e-ISSN 1983-4063 - *www.agro.ufg.br/pat* - Pesq. Agropec. Trop., Goiânia, v. 52, e72425, 2022

Special Supplement: Climate Change in Agriculture

Performance of low carbon intensified agriculture farm in the Brazilian Savanna by means of univariate and multivariate approaches[1]

Antonio Carlos Reis de Freitas[2], Geraldo da Silva e Souza[3],
Eliane Gonçalves Gomes[4], Falberni de Souza Costa[5], Dirceu Klepker[2]

ABSTRACT

The low-carbon agriculture is one of the central themes in the climate agenda. This study aimed to evaluate the performance of a low carbon farm in the Maranhão State, Brazil, using univariate and multidimensional approaches. The experimental design consisted of three replications of five treatments (land uses) (Cerrado as a reference area; no-tillage soybean-off-season corn; no-tillage corn-soybean-off-season corn; no-tillage corn-soybean; no-tillage soybean-off-season corn-*Brachiarya brizantha*), in five periods (Julian days: 28, 48, 83, 138 and 154), totaling 75 observations. The data were analyzed using univariate and multidimensional approaches. A statistically significant interaction was observed between treatment and period, indicating that the responses to the treatment vary with time. The plot that showed the best performance was the reference area, followed by the no-tillage soybean-off-season corn treatment.

KEYWORDS: Greenhouse gases, sustainable land use, carbon sequestration, carbon modeling.

RESUMO

Desempenho de fazenda de agricultura intensificada de baixo carbono no Cerrado brasileiro por meio de abordagens univariadas e multivariadas

A agricultura de baixo carbono é um dos temas centrais da agenda climática. Objetivou-se avaliar o desempenho de uma fazenda de agricultura de baixa emissão de carbono no estado do Maranhão, Brasil, por meio de abordagens univariadas e multivariadas. O delineamento experimental consistiu de três repetições de cinco tratamentos (usos da terra) (Cerrado como área de referência; plantio direto de soja-milho safrinha; plantio direto de milho-soja-milho safrinha; plantio direto de milho-soja; plantio direto de soja-milho safrinha-*Brachiarya brizantha*), em cinco períodos (dias julianos: 28, 48, 83, 138 e 154), totalizando 75 observações. Os dados foram analisados utilizando-se abordagens univariadas e multidimensionais. Observou-se interação estatisticamente significativa entre tratamento e período, indicando que as respostas ao tratamento variam com o tempo. A parcela com melhor desempenho foi a área de referência, seguida pelo tratamento plantio direto de soja-milho safrinha.

PALAVRAS-CHAVE: Gases de efeito estufa, uso sustentável da terra, sequestro de carbono, modelagem de carbono.

INTRODUCTION

The 26th session of the Conference of the Parties (COP26), held in Glasgow, in November 2021, shed light in the agricultural sector and the strategies and policies for a low carbon agriculture future. This is of particular importance, as the agricultural sector is one of the main sources of greenhouse gas emissions (Norse 2012). On the other hand, agriculture is an economic activity highly sensitive to climate change. International policy efforts of climatic agenda seek to make compatible the agricultural expansion based on low carbon economy (Embrapa 2018). In this perspective, the adoption of technologies and innovations that mitigate greenhouse gases emissions (GHG) by farmers gains worldwide importance. Thus, a decrease in institutional barriers to broad technological change that empower the agricultural research, in order to deliver robust and cost-effective mitigation technologies, is required.

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[1] Received: Mar. 30, 2022. Accepted: July 06, 2022. Published: Aug. 02, 2022. DOI : 10.1590/1983-40632022v5272425.

[2] Empresa Brasileira de Pesquisa Agropecuária (Embrapa Cocais), São Luís, MA, Brasil.
E-mail/ORCID: carlos.freitas@embrapa.br/0000-0002-3114-1450; dirceu.klepker@embrapa.br/0000-0001-5220-2913.
[3] Universidade de Brasília, Departamento de Estatística, Brasília, DF, Brasil.
E-mail/ORCID: geraldosouza@unb.br/0000-0002-6697-5383.
[4] Empresa Brasileira de Pesquisa Agropecuária (Secretaria de Inteligência e Relações Estratégicas), Brasília, DF, Brasil.
E-mail/ORCID: eliane.gomes@embrapa.br/0000-0002-2590-5223.
[5] Empresa Brasileira de Pesquisa Agropecuária (Embrapa Acre), Rio Branco, AC, Brasil.
E-mail/ORCID: falberni.costa@embrapa.br/0000-0002-0896-7967.

According to Lima & Harfuch (2021), the COP26 brought two main messages for the Brazilian agricultural sector: it is necessary to adopt actions to reduce or sequester GHG emissions and decrease methane emissions. In the first case, reducing deforestation and the illegal conversion of native vegetation may be the key issues. In the second case, the current phase of the Low Carbon Economy in Agriculture, so-called ABC+ plan (Brasil 2021), may be the main driver to achieve the Brazilian mitigation goals until 2030. In this context, it is also possible to mention the crop-livestock-forest integration as a production strategy for sustainable intensification and increase productivity and environmental performance, through the recovery of degraded pastures, as well as production diversification and intensification (Moraes et al. 2014, Gil et al. 2016, Skorupa & Manzatto 2019).

In addition, the environmental service of sequestering carbon from the atmosphere into the soils has become an important strategy to encourage the development of sustainable agriculture at the landscape scale (Freitas et al. 2007, Carvalho et al. 2014). Therefore, it is important to understand the GHG emissions dynamics and the carbon sequestration potential in different production systems (Lal 2005, Bernoux et al. 2009, Cerri et al. 2009, Batlle-Bayer et al. 2010, Carvalho et al. 2014, Corbeels et al. 2016, Freitas et al. 2019, Souza et al. 2021).

Under this scenario, a question that arises is how to evaluate the performance of agricultural production systems under the low carbon agriculture paradigm, and, at the same time, taking into account the carbon sequestration and GHG emissions mitigation. Thus, the present study aimed to use univariate and multivariate approaches to analyze an experimental design in a low carbon intensified agriculture farm located in the Brazilian Savanna, considering soil carbon stocks (SCS), management practices and meteorological conditions.

MATERIAL AND METHODS

The study was carried out in the 2016-2017 crop season, at the Santa Luzia farm, in São Raimundo das Mangabeiras, Maranhão State, Brazil (6º49'20.2"S, 45º24'30.7"W and 512 m of altitude), where the climate type is Aw, according to the Köppen classification, with average temperature of 28 ºC and annual rainfall of 1,200 mm. The area is located in the Cerrado (Brazilian Savanna) biome and the soil classified as Oxisols (USDA 2014), and, since 2005, it has been used as a place for experimentation and demonstration of technologies for crop and livestock integrated systems.

The experimental design consisted of three replications of five treatments, repeated in five periods (Julian days: 28, 48, 83, 138 and 154), with 75 observations, as it follows:

1) Cerrado (reference area): classified as forested Savanna (IBGE 2019), with 54.98 t ha^{-1} of total carbon stock, soil density of 1.1 g cm^{-3} and soil carbon stock of 49 t ha^{-1} in the layer of 0-30 cm;

2) No-tillage soybean-off-season corn, with soil density of 1.26 g cm^{-3} and soil carbon stock of 50 t ha^{-1} (0-30 cm). In the 2016 cycle, the soybean was planted at the end of January and harvested at the beginning of May. Therefore, there was a full adjustment of the soybean crop to the rainy season, offering good moisture conditions for a late cycle soybean cultivation (duration: 120 days). In the 2017 cycle, the soybean crop was planted at the beginning of December 2016. There was, therefore, an early-cycle cultivation (duration: 105 days), which was succeeded by the off-season corn crop;

3) No-tillage corn-soybean-off-season corn, with soil density of 1.22 g cm^{-3} and soil carbon stock of 47 t ha^{-1} (0-30 cm), referring to a strategy based on the reposition of the soil carbon stocks. In the 2016 cycle, the corn crop was planted at the end of January and harvested at the end of May. Therefore, there was a full adjustment of the corn crop to the rainy season, offering good moisture conditions for this crop. In the 2017 cycle, the soybean crop was planted at the beginning of the first quarter of the rainy season (November 2016) and harvested in the middle of March 2017. There was, therefore, an early cycle cultivation (duration: 110 days), which was succeeded by the off-season corn crop;

4) No-tillage corn-soybean, with soil density of 1.29 g cm^{-3} and soil carbon stock of 46 t ha^{-1} (0-30 cm). This treatment presented a high soil density and low carbon at the beginning of the cycle. In the 2016 cycle, corn was planted at the end of January and harvested at the end of June. The corn crop was adjusted to the moisture conditions. In the 2017 cycle, the soybean crop was planted at the beginning of November 2016 and harvested in the middle of March 2017, being succeeded by the off-season corn crop;

5) No-tillage soybean-off-season corn-*Brachiarya brizantha*, with soil density of 1.21 g cm^{-3} and soil carbon stock of 45 t ha^{-1} (0-30 cm). In the 2016 cycle, the soybean crop was planted at the end of the first quarter of the rainy season (January 2016) and harvested at the beginning of the last quarter (May 2016). Therefore, there was a full framing of the soybean crop to the rainy season, offering good moisture conditions for that crop. Under these conditions, it became feasible to use a late cycle soybean cultivation (duration: 120 days). In the 2017 cycle, the soybean crop was planted at the beginning of the first quarter of the rainy season (December 2016), being an early cultivation planting (duration: 105 days), which was succeeded by the off-season corn crop followed by *Brachiarya brizantha*.

When evaluating an experimental design, it is usual to measure a unidimensional or multidimensional response and proceed with Anova/Ancova (Cochran & Cox 1992). Although there are statistical methods to deal with a multidimensional response, the interpretation of results may be complex (Gomes et al. 2008). In this regard, it is of interest to define univariate measures and apply evaluation approaches that allow a direct interpretation. Gomes et al. (2008) proposed the use of data envelopment analysis (DEA) models to aggregate the multidimensional response of an experimental design into a unidimensional performance score. The authors advocate that the approach via DEA agrees with the classic analysis of variance (covariance) for multidimensional responses and simplifies the statistical analysis. This approach has already been used to assess the agricultural environmental performance in Brazil (Gomes et al. 2015, Souza et al. 2021) and to evaluate experimental plots (Gomes et al. 2008, Lima et al. 2014).

Considering the decision-making unit (DMU), which, in the DEA jargon, refers to each observation or unit to be evaluated, this model is represented by the following equation: $Max\ h_0 = \sum_r u_r w_{r0}$, subjected to $\sum_r u_r w_{rk} \leq 1, \forall k$, with $u_r \geq 0, \forall r$, where: h_0 is the efficiency of DMU 0 under evaluation; w_{rk} the output r, $r = 1 \ldots s$ of DMU k; and u_r the weight assigned to the output r. In this formulation, and under the unitary input assumption, the objective function maximizes the efficiency score of the DMU under evaluation, represented by the weighted average of the outputs for the DMU 0. The first restriction imposes that the weighted average of the outputs of all DMUs cannot be greater than 1 (highest value for the efficiency/performance score). The second restriction imposes positive weights for all outputs. This equation is derived from the classic DEA models (Caporaletti et al. 1999, Lovell & Pastor 1999, Gomes et al. 2008) and this model was run for each observation in the sample.

Here, an experimental design was considered to analyze a DEA performance measure of quality of the environment, represented by the soil carbon dynamics (carbon sequestration) and gases emissions (here, nitrous oxide and carbon dioxide). Thus, the response performance was measured using a production model with three outputs and a unitary input, under variable returns to scale (equivalently constant returns to scale). The outputs are ranks of soil carbon stock (SCS) up to 50 cm deep (SCS050), CO_2 and N_2O variables that relate to the environment quality. The experimental design consisted in three replications of four treatments (planting fields). The design was repeated in 5 periods (28, 48, 83, 138 and 154 days).

The outputs of the DEA model are ranks of the carbon stock in the soil up to 50 cm deep (rSCS050cm; $kgC.kgsoil^{-1}$), CO_2 flux (rCO_2; $kgC.kgsoil^{-1}$) and N_2O flux (rN_2O; $kgN.kgsoil^{-1}$). These variables are related to the environment quality.

The data were analyzed using univariate and multidimensional approaches, exploring distinct features of the design. Initially, the time was normalized and the period considered as a quantitative variable to fit the following model: $y_{ijt} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_t + \varepsilon_{ijt}$, with $i = 1, 2, 3$ and $j = 1, 2, 3, 4, 5$, where: y_{ijt} is the value of the response variable for replication i, treatment j and time t; μ an overall mean; α_i the replication effects; β_j the treatment effects; $(\alpha\beta)_{ij}$ the interaction effects (replication *vs*. treatments); t the time variable; and ε_{ijt} the random errors assumed to be iid $N(0, \sigma^2)$ random variables. The results of this analysis are reported in Table 1.

Since the efficiency response is a variable with response in (0,1), the fractional regression model of Papke & Wooldridge (1996) was also considered, where: $E(y_{ijt}) = \Phi[\mu + \sum^2_{i=1} \alpha_i D_i^{rep} + \sum^4_{j=1} \beta_j D_j^{treat} + \sum^2_{i=1} \sum^4_{j=1} (\alpha\beta)_{ij} D_i^{rep} D_j^{treat} + \gamma_t]$, with $\Phi(.)$ being the standard normal distribution function. The effects are adjusted to avoid singularities, and D_i^{rep} and D_j^{treat} are dummy variables indicating the presence of replications and planting fields, respectively. The results of the fractional regression fit are reported in Table 2.

Table 1. Anova model replications, treatments, interaction effect and quantitative normalized time (time_c; time/28). The dependent variable is the data envelopment analysis efficiency score.

Source	DF	Types I and III SS	Mean square	F value	Pr > F
Replications (R)	2	0.0435	0.0217	0.89	0.4177
Treatments (T)	4	0.6807	0.1702	6.93	0.0001
R * T	8	0.4461	0.0558	2.27	0.0343
Time_c	1	0.2346	0.2346	9.56	0.0030

Parameter	Estimate	Standard error	t value	Pr > |t|
time_c	-0.0324	0.0105	-3.09	0.0030

Table 2. Fractional regression model on replication, treatment, replication *vs.* treatment and quantitative normalized time (time_c; time/28). D denotes dummy for replications and T for treatment. The dependent variable is the data envelopment analysis efficiency score.

Source	Coefficient	Robust standard error	z	P > z
D1	-0.3363	0.3049	-1.10	0.270
D2	-0.4130	0.2503	-1.65	0.099
T1	4.2081	0.1715	24.54	0.000
T2	0.1447	0.2030	0.71	0.476
T3	-0.9220	0.1813	-5.08	0.000
T4	-0.8740	0.3041	-2.87	0.004
D1T1	-4.3412	0.3566	-12.18	0.000
D1T2	0.0645	0.4027	0.16	0.873
D1T3	0.7611	0.3812	2.00	0.046
D1T4	0.6575	0.5068	1.30	0.194
D2T1	-3.3822	0.2948	-11.47	0.000
D2T2	0.4082	0.3024	1.35	0.177
D2T3	1.2718	0.3356	3.79	0.000
D2T4	0.5239	0.4466	1.17	0.241
Time_c	-0.1186	0.0320	-3.70	0.000
Constant	1.4581	0.1762	8.28	0.000

T1: Cerrado as a reference area; T2: no-tillage soybean-off-season corn; T3: no-tillage corn-soybean-off-season corn; T4: no-tillage corn-soybean; T5: no-tillage soybean-off-season corn-*Brachiarya brizantha*.

Another way to analyze the data is to assume a repeated measure of Anova and disregard the quantitative nature of time. This model, as in Littell et al. (2002), is defined as it follows: $y_{ijt} = \mu + \beta_j + b_{ij} + \gamma_t + (\beta\gamma)_{it} + \varepsilon_{ijt}$, with $i = 1, 2, 3$, $j = 1, 2, 3, 4, 5$ and $t = 1, 2, 3, 4, 5$; where: y_{ijt} is the efficiency measurement at time t on the ith replication assigned to plant field j. The quantity $\mu + \beta_j + \gamma_t + (\beta\gamma)_{it}$ is the mean efficiency for the treatment j at time t. b_{ij} are random effects associated with the replication i and plant field j. These random variables are assumed to be iid $N(0, \sigma^2_B)$. The quantities ε_{ijt} are iid $N(0, \sigma^2)$ random errors independently distributed from the b_{ij}. It follows that: $E(y_{ijt}) = \mu + \beta_j + \gamma_t + (\beta\gamma)_{it}$; $Var(y_{ijt}) = Var(b_{ij} + \varepsilon_{ijt}) = \sigma^2_B + \sigma^2$; $Cov(y_{ijt}, y_{ijl}) = \sigma^2_B$.

If these assumptions are confirmed, then analysis of variance methods are valid for repeated measures data. The assumptions on the covariance matrix are known as H-F conditions (Huynh & Feldt 1970) and can be tested via multivariate analysis in the SAS-GLM, using the Mauchly's criterion (Littell et al. 2002). Sphericity should not be rejected. This is a likelihood ratio test applied to orthogonal components and test the null hypothesis that the model that imposes the H-F conditions fits, as well as the model that imposes no conditions at all.

RESULTS AND DISCUSSION

Table 1 reports the results of the Anova analysis. A significant interaction was noticed between replicates and planting fields. The linear effect indicates a significant 3 % decrease per unit of time. Similar results are presented in Tables 1 and 2. An interaction effect is also highly significant in Table 2. The assumption of repeated measures was not rejected by the Mauchly's criterion (p-value = 0.6848), meaning that the standard tests are appropriate.

These results show that there is statistical significance between soil carbon stock (SCS) and management practices in the operational sequence of integrated system of the Santa Luzia Farm, which indicates the producer's learning through the maintenance of SCS and obtaining satisfactory yields from the crops.

The treatments Cerrado (native vegetation) and soybean-off-season corn had similar results for SCS, with 99 t ha^{-1} (0-100 cm), and N_2O emissions (6 and 49 g ha^{-1} yr^{-1} of N, respectively). On the other hand, the corn-soybean-*Brachiarya brizantha* treatment showed the worst performance for SCS, with 86 t ha^{-1} (0-100 cm), and N_2O emissions (237 g ha^{-1} yr^{-1} of N). Comparing the SCS data from the Cerrado and soybean-off-season corn-*Brachiarya brizantha* treatments, it is possible to verify that the latter presented the lowest SCS (13 t ha^{-1}), indicating carbon losses in the management history of this area. Empirically, the producer monitors these carbon losses by observing the mulch on the ground. Thus, when verifying that the mulch is thin, the producer plants biomass replacement crops (corn) to provide the recovery of the mulch.

These findings are consistent with data from the literature. For example, as discussed by Bustamante et al. (2006), soil C stocks (0-100 cm) range from 100 to 200 t ha^{-1}, increasing for clay content. Braz et al. (2013) found that, in the conversion of native Cerrado to Brachiaria pasture, it is likely that there will be a loss of C from the biomass and emission to the atmosphere of 10 and 30 t ha^{-1}, respectively, as CO_2.

Regarding the time effect, Table 2 shows that the soybean-off-season corn treatment differed from the other treatments, that is, it presented the best fit among C stocks in the soil, land use, management practices and weather conditions. In general, the management of agricultural areas causes changes in the soil carbon stocks that result in an increase (pasture) or decrease (soybean) in the SCS (Rittl et al. 2017).

The test of the assumptions of variance-covariance in repeated measures for the application does not reject the H-F conditions (χ^2: 11.6392; p-value: 0.2344). Following the acceptance of the H-F conditions, Tables 3 and 4 show the results of the Anova with repeated measures, with a significant treatment *vs.* time interaction, indicating that responses to the treatments vary with time. However, separate combinations must be analyzed. Considering the five treatments as soil conditions (soil densities, soil texture and SCS) and the land use (crops) change at time during the crop season, the interactions among land use, weather conditions and management practices resulted in different performances for soil carbon sequestration and greenhouse gas fluxes (N_2O and CO_2).

Figure 1a shows the performance evolution, in which a similarity was observed between the Cerrado as a reference area and the no-tillage soybean-off-season corn, with efficiency levels above 0.82, indicating a high level of maturity of the producer in the adoption of the soybean-off-season corn treatment. On the other hand, the adoption of the soybean-off-season corn-*Brachiarya brizantha* system still requires adjustments in the learning curve. Therefore, there is a potential for growth in the mitigation of greenhouse gas emissions in the national agriculture to be achieved in the coming years.

The interaction is evident from Figure 1a. The treatment profiles are different when averaged

Table 3. Analysis of variance with repeated measures. The dependent variable is the data envelopment analysis efficiency score.

Source	DF	Type III SS	Mean square	F value	Pr > F
Treatment	4	0.6807	0.1702	11.30	< 0.0001
Replication (treatment)	10	0.4896	0.0490	3.25	0.0037
Time	4	0.4044	0.1011	6.71	0.0003
Treatment * time	16	0.6756	0.0422	2.80	0.0042

Source	Type III expected mean square
Treatment	Var(error) + 5 var[rep(treat)] + Q(treat, treat * time)
Replication (treatment)	Var(error) + 5 var[rep(treat)]
Time	Var(error) + Q(time, treat * time)
Treatment * time	Var(error) + Q(treat * time)

Table 4. Tests of hypotheses for mixed model analysis of variance. The dependent variable is the data envelopment analysis efficiency score.

Source	DF	Type III SS	Mean square	F value	Pr > F
Treatment*	4	0.6807	0.1702	3.48	0.0501
Replication (treatment)	10	0.4896	0.0490	3.25	0.0037
Time*	4	0.4044	0.1011	6.71	0.0003
Treatment * time	16	0.6756	0.0422	2.80	0.0042
Error: mean square	40	0.6026	0.0151	-	-

* This test assumes that one or more other fixed effects are zero.

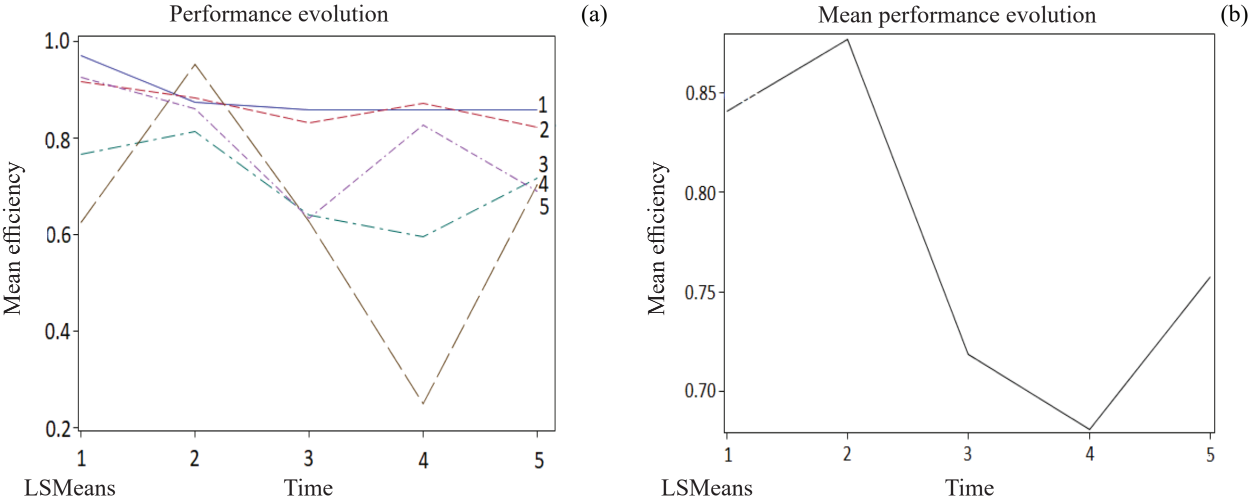

Figure 1. Treatment profiles of least squares means by treatment (a) and performance evolution (average least squares means) over time (b). Treatments: 1) Cerrado as a reference area; 2) no-tillage soybean-off-season corn; 3) no-tillage corn-soybean-off-season corn; 4) no-tillage corn-soybean; 5) no-tillage soybean-off-season corn-*Brachiarya brizantha*. Time: 1) Jan. 28, 2016; 2) Feb. 17, 2016; 3) Mar. 24, 2017; 4) May 18, 2017; 5) May 31, 2017.

over replications. The treatments Cerrado as a reference area and no-tillage soybean-off-season corn showed closer profiles. They are also dominant. Figure 1b shows evidence of a negative trend in the performance. It agrees with the regressions assuming time as a quantitative variable. In addition, it shows that there was a decrease in the average performance of the treatments over time. However, this trend may change after the incorporation of adjustments in the production system.

It is important to observe that the influence of other variables was tested in the Anova model. These variables were air temperature (0 and 40 min), soil temperature (0 and 40 min) and presence of nitrogen fertilization (0-1 variable). None of them were statistically significant, and, for this reason, they were not included in the final model.

The explanation for this performance must consider the combination adopted by farmers among appropriate crop management practices, soil density and meteorological conditions. On other hand, the public policy to face climate change in the country recognizes that there are producers with different performances. However, the biggest challenge is to identify the degree of maturity of producers in adopting agricultural practices based on low-carbon agriculture.

The approach here proposed may contribute to this theme, as it allows the identification of the treatments (here, production strategies) and environmental conditions.

CONCLUSIONS

The data envelopment analysis model was capable to assess the sustainability of integrated systems from the point of view of soil carbon stocks, management practices and meteorological conditions, with the best performance for the soybean-off-season corn treatment, with 50 t ha^{-1} (0-30 cm) of soil carbon stock, which showed to be closer to the natural system, i.e., the Cerrado biome.

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