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Model performance in estimating the yield of common bean cultivars[1]

Desempenho de modelos na estimativa da produtividade de cultivares de feijoeiro

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ABSTRACT - The use of vegetation indices has good potential for predicting the productivity of several crops, but factors such as the time of assessment, cultivar, and plant phenology can influence the performance of predictive models. The objective of this study was to evaluate and compare the precision of estimating the common bean grain yield, according to the normalized difference vegetation index (NDVI), using individual models per cultivar and a general model with all cultivars. The cultivars IAC Imperador and IPR Campos Gerais, with determined and indeterminate growth habits, respectively, were evaluated. They were subjected to different nitrogen management methods to provide grain yield variability. NDVI evaluations were conducted throughout the culture cycle on six dates during the vegetative and reproductive stages. The common bean grain yield was estimated with high precision as a function of NDVI, obtaining a precision of up to 78% and an average error close to 350 kg ha^{-1}. The greatest fit of estimation was obtained in the phenological reproductive stages of beans, especially after crop flowering. General models, composed of data from more than one cultivar, had similar precision and, in some cases, superiority to the fitted models for each cultivar, demonstrating the feasibility of using the same model for several genotypes.

Key words: Crop forecast. NDVI. *Phaseolus vulgaris* L.. Remote sensing. Vegetation index.

RESUMO - O uso de índices de vegetação apresenta bom potencial para a predição da produtividade de diversas culturas, porém fatores como a época de avaliação, cultivares e fenologia da planta podem influenciar na performance de modelos preditivos. O objetivo do trabalho foi avaliar e comparar a precisão de estimativa da produtividade do feijoeiro, em função do índice de vegetação NDVI, utilizando modelos individuais por cultivar e geral com todas as cultivares. Foram avaliadas as cultivares IAC Imperador e IPR Campos Gerais, de hábitos de crescimento determinado e indeterminado, respectivamente. Foram submetidas a diferentes manejos de fornecimento de nitrogênio, a fim de proporcionar variação da produtividade. Foram realizadas avaliações do NDVI ao longo do ciclo da cultura, em 6 datas, durante estádios vegetativos e reprodutivos. A produtividade de grãos do feijão pode ser estimada com elevada performance em função do índice de vegetação NDVI, obtendo-se R^2 de até 78% e erro médio próximo de 350 kg ha^{-1}. Os melhores ajuste de estimativa são obtidas em estádios fenológicos reprodutivos do feijão, especialmente após o florescimento da cultura (R_6). Modelos generalistas, compostos por dados de mais de uma cultivar, apresentam precisão semelhante e, em alguns casos, superior aos modelos ajustados para cada cultivar, demonstrando a viabilidade da utilização de um mesmo modelo para vários genótipos.
Palavras-chave: Previsão de safra. NDVI. *Phaseolus vulgaris* L.. Sensoriamento remoto. Índice de vegetação.

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INTRODUCTION

In agriculture, it is of substantial interest to develop techniques to aid in the estimation of the area, production, and yield of different crops. In large areas, the acquisition of this information can be costly when performed only by field researchers. Consequently, official national bodies have been using different methodologies to assist in agricultural monitoring and forecasts of crop areas and yield in the country (COMPANHIA NACIONAL DE ABASTECIMENTO, 2021). This information is essential for agribusiness because it contributes to the establishment of prices, insurance, and agricultural policies. Among these techniques, the use of remote sensing through vegetation indices stands out, presenting significant correlations with growth and yield attributes of different crops (COELHO *et al*., 2020; GROHS *et al*., 2009), which can assist in monitoring harvests on a large scale.

The application of vegetation indices in remote sensing, such as the normalized difference vegetation index (NDVI), has been widely studied for the prediction of biomass, the need for nitrogen fertilization, yield, and other attributes in crops such as wheat (HASSAN *et al*., 2019), corn (LEWIS; ROWLAND; NADEAU, 1998)), and rice (GUAN *et al*., 2019). The use of NDVI can improve the process of delimiting management zones in annual crops (DAMIAN *et al*., 2020). The estimation of plant attributes in an indirect way favors the adoption of more specific management by rural producers, resulting in greater sustainability.

The use of vegetation indices in the culture of common bean (*Phaseolus vulgaris* L.) was efficient in estimating leaf area, plant height, and grain yield (MONTEIRO *et al*., 2012; SANDRINI *et al*., 2019). Despite the importance of this crop to world food, which is a part of the Brazilian food base (SOUZA *et al*., 2013), there is a lack of studies that assess the accuracy of NDVI considering cultivars with different growth habits and in different phenological stages, allowing the elaboration of more precision models. This is necessary because, although there are good results reported in the literature with the use of this vegetation index, limitations have been reported, as it can suffer from variation caused by climate, plant phenology, and agricultural practices (COELHO *et al*., 2019; LEWIS; ROWLAND; NADEAU, 1998). It is necessary to establish assessments in phenological stages that present greater precision and lower estimation error, thereby increasing the probability of success.

In addition to knowing the best time to perform measurements, the performance of different models that can be used in the construction of prediction models should also be evaluated. Individual models have a limited capacity to estimate yield under different experimental conditions (LI *et al*., 2015). The elaboration of general models based on the combined use of data obtained when using different cultivars under different environmental conditions and crop systems allows the development of more robust models, which may even have national applicability (LEWIS; ROWLAND; NADEAU, 1998).

The hypotheses are as follows: (i) evaluations with NDVI in reproductive phenological stages have greater precision in estimating common bean grain yield; (ii) general models of grain yield estimation show precision similar to that of the individual models of each cultivar. The objectives of this study were to evaluate and compare the precision of estimating the common bean grain yield, according to the NDVI, using individual models per cultivar and a general model with all cultivars.

MATERIAL AND METHODS

The experiment was conducted during the agricultural year of 2016/2017 in the winter cropping season (3^{rd} cropping season), in the municipality of Jaboticabal, São Paulo, Brazil. The experimental area is located at 21°14′59″ S, 48°17′13″ W, and the average altitude is 575 m. The climate is classified as Aw, according to Köppen's classification (humid tropical with a rainy season in the summer and a dry winter). The soil is classified as Latossolo Vermelho eutroférrico according to the Brazilian Soil Classification System (SANTOS, 2018) and as Oxisol according to Soil Taxonomy (SOIL SURVEY STAFF, 2014), with clayey texture, and the relief is gently undulating, with a 6% slope.

The historical area was cultivated with annual crops (corn and common beans) in a conventional tillage system. The experimental area was in the first year of the no-tillage system, with millet (*Pennisetum americanum* L.) as the predecessor crop. Millet desiccation was performed 60 days after emergence (DAE) of the seedlings, using potassium glyphosate at a dose of 1.3 g ha^{-1} for the active ingredient. Then, the crop was crushed using a mechanized straw crusher, generating 5.1 Mg ha^{-1} of dry straw matter. The chemical attributes of soil fertility and granulometry in the 0.00–0.20 m deep layer were determined before sowing the common beans (Table 1).

Furrowing and fertilization at sowing were mechanically performed on June 27, 2017, using 250 kg ha^{-1} of a 08-28-16 formulation, supplying 20 kg·ha^{-1} of N, 70 kg ha^{-1} of P_2O_5, and 40 kg ha^{-1} of K_2O. On the morning of June 29, the manual sowing of common bean cultivars was conducted under millet straw. When sowing common beans, a 0.45-m spacing between rows with 15 seeds per meter was used. In each experimental unit, six rows of common beans at 5 m in length were planted, and the four central rows were considered the usable area, disregarding 0.50 m on each end. As a source of top-dressing N, polymer-coated urea was used and was applied in a continuous thread at 10 cm from the crop line, with an incorporation via water slide by irrigation. The control of weeds, pests, and diseases was conducted with the application of products recommended for the crop. Irrigation was of the conventional sprinkler type. The accumulated water depth was approximately 550 mm.

The experiment was implemented according to a randomized block design (RBD), in a 2 × 9 factorial scheme, with four replications. The first factor consisted of the following cultivars from the carioca commercial group: IAC Imperador, which has a determined growth habit (type I) and an early cycle (75 days from emergence to physiological maturity) and IPR Campos Gerais, with an indeterminate growth habit (type II) and average cycle (85 days from emergence to physiological maturity). The second factor was constituted by N management, as shown in Table 2. The objective of N management was to proportionate grain yield variability in the experiment.

Rhizobium tropici was applied through seed inoculations, on the night before sowing in the M_R, M_{R+Chl}, and $M_{R+Chl+A}$ treatments (Table 2). Foliar application of *Azospirillum brasilense* was performed in the $M_{R+Chl+A}$ management by foliar spraying during the V_4 stage, with a pressurized costal sprayer. An N dose of 90 kg ha^{-1} was adopted according to the recommendation of Bulletin 100 for the class with a high expected response because of the previous cultivation of grasses and the presence of irrigation (AMBROSANO *et al*., 1997).

In the N managements M_{R+Chl}, $M_{R+Chl+A}$, and M_{Chl} (Table 2), a portable chlorophyll meter (ClorofiLOG 1030®, Falker, Porto Alegre, RS, Brazil) was used to define the moment of N top-dressing application, through nitrogen sufficiency index (NSI) monitoring, according to the recommendations of Maia *et al*. (2017). Only an application of 30 kg ha^{-1} was necessary for treatments whose fertilization was determined by the use of a portable chlorophyll meter.

The terrestrial sensor used to obtain the NDVI values was the active canopy sensor GreenSeeker® (Trimble Navigation Limited, Sunnyvale, CA, USA). This sensor is active and automatically generates the NDVI (Equation 1), from the measurement of the spectral responses of the red (650 nm) and near-infrared (770 nm) bands. Data collection with the GreenSeeker was conducted manually, with a passage of 0.5 m above the bean canopy. The four central lines of each plot were measured, generating an average value of 20 to 30 NDVI measurements per plot.

$$NDVI = \frac{\rho nir - \rho r}{\rho nir + p1} \quad (1)$$

Table 1 - Soil physical and chemical attributes in experimental area (0.00-0.20 m) before sowing the common beans

Clay	Silt	Sand	pH	OM	P (resin)	K	Ca	Mg	S	H+Al	CEC	V	Cu	Fe	Mn	Zn
	(g kg^{-1})		($CaCl_2$)	(g dm^{-3})	(mg dm^{-3})				(mmol$_c$ dm^{-3})			%		(mg dm^{-3})		
540	230	230	5.5	25	45	4	22	14	8	16	55.8	72	0.8	25	2.8	0.2

OM = organic matter. CEC = cation exchange capacity. V = base saturation

Table 2 - Description of N managements evaluated and the total quantity of top-dressing nitrogen applied

N management	Description	N applied (kg ha^{-1})
M_C	Control without inoculation and without top-dressing N fertilization	0
M_R	Control inoculated with *Rhizobium tropici* without top-dressing N fertilization	0
M_R+_{Chl}	*R. tropici* + fertilization with 30 kg ha^{-1} of N when NSI < 90%	30
$M_{R+A+Chl}$	*R. tropici* + 30 kg ha^{-1} of N when NSI < 90% + *A. brasilense*	30
M_{Chl}	Fertilization with 30 kg ha^{-1} of N when NSI < 90%	30
M_{45}	45 kg ha^{-1} of N at 37 DAE	45
M_{90}	Recommended dose of 90 kg ha^{-1} of N at 37 DAE	90
M_{135}	135 kg ha^{-1} of N at 37 DAE	135
M_{Ref}	Splitting of 90 kg ha^{-1} of N at 18 DAE + 90 kg ha^{-1} of N at 37 DAE	180

NSI = nitrogen sufficiency index. DAE = days after emergence

Where:

NDVI: normalized difference vegetation index;

ρnir: near-infrared reflectance (770 nm);

ρr: red reflectance (650 nm).

NDVI readings were taken on the dates shown in Table 3. All evaluations were performed in the morning. The phenological scale of beans proposed by Fernández de Córdova, Gepts and López Genes (1986) was adopted.

Each repetition had an average NDVI value (considering an average of 30 values per plot). Before obtaining the average by repetition, the outliers were removed up to a limit of 10% of the total amount of readings per parcel, according to the methodology proposed by Belsley, Kuh and Welch (1980) (Equation 2), considering the values outside the limits proposed as outliers. After determining the average value of each repetition, it was correlated with the grain yield of each plot for analyses by simple linear regressions. The average of soil NDVI values was 0.115 (considering the six evaluations).

$$L = X \pm 2 \times SD \quad (2)$$

Where:

L = NDVI plot limits;

X = NDVI plot average;

SD = Standard deviation.

Harvest was performed by manually uprooting the plants present in two rows of the usable area of each plot. After drying under the sun, these plants were mechanically threshed. To obtain the grain yield, grain moisture was determined in kg ha^{-1}, after standardization to 0.13 kg kg^{-1} on a wet basis.

The average NDVI values obtained per plot per evaluation date were associated with grain yield values for the evaluation of the polynomial models. For the individual models per cultivar, only the NDVI values and productivity of the management of N supply for each cultivar were associated with the fit of the models, generating 36 points for each model. In the case of the general model, all plots with the two cultivars were used for adjustment, totaling 72 points. The quality of fit of the models was assessed by the adjusted coefficient of determination (R^2) (CORNELL; BERGER, 1987) and the root mean squared error (RMSE) (Equation 3). The RMSE was presented only for statistically significant models. The analysis of variance of the models was performed by the F test at 5% probability. Outliers were removed up to a limit of 10% of the original amount of data, according to the methodology proposed by Belsley, Kuh and Welch (1980).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left(Yobs_i - Yest_i\right)^2}{N}} \quad (3)$$

Where:

N = number of occurrences;

$Yobs_i$ = observed values of Y;

$Yest_i$ = estimated values of Y.

Table 3 - Evaluation dates of the normalized difference vegetation index (NDVI) and corresponding phenological stages

Cultivars	DAE					
	22	29	36	43	50	57
IAC Imperador	V3	V4	V4	R5	R6	R7
IPR Campos Gerais	V3	V4	V4	V4	R5	R6

Phenological scale by Fernández de Córdova, Gepts and López Genes (1986). V3 = first completely expanded trifoliate leaf; V4 = third trifoliate leaf completely expanded; R5 = pre-flowering; R6 = full flowering (at least 50% of open flowers); R7 = pod formation. DAE = days after emergence

RESULTS AND DISCUSSION

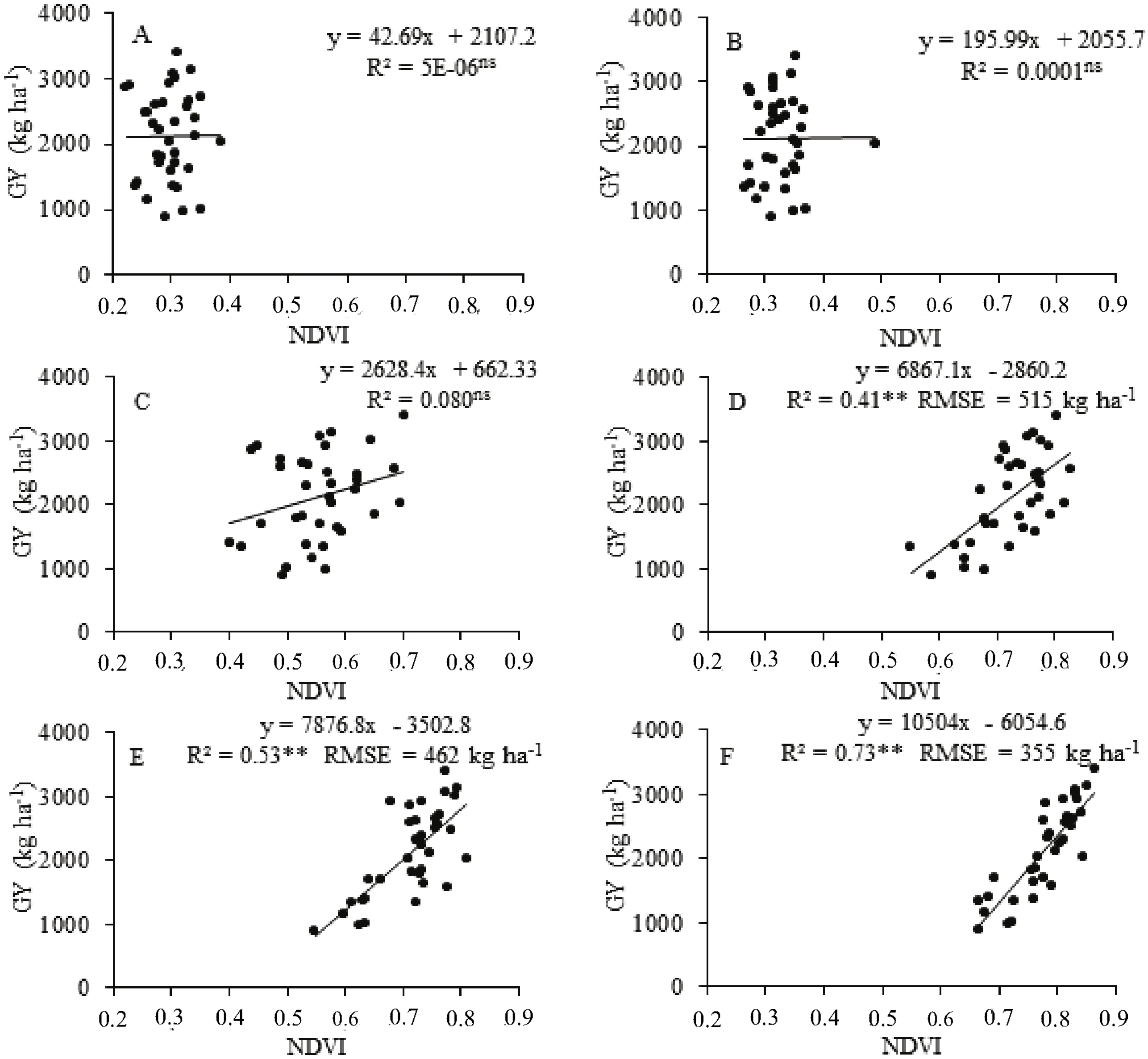
The estimated common bean grain yield was evaluated as a function of the NDVI from individual models, with data from each cultivar, and overall, using the data from the two cultivars in a single model. For the dataset of the present study, the most parsimonious model that best fit was the linear model, regardless of the cultivar and the type of model (individual or general).

For the cultivar IAC Imperador, from the assessment conducted at 43 DAE, the models were significant for estimating the productivity of the beans (Figure 1). The fit of the models increased during the evaluations.

The greatest precision of estimation was obtained in the last evaluation with the NDVI index, performed at 57 DAE (Figure 1F). On this date, precision (R^2 = 0.73) was the highest and error was the lowest (RMSE = 355 kg ha^{-1}), comparing all evaluations. In the last assessment, concerning average grain yield (2,164 kg ha^{-1}), the error was 16%.

For the cultivar IPR Campos Gerais, the precision tended to be similar to that observed in the model for the cultivar IAC Imperador, exhibiting growth throughout the evaluations (Figure 2). The models were significant during the evaluation performed at 43 DAE (Figure 2D), as well as in the cultivar IAC Imperador. In a study with oats, Coelho *et al.* (2020) demonstrated that models generated at more advanced stages of the cycle showed lower error than those generated at earlier stages.

Figure 1 - Fit of the individual models for estimating the grain yield of IAC Imperador as a function of the NDVI vegetation index in the evaluations carried out at 22 (A), 29 (B), 36 (C), 43 (D), 50 (E) and 57 (F) days after crop emergence. GY: grain yield, ns: nonsignificant; * Significant at 5% probability; ** Significant at 1% probability (F test)



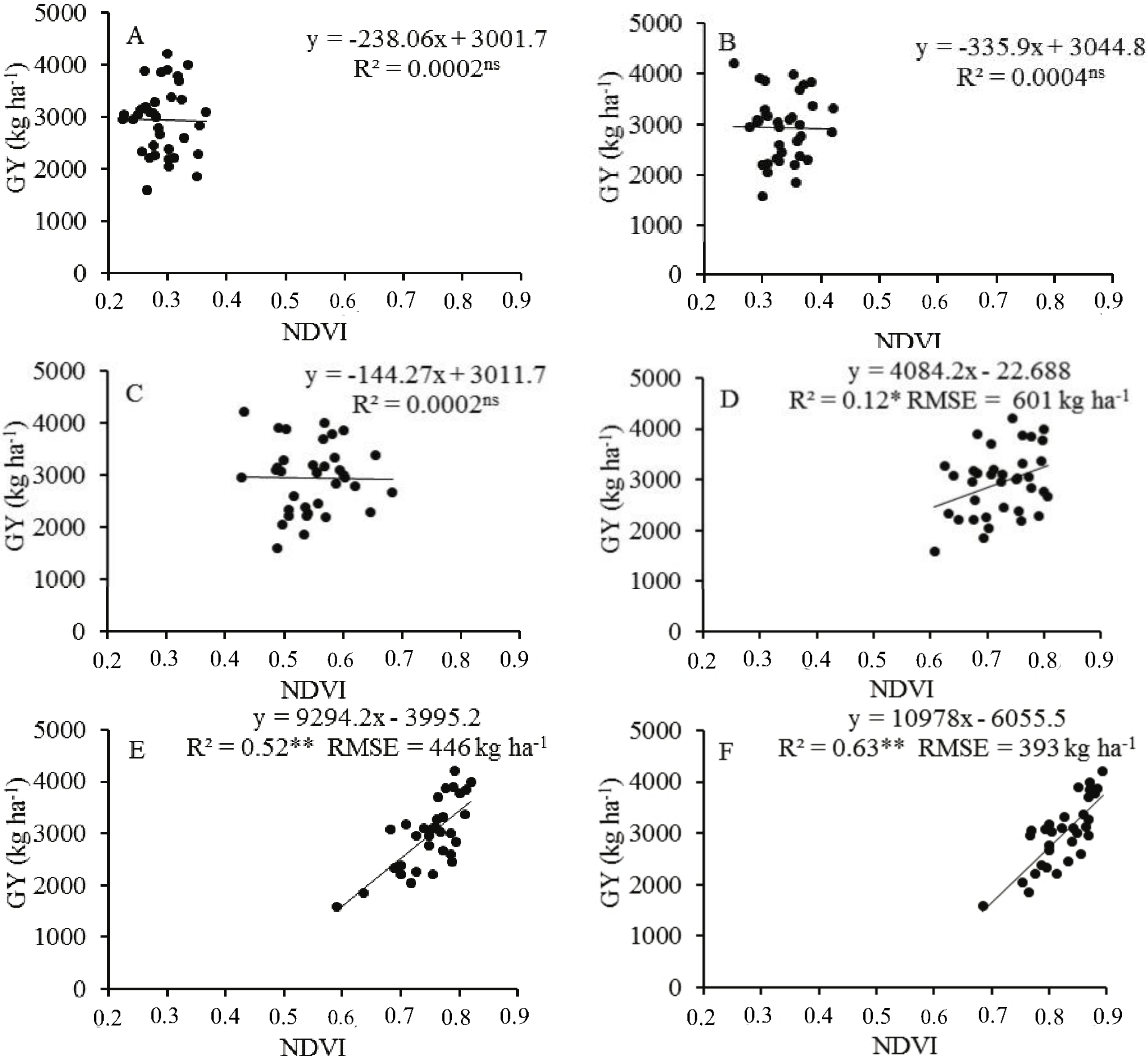
The best fit (R^2 = 0.63; RMSE = 393 kg ha^{-1}) were also observed in the last evaluation at 57 DAE (Figure 2F). In relation to the average, the error in estimating productivity for this cultivar was 13%, a value similar to that observed for the cultivar IAC Imperador (16%).

For the general model (Figure 3), using the data of the two cultivars in the same model, it was also found that during the assessment at 43 DAE, the models were significant for the estimation of grain yield (Figure 3D).

The best fit was obtained in the last evaluation (57 DAE) with an R^2 of 0.78 and an error of 367 kg ha^{-1} (Figure 3F). The error in relation to the average was 14%. Thus, the precision of the general model in estimating the common bean grain yield was similar to that of the individual models and, in some evaluations, even higher. In the case of the last evaluation, the precision of the general model was higher than that of the individual models, regardless of the cultivar, and the percent error was similar between the models.

With an increase in NDVI values, there was an increase in the common bean grain yield. Considering the models fitted in the last evaluation, for each decimal increase (0.1) of the NDVI values, grain yield increased equivalent to 1,050 kg ha^{-1}, 1,098 kg ha^{-1}, and 1,212 kg ha^{-1}

Figure 2 - Fit of the individual models for estimating the IPR Campos Gerais grain yield as a function of the NDVI vegetation index in the evaluations carried out at 22 (A), 29 (B), 36 (C), 43 (D), 50 (E) and 57 (F) days after crop emergence. GY: grain yield, ns: nonsignificant; * Significant at 5% probability; ** Significant at 1% probability (F test)

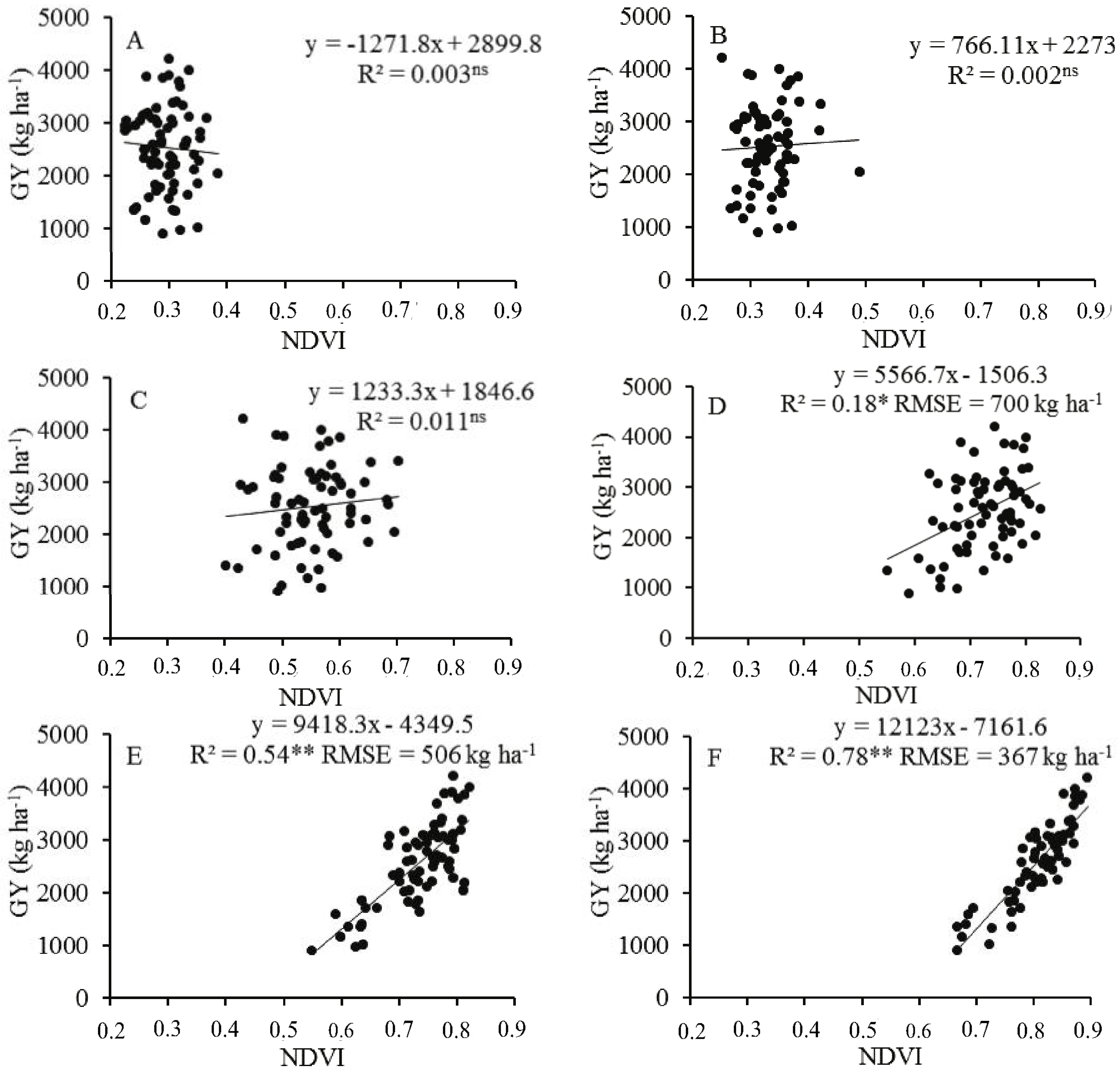


for the individual models of the cultivars IAC Imperador (Figure 1F) and IPR Campos Gerais (Figure 2F) and the general model (Figure 3F), respectively. These values were very close, confirming the similarity of the fit of the individual models with that of the general model.

Evaluating the variation of the average NDVI values as a function of time for the individual and general models, a similar trend was observed among all models (Figure 4). For the individual models of the cultivars IAC Imperador and IPR Campos Gerais and the general model, the NDVI values stabilized at 53, 54, and 54 DAE, respectively. The maximum values found for the cultivars IAC Imperador and IPR Campos Gerais and for the general model were 0.78, 0.83, and 0.81, respectively.

The best fit for all models was observed in the last evaluations conducted after the flowering of the cultivars (Figures 1F, 2F, and 3F). The best fit occurred for the evaluation at 57 DAE when the IAC Imperador cultivar was at the R7 phenological stage (pod formation) and the IPR Campos Gerais cultivar was at the R6 stage (full flowering). In a study with another bean cultivar with a normal cycle (Pérola), Monteiro *et al*. (2012) also obtained higher R^2 in the R6 phenological stage. Thus, it was observed that even though the cultivars were in

Figure 3 - Fit of the general model for estimating the bean yield, using both cultivars, as a function of the NDVI vegetation index in the evaluations performed at 22 (A), 29 (B), 36 (C), 43 (D), 50 (E) and 57 (F) days after crop emergence. GY: grain yield, ns: nonsignificant; * Significant at 5% probability; ** Significant at 1% probability (F test)

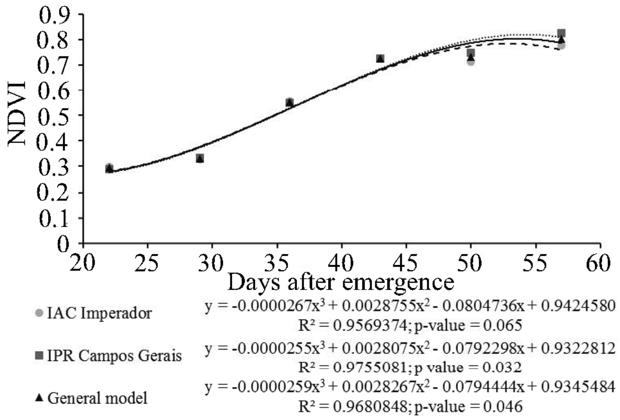


different phenological stages, the general model estimated the productivity of the beans with great precision. This demonstrated the high capacity of this model for the estimation of productivity from the flowering of the culture.

In later phenological stages, the plants were nearing their maximum vegetative development, and their growth was dependent on the availability of existing resources (light, water, and nutrients). As the NDVI is influenced by the leaf area and the chlorophyll content in the leaves, plants with a larger leaf area and chlorophyll content have a higher NDVI (COELHO *et al*., 2019; YANG *et al*., 2017).

At the beginning of crop development, the need for resources of the plants is low, with no differences in their growth in relation to the places with greater availability of resources, specifically N, justifying the low precision of estimates of the models at the beginning of the common bean development (SANDRINI *et al*., 2019). SANDRINI *et al*. (2019) evaluated early common bean grain yield estimation, cultivated under doses of N, as a function

Figure 4 - Temporal variation of average NDVI values for individual and general models



of the NDVI and inverse ratio vegetation index (IRVI) and observed a maximum precision of estimation in the R8 (grain filling) phenological stage. Additionally, the authors observed that until the phenological stage R5, the models were not significant in the estimation of crop yield. According to Casa and Castrignanò (2008), the spatial variability in the spectral index values was lower in more advanced stages of the crop cycle, indicating a greater precision of models in more advanced phenological stages.

After flowering (R6), the common bean has a lower rate of nutrient absorption (SORATTO *et al*., 2013); thus, the chance of plant recovery because of biotic and abiotic stresses after flowering is lower, especially for cultivars with a determined growth habit (type I). Furthermore, in later stages, the time available before harvesting for the occurrence of diseases and invasion of pests is lesser than that when the plant is in the early stages. This leads to greater reliability of NDVI readings taken after the flowering of crops because the values reflect the edaphoclimatic conditions that the plants were subjected to during a large part of the cycle (CASA; CASTRIGNANÒ, 2008; COELHO *et al*., 2019).

It was verified for the individual model of the IAC Imperador cultivar that the model's fit of the evaluation at 43 DAE (Figure 1D) was greater than that of the same evaluation of the model for the cultivar IPR Campos Gerais (Figure 2D). As the IAC Imperador cultivar has an early cycle, at 43 DAE, it was in the final phenological stage R5 (appearance of flower buds) and close to full flowering, whereas the cultivar IPR Campos Gerais was at the end of the vegetative phenological stage V4. Thus, in this assessment, the demand for resources of the IAC Imperador cultivar was greater, presenting greater growth variability as a result of treatments, than that of the IPR Campos Gerais cultivar, leading to greater sensitivity of NDVI in detecting areas with greater and lesser growth (CASA; CASTRIGNANÒ, 2008).

The variability of NDVI values as a function of treatments under N fertilization is small (SANDRINI *et al*., 2019). Sandrini *et al*. (2019) observed variation of only 0.05 in NDVI values between treatments without N fertilization and with N application (129 kg ha^{-1} of N), which generated the highest NDVI value. However, even though the variability was low, it was observed that the models were precision in estimating common bean grain yield, indicating the high sensitivity of the NDVI in detecting minimal differences in plant growth when subjected to different N fertilization conditions.

The use of models with a high generalization capacity in the estimation of agronomic and soil attributes in agriculture is always desirable. With the definition of general models with high estimation precision, there is no need to fit models for each situation, such as by cultivar, soil type, and plant density. In the present study, the use of a general model to estimate the grain yield of common bean cultivars with different growth habits showed fit similar to that of the individual models per cultivar.

Grohs *et al*. (2009) evaluated the accuracy of models for estimating the yield potential of wheat and barley as a function of NDVI and observed an absence of an effect for both species and cultivars, allowing the use of a general model for these agricultural species. For N fertilization at a variable rate in wheat, Vian *et al*. (2018) observed that NDVI was viable for management, regardless of the cultivar used. To estimate corn production in Kenya, Lewis, Rowland and Nadeau (1998) concluded that the estimation model based on NDVI showed national applicability, with no need for model fit for each geographic region of the country. Factors such as soil and plant residues influence NDVI value (TRINDADE *et al*., 2019). Thus, there is a need to acquire a database involving different conditions, such as soil, climate, cultivars, and crop systems, for the development of more robust general models for predictive capacity, as observed in the present study with the use of bean cultivars with different growth habits.

Regarding NDVI variation as a function of time (Figure 4), it was observed that the IAC Imperador cultivar with a determined growth habit, presented a maximum NDVI value (0.78) that was lower than that of IPR Campos Gerais (0.83) having an indeterminate growth habit. This occurred because the IAC Imperador cultivar has an early cycle; precisely, it does not present leaf and branch emissions after the beginning of the reproductive phase, unlike the IPR Campos Gerais cultivar. As a result, this cultivar has a higher number of leaves, directly interfering with the NDVI values.

The stabilization of NDVI values occurred from 53 and 54 DAE for the IAC Imperador and IPR Campos Gerais cultivars, respectively (Figure 4). This information could be used as a criterion for the definition of the best evaluation date for the bean culture because this maximum value may indicate the stabilization of crop growth and the saturation of the NDVI index (CAO *et al*., 2017; HASSAN *et al*., 2019; LUMBIERRES *et al*., 2017). Thus, from the 53 DAE evaluations with the NDVI, greater fit was generated in the estimation of common bean grain yield. After this period, the plants exhibit little growth, and the accumulated biomass is proportional to the edaphoclimatic conditions maintained during the cycle, generating spatial variability of NDVI values as a function of the conditions in which the plants grew (HASSAN *et al*., 2019; LUMBIERRES *et al*., 2017). Additionally, from a given leaf area index, the NDVI may show saturation and not increase in value with the increase in crop biomass (CAO *et al*., 2017).

CONCLUSIONS

The results found in the present study may assist producers and technicians in estimating the common bean grain yield, indicating the phenological stages with greater precision. A single model can be applied to more than one cultivar and presents a precision similar to that of the individual models per cultivar. Thus, activities such as harvest management, crop forecasting, and definition of agricultural management can be conducted based on the evaluation of beans with the NDVI. The common bean grain yield can be estimated with high precision as a function of the NDVI, obtaining an R^2 of up to 78% and an average error close to 350 kg ha^{-1}. The greatest fit of estimation was obtained in the phenological reproductive stages of the common bean, especially after crop flowering (R6). Additionally, general models composed of data from more than one cultivar present similar accuracy and, in some cases, are superior to the fitted models for each cultivar, demonstrating the feasibility of using the same model for several genotypes.

REFERENCES

AMBROSANO, E. J. *et al*. Feijão. In: RAIJ, B. V. *et al*. Recomendação de adubação e calagem para o Estado de São Paulo. 2. ed. Campinas: Instituto Agronômico, 1997. cap. 19, p. 194-195. (Boletim técnico, 100)

BELSLEY, D. A.; KUH, E.; WELCH, R. E. **Regression diagnostics**: identifying data and sources of collinearity. New York: John Wiley & Sons, 1980. 292 p.

CAO, Z. *et al*. A new three-band spectral index for mitigating the saturation in the estimation of leaf area index in wheat. International. **Journal of Remote Sensing**, v. 38, n. 13, p. 3865-3885, 2017.

CASA, R.; CASTRIGNANÒ, A. Analysis of spatial relationships between soil and crop variables in a durum wheat field using a multivariate geostatistical approach. **European Journal of Agronomy**, v. 28, n. 3, p. 331-342, 2008.

COELHO, A. P. *et al*. Estimation of irrigated oats yield using spectral indices. **Agricultural Water Management**, v. 223, 105700, 2019.

COELHO, A. P. *et al*. Validation of white oat yield estimation models using vegetation indices. **Bragantia**, v. 79, n. 2, p. 236-241, 2020.

COMPANHIA NACIONAL DE ABASTECIMENTO (BRASIL). **Acompanhamento da safra brasileira de grãos**: safra 2020/2021: quarto levantamento. Brasília, DF: CONAB, 2021. 85 p.

CORNELL, J. A.; BERGER, R. D. Factors that influence the value of the coefficient of determination in simple linear and nonlinear regression models. **Phytopathology**, v. 77, n. 1, p. 63-70, 1987.

DAMIAN, J. M. *et al*. Applying the NDVI from satellite images in delimiting management zones for annual crops. **Scientia Agricola**, v.77, n. 1, e20180055, 2020.

FERNÁNDEZ DE CÓRDOVA, F.; GEPTS, P. L.; LÓPEZ GENES, M. **Etapas de desarrollo de la planta de frijol comúm (*Phaseolus vulgaris* L.)**. Cali: CIAT, 1986. 33 p.

GROHS, D. S. *et al*. Modelo para estimativa do potencial produtivo em trigo e cevada por meio do sensor GreenSeeker. **Engenharia Agrícola**, v. 29, n. 1, p. 101-112, 2009.

GUAN, S. K. *et al*. Assessing correlation of high-resolution NDVI with fertilizer application level and yield of rice and wheat crops using small UAVs. **Remote Sensing**, v. 11, n. 2, p. 112, 2019.

HASSAN, M. A. *et al*. A rapid monitoring of NDVI across the wheat growth cycle for grain yield prediction using a multi-spectral UAV platform. **Plant Science**, v. 282, p. 95-103, 2019.

LEWIS, J. E.; ROWLAND, J.; NADEAU, A. Estimating maize production in Kenya using NDVI: some statistical considerations. **International Journal of Remote Sensing**, v. 19, n. 13, p. 2609-2617, 1998.

LI, T. *et al*. Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. **Global Change Biology**, v. 21, n. 3, p. 1328-1341, 2015.

LUMBIERRES, M. *et al*. Modeling biomass production in seasonal wetlands using MODIS NDVI land surface phenology. **Remote Sensing**, v. 9, n. 4, p. 392, 2017.

MAIA, S. C. M. *et al*. Criteria for topdressing nitrogen application to common bean using chlorophyll meter. **Pesquisa Agropecuária Brasileira**, v. 52, n. 7, p. 512-520, 2017.

MONTEIRO, P. F. C. *et al*. Assessing biophysical variable parameters of bean crop with hyperspectral measurements. **Scientia Agricola**, v. 69, n. 2, p. 87-94, 2012.

SANDRINI, F. D. O. T. *et al*. Índices de vegetação na estimativa da produtividade do feijoeiro cultivado sob doses de nitrogênio. **Revista Brasileira de Ciências Agrárias (Agrária)**, v. 14, n. 4, e7310, 2019.

SANTOS, H. G. *et al*. **Sistema brasileiro de classificação de solos**. 5. ed. Brasília, DF: Embrapa, 2018. 356 p.

SOIL SURVEY STAFF. **Soil taxonomy**. 12. ed. Washington, DC: USDA, 2014. 360 p.

SORATTO, R. P. *et al*. Nutrient extraction and exportation by common bean cultivars under different fertilization levels: I-macronutrients. **Revista Brasileira de Ciência do Solo**, v. 37, n. 4, p. 1027-1042, 2013.

SOUZA, A. M. *et al*. Most consumed food in Brazil: National Dietary Survey 2008-2009. **Revista Saúde Pública**, v. 47, p. 190s-199s, 2013. Supplement 1.

TRINDADE, F. S. *et al*. Relação espectro-temporal de índices de vegetação com atributos do solo e produtividade da soja. **Revista de Ciências: Agrárias Amazonian Journal of Agricultural and Environmental Sciences**, v. 62, 2019.

VIAN, A. L. *et al*. Nitrogen management in wheat based on the normalized difference vegetation index (NDVI). **Ciência Rural**, v. 48, n. 9, e20170743, 2018.

YANG, H. *et al*. Seasonal variations of leaf and canopy properties tracked by ground-based NDVI imagery in a temperate forest. **Scientific Reports**, v. 7, p. 1267, 2017.