








OPTIMAL LIMA BEAN PLOT SIZE

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Abstract

It is important to determine optimal experimental plot size in order to ensure accurate results and correct decision making. There are no studies of this nature for lima bean cultivation. As such, the aim of this study was to determine the optimal plot size to estimate lima bean yield in family farming and experimental areas, combining the number of treatments, repetitions, and accuracy levels. Experiments were conducted in two 12 m × 16 m plots, each subdivided into 192 basic units (BUs) measuring 1 m². Bean weight was assessed in each of the units (g). Smith's

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index of soil heterogeneity and optimal plot size were estimated using the Modified Maximum Curvature Method and Hatheway's Method. The index of soil heterogeneity was higher than 0.7 for all the variables analyzed. Plot size between 10 m² and 15 m² is considered efficient in estimating lima bean weight. These first estimated optimal plot sizes will allow researchers and farmers who work with the crop to obtain more robust yield estimates.

Keywords: Family Farming; Yield Estimates; Experimental Accuracy; Hatheway.

1. INTRODUCTION

Lima bean is an important crop in Northeastern Brazil, and a major food and income source for many family farmers. This region accounts for about 99.7% of the national yield, grown in an area covering 33,374 hectares in 2021, with average production of 315 kg·ha⁻¹.¹ The lima bean yield under experimental conditions in research institutions exceeds 3500 kg·ha⁻¹ in Brazil.²

This yield difference occurs because most family farmers do not have fertilizers, irrigation, or planting technologies to produce uniform plant stands. In addition, loss of lima bean yield has been attributed to planting at temperatures above 30–35°C, low soil N availability, and weed competition.^{2–5}

In order to attenuate these limiting factors, studies should be conducted in collaboration with farmers to more easily identify demand and enable proper transfer of the information produced. These studies should be planned to reduce experimental errors in order to ensure reliable results and correct decision making.

Correct experimental planning involves adhering to basic experimentation principles, correct study design, and suitable plot size, number of repetitions and number of samples.^{6,7}

Experimental plot size is often determined as a function of the experimental area available, number of treatments, and researcher experience. These practices are not statistically suitable, but may be complementary to methodologies described in the literature. Among the most widely used methodologies are the Maximum Curvature Method,⁸ Modified Maximum Curvature Method,⁹ Hatheway's Method^{10,11} and the Pimentel Gomes Method.¹²

Research on optimal experimental plot size has been conducted with different crops: black-eyed peas,¹³ common bean,¹⁴ sunflower,¹⁵ cochineal cactus,¹⁶ buckwheat,¹⁷ arabica coffee,¹⁸ and chickpea.¹⁹ However, no recent studies on this topic were found for lima bean.

Thus, the aim of this study was to determine the optimal plot size in order to estimate lima bean yield in family farm and experimental areas, combining the number of treatments, number of repetitions, and accuracy levels.

The rest of the paper is organized as follows. In Sec. 2, we present the experimental area, genetic material, and statistics for estimated optimal plot sizes. In Sec. 3, we describe the results found and compare them with the literature. In Sec. 4, we conclude our findings in this paper.

2. MATERIAL AND METHODS

2.1. Location and Characterization of the Experimental Area

This study was conducted on two properties in the municipality of Tanque, Piauí state. The first is located at 6°36'44.05" S and 42°16' 32.28" W, and the second at 6°34'1.05" S and 42°19'5.26" W". According to Köppen's classification, climate in the region is Awi — tropical rainy with a well-defined dry season, temperatures between 22°C and 34°C and an average of 29°C with high rainfall, at times over 1300 mm.²⁰ The soil of the first property was classified as Yellow Latosol and the second Litholic Neosol.²¹

Soil samples were collected (0–20 cm) for chemical and physical characterization of the experimental area before experiment setup. On property I, the results of soil granulometric composition were 462 g kg⁻¹, silt: 200 g kg⁻¹ and clay: 338 g kg⁻¹. For chemical attributes, the results were organic matter (OM): 29.8.3 g kg⁻¹, pH (H 0): 6.63, P (Mehlich-1): 13.9 mg dm⁻³, K (Mehlich-1): 0.2 mg dm⁻³, Ca: 7.52 cmol_cdm⁻³, Mg: 2.03 cmol_cdm⁻³, Al (KCl): 0.00 cmol_cdm⁻³, H + Al: 2.84 cmol_cdm⁻³, SB: 9.74 cmol_cdm⁻³, and T: 12.59 cmol_cdm⁻³, base saturation (V%): 77.4.

On property II, soil granulometric composition was 637 g kg⁻¹, silt: 138 g kg⁻¹, and clay: 225 g kg⁻¹

and chemical attribute results were organic matter (OM): 28.2 g kg⁻¹, pH (H 0): 6.6, P (Mehlich-1): 10.4 mg dm⁻³, K (Mehlich-1): 0.24 mg dm⁻³, Ca: 7.03 cmol_cdm⁻³, Mg: 1.2 cmol_cdm⁻³, Al (KCl): 0.00 cmol_cdm⁻³, H + Al: 3.00 cmol_cdm⁻³, SB: 8.47 cmol_cdm⁻³, T: 11.47 cmol_cdm⁻³, and base saturation (V%): 73.9.

2.2. Genetic Material and Experiment Setup

The Lamb's Ear heirloom variety, traditionally grown by farmers in the region, was used. The areas were planted in December by family farmers with 2 ha each. Planting was manual, sowing two lima bean and two maize seeds per hole. The maize plants served as support for the lima bean plants. Planting was conducted in a rainfed regime, with no fertilizer or agricultural pesticides. Weeds were controlled manually, when necessary.

In August 2022, an area in each of the properties was randomly selected before the harvest, to assess optimal plot size. The assessment area on each of the properties was 192 m² (12 m × 16 m). This was subdivided into 192 basic units (BUs) measuring 1 m². Bean weight (g) was determined in each of the BUs.

2.3. Statistical Analysis

The modified maximum curvature method,⁸ adapted by Meier and Lessman,⁹ was used to algebraically estimate the maximum point on the curvature, which corresponds to the optimal plot size, according to the exponential regression equation:

$$y = \frac{A}{X^B}, \quad (1)$$

where y = indicates the coefficient of variation; X = represents plot size in basic units; and, A and B — constants suitable for the model.

The maximum curvature point was given by

$$\text{XMC} = \left[\frac{\hat{A}^2 \hat{B}^2 (2\hat{B} + 1)}{\hat{B} + 2} \right]^{\frac{1}{(2+2\hat{B})}}, \quad (2)$$

where: XMC — X-axis value corresponding to the maximum curvature point, that is, the estimator of optimal size; and, \hat{A} and \hat{B} — respective estimates of A and B , constants suitable for the equation.

Given that the maximum curvature point XMC is defined as the critical point of the plot, Lúcio *et al.*²² reported that decimal transformation of this value

must meet the criteria of the discrete variables with approximation to the immediately superior integer.

Statistical determinations to estimate plot size using the modified maximum curvature method were conducted in R statistical software.²³

The experimental trials were simulated for an experiment in randomized blocks, comprising a combination of I treatments ($i = 4, 8, 12,$ and 16), r replications ($r = 3, 4, 5, 6, 7,$ and 8) and the least significant difference between the mean values of these treatments, which were detected at 5% probability and expressed as a percentage (LSD = 30%, 40%, and 50%).

To determine optimal plot size, the formula proposed by Hatheway^{10,11} was used, given by

$$X_0 = \sqrt[b]{\frac{2(t_1 + t_2)^2}{r\text{LSD}^2}}, \quad (3)$$

where X_0 is the optimal plot size in BUs; b is the Smith index of soil heterogeneity (1938); t_1 is the critical value of Student's t -distribution for tests of significance (bilateral at 5%); t_2 is the critical value of Student's t -distribution, corresponding to $2(1 - p)$, where p is the probability of obtaining a significant result, ($p = 0.80$ in this study), and t_1 and t_2 with degrees of freedom (DF). The DF values were obtained from the expression $\text{DF} = (i - 1) \times (r - 1)$ for a randomized block design, where i is the number of treatments and r is the number of replications.

For this study, t_1 and t_2 values were obtained using Microsoft Office Excel software, employing the following functions: $t_1 = \text{INVT}(0.05; \text{DF})$ and $t_2 = \text{INVT}(0.4; \text{DF})$, respectively. CV is the coefficient of variation expressed as a percentage (%) for plots one BU in size; r is the number of replications and LSD the least significant difference to be detected between the mean values of the treatments, expressed as a percentage (%).

The index of soil heterogeneity (b) was estimated after logarithmic transformation and linearization of the Smith equation²⁴:

$$VU_x = \frac{V_1}{V^b}, \quad (4)$$

i.e. by logarithmic transformation, $\log(VU_x) = \log(V_t) - b \cdot \log(X)$, where $VU(x)$ is the variance in BUs of plots comprising X BUs, V_1 is the variance of plots comprising one BU, and X is the number of BUs that make up the plot (plot size).

The statistical analysis was conducted using the R software. The heat map and regression plots were

created using the *ggplot2* package.²⁵ Meanwhile, the response surface plot, to determine the optimal number of repetitions as a function of the number of treatments, was done using the *directlabels* package.²⁶

3. RESULTS AND DISCUSSION

The heat maps indicated no variability pattern between and within the properties for bean weight per BU, thus obtaining results with random variation (Fig. 1). This large variability provides credibility to plot size determination, since it considers real situations that occur in field experiments.¹⁷ Magalhães *et al.*¹⁹ also observed random variation in optimal plot size for chickpea experiments.

The coefficients of variation (CV) for the bean weight of 1 m² basic experimental units were 103.36% and 77.71%, respectively, for areas I and II (Fig. 2). No CV classification ranges were found in the literature specific to lima bean. Thus, taking the CV classification ranges established by Pimentel-Gomes²⁷ for agricultural field tests as reference, these values are considered very high (CV above 30%). This variation in CV values (%) may be due to the wide variation in bean weight between the BUs because lima bean is an autogamous species with frequent allogamy.²⁸ In experiment I, it varied between 0 and 1120 g per BU and in experiment II between 0 and 710 g per BU. This demonstrates the need to use plots larger than 1 m² to improve experimental accuracy.

In the two areas, the Maximum Curvature Method found a reduction in variance — $VU(x)$ per

BU with an increase in plot size (Fig. 2). There was a significant decline of approximately 15 BUs for area I and 10 for area II, after which $VU(x)$ tended to stabilize (Fig. 2). The coefficient of determination (R^2) of 78.22% for area I and 97.23% for area II indicated high explanation of $VU(x)$ per BU according to the function selected (Fig. 3). This behavior was also observed by Cargnelutti Filho *et al.*¹⁷ and Magalhães *et al.*,¹⁹ in studies with buckwheat and chickpea, respectively. Thus, 20 m² plots should be used to assess lima bean weight.

These optimal plot sizes, varying between 10 m² and 15 m², could be useful for institutions and academics/researchers, in estimating yields. It could help the Ministry of Agriculture, Livestock, and Supply to create forms for determining the value for cultivation and use (VCU) of new lima bean varieties. This form could also be used by farmers to estimate yield in their areas in order to determine crop viability.

The index of soil heterogeneity b was 1.061 for the first experiment and 0.701 for the second (Fig. 3). Values near zero indicate that the soil is more homogeneous, with a greater correlation between plots, thereby allowing smaller plots with the same accuracy, while b values near one indicate greater soil heterogeneity and lower correlation between plots.²⁹ According to Lin and Binns,³⁰ for b higher than 0.7, an increase in plot size is the most efficient method to improve accuracy in terms of the increase in repetitions. In this respect, for the results obtained here, the best strategy is to increase the plot size.

In Hatheway's methodology,^{10,11} based on the fixed value of Smith's index of heterogeneity of the

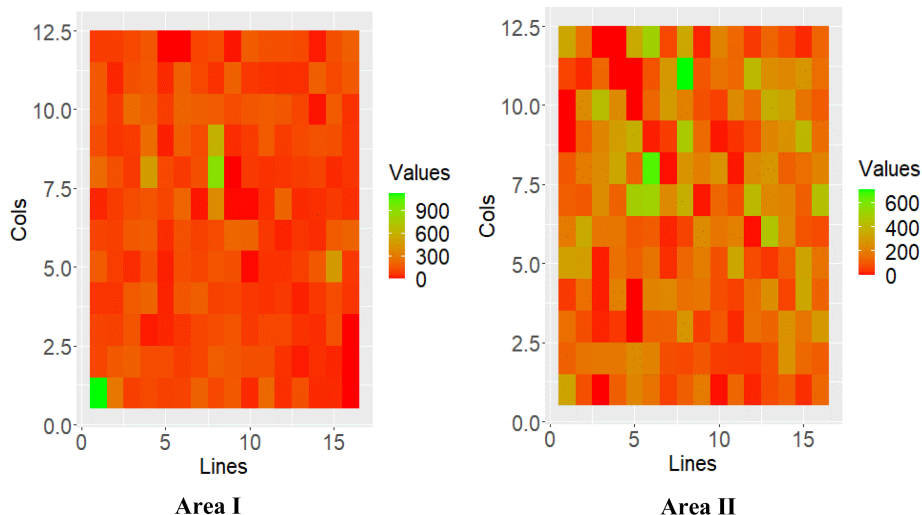


Fig. 1 Heat maps for lima bean weight in two experimental areas.

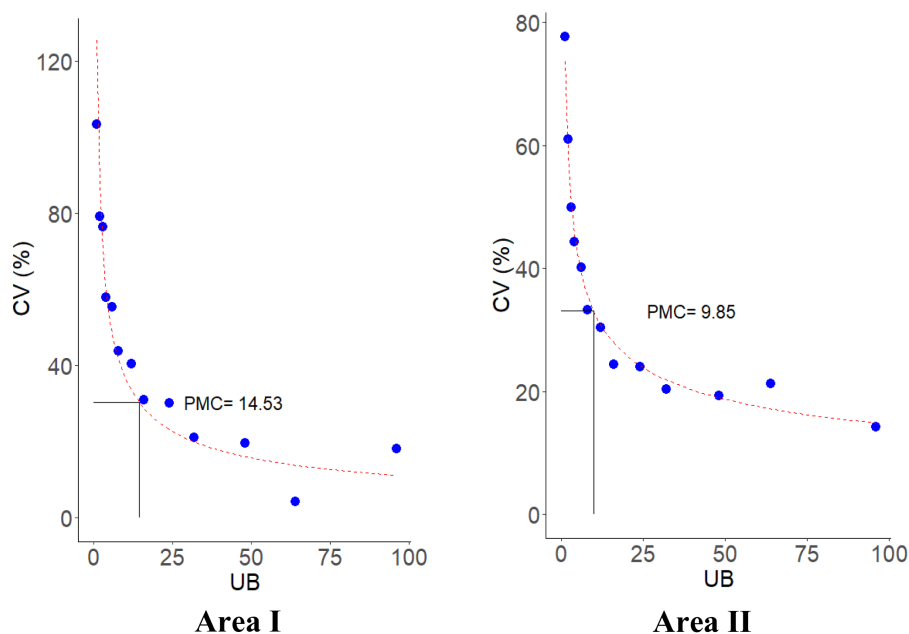


Fig. 2 Graphical representation of the relationship between the experimental coefficient of variation (CV %) and plot size in basic experimental units (BUs) for the estimate of maximum curvature (PMC) of the variable lima bean weight in two experimental areas.

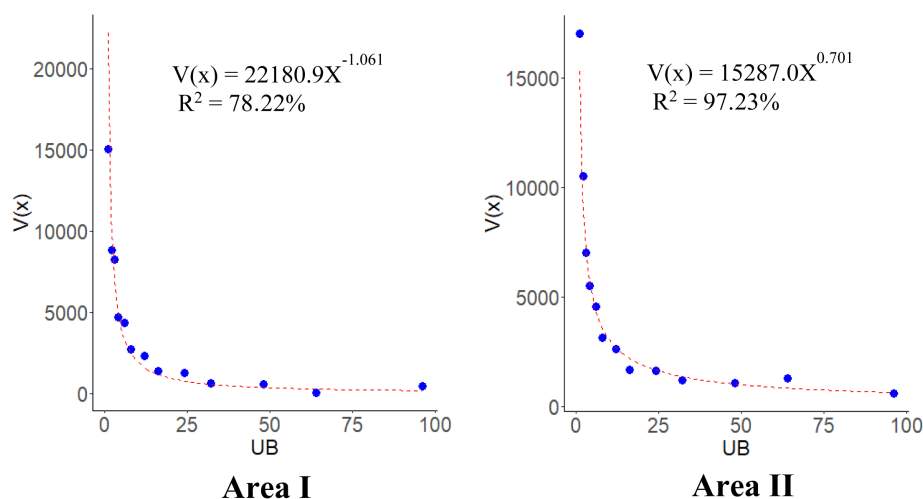


Fig. 3 Graphical representation of the relationship between variance per basic unit (BU), between X BU plots in size and planned plot size, and estimates for the parameters of the Smith (1938) function $VU_X = V_1/X^b$. Data for the variable lima bean weight in two experimental areas.

soil b^{24} and CV, X_0 depends on the number of treatments, repetitions, and least significant difference. Thus, based on the b and CV values (%) obtained for each of the areas (Fig. 4), plot sizes were estimated by simulating different experiments, considering treatments ($i = 4, 8, 12,$ and 16), r replications ($r = 3, 4, 5, 6, 7,$ and 8) and the LSD between the mean values of these treatments, which were significant at 5% probability and expressed as a percentage (LSD = 30%, 40%, and 50%). There are no

previous optimal plot size simulation values for the lima bean in the literature. As such, a variation was adopted to consider the number of treatments and repetitions most widely used in lima bean experiments reported in the literature (Fig. 4).

Fixing the number of treatments resulted in a decline in plot size as the number of repetitions increased. In addition, with fixed values for the number of repetitions and the same LSD, plot size decreased as the number of treatments rose

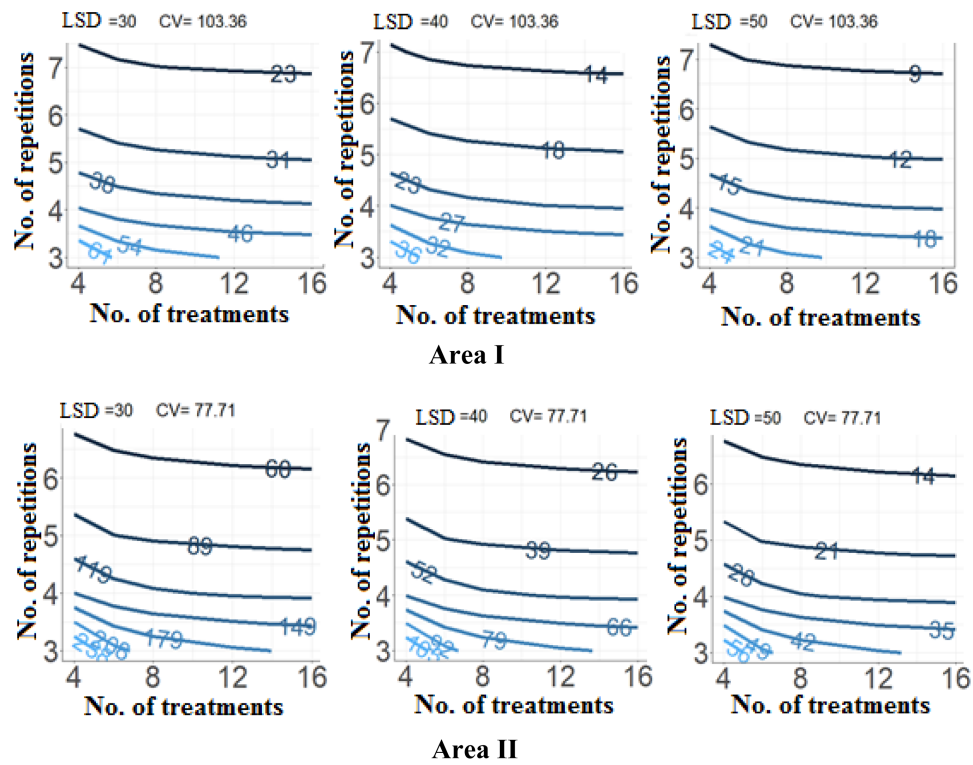


Fig. 4 Optimum plot size in basic units (BUs), for combinations of (i) treatments, (r) repetitions, and (LSD) least significant difference, for lima bean weight in two experiments.

(Fig. 3). These results are expected, since with a larger number of treatments and repetitions, estimated residual variance (root mean square) will be lower (greater accuracy) due to the higher number of degrees of freedom for error.³¹ However, the type of variable response that will be analyzed should be considered, because if the characteristic is difficult to measure, using a larger plot size may be more advantageous, provided there is enough experimental area. In addition, it would make it possible to assess the plants in the experimental area and disregard those on the borders, thereby reducing interference from plants in adjacent areas and consequently the experimental error.⁷

The optimal plot size (X_0), estimated by the fixed number of treatments (i) and repetitions (r), declines with a decrease in desired accuracy (LSD). For example, if the researcher wants to accurately assess yield in an experiment with eight treatments and four repetitions (LSD = 30%), the plot will consist of 38 plants in experiment I and 149 in experiment II. If less accuracy is desired in treatment comparison (LSD = 50%), 12 plants in experiment I, and 28 in experiment II would be enough.

A comparison between the results of the two experiments revealed a lower CV for experiment II and an increase in the plot size proposed. Considering the CV separately, this result was not expected but may be explained by the fact that Hatheway's formula^{10,11} considers several other factors beyond the CV (%). Magalhães *et al.*¹⁸ also obtained higher estimates of plot sizes even for experiments with higher CVs (%), working with chickpea.

These studies also reinforce the fact that high-accuracy experiments (values below the LSD) are difficult to achieve in practice, as a function of the large plot size required. Given an LSD of 30%, plots should contain 23–61 plants, considering experiment I and II for 60 and 238 plants, respectively. Since the plant spacing of lima bean is generally 1 m × 1 m, the plots would be between 21 and 238 m².


4. CONCLUSION

Plot sizes between 10 and 15 m² are considered efficient in estimating lima bean weight. These estimates of optimal plot sizes for different combinations of number of treatments, number of

replications, and LSDs will allow farmers and researchers to plan studies and obtain more accurate yields.


Future work should involve erect lima beans without intercropping with corn.


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REFERENCES

- IBGE — Instituto Brasileiro de Geografia e Estatística. Produção Agrícola Municipal 2021. Quantidade produzida (toneladas) de fava (em grão). Disponível em: <<https://sidra.ibge.gov.br/tabela/1612#resultado>>. Acesso em: 16 jan 2023.
- S. I. A. Silva *et al.*, Evaluation of yield components in lima bean landraces grown in the Agreste region of Paraíba, *Rev. Ciências Agrárias* **42**(3) (2019) 731–742.
- M. J. Vangessel, D. W. Monks and Q. R. Johnson, Herbicides for potential use in lima bean (*Phaseolus lunatus*) production, *Weed Technol.* **14**(2) (2000) 279–286.
- C. N. Costa *et al.*, Inoculation of rhizobia increases lima bean (*Phaseolus lunatus*) yield in soils from Piauí and Ceará states, Brazil, *Rev. Ceres, Viçosa* **67**(5) (2020) 419–423.
- E. O. Machado *et al.*, Evaluation of lima bean accessions at high temperatures, *Rev. Caatinga, Mossoró* **35**(4) (2022) 791–798.
- M. A. Masood and I. Raza, Estimation of optimum field plot size and shape in paddy yield trial, *Am.-Eurasian J. Sci. Res.* **7**(6) (2012) 264–269.
- L. Storck, *Experimentação vegetal*, 3rd edn. (Santa Maria, 2016), 198p.
- K. J. Lessman and R. E. Atkins, Optimum plot size and relative efficiency of lattice designs for grain sorghum yield test, *Crop Sci.* **3** (1963) 477–481.
- V. D. Meier and K. J. Lessman, Estimation of optimum field plot shape and size for testing yield in *Crambe abyssinica* hordnt, *Crop Sci.* **11** (1971) 648–650.
- W. H. Hatheway, Convenient plot size, *Agron. J.* **53** (1961) 279–280.
- T. D. Hocking, Direct labels for color decoding, R package version 1.13. [S.l.: s.n.] (2021).
- F. Pimentel Gomes, O problema de tamanho das parcelas em experimentos com plantas arboreas, *Pesqu. Agropecu. Brasil.* **19**(12) (1984) 1507–1512.
- V. Q. Ribeiro, E. C. Silva and F. R. Freire Filho, Tamanho e forma de parcelas de culturas consorciadas e solteiras de caupi e milho, *Pesqui. Agropecu. Brasil* **19**(11) (1984) 1365–1371.
- É. C. Smiderle *et al.*, Tamanho de parcelas experimentais para a seleção de genótipos na cultura do feijoeiro, *Comun. Sci.* **51** (2014) 51–58.
- R. P. de Sousa *et al.*, Tamanho ótimo de parcela para avaliação do rendimento de grãos do girassol, *Rev. Brasil. Engenharia Agríc. Ambiental* **19** (2015) 21–26.
- B. V. C. Guimarães *et al.*, Size of plots for experiments with cactus pear cv. Gigante, *Rev. Brasil. Engenharia Agrícola e Ambiental.* **23** (2019) 347–351.
- A. Cargnelutti Filho *et al.*, Optimal plot size for experiments with black oats and the common vetch, *Ciência Rural* **50**(3) (2020) 1–10.
- R. C. Guarçoni *et al.*, Tamanho de parcela para avaliação de características agrônomicas e sensoriais de café arábica, *Rev. Brasil. Biometria* **38**(1) (2020) 57–68.
- J. R. Magalhães *et al.*, Optimum plot size and number of replications for experiments with the chickpea, *Rev. Ciência Agrônôm.* **54** (2023) e20228506.
- A. S. de Andrade Júnior *et al.*, *Atlas Climatológico do Estado do Piauí* (2004).
- J. A. Deckers *et al.* World reference base for soil resources, in *Encyclopedia of Soil Science* (Marcel Dekker, 2002), pp. 1446–1451.
- A. D. Lucio *et al.*, Tamanhos de amostras e de parcelas para variáveis de crescimento e produtivas de tomateiro, *Horticult. Brasil.* **30** (2012) 660–668.
- R Equipe Núcleo de Desenvolvimento, R: Uma linguagem e ambiente para computação estatística. R Foundation for Statistical Computing (2019). Disponível em: <http://www.r-project.org>. Acesso em: 25 agosto (2022).
- H. F. Smith, An empirical law describing heterogeneity in the yields of agricultural crops, *J. Agric. Sci.* **28** (1938) 1–23.
- T. L. Pederson *et al.*, Ggplot2: Create elegant data visualisations using the grammar of graphics, R package version 3.3.0. [S.l.: s.n.] (2020).

26. T. D. Hocking, Direct labels for color decoding, R package version 1.13. [S.l.: s.n.] (2021).
27. F. Pimentel-Gomes, *Curso de estatística experimental*, 15th edn. (Piracicaba, 2009) 451p.
28. J. S. Penha *et al.* Estimation of natural outcrossing rate and genetic diversity in Lima bean (*Phaseolus lunatus* L. var. *lunatus*) from Brazil using SSR markers: Implications for conservation and breeding, *Genetic Resour. Crop Evol.* **64** (2017) 1355–1364.
29. D. Santos *et al.*, Tamanho ótimo de parcela para a cultura do feijão-vagem, *Rev. Ciência Agrônôm.* **43**(1) (2012) 119–128.
30. C. S. Lin and M. R. Binns, Eficiência relativa de dois delineamentos de blocos aleatórios com diferentes tamanhos de parcela e número de repetições e de parcelas por bloco, *Agronomia Diário* **78**(3) (1986) 531–534.
31. A. Cargnelutti Filho *et al.*, Tamanho de parcela para avaliar a massa de plantas de mucuna cinza, *Comun. Sci.* **5**(2) (2014) 196–204.