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ORIGINAL ARTICLE

Experimental precision of spatial analysis methods to evaluate the productivity of common bean families

Precisão experimental de métodos de análise espacial para avaliação da produtividade de famílias de feijão comum

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ABSTRACT: The analysis strategies that model spatial dependence, in the form of covariance analysis, have been suggested in plant breeding, in order to exert greater local control and to increase experimental precision. This study aimed to evaluate the degree of spatial dependence of errors in productivity experiments to evaluate common bean families, to compare the experimental precision of the methods of spatial analysis, moving average and Papadakis, identify the most suitable neighboring plots for the calculation of the environmental index, besides proposing and evaluating changes in the application of these methods of spatial analysis. Data of grain yield of common bean families of the winter season 2006/2007 and drought season 2007/2008 were used. In these experiments, the number of families evaluated ranged from 25 to 400, characterizing the 5 × 5 to 20 × 20 square lattice. The moving averages and Papadakis methods, combined with the randomized block design, ensure spatial independence of the errors and presented experimental precision similar to that of the lattice analysis. For the calculation of the environmental index, the highest experimental precision was obtained from the use of two neighboring plots, one upper and one lower than the reference plot. The proposed modification in the application of the methods of spatial analysis provided greater experimental precision in relation to the lattice analysis, especially in experiments with moderate spatial dependence and using the reapplication of the Papadakis method.

RESUMO: *As estratégias de análise que modelam a dependência espacial, na forma de análise de covariância, têm sido sugeridas no melhoramento de plantas, a fim de exercer maior controle local e aumentar a precisão experimental. Este estudo teve como objetivo avaliar o grau de dependência espacial de erros em ensaios de produtividade para avaliar famílias de feijão comum; comparar a precisão experimental dos métodos de análise espacial, média móvel e Papadakis; identificar as parcelas vizinhas mais adequadas para o cálculo do índice ambiente; e propor e avaliar mudanças na aplicação desses métodos de análise espacial. Foram utilizados dados de rendimento de grãos de famílias de feijoeiro da temporada de inverno 2006/2007 e seca 2007/2008. Nesses ensaios, o número de famílias avaliadas variou de 25 a 400, caracterizando a rede quadrada de 5 × 5 a 20 × 20. As médias móveis e os métodos de Papadakis, combinados com o delineamento de blocos ao acaso, garantem independência espacial dos erros e apresentaram precisão experimental semelhante à da análise em látice. Para o cálculo do índice ambiental, a maior precisão experimental foi obtida a partir do uso de duas parcelas vizinhas, uma superior e outra inferior à parcela de referência. A modificação proposta na aplicação dos métodos de análise espacial proporcionou maior precisão experimental em relação à análise em látice, principalmente em ensaios com moderada dependência espacial e com a reaplicação do método de Papadakis.*

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1 Introduction

Beans (*Phaseolus vulgaris* L.) are of great importance to the Brazilian population as it is an excellent source of protein, besides having carbohydrates, vitamins, minerals and fibers (Perazzini et al., 2008). Brazil is the largest producer and consumer of this legume that is grown by small, medium and large producers, in various production systems and practices throughout the national territory (MAPA, 2019).

The initial selection phase involves the evaluation of a large number of families in the beans breeding programs. The evaluation of these families in experiments with repetitions becomes difficult due to the requirement of large experimental areas. With few repetitions and the need for large areas, such experiments rely on more sophisticated forms of planning and analysis that ensure high experimental precision (Campos et al., 2016).

Family evaluation experiments should be planned and conducted so that the experimental error is as minimum as possible, thus providing accurate information of the research results. In the field experiments, the independence between errors is presupposed, but this assumption is not always attended, compromising the results obtained (Cargnelutti Filho et al., 2012a, 2012b; Silva et al., 2016). The usual analysis of the field experiments does not consider that observations taken on neighboring plots or plots can be correlated since one of the assumptions of the model is the independence of errors. According to Candido et al. (2009) and Negash et al. (2014) one of the alternatives to mitigate the effects of error dependence is by what is called spatial modeling. Maia et al. (2013) also demonstrated that the adoption of models that consider spatial dependence between plots can bring gains to breeding programs. Thus, analysis strategies that model spatial dependence, in the form of covariance analysis, have been suggested in plant breeding, in order to exert greater local control and to increase experimental precision.

Among the methodologies of analysis based on spatial modeling that have been suggested in plant breeding, to exercise local control and to increase experimental precision, we have the Papadakis and moving averages methods, which model the spatial dependence in the form of analysis of covariance. Rickey (1924) was the pioneer in the use of the moving average method, which adjusted maize progenies by the ratio of the means of the neighboring rows and, since each row had different neighbors, the author called the moving averages technique. The author detected reductions in the standard error of the means, after adjustment by this technique (Rios, 1997). The Papadakis method (Papadakis, 1937) consists in correcting the observed value of each plot by the random effect of the neighboring plots, the average of the estimated errors in neighboring plots is used as a covariate and is called the environmental index. While in the moving averages method, the observed value of each plot is corrected by the average of the values observed in the neighboring plots, and not by the effect of the error, as in the Papadakis method.

Although several studies have evaluated the efficiency of spatial analysis methods in bean and other crop productivity experiments, few studies have quantified the degree of spatial dependence of errors (Costa et al., 2005; Storck et al., 2011; Vivaldi, 1990). Moreover, in most of these studies, there was no comparison between the experimental precision of these methods with lattice analysis, which is a widely used design in productivity experiments for large numbers of families (Storck et al., 2011).

Thus, this study aimed to evaluate the degree of spatial dependence of the errors, in productivity experiments for evaluation of common bean families; to compare the experimental precision of the methods of spatial analysis, moving averages and Papadakis, in relation to the randomized block and lattice analysis; identify the most suitable neighboring plots for the calculation of the environmental index; besides proposing and evaluating modifications in the application of these methods of spatial analysis.

2 Materials and Methods

Grain yield data (g/plot) of common bean families of the winter season 2006/2007 and drought season 2007/2008 were used in experiments conducted at the experimental station of Coimbra city, Minas Gerais (690 m altitude, 20º45 'S and 42º51' W) belonging to bean breeding program of the Department of Plant Science of the Federal University of Viçosa (UFV).

Data were analyzed from eight experiments installed in square lattice and analyzed in lattice and randomized complete blocks. The number of families evaluated varied from 25 to 400, characterizing the designs in square lattice of type 5 × 5 to 20 × 20. In the usual analyzes it was assumed that the random errors associated with each observation are independent, with normal distribution, zero mean and homogeneous variances: $e \sim NID(0, \sigma^2)$.

In addition to the usual analyzes, grain yield data were also analyzed using the following methods of spatial statistical analysis in conjunction with the local control for blocks: the moving average method (M) and the Papadakis (P) method. Modifications were also proposed and evaluated in the M and P methods consisting of the reapplication of the moving average method (RM) and reapplication of the Papadakis (RP) method. Although the greater precision of the lattice design, this presents several disadvantages due to the restriction of the number of families being a perfect square. This restriction may require the disposal of some families with high potential or addition of controls that lead to the need for a larger experimental area and also to increase costs. Thus, the neighborhood analysis methods (moving averages and Papadakis) were used to complement the local control carried out by the randomized block design, thus being able to replace the installation of lattice experiments.

The following statistical models were used, assuming a fixed effect for all factors, except for the errors:

Model 1 (Lattice Analysis):

$$y_{ijk} = \mu + f_i + r_k + b_{j(k)} + e_{ijk}$$

where: y_{ijk} is the value observed for grain yield of the family *i* in block *j* within *k* the repetition;

"μ" is the constant associated with all observations;

f_i is the effect of the *i* family;

r_k the effect of the *k* repetition;

$b_{j(k)}$ is the effect of block *j* within the repetition *k*;

e_{ijk} is the random error associated with the observations assuming independence between errors.

Model 2 (Randomized block analysis):

$$y_{ik} = \mu + f_i + r_k + e_{ik}$$

where: y_{ik} is the observed value for grain yield of family *i*, in repetition *k*; The other factors were described previously.

Model 3 (Moving averages – M):

$$y_{ik} = \mu + f_i + r_k + \beta_1 I_{Mik} + e_{ik}$$

where: β_1 is the linear regression coefficient for grain yield and the covariable environmental index;

I_{Mik} is the environmental index for the plot *ik* calculated by method M.

Model 4 (Moving average replication – RM):

$$y_{ik} = \mu + f_i + r_k + \beta_1 I_{RMik} + e_{ik}$$

where: I_{RMik} is the environmental index for plot *ik*, calculated by the RM method.

Modelo 5 (Papadakis – P):

$$y_{ik} = \mu + f_i + r_k + \beta_1 I_{Pik} + e_{ik}$$

where: I_{Pik} is the environmental index for plot *ik*, calculated by method P.

Model 6 (Reapplication of Papadakis – RP):

$$y_{ik} = \mu + f_i + r_k + \beta_1 I_{RPik} + e_{ik}$$

where: I_{RPik} is the environmental index for plot *ik*, calculated by the RP method.

The methods M, RM, P and RP (models 3, 4, 5 and 6) correspond to a covariance analysis where the environmental index is used as a covariate, adjusting the productivity of each plot by the average of neighboring plots. In the moving average method (M), the environmental index is calculated as the average of the observed values of the plots next to plot *ik*. While in the Papadakis (P) method, the environmental index is calculated as the average of the errors of the neighboring plots, so in this method the environmental index is calculated considering the other factors included in the model.

In the proposed changes in methods M and P, the environmental index IR_{Mik} was calculated twice. In the RM method, the environmental index was calculated as the average of the values of the environmental indices of neighboring plots calculated initially in the method M. And in the RP method, the environmental index I_{RPik} was calculated as the average of the errors of neighboring plots, these errors being estimated after the application of method P.

For the calculation of the environmental indices, four forms of neighborhood (V) were evaluated, with variations in the number and position of neighboring plots considered. These are: V_{2UL} – two neighboring plots, one upper and one lower than the reference plot for which one wishes to calculate the environmental index; V_{4UL} – four neighboring plots, two upper and two lower plots; V_{4L} – four lateral plots, upper, lower, right and left; and V_{8L} – eight lateral plots, considering all the plots that make "frontier" with the reference plot.

The spatial dependence of the errors was evaluated using the Durbin-Watson(d), statistic, which tests the hypothesis of null spatial autocorrelation, $(H_0 = \rho = 0)$ being defined as:

$$d = \frac{\sum_{l=2}^{n} (\hat{e}_l - \hat{e}_{l-1})^2}{\sum_{l=1}^{n} \hat{e}_l^2}$$

where $\hat{e}_l$ is the estimated random error in plot *l*, where $l = 1, 2, 3, \ldots, n$ is the sequential order of plot positioning in the experimental area. This order was followed by successive numbering of the plots, so that $\hat{e}_l$ and $\hat{e}_{l-1}$ indicate errors of adjacent plots.

The experimental precision of the lattice analysis and of the other methods was compared through the CV, coefficient of experimental variation. The analyzes were performed using the *proc autoreg* for the Durbin-Watson test and the *proc-glm* for the other analyzes using the SAS program (version 9.2) (SAS INSTITUTE, 2014).

3 Results and Discussion

The experiments 1 and 2, installed in 7 × 7 and 5 × 5 square lattice, respectively, did not present significant spatial autocorrelation (p-value > 0.05) by the Durbin-Watson test. Thus, no spatial analysis methodology was used for these two experiments. In experiments 3, 4 and 5, spatial autocorrelation was significant (p-value < 0.05) and ranged from 7.75 to 32.46%, indicating spatial dependence of the weak to moderate residues in the randomized block analyzes (Table 1). However, the lattice analysis was efficient in ensure the spatial independence of the residues, since in this analysis the spatial autocorrelation was not significant for most of the experiments. Except for experiment 5, where even in the lattice analysis, the residues presented spatial dependence. However, spatial autocorrelation decreased from 32.46 to 17.07% (Table 1).

The coefficient of experimental variation (CV) ranged from 8.14% to 13.92%, and from 9.64% to 14.46%, respectively for lattice and randomized blocks (Table 1). This result was expected, as it has been reported higher precision of the lattice analysis in productivity experiments of different cultures, especially in experiments with large number of traits (Ramalho et al., 2012). However, the evaluation of the spatial autocorrelation of the residues, performed in this study, indicated that the greater efficiency of the local control performed by the lattice design is associated with its effectiveness in eliminating or at least reducing the spatial dependence of the residues.

Table 1. Estimated spatial autocorrelation between residues (, %), p-value for the Durbin-Watson test for spatial dependence, coefficient of experimental variation (CV) and reduction (R) of CV in relation to lattice analysis, for different types of analyzes for experiments 3, 4 and 5.

Tabela 1. Autocorrelação espacial estimada entre resíduos (, %), p-valor do *Durbin-Watson* teste para dependência espacial, coeficiente de variação experimental (CV) e redução (R) do CV em relação à análise de látice, para diferentes tipos de análises para o experimento 3, 4 e 5.

Experiment 3					Experiment 4					Experiment 5				
Analyze	$\hat{\rho}$ (%)	p-value	CV (%)	R (%)	Analyze	$\hat{\rho}$ (%)	p-value	CV (%)	R (%)	Analyze	$\hat{\rho}$ (%)	p-value	CV (%)	R (%)
Lattice	2.77	0. 2164^{ns}	13.92	-	Lattice	−8.01	0. 1649^{ns}	8.14	-	Lattice	17.07	0.0014**	12.75	-
Block	7.75	0. 0141*	14.46	−3.88	Block	20.77	0. 0054**	9.64	−40.15	Block	32.46	< 0. 0001**	13.61	−13.7
1M2UL5	5.04	0. 077^{ns}	14.04	−0.86	1M2UL5	9.44	0. 1254^{ns}	8.63	−12.34	1M2UL5	24.32	< 0. 0001**	12.87	−1.8
M4UL	7.82	0. 0134*	14.43	−3.66	M4UL	7.69	0. 1749^{ns}	8.6	−11.61	M4UL	18.59	0. 0006**	12.53	3.5
M4L	−4.3	0. 112^{ns}	13.89	0.44	M4L	−4.62	0. 2871^{ns}	8.8	−16.84	M4L	2.38	0. 34^{ns}	12.31	6.9
M8L	−3.28	0. 1766^{ns}	13.8	1.78	M8L	3.78	0. 3229^{ns}	8.08	1.61	M8L	7.74	0. 0894^{ns}	12.25	7.8
3P2UL	6.09	0. 0421*	14.26	−4.87	3P2UL	19.79	0. 0076**	9.59	−38.6	3P2UL	7.74	< 0. 0001^{ns}	12.99	−3.7
P4UL	5.46	0. 0612^{ns}	13.96	−0.52	P4UL	8.73	0. 1441^{ns}	9.07	−24.1	P4UL	20.85	0. 0001**	12.71	−9.9
P4L	−5.36	0. 0646^{ns}	14.18	−3.7	P4L	−19.64	0. 008**	8.86	−18.33	P4L	−6.48	0. 1307^{ns}	10.89	27.4
P8L	−4.61	0. 0958^{ns}	13.93	−0.19	P8L	−7.55	0. 1792^{ns}	9.05	−23.63	P8L	11.48	0. 0229^{ns}	12.3	7
2RM2UL	2.54	0. 2362^{ns}	9.95	28.52	2RM2UL	−2.14	0. 3974^{ns}	5.4	56.09	2RM2UL	1.95	0. 3677^{ns}	7.35	66.7
RM4UL	4.96	0. 0804^{ns}	11.56	31.06	RM4UL	5.4	0. 2559^{ns}	7.39	17.56	RM4UL	11.69	0. 021^{ns}	9.25	47.3
RM4L	−3.14	0. 1874^{ns}	11.13	36.02	RM4L	0.86	0. 4583^{ns}	7.07	24.53	RM4L	5.61	0. 1649^{ns}	9.25	47.4
RM8L	−0.1	0. 3899^{ns}	11.75	15.59	RM8L	3.78	0. 3229^{ns}	8.08	1.62	RM8L	10.94	0. 0285^{ns}	9.88	40
4RP2UL	5.44	0. 0619^{ns}	7.51	46.05	4RP2UL	−11.26	0. 0851^{ns}	4.37	71.15	4RP2UL	9.49	0. 0496^{ns}	5.82	79.2
RP4UL	7.4	0. 018*	9.18	56.5	RP4UL	−6.38	0. 2191^{ns}	5.2	59.15	RP4UL	17.03	0. 0015**	8.17	59
RP4L	4.48	0. 1022^{ns}	12.95	6.97	RP4L	−2.15	0. 3969^{ns}	5.61	52.85	RP4L	11.17	0. 0261^{ns}	7.75	63.1
RP8L	−1.72	0. 3136^{ns}	10.71	40.78	RP8L	−4.01	0. 3131^{ns}	6.4	38.12	RP8L	5.53	0. 1685^{ns}	8.96	50.6

*, ns: significant and non-significant spatial autocorrelation, respectively, by DW test at 5% probability; [1]M: moving average method; [2]RM: reapplication of moving averages; [3]P: Papadakis method; [4]RP: reapplication of the Papadakis method; [5]2UL, 4UL , 4L and 8L (UL: Upper and Lower, L: Lateral): number and position of the plots composing the neighborhood in the calculation of the environmental index.

The experiment 3, installed in 20 × 20 lattice, showed weak spatial dependence among the residues estimated in the block analysis. The estimated spatial autocorrelation was 7.75% (Table 1), being significant by the Durbin-Watson test (p-value = 0.0141). In the majority of analyzes the spatial independence between residues was ensured (p-value > 0.05). In this experiment, the CV ranged from 13.8% to 14.43% and from 13.93% to 14.26% respectively for the moving average (M) and Papadakis (P) methods. These values were very close to the CV of the block analyzes (14.46%) and the lattice (13.92%), indicating that the spatial analysis methods did not improve the experimental precision in this experiment. However, the reapplication of the moving average and Papadakis (RM and RP) methods provided significant increases in experimental precision. The CV ranged from 9.95% to 11.75% and from 7.51% to 12.95%, respectively, for the RM and RP methods. Regarding the CV of the lattice analysis (13.92%), there were reductions from 28.52% to 15.59% for the RM method and from 46.05% to 6.97% for the RP method (Table 1). The number and position of the plots used to calculate the environmental index also affected the experimental precision. The highest experimental precision was obtained from the use of two neighboring plots, one upper and one lower than the reference plot (RM_{2UL} and RP_{2UL}). Considering this neighborhood, the CV was 9.95% and 7.51%, respectively for the RM and RP methods, which represented reductions of 28.52% and 46.05% in relation to the CV of the lattice analysis.

In the randomized block analysis, experiment 4, installed in a 7 × 7 lattice, presented moderate spatial dependence of 20.77% and the highest CV, 9.64% (Table 1). In both the lattice and spatial methods, the spatial independence between residues was ensured (p-value > 0.05). In this experiment, the CV ranged from 8.08 to 9.59% for the spatial analysis methods M and P, being close to the CV of the lattice analysis (8.14%). While, the reapplication of the moving averages and Papadakis (RM and RP) methods provided the highest reductions in the CV, that ranged from 5.4% to 8.08% and from 4.37% to 6.4%, respectively for the RM and RP methods (Table 1). The higher experimental precision was also obtained from the use of two neighboring plots, one upper and one lower than the reference plot (RM_{2UL} and RP_{2UL}).

The experiment 5, installed in 10 × 10 lattice, spatial dependence was moderate in both block and lattice analysis. The spatial autocorrelation was 32.46% and 17.07%, respectively (Table 1). While, in the analyzes with spatial methods, the estimates of spatial autocorrelation of residues were reduced, most of them were not significant (p-value > 0.05). Both in this experiment and in the two mentioned previously, the direct relationship between the reduction of the spatial autocorrelation estimates and the CV values was observed. In experiment 5, the CV for the spatial analysis methods M and P were close to the CV of

the lattice analysis (12.75%). However, with the reapplication of the moving average methods and Papadakis (RM and RP), CV ranged from 7.35% to 9.88% and from 5.82% to 8.96%, respectively, for the RM and RP methods. For the RM_{2UL} and RP_{UL} methods the CV reductions were 42.35% and 54.35%, respectively, in relation to the lattice analysis (Table 1). The results for experiments 6, 7 and 8 were similar to those presented for experiments 4 and 5.

In general, the results indicated that in bean productivity experiments, it is appropriate to replace the lattice design with the randomized block design combined with spatial analysis methods. Because, even when spatial dependence was low or moderate, the spatial analysis methods M and P were efficient in ensured the independence of the residues and presented experimental precision similar to that of the lattice analyzes. The modification proposed in these two methods of spatial analysis, which consists of the reapplication of the M and P methods, provided greater experimental precision in relation to the lattice analysis, especially in experiments with moderate spatial dependence and using reapplication of the Papadakis method. The number and position of the neighboring plots used to calculate the environmental index also affected the precision of spatial analysis methods. In the experiments evaluated, the highest experimental precision was obtained from the use of two neighboring plots, one upper and one lower to the reference plot.

Analyzing different ways of calculating the environmental index, other authors also concluded that the number and location of neighboring plots interfere with the efficiency of the Papadakis method. In the evaluation of corn and bean experiments, Storck et al. (2011) concluded that the use of four lateral plots was efficient in reducing experimental error. According to several authors, the Papadakis method has precision of the estimates of means and / or genetic parameters, at least equal to other methods of spatial analysis (Candido et al., 2009; Costa et al., 2005; Vivaldi, 1990). Simulation studies have shown that the use of the Papadakis method provided estimates of non-biased contrasts and reduced estimation of experimental error, especially in rectangular plots (Pearce, 1998; Piepho et al., 2008). According to several authors, the Papadakis method has precision of the estimates of means and / or genetic parameters, at least equal to other methods of spatial analysis (Candido et al., 2009; Costa et al., 2005; Vivaldi, 1990). Simulation studies have shown that the use of the Papadakis method provided estimates of non-biased contrasts and reduced estimation of experimental error, especially in rectangular plots (Pearce, 1998; Piepho et al., 2008). The efficiency of the Papadakis method was tested by several authors in the genetic evaluation of maize (Storck et al., 2010), soybean (Storck et al., 2008, 2009), bean (Storck et al., 2011) and wheat (Benin et al., 2013, Storck & Silva, 2014). These authors have shown the advantages of this method, such as improvements in the indices that depict the experimental precision and reduction in the number of replications necessary for the prediction of the performance of the cultivars in terms of grain production.

Storck et al. (2011) used the Papadakis method in the analysis of 26 bean competition experiments, conducted in Santa Maria (RS) from 1998 to 2009. The authors concluded that the use of this method improved the indicators of experimental precision, reduced the number in repetitions needed to predict the performance of bean cultivars (from 7 to 3 replicates), besides maintaining adequate the assumptions of the analysis of variance (homogeneity, additivity, randomness and normality of the errors). Costa et al. (2005), in maize and bean progeny evaluation studies, concluded that the moving average and Papadakis methods were more efficient than the lattice analysis. The relative efficiency of the lattice in relation to these two methods was 94.5% and 93.8%, respectively. Souza et al. (2000), evaluating bean families, verified that the neighborhood methods were efficient in the control of the heterogeneity within the blocks, being this efficiency similar to that provided by the lattice analysis. The estimates of CV were very close to the Papadakis method (30.28%), moving averages (29.94%) and lattice analysis (33.93%). Lúcio et al. (2016), evaluating lettuce crop in different growing conditions (field and greenhouses) and different size of plots, showed that in 100% of the situations tested (environments and plot size), the adjustment with the covariate estimated by the method Papadakis generated reduction of the CV.

In general, the results indicated that in bean productivity experiments, it is appropriate to replace the lattice design in order to use the randomized block design combined with spatial analysis methods. Because, even when spatial dependence was low or moderate, the spatial analysis methods M and P were efficient in ensured the independence of the residues and presented experimental precision similar to that of the lattice analyzes. The modification proposed in these two methods of spatial analysis, which consists of the reapplication of the M and P methods, provided greater experimental precision in relation to the lattice analysis, especially in experiments with moderate spatial dependence and using reapplication of the Papadakis method. The number and position of the neighboring plots used to calculate the environmental index also affected the precision of spatial analysis methods. In the experiments evaluated, the highest experimental precision was obtained from the use of two neighboring plots, one upper and one lower to the reference plot.

4 Conclusions

The spatial dependence was moderate for the estimated errors in the randomized block analysis for most bean productivity experiments evaluated. The moving averages and Papadakis methods, combined with the randomized block design, ensure spatial independence of the errors and presented experimental precision similar to that of the lattice analysis. For the calculation of the environmental index, the highest experimental precision was obtained from the use of two neighboring plots, one upper and one lower than the reference plot. The proposed modification in the application of the spatial analysis methods provided greater experimental precision in relation to the lattice analysis, especially in experiments with moderate spatial dependence and using the reapplication of the Papadakis method.

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