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Optimal plot size in forage sorghum with comparison of the methods of modified maximum curvature, linear response and plateau model and quadratic response and plateau model

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Abstract
The objective of this study was to compare three methods for estimating the optimal plot size to evaluate the fresh matter productivity of forage sorghum (*Sorghum bicolor* (L.) Moench) sown in rows, evaluated in three cuts. Two uniformity trials (repetitions) were carried out. In each trial, three plant cuts were performed, totaling six uniformity trials (2 trials per cut × 3 cuts). The first cut was performed at 41 days after sowing (DAS), the second at 82 DAS and the third at 133 DAS. Fresh matter productivity was evaluated in 216 basic experimental units (BEU) of 1 m × 1 m (36 BEU per trial). The BEU was formed by two rows of 1.0 m in length, spaced 0.50 m apart, totaling 1.0 m^2. The optimal plot size was determined using the methods of modified maximum curvature, linear response and plateau model and quadratic response and plateau model. The optimal plot size differs between the methods and decreases in the following order: quadratic response and plateau model (9.10 m^2), linear response and plateau model (7.16 m^2) and modified maximum curvature (4.13 m^2). The optimal plot size to evaluate the fresh matter productivity of forage sorghum, sown in rows, evaluated in three cuts, is 7.16 m^2 and the experimental precision stabilizes from this size on.
Keywords: fresh matter productivity; *Sorghum bicolor* (L.) Moench; uniformity trial.

Tamanho ótimo de parcela em sorgo forrageiro com comparação dos métodos da curvatura máxima modificado, modelo linear de resposta com platô e modelo quadrático de resposta com platô

Resumo
O objetivo deste estudo foi comparar três métodos de estimação do tamanho ótimo de parcela para avaliar a produtividade de matéria fresca de sorgo forrageiro (*Sorghum bicolor* (L.) Moench) semeado em fileiras, avaliada em três cortes. Foram conduzidos dois ensaios de uniformidade (repetições). Em cada ensaio foram realizados três cortes das plantas, totalizando seis ensaios de uniformidade (2 ensaios por corte × 3 cortes). O primeiro corte foi realizado aos 41 dias após a semeadura (DAS), o segundo aos 82 DAS e o terceiro aos 133 DAS. Foi avaliada a produtividade de matéria fresca em 216 unidades experimentais básicas (UEB) de 1 m × 1 m (36 UEB por ensaio). A UEB foi formada por duas fileiras de 1,0 m de comprimento, espaçadas 0,50 m entre fileiras, totalizando 1,0 m^2. Foi determinado o tamanho ótimo de parcela por meio dos métodos da curvatura máxima modificado, do modelo linear de resposta com platô e do modelo quadrático de resposta com platô. O tamanho ótimo de parcela difere entre os métodos e decresce na seguinte ordem: modelo quadrático de resposta com platô (9,10 m^2), modelo linear de resposta com platô (7,16 m^2) e curvatura máxima modificado (4,13 m^2). O tamanho ótimo de parcela para avaliar a produtividade de matéria fresca de sorgo forrageiro semeado em fileiras, avaliada em três cortes, é 7,16 m^2 e a precisão experimental estabiliza a partir desse tamanho.
Palavras-chave: ensaio de uniformidade; produtividade de matéria fresca; *Sorghum bicolor* (L.) Moench.

Introduction

Forage sorghum (*Sorghum bicolor* (L.) Moench) is an annual plant belonging to the Poaceae family. It is used for the production of grains, forage (grazing or conservation in the form of silage) and alternatively for bioenergy and biomass production (FORTES *et al*., 2018; BHAT, 2019). It stands out in terms of dry matter production when compared to grain sorghum (RIBEIRO *et al*., 2017; REZENDE *et al*., 2020).

There are other types of sorghum, such as: grain sorghum, which has intermediate potential for dry matter production, being used for grain production (RIBEIRO *et al*., 2015); broom sorghum, which is intended for the manufacture of brooms; and saccharine sorghum, whose stem is rich in fermentable sugars that can serve for ethanol production (BHAT, 2019). Sorghum is an alternative as a forage crop during the summer, because it is a C4 metabolism plant, with better water use efficiency, drought tolerance and lower need for fertilizer (BHAT, 2019).

Due to the importance of the crop, numerous studies are conducted. In these studies, plot size is an important aspect to be considered in experimental planning, aiming at minimizing experimental error. The methods of modified maximum curvature (MMC) (MEIER; LESSMAN, 1971), linear response and plateau model (LRP) (PARANAÍBA *et al*., 2009) and quadratic response and plateau model (QRP) (PEIXOTO *et al*., 2011) make it possible to determine the optimal plot size (Xo) and the coefficient of variation in the optimal plot size (CV_{Xo}).

From uniformity trials (blank experiments) it is possible to plan different plot sizes (X) by grouping adjacent basic experimental units (BEU) and estimate the coefficient of variation ($CV_{(X)}$) between BEU. The values of $CV_{(X)}$ as a function of X can be related by the MMC, LRP and QRP methods for the determination of Xo and CV_{Xo}.

Comparative studies involving the MMC, LRP and QRP methods have been conducted with radish (SILVA *et al*., 2012), sweet potato (GONZÁLEZ *et al*., 2018), millet + slender leaf rattlebox + showy rattlebox (CARGNELUTTI FILHO *et al*., 2021a) and buckwheat (CARGNELUTTI FILHO *et al*., 2021b), evidencing distinct results between the methods. Plot size determinations to evaluate the grain yield of grain sorghum have been carried out by Lopes *et al*. (2005) and Brum *et al*. (2008). However, the plot sizes determined may be different from those necessary to evaluate the fresh matter productivity of forage sorghum.

The objective of this study was to compare three methods for estimating the optimal plot size to evaluate the fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench) sown in rows, evaluated in three cuts.

Material and Methods

Uniformity trials with forage sorghum (*S. bicolor* (L.) Moench), Nutribem (S) cultivar, were conducted in an experimental area from the Department of Plant Science of the Federal University of Santa Maria, in the municipality of Santa Maria, Rio Grande do Sul State, located at 29°42'S, 53°49'W and at 95 m altitude. In this place, the climate is humid subtropical - Cfa (ALVARES *et al*., 2013) and the soil is *Argissolo Vermelho Distrófico Arênico* (Ultisol) (SANTOS *et al*., 2018).

In the experimental area with dimensions of 8 m × 18 m, harrowing was performed and basal fertilization with 35 kg ha^{-1} of N, 135 kg ha^{-1} of P_2O_5 and 135 kg ha^{-1} of K_2O was incorporated on November 18, 2020. On that same day, sowing was performed by manually placing 40 seeds per meter of row, with rows spaced 0.50 m apart, totaling 80 seeds m^{-2}.

In this area, two uniformity trials (repetitions) were demarcated. Each trial with dimensions of 6 m × 6 m (36 m^2) was divided into 36 basic experimental units (BEU) of 1 m × 1 m (1 m^2), forming a matrix of six rows and six columns. BEU was formed by two rows of 1.0 m in length, spaced 0.50 m apart, totaling 1.0 m^2. In each trial, three cuts of the plants were performed, totaling six uniformity trials (2 trials per cut × 3 cuts).

The first cut was performed at 41 days after sowing (DAS), the second at 82 DAS and the third at 133 DAS. When the crop reached between 1.0 m and 1.80 m height in each BEU, the plants were cut at 20 cm height from the soil surface, and their fresh matter was weighed on a digital scale (accuracy: 1 g), obtaining fresh matter productivity (FM, in g m^{-2}) in 216 BEU (6 trials × 36 BEU per trial).

In each uniformity trial, the FM data from the 36 BEU were used to plan plots with X_R BEU adjacent in the row and X_C BEU adjacent in the column. Plots with different sizes and/or shapes were planned as being ($X=X_R \times X_C$), that is, (1×1), (1×2), (1×3), (1×6), (2×1), (2×2), (2×3), (2×6), (3×1), (3×2), (3×3), (3×6), (6×1), (6×2) and (6×3). The acronyms X_R, X_C and X mean, respectively, number of BEU adjacent in the row, number of BEU adjacent in the column, and plot size in number of BEU.

For each plot size (X), the following parameters were determined: n - number of plots with size of X BEU (n=36/X) and $CV_{(X)}$ - coefficient of variation (in %) between the plots with size of X BEU. For each trial, the optimal plot size (Xo) was determined using the methods of modified maximum curvature (MMC) (MEIER; LESSMAN, 1971), linear response and plateau model (LRP) (PARANAÍBA *et al*., 2009) and quadratic response and plateau model (QRP) (PEIXOTO *et al*., 2011). In these three methods, models of the dependent variable ($CV_{(X)}$, in %) are fitted as a function of the independent variable (X, in BEU).

In the MMC method, parameters *a* and b and the coefficient of determination (R^2) of the model $\mathrm{CV_{(X)} = a/X^b + \varepsilon}$ were estimated. These parameters were estimated by logarithmic transformation and linearization of $\mathrm{CV_{(X)} = a/X^b + \varepsilon}$, that is, $\mathrm{\log CV_{(X)} = \log a - b \log X + \varepsilon}$, whose estimation was weighted by the degrees of freedom (DF = n-1), associated with each plot size, according to the application of Sousa *et al*. (2016). Xo was determined by the expression: $Xo = [a^2b^2(2b+1)/(b+2)]^{1/(2b+2)}$. The coefficient of variation corresponding to the optimal plot size (CV_{Xo}) was determined by $CV_{Xo} = \mathrm{a}/Xo^{\mathrm{b}}$.

For the LRP model, two segmented lines were fitted and the estimates of parameters *a*, *b* and *p* and coefficient of determination (R^2) were obtained. The first line $\left(CV_{(X)} = a + bX + \varepsilon\right)$ was fitted up to the point corresponding to Xo, with angular coefficient (b) different from zero. The second line $\left(CV_{(X)} = p + \varepsilon\right)$ starts from Xo and has angular coefficient equal to zero (line parallel to the abscissa), where p = plateau, that is, p corresponds to the CV_{Xo}. The LRP model was as follows: $CV_{(X)} = \begin{cases} a + bX + \varepsilon & if\ X \le Xo \\ p + \varepsilon & if\ X > Xo \end{cases}$. In the LRP model, $Xo = (p-a)/b$ and $CV_{Xo} = a + bXo$.

For the QRP model, the fit was performed using two segmented equations. Estimates of parameters *a, b, c* and *p* and coefficient of determination (R^2) were obtained. The quadratic part of the model $\left(CV_{(X)} = a + bX + cX^2 + \varepsilon\right)$ was fitted up to the *Xo* point. After Xo, the model turns into a zero-slope line, called plateau, whose model is described by $\left(\mathrm{CV_{(X)} = p + \varepsilon}\right)$, where p = plateau, that is, p = CV_{Xo}. Thus, the QRP model was as follows: $CV_{(X)} = \begin{cases} a + bX + cX^2 + \varepsilon & if\ X \le Xo \\ p + \varepsilon & if\ X > Xo \end{cases}$. In the QRP model, $Xo = -b/2c$ and $CV_{Xo} = a - b^2/4c$. In the LRP and QRP models, the point of union between the two segments corresponds to the Xo in the abscissa and CV_{Xo} in the ordinate. In the three models (MMC, LRP and QRP), the ε is the residual or random error of the model.

Thus, for the six uniformity trials, the fresh matter of the trial (FM, g m^{-2}), the coefficient of variation of the trial (CV, %) and the estimates of the coefficient of determination (R^2), the optimal plot size (Xo) and the coefficient of variation in the optimal plot size (CV_{Xo}), in relation to the MMC, LRP and QRP methods were obtained. The comparisons of means of the estimates of R^2, Xo and CV_{Xo} between the methods (MMC *versus* LRP, MMC *versus* QRP and LRP *versus* QRP), regardless of cut (n = 6 uniformity trials), were performed by Student's t-test (two-tailed), for dependent samples, at 5% significance level. The results of these comparisons were represented by letters next to the means. The statistical analyses were performed with the Microsoft Office Excel® application and R (R DEVELOPMENT CORE TEAM, 2021) and Sisvar (FERREIRA, 2019) software programs.

Results and Discussion

Based on the Student's t-test (two-tailed), for independent samples, at 5% significance level, the mean fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench), Nutribem cultivar, obtained in the second cut (3850 g m^{-2}) was higher than the means of 2655 g m^{-2} and 2121 g m^{-2} obtained in the first and third cuts, respectively, which did not differ from each other. The accumulated fresh matter productivity in the three cuts was 8626 g m^{-2}, which is equivalent to 86.26 Mg ha^{-1} (Table 1). This high fresh matter productivity characterizes good development of plants in this cultivation site.

Table 1. Fresh matter productivity (FM, in g m^{-2}), coefficient of variation (CV, in %), estimates of parameters *a*, *b* and *c*, coefficient of determination (R^2), optimal plot size (Xo, in m^2) and coefficient of variation in the optimal plot size (CV_{Xo}, in %), in relation to the methods of modified maximum curvature (MMC), linear response and plateau model (LRP) and quadratic response and plateau model (QRP), obtained from the fresh matter productivity of forage sorghum (*Sorghum bicolor* (L.) Moench), evaluated in cuts performed at 41, 82 and 133 days after sowing (DAS).

Cut	Trial[(1)]	DAS	FM (g m^{-2})	CV (%)	*a*	*b*	c	R^2	Xo (m^2)	CV_{Xo} (%)
					MMC					
First	1	41	2611	22.72	23.031	0.254	-	0.84	3.48	16.79
First	2	41	2699	13.53	13.802	0.531	-	0.76	3.44	7.16
Second	1	82	3847	18.34	18.655	0.474	-	0.77	4.04	9.63
Second	2	82	3854	13.54	14.279	0.567	-	0.84	3.58	6.92
Third	1	133	2292	23.20	23.672	0.474	-	0.62	4.76	11.30
Third	2	133	1949	25.79	27.325	0.634	-	0.78	5.47	9.29
Mean			2875	19.52				0.77ab	4.13c	10.18a
					LRP					
First	1	41	2611	22.72	22.706	-1.436	-	0.75	7.28	12.25
First	2	41	2699	13.53	12.708	-1.278	-	0.61	6.53	4.36
Second	1	82	3847	18.34	17.137	-1.563	-	0.69	6.97	6.25
Second	2	82	3854	13.54	13.345	-1.445	-	0.84	6.78	3.55
Third	1	133	2292	23.20	20.878	-1.673	-	0.66	7.86	7.73
Third	2	133	1949	25.79	24.478	-2.591	-	0.80	7.52	4.98
Mean			2875	19.52				0.72b	7.16b	6.52b
					QRP					
First	1	41	2611	22.72	24.180	-2.390	0.120	0.76	9.98	12.25
First	2	41	2699	13.53	17.484	-4.429	0.389	0.66	5.69	4.87
Second	1	82	3847	18.34	19.597	-3.085	0.181	0.72	8.53	6.44
Second	2	82	3854	13.54	15.355	-2.739	0.160	0.86	8.55	3.64
Third	1	133	2292	23.20	22.290	-2.550	0.110	0.69	11.60	7.50
Third	2	133	1949	25.79	27.284	-4.347	0.213	0.81	10.23	5.05
Mean			2875	19.52				0.75a	9.10a	6.62b

[(1)] Each uniformity trial with size of 6 m × 6 m (36 m^2) was divided into 36 BEU of 1 m × 1 m (1 m^2), forming a matrix of six rows and six columns. Means of R^2, Xo and CV_{Xo} not followed by the same lowercase letter in the column (comparison of methods regardless of cut, n = 6 uniformity trials) differ at 5% significance level by the Student's t-test (two-tailed), for dependent samples with 5 degrees of freedom.

The means of the coefficients of variation were 18.12%, 15.94% and 24.50%, for the trials of the first, second and third cut, respectively, and by the Student's t-test (two-tailed), for independent samples, at 5% significance level, did not differ from each other. This suggests similar experimental precision between these cutting dates, with an average CV of 19.52%, obtained from plots with 1 m^2. Taking as reference the classification ranges of the coefficients of variation, established by Pimentel-Gomes (2009) for field agricultural trials, this CV of 19.52% is within the class of medium experimental precision (CV between 10% and 20%). Visually, there is a nonlinear decrease in the coefficient of variation [$CV_{(X)}$] with the increase in the planned plot size (X) (Figures 1, 2 and 3). There is also a trend of stabilization of $CV_{(X)}$, which demonstrates the importance of using the MMC, LRP and QRP methods to determine the optimal plot size.

Figure 1. Representation of the optimal plot size (Xo, in m^2) and the coefficient of variation in the optimal plot size (CV_{Xo}, in %), obtained by the modified maximum curvature (MMC) method, in relation to the fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench), evaluated in cuts performed at 41, 82 and 133 days after sowing (DAS).

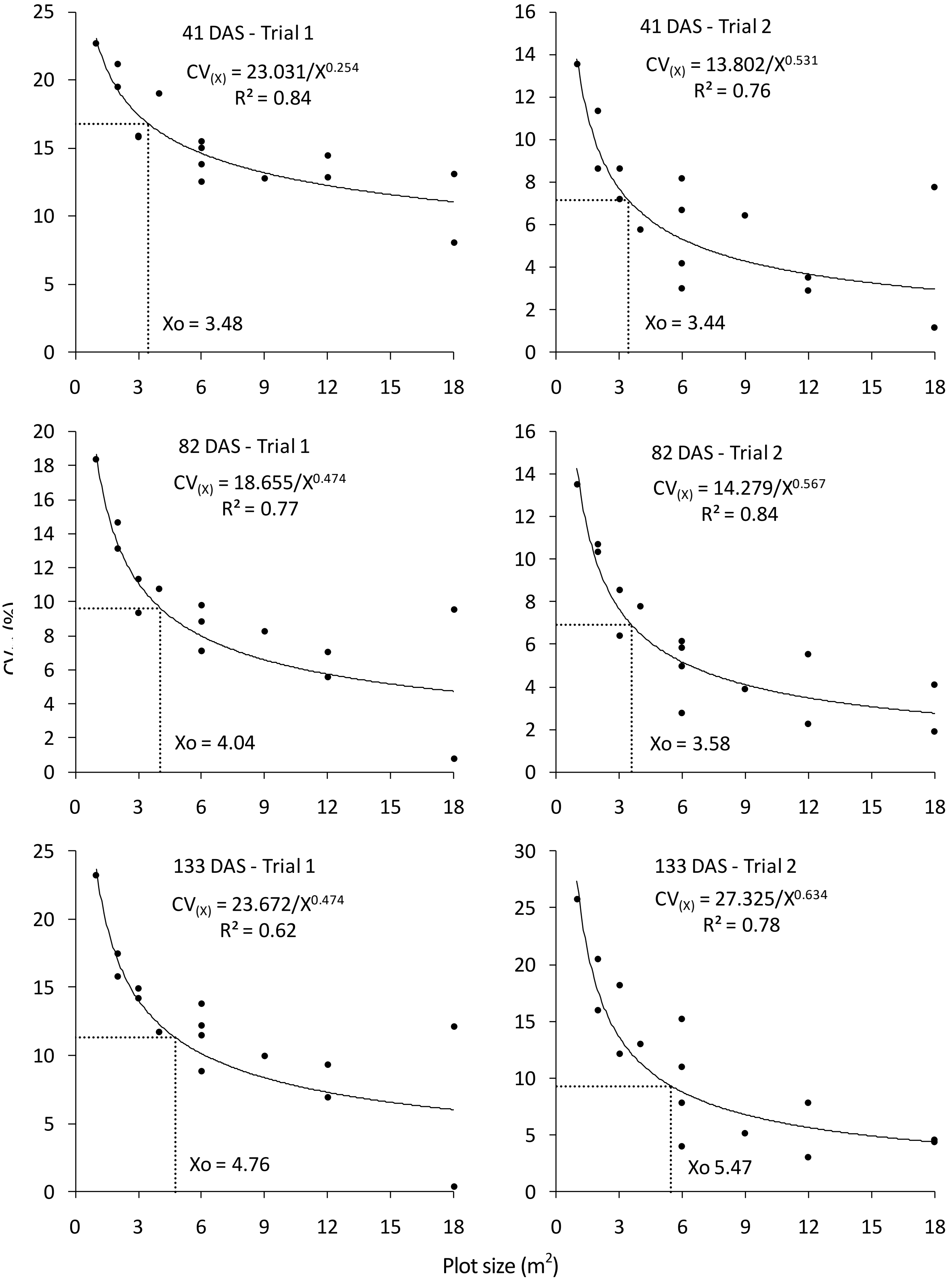


Figure 2. Representation of the optimal plot size (Xo, in m²) and the coefficient of variation in the optimal plot size (CV_{Xo}, in %), obtained by the linear response and plateau model (LRP), in relation to the fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench), evaluated in cuts performed at 41, 82 and 133 days after sowing (DAS).

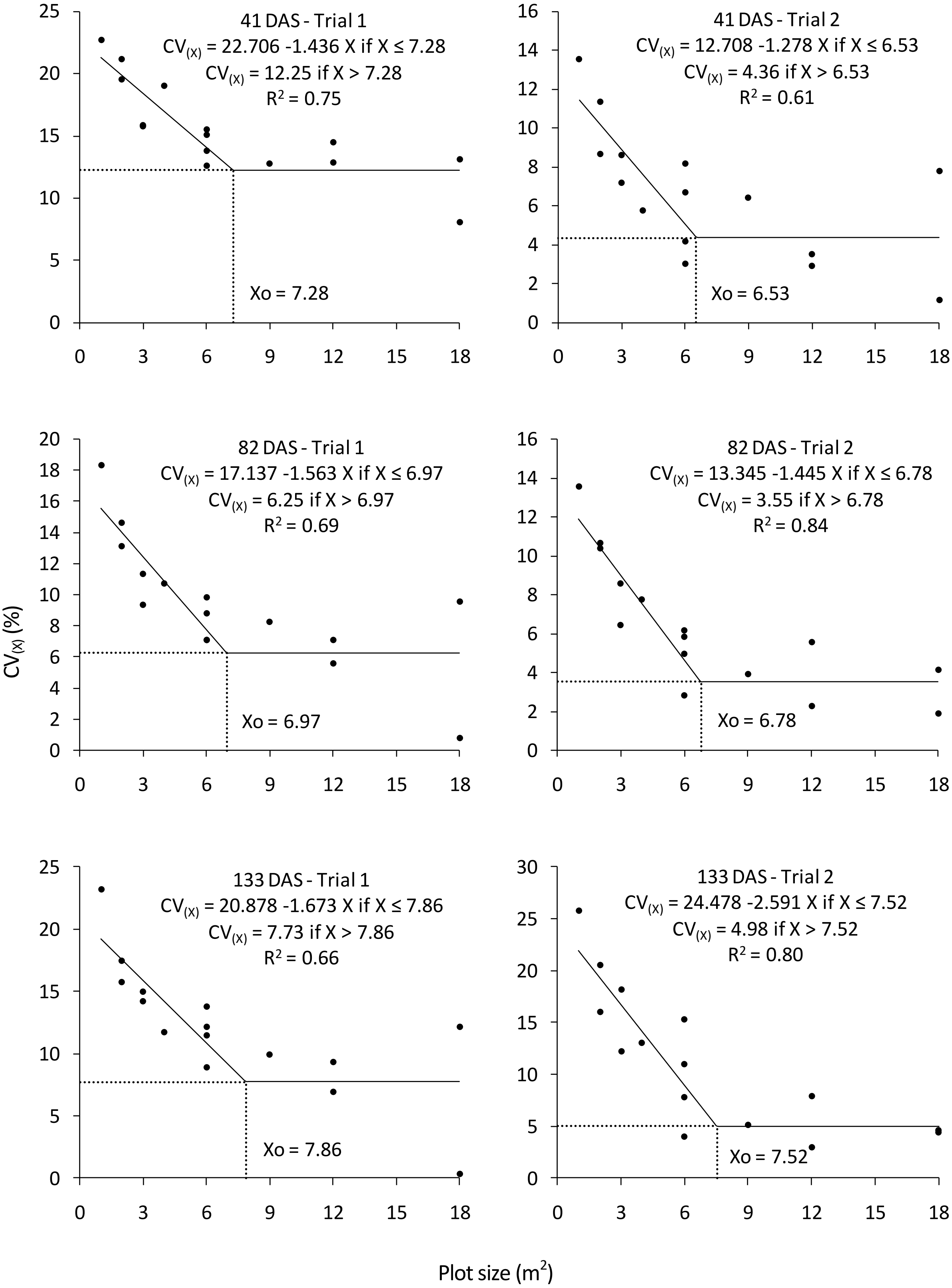
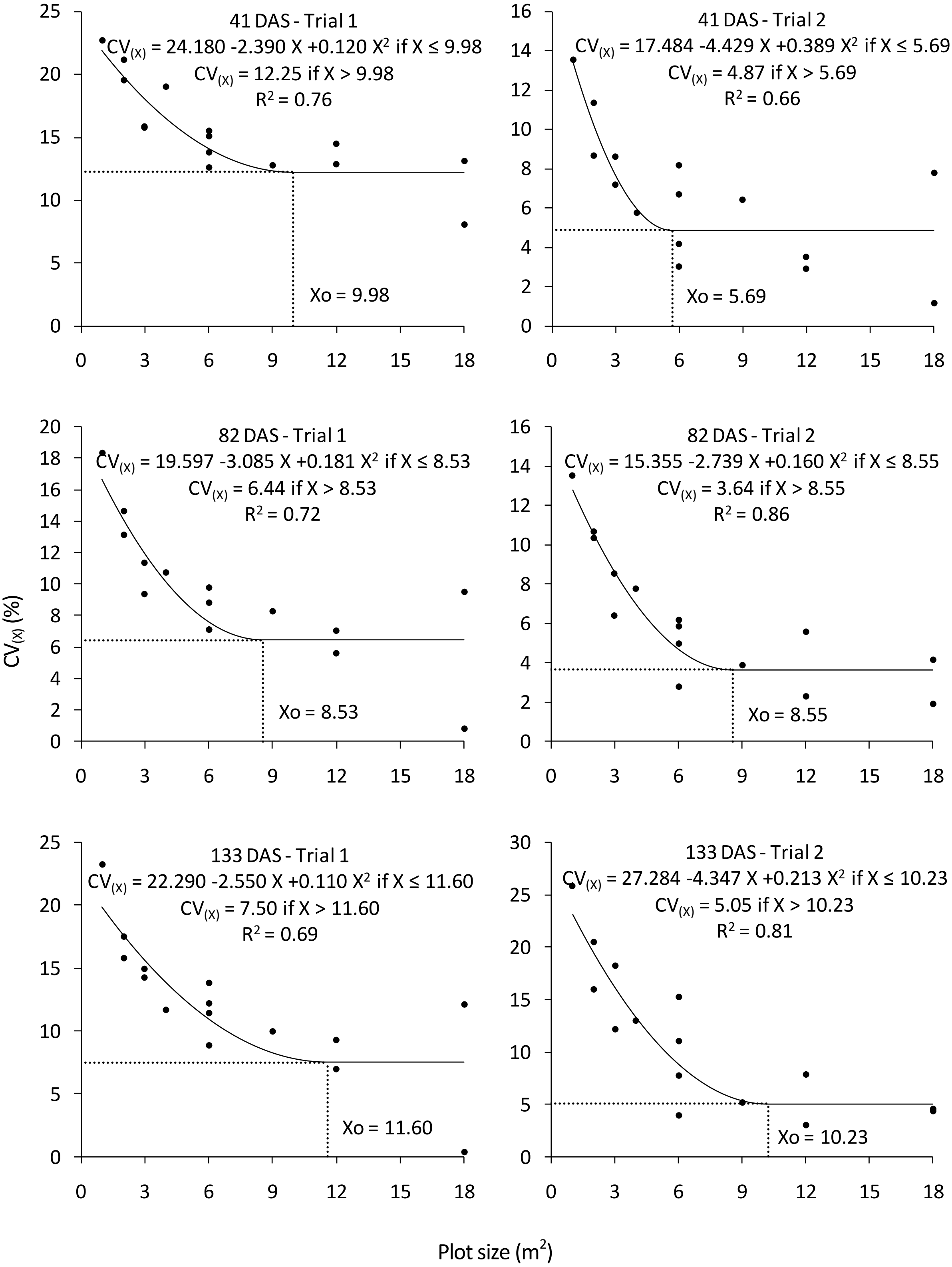


Figure 3. Representation of the optimal plot size (Xo, in m^2) and the coefficient of variation in the optimal plot size (CV_{Xo}, in %), obtained by the quadratic response and plateau model (QRP), in relation to the fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench), evaluated in cuts performed at 41, 82 and 133 days after sowing (DAS).



The coefficients of determination (R^2), among the six uniformity trials, varied from 0.62 to 0.84, 0.61 to 0.84, and 0.66 to 0.86, for the methods of modified maximum curvature (MMC), linear response and plateau model (LRP) and quadratic response and plateau model (QRP), respectively

(Table 1, Figures 1, 2 and 3). It should be considered that $0.00 \leq R^2 \leq 1.00$, and it is interpreted that the closer to 1.00 the better the model fits the data. In the comparisons of the methods, regardless of the plant cutting date, higher means of R^2 (better fits) were observed in MMC (0.77) and QRP (0.75), and the three methods showed R^2 close to one ($R^2 \geq$ 0.72).

The optimal plot sizes (Xo), among the six uniformity trials, were larger in the QRP method ($5.69 \leq Xo \leq 11.60$ m^2), intermediate in LRP ($6.53 \leq Xo \leq 7.86$ m^2) and smaller in MMC ($3.44 \leq Xo \leq 5.47$ m^2) (Table 1, Figures 1, 2 and 3). The Xo differed among the three methods, being 9.10 m^2 by QRP, 7.16 m^2 by LRP and 4.13 m^2 by MMC. Thus, it can be inferred that plot size depends on the estimation method.

The coefficients of variation in the optimal plot size (CV_{Xo}, in %), among the six uniformity trials, varied from 6.92 to 16.79%, 3.55 to 12.25%, and 3.64 to 12.25% for the MMC, LRP and QRP methods, respectively (Table 1, Figures 1, 2 and 3). The CV_{Xo} was higher in MMC (10.18%) than in LRP (6.52%) and QRP (6.62%), which did not differ from each other. These results indicate better experimental precision with the use of plot sizes determined by the LRP and QRP methods compared to MMC.

Among the methods, differences were found in the means of R^2 (MMC = 0.77; LRP = 0.72; QRP = 0.75). The means of Xo were decreasing in the following order: QRP = 9.10 m^2; LRP = 7.16 m^2; and MMC = 4.13 m^2. CV_{Xo} was higher in MMC (10.18%) and there was no difference between LRP (6.52%) and QRP (6.62%). Therefore, although the plot sizes are different between the LRP (7.16 m^2) and QRP (9.10 m^2) methods, they result in similar experimental precision, because the CV_{Xo} values did not differ. This absence of difference is explained by the fact that, from a certain plot size, the gains in precision (decrease in CV_{Xo}) with the increment in plot area are insignificant (Figures 1, 2 and 3). Thus, it can be inferred that plots with 7.16 m^2 are suitable for experimental planning. This indication of plots of 7.16 m^2 is supported by practical viability in the field and stabilization of precision from this size and can be used as a reference for planning experiments with forage sorghum, sown in rows. This plot size is relatively larger than the 3.2 m^2 (LOPES *et al.*, 2005) and 0.5 m^2 or eight plants per row meter (BRUM *et al.*, 2008) necessary to evaluate the grain yield of grain sorghum.

Results similar to those of the present study, i.e., decreasing estimates of Xo in the following order: quadratic response and plateau model, linear response and plateau model and modified maximum curvature, have been obtained in radish (SILVA *et al.*, 2012), sweet potato (GONZÁLEZ *et al.*, 2018), millet + slender leaf rattlebox + showy rattlebox (CARGNELUTTI FILHO *et al.*, 2021a) and buckwheat (CARGNELUTTI FILHO *et al.*, 2021b).

Conclusions

The optimal plot size differs between the methods and decreases in the following order: quadratic response and plateau model (9.10 m^2), linear response and plateau model (7.16 m^2) and modified maximum curvature (4.13 m^2). The optimal plot size to evaluate the fresh matter productivity of forage sorghum (*S. bicolor* (L.) Moench) sown in rows, evaluated in three cuts, is 7.16 m^2 and the experimental precision stabilizes from this size.

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