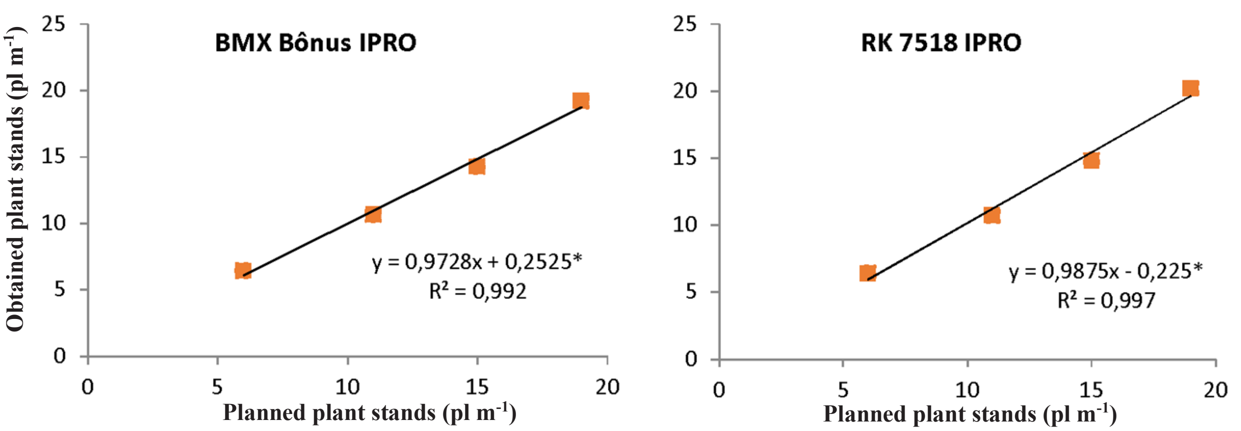

Figure 2. Final average soybean plant population per linear meter (plants m^{-1}) for two cultivars (BMX Bônus IPRO; RK 7518 IPRO) cultivated in Paraíso do Tocantins/TO, 2019/2020. * Significant at $p \leq 0.05\%$. CV = 11.91%; RK = 9.14%.

The height of 10 plants per plot at the time of harvest was measured from the soil level to apex of the plant using a measuring tape. Grain productivity was assessed in 4 m^2 of each plot by manually harvesting plants from the two central rows. These plants were subsequently threshed on a stationary threshing machine, and the resulting grains were weighed. The moisture content was determined using an automatic portable grain moisture meter (G610i Gehaka), and the values were corrected to 13% moisture to express grain productivity (kg ha^{-1}).

Prior to conducting the analysis of variance, homoscedasticity of variance, normality and independence of residuals, sphericity, and Bartlett's tests were performed. Once the assumptions of analysis of variance (ANOVA) were met, ANOVA was performed at 5% significance using the F test. The analyses were carried out with SISVAR (Ferreira, 2011) and R (R Core Team [R], 2021) software, using the FactoMineR (Lê et al., 2008), factoextra (Kassambara & Mundt, 2022), and Factoshiny (Vaissie et al., 2021) packages.

Results and Discussion

The amount of gravel (plinthites) present in Petric Plinthosols influences physical characteristics that decrease water retention in surface horizons (Nikkel & Lima, 2019a). These physical characteristics also imply a decreased contact area between the seeds and soil, which may lead to a reduction in plant stand size.

In the present study, no significant reductions in the planned stands were observed (Figure 2). Plots with programmed populations were established in both soil types, resulting in four uniform populations that differed from each other, as predicted for the different populations. The soil type had no influence on the formation of planned stands for either the BMX Bônus IPRO or RK 7518 IPRO cultivars (Figure 2). Despite the reduced rainfall in the third ten-year period in November (16 mm; Figure 1), the seeds sown on November 21, 2022 were adequately supplied with water through rain experienced in the second ten-year period. Therefore, planned plant densities were achieved in both soil types for the two cultivars (Figure 2), indicating that soil type did not interfere with seedling emergence.

Lai was quantified during the R1/R2 stages of the cultivars, similar to the results reported by other researchers (Evangelista et al., 2022). In relation to the cultivar BMX Bônus IPRO, the leaf area index (Lai) remained unchanged across different soil types (Figure 3). A positive linear regression was observed between the plant populations of this cultivar and Lai, both in the Ferralsols and Petric Plinthosols (Figure 3).

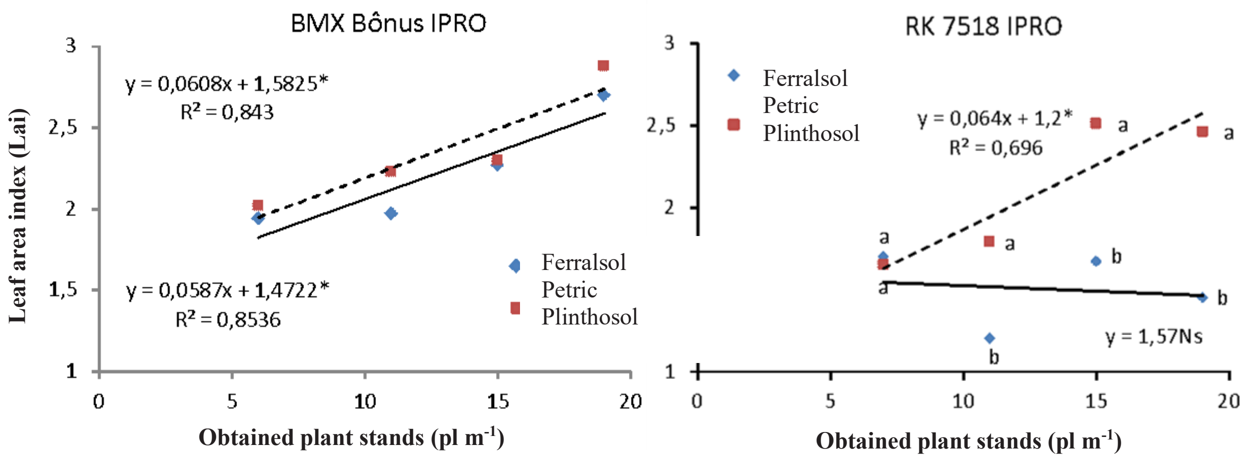

Figure 3. Leaf area index (Lai) of the BMX Bônus IPRO and RK 7518 IPRO cultivars in Ferralsols and Petric Plinthosols across different populations (6, 11, 15, and 19 plants m-1). * Significant regression at p ≤ 0.05%. Means denoted by the same letter (lower case) among soil types within the same population are not significantly different as per the Scott–Knott test; p ≤ 0.05%, CV (%) = 13.34.

In the RK 7518 IPRO cultivar, variations were observed between soil type and plant population for Lai. In Petric Plinthosols, the population increase in was proportional to the increase in Lai, a trend not observed in Ferralsols (Figure 3). Compared to the average Lai of this cultivar in the two soil types, a greater Lai was observed in the largest populations of Petric Plinthosol, except for the Lai of the population of six plants per linear meter (plm), which was the same in both soil types (Figure 3).

Nikkel and Lima (2019b) confirmed that in corn plants, the leaf area of the BMX Bônus IPRO soybean cultivar remained unaffected by the soil type, whereas it increased with population density (Figure 3). However, the Lai of the RK 7518 IPRO cultivar did not increase in response to the increase in plant population in the Ferralsols (Figure 3). This highlights the different behaviors of the soybean cultivars. This finding may be explained by the branching capacity. Therefore, plants with greater branching potential, such as the BMX Bônus IPRO cultivar, are likely to exhibit a greater potential for increasing their Lai, a phenomenon not observed in plant populations with lower branching capacity, such as RK 7518 IPRO.

Soybean plants have the distinct ability to adapt to environments with varying levels of intraspecific competition by changing their leaf area or growth rate per plant (Andrade et al., 2010). This ability is known as phenotypic plasticity. The growth and development of soybean plants in different populations tend to vary because of the interrelationship between the environment and phenotypic plasticity of each cultivar (Carciochi et al., 2019). The BMX Bônus IPRO cultivar showed greater phenotypic plasticity than that of the RK 7518 IPRO cultivar, indicating that Lai da Bônus is more responsive to population variations than the RK7518 cultivar. Other researchers have demonstrated that different soybean cultivars respond differently to Lai (Ferreira et al., 2020). In addition, the cover (straw) and available water content of the soil can directly influence the leaf area (Anjos et al., 2017). Andrade et al. (2005) stated that plants with early cycles and low phenotypic plasticity might derive greater benefits from increased density, a phenomenon potentially observed in this experiment.

Diffuse non-intercepted light (Difn) can be defined as the amount of diffuse light reaching the ground level, going beyond the canopy of the examined plants. This measure relates to the Lai, plant architecture, and leaf insertion angle, which collectively can either facilitate or obstruct the passage of light. A larger measurement corresponds to an increased amount of light captured at ground level. Consequently, the Difn is inversely proportional to Lai and reflects the uniformity of the vegetation cover, integrating both leaf area and the architecture of canopy plants (Pokorný & Stojnič, 2012). The Difn results were similar to those observed for Lai exclusively in the BMX Bônus cultivar (Figures 3 and 4). The BMX Bônus IPRO cultivar exhibited greater canopy uniformity, which responded uniformly to population variations in both Ferralsols and Petric Plinthosols. This resulted in a more uniform leaf architecture across soil types, indicating stability in the plant architecture and leaf insertion angle of this cultivar in both soil types. In RK 7518 IPRO, the two soil types exhibited different behaviors. With increasing population, a negative linear regression was observed for Difn in the Petric Plinthosols, and a negative quadratic regression was noted in the Ferralsols, albeit with a poor fit (R2 = 0.223; Figure 4).

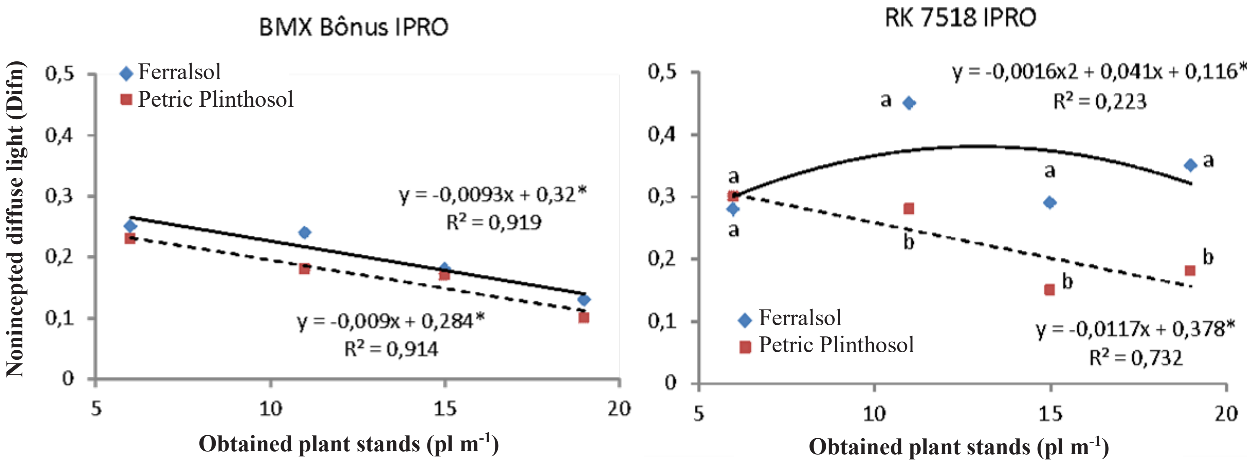

Figure 4. Nonintercepted diffuse light (Difn) of the BMX Bônus IPRO and cultivar RK 7518 IPRO cultivars in Ferralsols and Petric Plinthosol across different populations (6, 11, 15, and 19 plants m^{-1}). * Significant at $p \leq 0.05\%$. Means denoted by the same letter are not significantly different as per the Scott–Knott test; $p \leq 0.05\%$, CV (%) = 22.19.

The responses of each cultivar to plant height varied. The BMX Bônus IPRO cultivar (considered more sensitive to drought) was taller in the Ferralsols than in the Petric Plinthosol, and RK 7518 IPRO displayed no variation in height in response to the soil type (Figure 5). BMX Bônus IPRO showed a positive quadratic response between population density and soil type, and the cultivar RK 7518 IPRO showed a linear increase in height in different populations (Figure 5).

Height is an important component of shoot composition and soybean productivity, which is controlled by genetic and environmental factors (Yang & Jeong, 2021). Because of the physical composition of Petric Plinthosol, which contains a large amount of concrete (gravel with plinthite), a lower water retention capacity is expected (Nikkel & Lima, 2019a). Gava et al. (2015) reported a reduction in the height of soybean plants owing to water restrictions. Thus, the most drought-sensitive cultivar, BMX Bônus IPRO, appeared to be affected by soil type, with reduced growth in the Petric Plinthosols, whereas the most drought-tolerant cultivar, RK 7518 IPRO, maintained its height in the two examined soil types.

The greatest heights were observed in the largest populations (Figure 5), which increased the soybean lodging risk. Yang & Jeong (2021) reported that, in shaded environments (greater competition for light), the growth of the main stem is positively affected at the expense of that of the lateral buds.

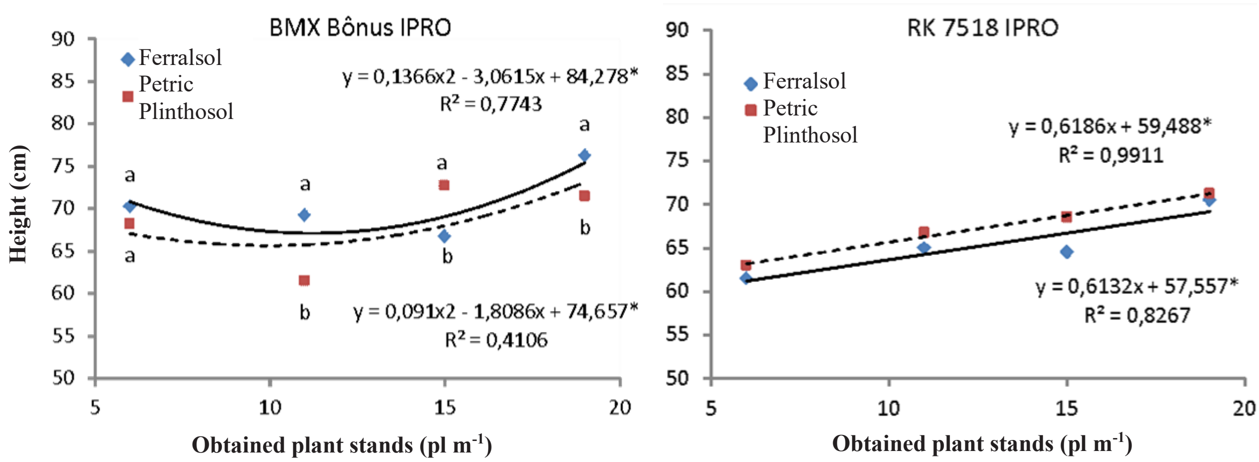

Figure 5. Plant heights of the BMX Bônus IPRO and RK 7518 IPRO cultivars in Ferralsols and Petric Plinthosols assessed across different populations (6, 11, 15, and 19 plants m^{-1}). Means denoted by the same letter within the same plant population are not significantly different as per the Scott–Knott test, at $p \leq 0.05\%$, CV (%) = 4.74. * Significant regression at $p \leq 0.05\%$.

Productivity is mostly influenced by leaf coverage and light interception, both of which are also associated with plant density. However, minor population fluctuations typically do not translate into large variations in productivity (Pereira et al., 2021; Procópio et al., 2013). However, large population variations combined with water restrictions can affect productivity and alter the responses of these plants to the tested population levels (Ferreira et al., 2020).

The increase in plant population resulted in increased productivity exclusively in the Ferralsols for both cultivars (Figure 6). The highest productivity was observed in the Ferralsols, which exhibited the largest population (19 plants m^{-1}; Figure 6). In the two cultivars sown in the Petric Plinthosols, no responses were noted in terms of productivity to population increase (Figure 6).

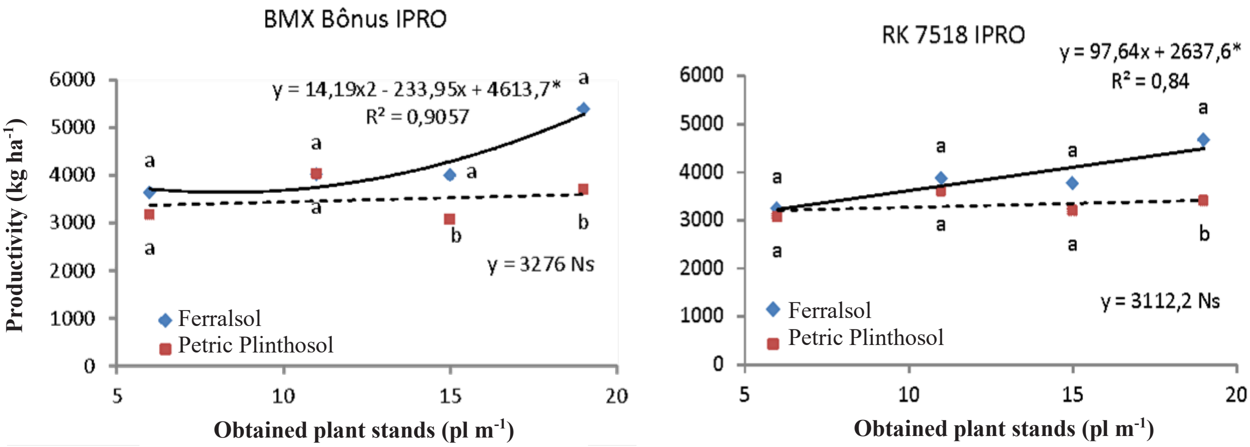

Figure 6. Yields of the BMX Bônus IPRO and RK 7518 IPRO cultivars cultivated in Ferralsols and Petric Plinthosols, with different populations (6, 11, 15, and 19 plants m^{-1}). Means denoted by the same letter within the same population level are not significantly different as per the Scott–Knott test, at $p \leq 0.05\%$, CV (%) = 11.06.

In general, population increases correlate with heightened productivity up to the point where stabilization occurs. This point, also known as the optimal plant density, depends on the growing environment (Corassa et al., 2018; Carciochi et al., 2019). Therefore, environments with superior resource availability require smaller populations to achieve maximum productivity. The data from this study showed that increases in the plant stand (up to 400 thousand plants ha^{-1}) could increase the productivity of Ferralsols. However, Ferreira et al. (2020) showed that increases in seeding rates failed to increase productivity only when the rates were greater than 35/75%, depending on the cultivar. In this study, seeding rates that were always lower than 40% of the recommendation for cultivars were studied, which generated productivity gains in Ferralsols but not in Petric Plinthosols.

Compared with Petric Plinthosols, Ferralsols are characterized as a more favorable environment for plant development (Campos et al., 2019; Ramos, 2022; Marquardt et al., 2023), demonstrating enhanced productivity gains with increasing population elevation. Petric Plinthosols contain large amounts of gravel, which results in low water retention (Almeida et al., 2024). Consequently, Petric Plinthosols, being less favorable environments for crop growth, did not exhibit gains with increased soybean populations. In this context, an increase in Plinthosol plant populations did not result in an increase in productivity (Figure 6). The reproductive plasticity (ability to balance its reproductive drains, such as flowers and grains, with available photoassimilates) (Andrade et al., 2005) of soybean plants can also explain the productivity response variations in the two examined cultivars.

Some studies have linked the occurrence of plinthite concretions (materials with particle sizes above 3.1 mm) to adverse effects on the growth of cotton (Nikkel & Lima, 2020), corn (Nikkel & Lima, 2019b), and soybeans (Nikkel & Lima, 2019a). However, despite approximately 50% gravel (materials with particle sizes above 2 mm) in the Petric Plinthosols, this phenomenon was not observed in the present study (Figures 2, 3, 4, and 5).

The effects of water restriction on productivity are highly variable and depend on several factors, such as the plant growth phase, growing environment characteristics, and stress intensity and duration (Andrade et al., 2015). The question that arises is whether larger stands of drought-sensitive soybean plants may be affected when cultivated in environments with Petric Plinthosols. Utilizing drought tolerance indices, Cabral et al. (2020, 2021) classified the RK 7518 IPRO cultivar as moderately tolerant, whereas the BMX Bônus IPRO cultivar was characterized as moderately susceptible. This difference may indicate varied responses of these cultivars to Plinthosols because the amount of water available in these locations is less than that available in environments with Ferralsols. Comparing the productivity of each population in the two soil types revealed a differential response in populations of 15 and 19 plants m^{-1} for the BMX Bônus IPRO cultivar and a population of 19 plants m^{-1} for the RK 7518 IPRO cultivar (Figure 6). Therefore, the cultivar most sensitive to drought already showed a difference in productivity in smaller populations, whereas the more tolerant cultivar only showed differences in productivity in the largest population tested. Holshouser and Whittaker (2002) reported that, under low levels of water stress, variation in plant population did not influence productivity. However, under severe drought conditions in which water becomes the limiting factor for growth, taller populations may experience lower transpiration and stomatal conductance and lead to impaired photosynthesis and reduced productivity.

Similarly, the prevalence of intense drought and adequate soil management (forming plant cover and increasing infiltration and water retention in the soil) can influence plant growth in Petric Plinthosols, thereby influencing productivity both positively and negatively. Sandy soils exhibit a reduced productive potential than that of clayey soils (approximately 10%); however, when managed with appropriate technology, they can attain levels similar to those of Ferralsols (Sediyama et al., 2016). This observation can also be extrapolated to Petric Plinthosols. In a well-managed area, Almeida et al. (2023) found no differences in productivity between a soybean population sown in a Ferralsol and that sown in a Petric Plinthosol.

Principal component analysis (PCA) indicates an interrelationship between variables [components, such as productivity (Prod), height (Height), plm, Difn, and Lai] and treatments [such as different populations (6, 11, 15, and 19 plants m^{-1}) in Latosol (L) or Plintosol (P)], condensing the set of responses and allowing a global view of cultivar responses in both soil types. This approach allows for examining the interrelationships between variables and their relationships with the treatments. Therefore, antagonistic behaviors between Lai and Difn (in Bônus and RK 7518) and a positive correlation between productivity and height in the Bônus cultivar could be observed (Figure 7).

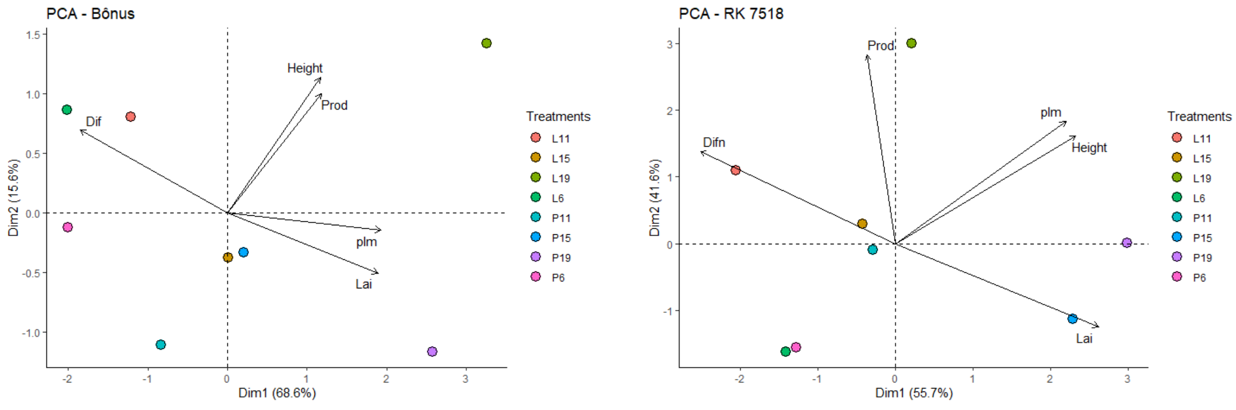

Figure 7. Principal component analysis (PCA; categorical and numerical variables) for the BMX Bônus IPRO (PCA Bônus) and RK 7518 IPRO (PCA – RK 7518) soybean cultivars. This analysis is based on variables obtained from plants cultivated in Ferralsols (L) and Petric Plinthosols (P), with different populations (6, 11, 15, and 19 plants m^{-1}), in Paraíso do Tocantins/TO, Brazil. The variables used were as follows: the leaf area index (Lai), non-intercepted diffuse light captured at ground level (Difn), height (Height), number of plants per linear meter (plm), and productivity (Prod). The categorical variables were formed by combining the type of soil (L or P) and the observed stand (6, 11, 15, and 19 plants m^{-1}).

Aside from the aforementioned scenario, the PCA did not reveal strong relationships between productivity and examined variables in the two cultivars cultivated in the two soil types (Figure 7). The PCA of the BMX Bônus IPRO cultivar revealed a positive relationship between the Lai and plm. In the PCA of the RK 7518 cultivar, a positive correlation was observed between the height and plm. In this analysis (Figure 7), the population of 19 plants m^{-1} stood out in both the Ferralsols (L19) and Petric Plinthosols (P19), thereby revealing an association between these populations and productivity. In contrast, the smallest populations were associated with high Difn, indicating less canopy closure (Figure 7) and lower productivity.

In relation to the RK 7518 IPRO cultivar, PCA analysis did not reveal a strong association between the productivity variable and other variables (Figure 7). However, the proximity between productivity and the population of 19 plants m^{-1} sown in the Ferralsols (L19; Figure 7, PCA – RK 7518) should be noted, as well as the smallest leaf area in L11, L6, and P6, and largest in P19.

This distinct behavior in the two soil types is the result of favorable interactions (higher available water content in the soil, greater activity of the clay fraction, and absence of physical barriers) in the Ferralsols and less favorable interactions in the Petric Plinthosols. In other words, in environments with greater water availability, increasing population can increase productivity.

Although increases in soybean populations has not been converted into significant productivity gains in Petric Plinthosols, it is suggested to use larger populations. This approach minimizes Difn, thereby reducing the incidence of light in the soil and evaporation of water from the soil, as previously documented (Figures 4 and 6). Special attention should be paid to the branching capacity and cycle of cultivars, as those with lower cycles and stemming capacities derive greater benefits from population increase.

Conclusion

The responses of the two cultivars to the two soils varied; however, increased population densities only resulted in productivity gains solely in the Ferralsols, indicating a greater environmental supply in this soil that was utilized by higher sowing density. Although productivity was not directly proportional to the increase in plant stand in Petric Plinthosols, this increase resulted in greater leaf area and plant height, thereby increasing the risks of soybean lodging.

Therefore, soybean cultivation in Petric Plinthosols can result in greater productivity gains, necessitating additional management practices, including the augmentation of soil organic matter and maintenance of straw. Therefore, soil and crop management that enhance water retention and nutrient supply in Petric Plinthosols can lead to productivity gains. This improvement is attributed to a more favorable environmental supply that supports higher plant density in Petric Plinthosols, as observed in Ferralsols.

The variables examined presented distinct behaviors between the two cultivars. However, the results indicate the need to explore other variables that may correlate more closely with productivity, such as the acquisition of specific spectral indices, to monitor the adaptation of soybeans to Petric Plinthosols more directly.

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References

Almeida, R. E. M., Custódio, D. P., Oliveira, S. M. de, Lima, L. S., Costa, R. V. da, & Campos, L. J. M. (2023). Recommendation of soil fertilization with copper and zinc for soybean crops grown in Petric Plinthosol. *Ciencia Rural, 53*(4), e20210722. doi: 10.1590/0103-8478cr20210722

Almeida, R. C. D., Cunha, M., Fo., Leite, O. D. C., Fernandes, M. M., & Araújo, R. N. D., Fo. (2024). Impact of land use change on nitrogen stocks in plinthosols of cerrado. *Revista Caatinga, 37,* e12299. doi: 10.1590/1983-21252024v3712299rc

Andrade, F. H., Abbate, P. E., Otegui, M. E., Cirilo, A. G., & Cerrudo, A. (2010). Ecophysiological bases for crop management. *The Americas Journal of Plant Science and Biotechnology, 4*(Special Issue 1), 24-34.

Andrade, F. H., Sadras, V. O., Vega, C. R. C., & Echarte, L. (2005). Physiological determinants of crop growth and yield in maize, sunflower and soybean. *Journal of Crop Improvement, 14*(1-2), 51-101. doi: 10.1300/J411v14n01_05

Andrade, F. H., Sala, R. G., Pontaroli, A. C., León, A., & Castro, S. (2015). Integration of biotechnology, plant breeding and crop physiology. Dealing with complex interactions from a physiological perspective. In V. O., Sadras & D. F., Calderini (Eds.), *Crop physiology: applications for genetic improvement and agronomy* (2nd ed., pp. 487-503). New York. doi: 10.1016/B978-0-12-417104-6.00019-4

Anjos, J. C. R. D., Andrade, A. S. D., Bastos, E. A., Noleto, D. H., Melo, F. D. B., & Brito, R. R. D. (2017). Water storage in a Plinthaqualf cultivated with sugarcane under straw levels. *Pesquisa Agropecuária Brasileira, 52*(06), 464-473. doi: 10.1590/S0100-204X2017000600010

Balbinot, A. A., Jr., Oliveira, M. C. N. de, Franchini, J. C., Debiasi, H., Zucareli, C., Ferreira, A. S., & Werner, F. (2018). Phenotypic plasticity in a soybean cultivar with indeterminate growth type. *Pesquisa Agropecuaria Brasileira, 53*(9), 1038-1044. doi: 10.1590/S0100-204X2018000900007

Board, J. (2000). Light interception efficiency and light quality affect yield compensation of soybean at low plant populations. *Crop Science, 40*(5), 1285-1294. doi: 10.2135/cropsci2000.4051285x

Cabral, R. do C., Maekawa, S. C. E., Zuffo, A. M., & Steiner, F. (2020). Índices de seleção para identificar cultivares de soja tolerantes à seca. *Research, Society and Development, 9*(7), e259973812. doi: 10.33448/rsd-v9i7.3812

Cabral, R. do C., Zuffo, A. M., Maekawa, S. C. E., Silva, K. C. da, & Steiner, F. (2021). Identificação de cultivares de soja para tolerância aos estresses hídrico e salino durante a fase de estabelecimento da plântula. *Revista em Agronegócio e Meio Ambiente, 15*(4), 1-20. doi: 10.17765/2176-9168.2022v15n4e9789

Campos, L. J. M., Almeida, R. E. M., Evaristo, A. B., Evangelista, B. A., Santos, D., Custódio, D. P., Tubiana, D. de O., Naoe, A. M. L., Peluzio, J. M., & Costa, R. V. (2022). *Produtividade de cultivares de soja em Plintossolos e Latossolos do Tocantins.* (Boletim de Pesquisa e Desenvolvimento, 28). EMBRAPA Soja.

Campos, L. J. M., Costa, R. V. da, Almeida, R. E. M. de, Evangelista, B. A., Simon, J., Silva, K. J. N. da, Pereira, A. A., & Evaristo, A. B. (2019). *Produtividade de cultivares de soja em três ambientes do Tocantins.* (Boletim de Pesquisa e Desenvolvimento, 21). EMBRAPA Soja.

Carciochi, W. D., Schwalbert, R., Andrade, F. H., Corassa, G. M., Carter, P., Gaspar, A. P., Schmidt, J., & Ciampitti, I. A. (2019). Soybean seed yield response to plant density by yield environment in North America. *Agronomy Journal, 111*(4), 1923-1932. doi: 10.2134/agronj2018.10.0635

Corassa, G. M., Amado, T. J. C., Strieder, M. L., Schwalbert, R., Pires, J. L. F., Carter, P. R., & Ciampitti, I. A. (2018). Optimum soybean seeding rates by yield environment in southern Brazil. *Agronomy Journal, 110*(6), 2430-2438. doi: 10.2134/agronj2018.04.0239

Evangelista, B. A., Campos, L. J. M., Silva, F. A. M. da, Simon, J., Ribeiro, I. L., & Vale, T. M. do. (2022). Possíveis impactos das mudanças climáticas sobre o zoneamento agrícola de risco climático da cultura da soja no estado do Tocantins. In E. Collicchio, & H. R., Rocha (Orgs.), *Agricultura e mudanças do clima no estado do Tocantins: vulnerabilidades, projeções e desenvolvimento* (pp. 167-184).

Ferreira, A. S., Zucareli, C., Werner, F., Fonseca, I. C. D. B., & Balbinot, A. A., Jr. (2020). Minimum optimal seeding rate for indeterminate soybean cultivars grown in the tropics. *Agronomy Journal, 112*(3), 2092-2102. doi: 10.1002/agj2.20188

Ferreira, D. F. (2011). Sisvar: a computer statistical analysis system. *Ciência e Agrotecnologia, 35*(6), 1039-1042. doi: 10.1590/s1413-70542011000600001

Gava, R., Frizzone, J. A., Snyder, R. L., Jose, J. V., Fraga, E. F. Jr., & Perboni, A. (2015). Estresse hídrico em diferentes fases da cultura da soja. *Revista Brasileira de Agricultura Irrigada, 9*(6), 349-359. doi: 10.7127/rbai.v9n600368

Hirakuri, M. H., Conte, O., Prando, A. M., Castro, C., & Balbinot, A. A., Jr. (2018). *Diagnóstico da produção de soja na macrorregião sojícola 5.* (Documentos, 405). EMBRAPA Soja.

Holshouser, D. L., & Whittaker, J. P. (2002). Plant population and row-spacing effects on early soybean production systems in the mid-Atlantic USA. *Agronomy Journal, 94*(3), 603-611. doi: 10.2134/agronj2002.6030

Kassambara, A., & Mundt, F. (2022). *Package 'factoextra.' R Package.* https://cran.r-project.org/web/packages/factoextra/factoextra.pdf

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR: an R package for multivariate analysis. *Journal of Statistical Software, 25*(1), 1-18. doi: 18637/jss.v025.i01

Lumbreras, J. F., Carvalho, A. de, Fº., Motta, P. E. F. da, Barros, A. H. C., Aglio, M. L. D., Dart, R. de O., Silveira, H. L. F. da, Quartaroli, C. F., Almeida, R. E. M. de, & Freitas, P. L. de. (2015). *Aptidão agrícola das terras do Matopiba.* (Documentos, 179). EMBRAPA Solos. http://www.infoteca.cnptia.embrapa.br/handle/doc/1025303

Mantel, S., Dondeyne, S., & Deckers, S. (2023). World reference base for soil resources (WRB). *Encyclopedia of soils in the environment* (2nd ed.). Elsevier. doi: 10.1016/B978-0-12-822974-3.00161-0

Marquardt, L., Ramos, M. R., Santos, D. M. A. dos, & Marquardt, G. (2023). Produtividade de cultivares de soja sob diferentes manejos em plintossolo pétrico. *Cuadernos de Educación y Desarrollo, 15*(1), 199-217. doi: 10.55905/cuadv15n1-012

Nikkel, M., & Lima, S. D. O. (2019a). Growth and vegetative development of soybean plants in soil type concrectionary petric plinthosol. *Scientia Agraria Paranaensis, 18*(4), 351-356. doi: 10.18188/sap.v18i4.22452

Nikkel, M., & Lima, S. O. (2019b). Maize (Zea mays) cultivated in concrectionary petric plinthosol. *Journal of Agricultural Science, 11*(14), 131-140. doi: 10.5539/jas.v11n14p131

Nikkel, M., & Lima, S. de O. (2020). Crescimento inicial de algodão cultivado em plintossolo pétrico concrecionário. *Energia na Agricultura, 35*(3), 360-369. doi: 10.17224/energagric.2020v35n3p360-369

Pereira, A. F., Silva, A. G., Campos, L. J. M., & Silva, S. P., Neto. (2021). *Respostas de soja a diferentes arranjos de plantas nas regiões Centro- Oeste e Norte do Brasil.* (Documentos, 379). EMBRAPA Cerrados.

Pokorný, R., & Stojnič, S. (2012). Leaf area index of Norway spruce stands in relation to age and defoliation. *Beskydy, 5*(2), 173-180. doi: 10.11118/beskyd201205020173

Procópio, S. de O., Balbinot, A. A., Debiasi, H., Franchini, J. C., & Panison, F. (2013). Plantio cruzado na cultura da soja utilizando uma cultivar de hábito de crescimento indeterminado. *Revista de Ciências Agrarias - Amazon Journal of Agricultural and Environmental Sciences, 56*(4), 319-325. doi: 10.4322/rca.2013.048

R Core Team (2021). *R: a language and environment for statistical computing.* R Foundation for Statistical Computing. https://www.r-project.org/

Ramalho, A. F. Fo., & Pereira, L. C. (1999). *Aptidão agrícola das terras do Brasil: potencial de terras e análise dos principais métodos de avaliação.* (Documentos, 1). EMBRAPA Solos.

Ramos, M. R. (2022). A review of soybean cultivation on stony soils in Tocantins, Brazil. *International Journal of Science and Research, 11*(3), 367-371. doi: 10.21275/SR22305001852

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo, J. C. Fo., Oliveira, J. B. & Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos* (5a ed. Rer. e Ampl.). EMBRAPA.

Sediyama, T., Oliveira, R. C. T. O., & Sediyama, H. A. (2016). A soja. In T. Sediyama (Ed.), *Produtividade da soja* (pp. 11-18). Londrina.

Tourino, M. C. C., Rezende, P. M. de, & Salvador, N. (2002). Row spacing, plant density and intrarow plant spacing uniformity effect on soybean yield and agronomic characteristics. *Pesquisa Agropecuária Brasileira, 37*(8), 1071-1077. doi: 10.1590/s0100-204x2002000800004

Vaissie, P., Monge, A., & Husson, F. (2021). *Factoshiny-package: perform factorial analysis from "FactoMineR" with a shiny application.* http://factominer.free.fr/graphs/factoshiny.html

Watanabe, R. T., Fioretto, R. A., Fonseca, I. B. da, Seifert, A. L., Santiago, D. C., Creste, J. E., Harada, A., & Cucolotto, M. (2005). Produtividade da cultura de soja em função da densidade populacional e da porcentagem de cátions (Ca, Mg e K) no complexo sortivo do solo. *Semina: Ciências Agrárias, 26*(4), 477-484. doi: 10.5433/1679-0359.2005v26n4p477

Xu, C., Li, R., Song, W., Wu, T., Sun, S., Han, T., & Wu, C. (2021a). High density and uniform plant distribution improve soybean yield by regulating population uniformity and canopy light interception. *Agronomy, 11*(9), 1880. doi: 10.3390/agronomy11091880

Xu, C., Li, R., Song, W., Wu, T., Sun, S., Hu, S., Han, T., & Wu, C. (2021b). Responses of branch number and yield component of soybean cultivars tested in different planting densities. *Agriculture, 11*(1), 1-12. doi: 10.3390/agriculture11010069

Yang, J., & Jeong, B. R. (2021). Side lighting enhances morphophysiology by inducing more branching and flowering in chrysanthemum grown in controlled environment. *International Journal of Molecular Sciences, 22*(21), 12019. doi: 10.3390/ijms222112019