Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43n6e20230136/2023

MODEL FOR INDICATION OF NITROGEN FERTILIZATION IN WHEAT USING VEGETATION SENSOR

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KEYWORDS

Algorithm, Fertilization management, *Triticum aestivum* L. NDVI

ABSTRACT

Adjustments in the nitrogen fertilization recommendation in wheat fields are essential to promote an increase in nitrogen (N) use efficiency by the crop. The real-time estimation of the nutritional demand of plants considering the spatial variability is one of the efficient ways to perform this adjustment. This study aimed to develop a model for the indication of topdressing nitrogen fertilization as a function of nutritional N demand using NDVI. Data from field experiments conducted in four regions of the State of Rio Grande do Sul, Brazil, during the 2015, 2017, 2018, and 2019 agricultural years using cultivars with significant sowing areas in the state, were used to construct the model. The analysis of the relationship between the amounts of N accumulated in the shoot and NDVI values allowed establishing a single model for different cultivars. The proposed model is sensitive to capturing regional edaphoclimatic differences and variability in N dynamics in cultivated areas. A consistent relationship was found between NDVI values and biomass and N content, which supported the generation of the topdressing N indication model for wheat. Therefore, the proposed model has the potential to maximize N use and grain yield, in addition to optimizing the economic return of the crop.

INTRODUCTION

The indication of nitrogen (N) fertilization doses for wheat in the states of Rio Grande do Sul (RS) and Santa Catarina (SC), in southern Brazil, is defined as a function of soil organic matter content, predecessor crop, and grain yield expectation (Reunião…, 2020). This way of defining the N dose to be applied, although consolidated in practice, disregards the spatial variability of plant growth in the field and the dynamics of nitrogen availability throughout the growing season, which is influenced by soil type, organic matter mineralization, relief variations, variability in straw distribution from the predecessor crop, weather conditions, among others (Drum et al., 2018). In this sense, there is room for improving the topdressing nitrogen fertilization methodology in wheat by incorporating, for example, precision agriculture tools.

Increasing N use efficiency in wheat by adjusting nitrogen fertilization according to the nutritional demand of plants and grain yield expectation, considering the spatial variability of plant growth, is a viable way to obtain productive and sustainable gains in agriculture, with a reduction in N losses to the environment (Vian et al., 2018). Some models to recommend the topdressing nitrogen dose as a function of the nutritional demand of plants have been developed so that variable rate applications could become a reality. These models consider variables such as soil N availability, weather conditions, crop development stage, leaf chlorophyll content, nutritional demand, and yield

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Area Editor: Teresa Cristina Tarlé Pissarra
Received in: 10-4-2023
Accepted in: 11-7-2023

potential (Raun et al., 2005; Shanahan et al., 2008; Holland & Schepers, 2013; Torres-Dorante, 2016; Padilla et al., 2018). However, the difficulty in working with the numerous variables necessary to enable the use of the algorithms generated the need to develop simpler models for field application. Thus, the implementation and use of the models are related to their ease of use, in addition to being calibrated and validated for the different edaphoclimatic conditions of the South region of Brazil.

Some studies on sugarcane, cotton, and corn have been developed under the edaphoclimatic conditions of the Brazilian Cerrado (Rosa et al., 2015; Terpley et al., 2000). However, these models do not have the same performance in crops in the South region. Thus, this study aimed to develop a model to indicate the topdressing nitrogen fertilization dose in wheat as a function of the nutritional N demand of the plant, using the Normalized Difference Vegetation Index (NDVI).

MATERIAL AND METHODS

The experiments for the development of the model to indicate the topdressing N dose to be applied to wheat were conducted under field conditions in 2015, 2017, 2018, and 2019 in four municipalities of the State of Rio Grande do Sul, southern Brazil: Coxilha and Vacaria, belonging to the Homogeneous Region of Cultivar Adaptation 1 (RHACT 1), considered cold and humid, and Eldorado do Sul and Três de Maio, belonging to RHACT 2, considered moderately hot and humid (Reunião…, 2020) (Figure 1).

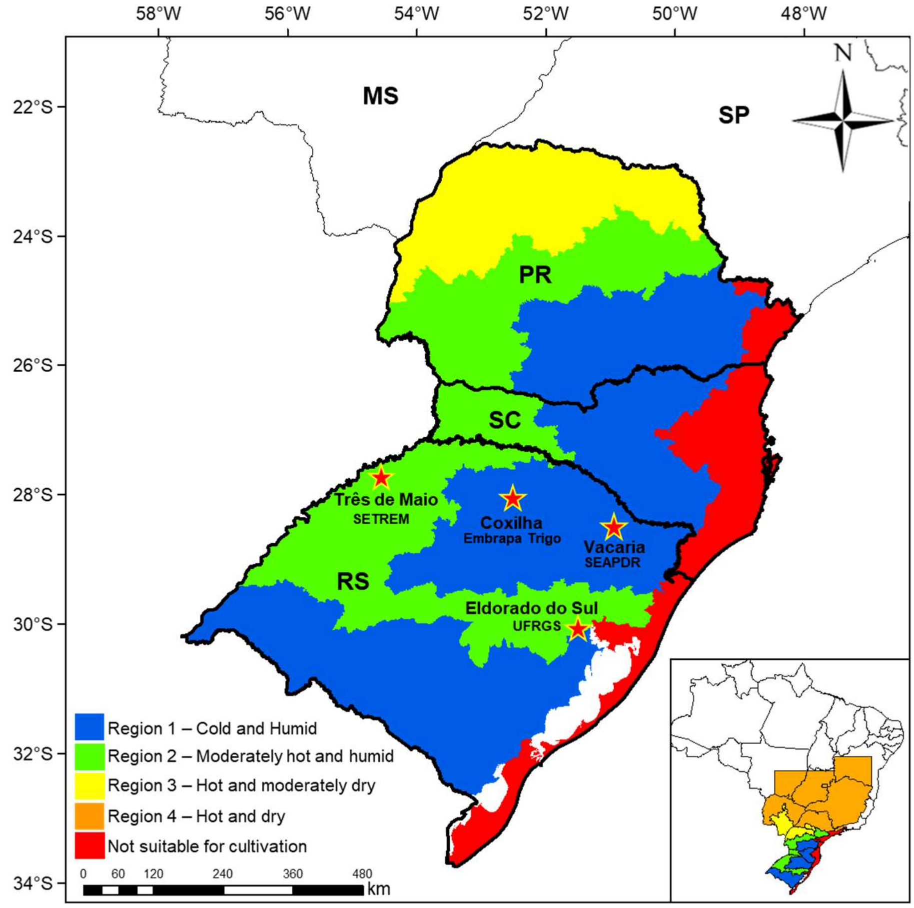

FIGURE 1. Location of the field experiments in four municipalities of the State of Rio Grande do Sul (markers in red).

Edaphoclimatic characteristics

RHACT 1 encompasses the experimental sites belonging to the Brazilian Agricultural Research Corporation (EMBRAPA - National Research Center for Wheat), in Coxilha (RS), and the Secretariat of Agriculture, Livestock, and Rural Development of Rio Grande do Sul State (SEAPDR), in Vacaria (RS), located in the physiographic regions Planalto Médio and Campos de Cima da Serra, respectively (Silva et al., 2015). The climate is subtropical with a hot humid summer (Cfa) in Coxilha and subtropical with a mild summer (Cfb) in Vacaria, according to the Köppen classification (INMET, 2016) (Table 1). RHACT 2 encompasses the Agricultural Experimental Station of the Federal University of Rio Grande do Sul (EEA/UFRGS), in Eldorado do Sul (RS), and the experimental area of the Três de Maio Educational Society (SETREM), in Três de Maio (RS), located in the physiographic regions Depressão Central and Missões, respectively. The climate in both locations is subtropical with a hot humid summer (Cfa) (INMET, 2016) (Table 1).

TABLE 1. Description of the main edaphoclimatic characteristics in the regions where the experiments were carried out.

Municipality (Institution)	Rainfall[1] (mm)	Soil type in the experimental area[2]	Average temperature[3] (°C)		Altitude (m)
			Minimum	Maximum	
Coxilha (Embrapa Wheat)	1.788	Rhodic Ferritic Ferralsol	12.9	22.0	689
Vacaria (SEAPDR)	1.800	Humbric Ferritic Ferralsol	7.3	25.6	955
Eldorado do Sul (EEA/UFRGS)	1.440	Rhodic Acrisol	14.0	25.0	46
Três de Maio (SETREM)	1.725	Rhodic Ferralsol	15.0	25.8	343

[1]Average annual rainfall (Period 1991–2010). [2]According to the classification proposed by Streck et al. (2008). [3]Average annual air temperature in the coldest (minimum) and hottest (maximum) months (Period 1991–2010) (INMET, 2016).

Description of treatments and evaluated parameters

The treatments consisted of different wheat cultivars and topdressing N application strategies. The experiments were conducted in a randomized block experimental design with split plots and four replicates. The cultivars were allocated in the main plots, while topdressing N application strategies were allocated in the subplots. The experimental unit consisted of ten rows of 3.0 m in length with row spacing of 0.17 m, totaling 5.1 m^2.

Six cultivars were used, with variations depending on the year and location (Table 2), all of which are indicated for cultivation in RHACT 1 and 2 (Table 2). The criterion for choosing the cultivars was based on the representativeness in the cultivated area in southern Brazil in the different years of the experiments.

TABLE 2. Description of the main agronomic characteristics of the wheat cultivars used in the experiments (Reunião…, 2020).

Cultivar	Cycle (Days)	Plant height	Experiment (Institution)	Growing season
BRS Parrudo	135	Medium	Embrapa Wheat[1], SEAPDR[2] UFRGS[3], SETREM[4]	2017, 2018, 2019
BRS Marcante	133	Medium	Embrapa Wheat[1], SEAPDR[2]	2018
TBIO Sossego	130	Medium	Embrapa Wheat[1], SEAPDR[2] UFRGS[3], SETREM[4]	2017, 2018
TBIO Toruk	145	Low	UFRGS[3]	2015, 2019
TBIO Sinuelo	150	Medium	UFRGS[3]	2015
TBIO Sintonia	128	Medium	UFRGS[3]	2015

[1]Embrapa Wheat – Coxilha (RHACT 1); [2]SEAPDR – Vacaria (RHACT 1); [3]UFRGS – Eldorado do Sul (RHACT 2); [4]SETREM – Três de Maio (RHACT 2).

The topdressing N application strategies in the subplots consisted of the application of different nitrogen doses (0, 15, 30, 45, and 60 kg N ha^{-1}) at plant emergence, with urea as nitrogen source (45% N). The topdressing N dose was applied at the stage of six fully expanded leaves in each subplot, adjusted according to the model indicated below.

The application of different N doses at plant emergence had the purpose of promoting variability in plant development, changing the shoot biomass production and the amount of N uptake at the stage of six fully expanded leaves to simulate the variability found in commercial fields, thus creating different potential N demands on plants.

The experiments were carried out under a no-tillage system after soybean cultivation, as it is the crop that most frequently precedes wheat in the South region of Brazil. Sowing was carried out at the beginning of the period indicated by the Agricultural Zoning of Climate Risk for each location, at a density of 300 viable seeds per m^2. The phosphorus and potassium fertilization at sowing followed the technical indications for wheat cultivation for yield potential of 5,000 kg ha^{-1} (Reunião…, 2016). Soil samples were collected before setting up the field experiments to support phosphate and potassium fertilization recommendations based on the chemical characterization of the areas (Appendix 1).

The Normalized Difference Vegetation Index (NDVI), biomass production and shoot N accumulation were evaluated at the stage of six fully expanded leaves. NDVI evaluation was performed by reading the canopy reflectance with a GreenSeeker® active optical sensor (Trimble, Sunnyvale, CA, USA). The readings were taken at the central rows of the plot with the equipment positioned parallel to the crop rows, 0.8 m above the canopy. The NDVI is calculated according to [eq. (1)].

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R}) / (\mathrm{NIR} + \mathrm{R}) \tag{1}$$

in which:

R - reflectance in the red (680 ± 10 nm);

NIR - reflectance in the near-infrared region (770 ± 15 nm).

The shoot biomass was quantified by sampling three sowing rows with 0.5 m in length, totaling 0.27 m^2. Subsequently, the samples were dried in a forced-air oven at a temperature of 60 °C until a constant weight is reached and then weighed. Afterward, N concentration was quantified in the plant tissue, following the Kjeldahl method (Tedesco et al., 1995). The amount of N accumulated in the shoot was evaluated by multiplying the shoot dry biomass by the N concentration in the tissue, expressed in kg N ha^{-1}.

Development of the topdressing nitrogen fertilization indication model

The model proposed in this study was developed considering the nutritional nitrogen demand by the wheat crop at the stage of six fully expanded leaves of the scale proposed by Haun (1973), stage 3 of the scale proposed by Large (1954), and stage 23 of the scale proposed by Zadoks et al. (1974). This stage marks the beginning of the previous period of higher N demand by the plant, which can be more easily identified using vegetation indices and topdressing nitrogen fertilization can be recommended (Bredemeier & Mundstock, 2001).

The "ideal" N uptake curve by the wheat crop was considered to obtain a high grain yield, as proposed by Wiethölter (2011). This curve is characterized by the high N uptake between the stages of internode elongation and heading, reaching the maximum uptake close to 100 days after plant emergence (Figure 2).

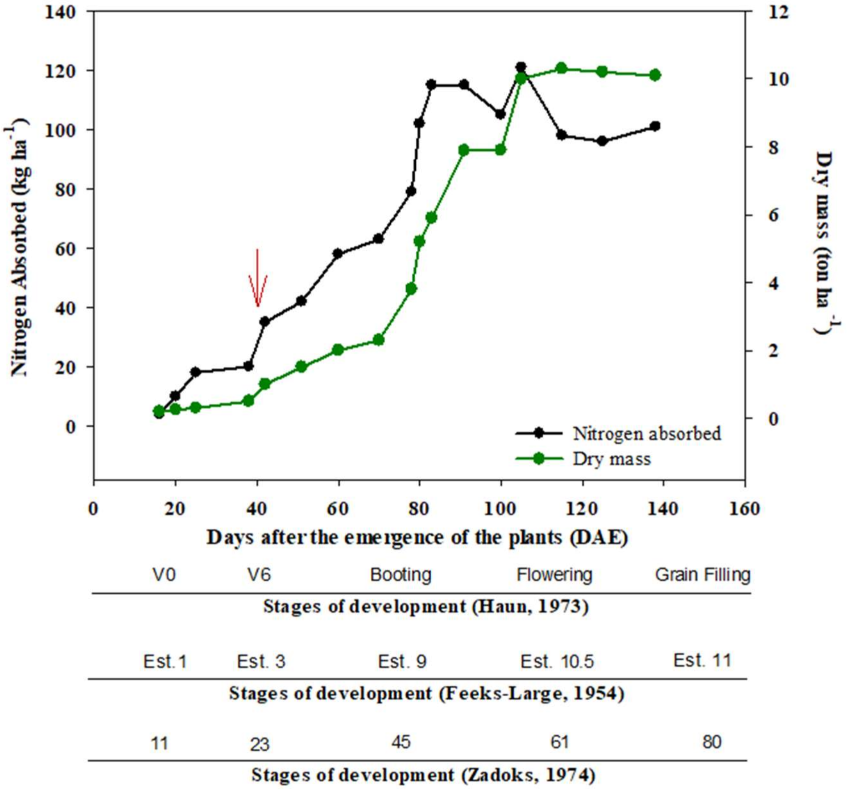

FIGURE 2. Nitrogen uptake and shoot biomass production curve for wheat at different phenological stages (adapted from Wiethölter, 2011). The red arrow indicates the amount of nitrogen uptake at the stage of six fully expanded leaves.

Nitrogen absorbed (kg ha^{-1}); Dry mass (t ha^{-1}); Days after plant emergence (DAE).

Wheat plants need to accumulate approximately 35 kg N ha^{-1} in the shoot tissues at the stage of six fully expanded leaves to achieve a grain yield close to 5,000 kg ha^{-1} (Figure 2). Thus, the proposed model aims to indicate the topdressing N dose indicated by the Brazilian Wheat and Triticale Research Commission for RHACT 1 (100 kg N ha^{-1}) and RHACT 2 (80 kg N ha^{-1}) (Reunião…, 2020) plus the amount of missing N or reduction of the excess amount relative to the standard of 35 kg N ha^{-1}, which will be estimated by reading NDVI and predicted by the validated models for the experiments. Equation (2) must be followed to indicate the dose to be used in commercial areas.

$$\text{Indicated topdressing N dose (kg ha}^{-1}\text{)} = 35 - \text{[N] uptake} + \text{Standard} \quad (2)$$

in which:

35 - standard amount of N (kg ha^{-1}) that the plant must have accumulated in the shoot up to the stage of six fully expanded leaves;

[N] uptake - the actual amount of N accumulated in a given location/year (kg ha^{-1}),

Standard - the topdressing N dose indicated by the Brazilian Wheat and Triticale Research Commission (2020), estimated, for example, at 80 kg ha^{-1} for RHACT 2 and 100 kg ha^{-1} for RHACT 1 for a grain yield potential of 5,000 kg ha^{-1}.

The steps for constructing the model were as follows: 1 – generation of the variability of N uptake by plants up to the stage of six fully expanded leaves; 2 – normalized difference vegetation index (NDVI) readings with a vegetation sensor; and 3 – quantification of tissue N content and the amount of N uptake by plants.

Statistical analysis

The data were subjected to analysis of variance using the F-test and, subsequently, regression analysis between the analyzed variables at the level of $p<0.05$, using the SAS$^{\text{TM}}$ statistical package (Statistical Analysis System – SAS 8.0).

RESULTS AND DISCUSSION

Figure 3 shows the relationship between shoot dry biomass and NDVI values at the stage of six fully expanded leaves. The values of dry biomass increase as NDVI values increase ($R^2 = 0.65$), with r^2 values similar to those found by Vian et al. (2018) when working with wheat using vegetation sensors. The values of shoot dry biomass ranged from 185 to 1,190 kg ha^{-1}, while NDVI values varied between 0.26 and 0.78, respectively (Figure 3).

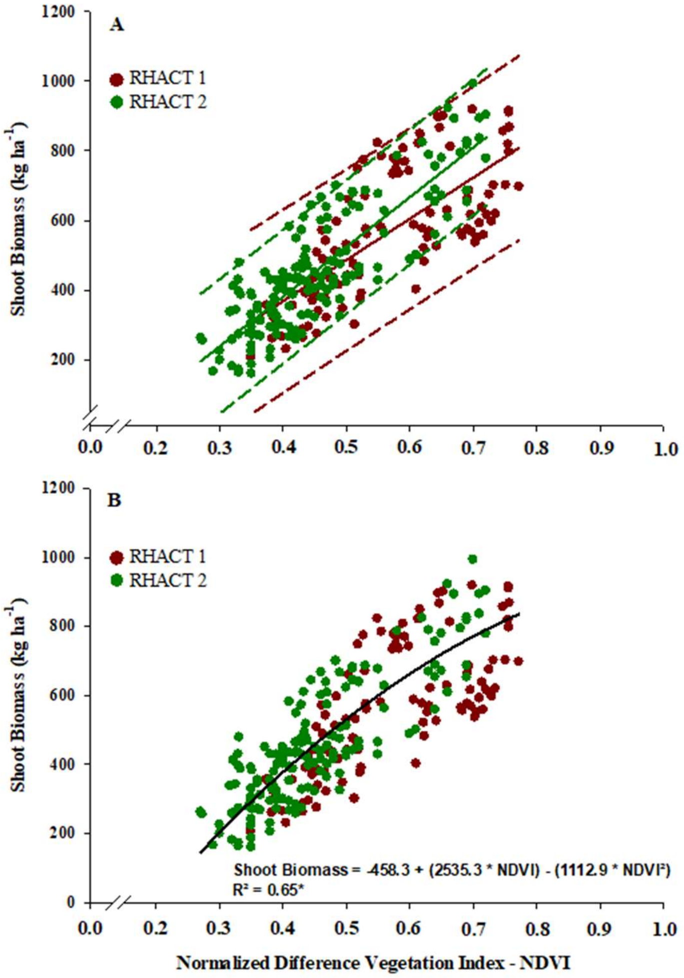

FIGURE 3. Relationship between shoot biomass in two homogeneous regions of adaptation of wheat cultivars in the South of Brazil (wheat cultivation regions RHACT 1 – red and RHACT 2 – green) with normalized difference vegetation index (NDVI) using different nitrogen doses and seasons at the stage of six fully expanded leaves. The behavior of the relationship between shoot biomass and NDVI in different regions considering the confidence interval at 95% probability (A). Proposed model for estimating shoot biomass using NDVI (B). *Significant $p<0.05$.

Shoot biomass production is important in wheat, as it is responsible for its photosynthetic rate. The amount of shoot biomass of wheat is highly related to the amounts of N available to plants, when collected at the stage of six fully expanded leaves, in addition to showing a consistent relationship with NDVI values (Li et al., 2018; Vian et al., 2018).

The variation in biomass production and, consequently, N accumulation in plant tissues can be indirectly estimated using vegetation sensors, which show a vegetation index, such as NDVI. This vegetation index is formed by two wavelengths, red and near-infrared. The higher N availability for plants provides higher photosynthetically active biomass accumulation. Thus, there is a higher reflectance in the infrared and higher absorption of radiation in the red due to the concentration of chlorophylls and an increase in NDVI values (Coelho et al., 2018).

Moreover, the amount of N accumulated in the shoot is related to soil N availability because changes in soil N availability (e.g., nitrate, nitrite, and ammonia) lead to a variation in the amount of N uptake and accumulated in the plant canopy (Meng et al., 2013; Carvalho et al., 2016). A single regression model could represent the relationship between the amounts of N accumulated in the shoot and NDVI values for the studied cultivars. The relationship between the amount of N accumulated and NDVI is high (Figure 4), with increased values of the amount of N accumulated in the shoot as NDVI values increased. The values of accumulated N ranged from 5 to 45 kg N ha^{-1}, whereas NDVI values varied between 0.26 and 0.78, respectively (Figure 4).

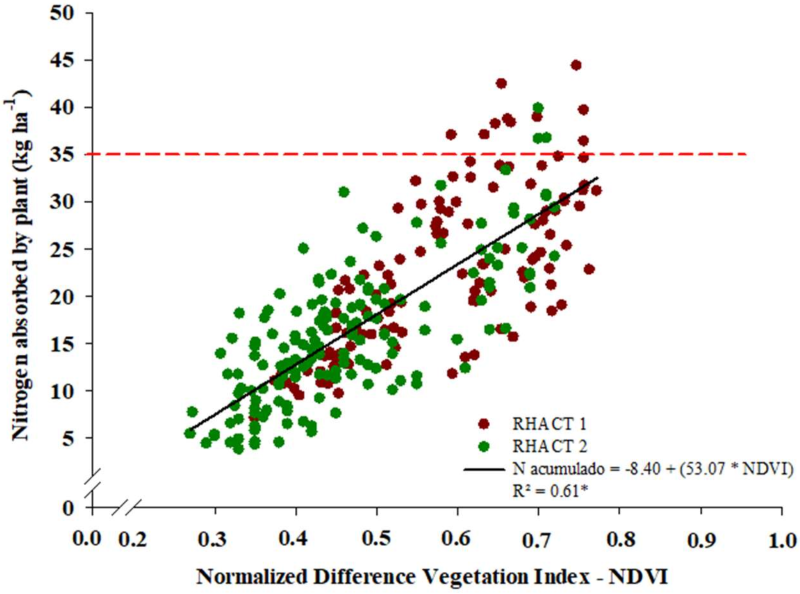

FIGURE 4. Relationship between the amount of nitrogen uptake in the aboveground wheat biomass and the normalized difference vegetation index (NDVI) as a function of nitrogen doses applied during the crop sowing. The red dashed line indicates the necessary nitrogen concentration that the crop needs to absorb (kg N ha^{-1}) up to the stage of six fully expanded leaves. *Significant at $p<0.05$. Wheat cultivation regions in the South of Brazil (RHACT 1 – red and RHACT 2 – green). Nitrogen absorbeb by plants (kg ha^{-1}).

The red dashed line shown in Figure 4 indicates the minimum amount of nitrogen accumulated in the shoot the plants at the stage of six fully expanded leaves, aiming at obtaining a high grain yield. The estimate of N balance in the plant was based on [eq. (3)]:

N balance in the plant = 35 kg of N ha^{-1} − N accumulated in the tissue (kg N ha^{-1}) (3)

in which:

35 - standard amount of N (kg ha^{-1}) that the plant must have accumulated in the shoot up to the stage of six fully expanded leaves,

N accumulated in the tissue (kg ha^{-1}) - estimated by the mathematical model $y = -8.40 + 53.07*NDVI$, as shown in Figure 4.

The optical canopy sensors can perform the real-time estimation of the N content in the tissue with an adequate precision level. This tool enables the real-time estimation of the shoot N uptake throughout the crop growth cycle. Figure 5 shows the values of N demand by the crop, with the lowest NDVI values being associated with the highest demands, that is, around 30 kg N ha^{-1} (deficient nutrition), while the highest NDVI values are associated with lower demands, around 0 kg N ha^{-1}, or even negative values (adequate or even excess nutrition).

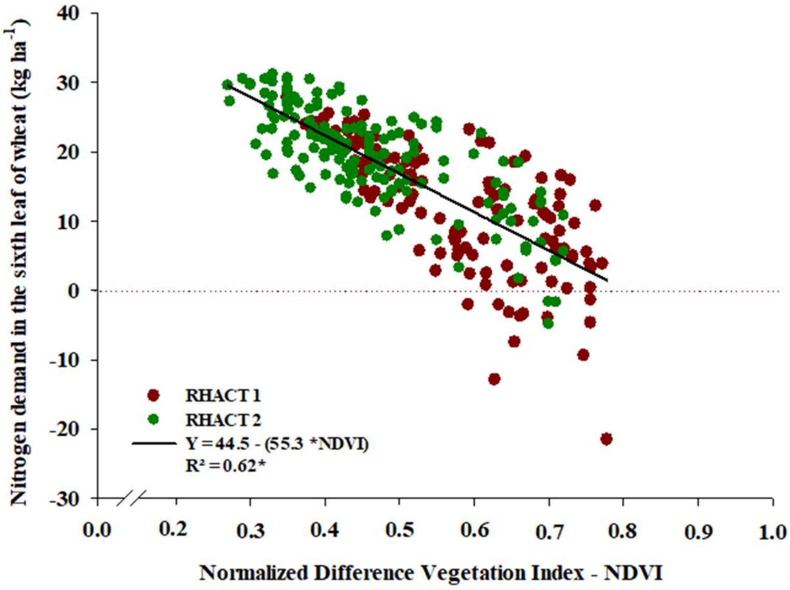

FIGURE 5. Nitrogen demand as a function of the normalized difference vegetation index (NDVI). *Significant at $p<0.05$. Wheat cultivation regions in the South of Brazil (RHACT 1 – red and RHACT 2 – green). Nitrogen demand at six fully expanded wheat leaves (kg ha^{-1}).

The previous stages of constructing the model served to estimate the amounts of N accumulated in the vegetative canopy (kg ha^{-1}) and quantify the crop N demand at the stage of six fully expanded leaves, allowing the development of the third stage, that is, the development of a model for N application at variable rates based on the NDVI values evaluated at the stage of six fully expanded leaves.

The model was defined to be simple and practical for use in the field. The mathematical model follows Equation (2), presented in the Material and methods section (Indicated topdressing N dose (kg ha^{-1}) = 35 − [N] uptake + Standard). It allowed the construction of two topdressing N indication curves, one for RHACT 1 (100 kg ha^{-1}) and another for RHACT 2 (80 kg ha^{-1}), as foreseen by the Brazilian Wheat and Triticale Research Commission (Reunião…, 2020).

Figure 6 shows the topdressing nitrogen fertilization indication curves considering the amount of N (Figure 6A and B) and urea (Figure 6C and D), respectively. The proposed model showed correlation coefficient values of r = 0.72 (RHACT 1) and r = 0.79 (RHACT 2), considering all cultivars, locations, and years (Figure 6A). The dose varies as a function of NDVI values and is calculated using the equations RHACT 1 → N dose (kg ha^{-1}) = 142.2 + (50.8*NDVI) and RHACT 2 → N dose (kg ha^{-1}) = 123.9 + (54.0*NDVI). A variation was found between the lowest and highest NDVI values, thus promoting a variation in the indicated N doses between 130 and 90 kg N ha^{-1} for RHACT 1, respectively (Figure 6A). A variation ranging from 110 and 75 kg N ha^{-1} was observed between the lowest and highest NDVI values for RHACT 2 (Figure 6B).

We defined that the urea dose varies depending on NDVI values, being calculated using the equation RHACT 1 – Urea dose (45% N) (kg ha^{-1}) = 316.0 + (112.9*NDVI) and RHACT 2 – Urea dose (45% N) (kg ha^{-1}) = 275.4 + (120.0*NDVI) (Figure 6C and 6D). A variation was observed between the lowest to the highest NDVI values, thus promoting a variation in the indicated urea doses between 280 and 200 kg urea ha^{-1} (RHACT 1), while RHACT 2 showed a variation ranging from 250 to 175 kg urea ha^{-1}.

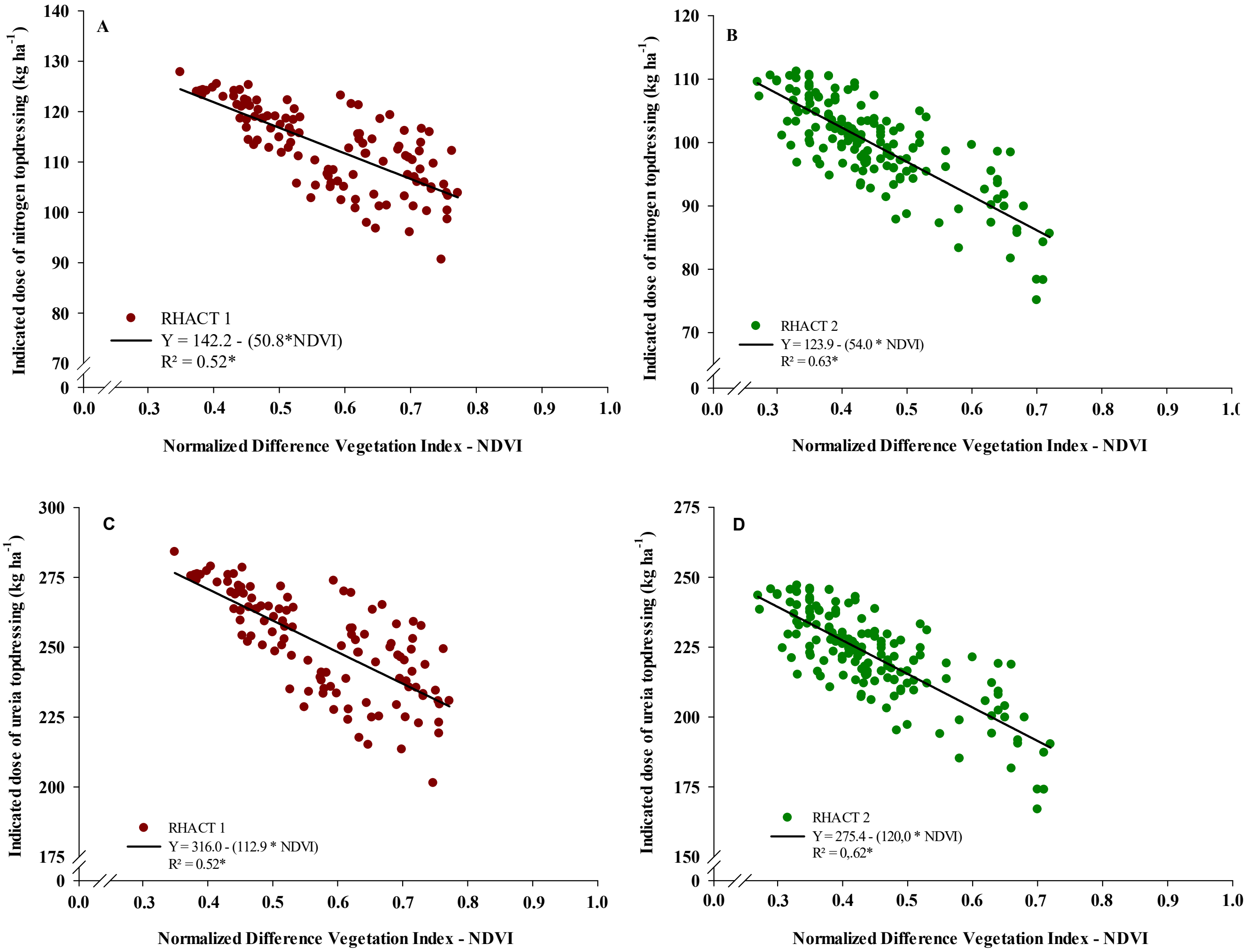

FIGURE 6. Topdressing nitrogen fertilization model at the stage of six fully expanded leaves as a function of the variation in the normalized difference vegetation index (NDVI) values, with doses indicated in absolute nitrogen values for RHACT 1 (A) and RHACT 2 (B) and urea (45% N) values for RHACT 1 (C) and RHACT 2 (D). *Significant at $p<0.05$.
Indicated topdressing nitrogen dose (kg ha^{-1}); Indicated topdressing urea dose (kg ha^{-1}).

This variation occurs because the plants have high contents of N accumulated in the plant tissue at the stage of six fully expanded leaves. However, N accumulated in the tissue is low for low NDVI values and, consequently, it should receive a higher N dose, that is, doses close to 130 kg N ha^{-1}. Thus, the model aims to distribute adequately the nitrogen that would be applied in a uniform dose throughout the area, which promotes the best N use by the plants, maximizes grain yield, reduces environmental contamination, and results in lower production cost, according to the situation.

Figure 6 also shows the difference between RHACT 1 and RHACT 2, which is mainly explained by the different thermal regimes between regions. RHACT 2 has a lower altitude and tends to show temperatures higher than those found in RHACT 1, influencing the N dynamics, with the availability of soil N usually occurring earlier during the cycle than in RHACT 1, promoting nutritional improvement, on average, at the stage of six fully expanded leaves. Thus, the model captures this higher availability and indicates lower N doses for application.

The development of robust algorithms for nitrogen fertilization for different crops in Brazil and the world, with practicality and efficiency of use, has been discussed by several authors and is increasingly available for use in the field. However, the use of regional variables is essential for the development and validation of these models, characterizing edaphoclimatic variables of the growing region and the interaction genotype x environment. Terpley et al. (2000) developed algorithms for topdressing nitrogen fertilization for cotton cultivation based on vegetation sensors. Vian et al. (2018) developed a method for the topdressing N application in wheat relative to the maximum technical efficiency dose, using NDVI.

The average costs in dollar (US\$) ha^{-1} can be estimated using the topdressing N indication model at a variable rate (ACI, 2021), considering an average urea value of US\$ 0.37 kg^{-1} urea (2015 and 2017 growing seasons), US\$ 0.43 kg^{-1} urea (2018 growing season), and US\$ 0.39 kg^{-1} urea (2019 growing season) (CONAB, 2021). Figure 7 shows the curves with costs for RHACT 1 and RHACT 2. The regions presented a variation above US\$ 25.00 ha^{-1}. RHACT 1 had a variation between US\$ 75.00 and 125.00 ha^{-1}, while RHACT 2 showed a variation ranging from US\$ 62.00 and 98.00 ha^{-1} between the lowest and highest NDVI values used in the model.

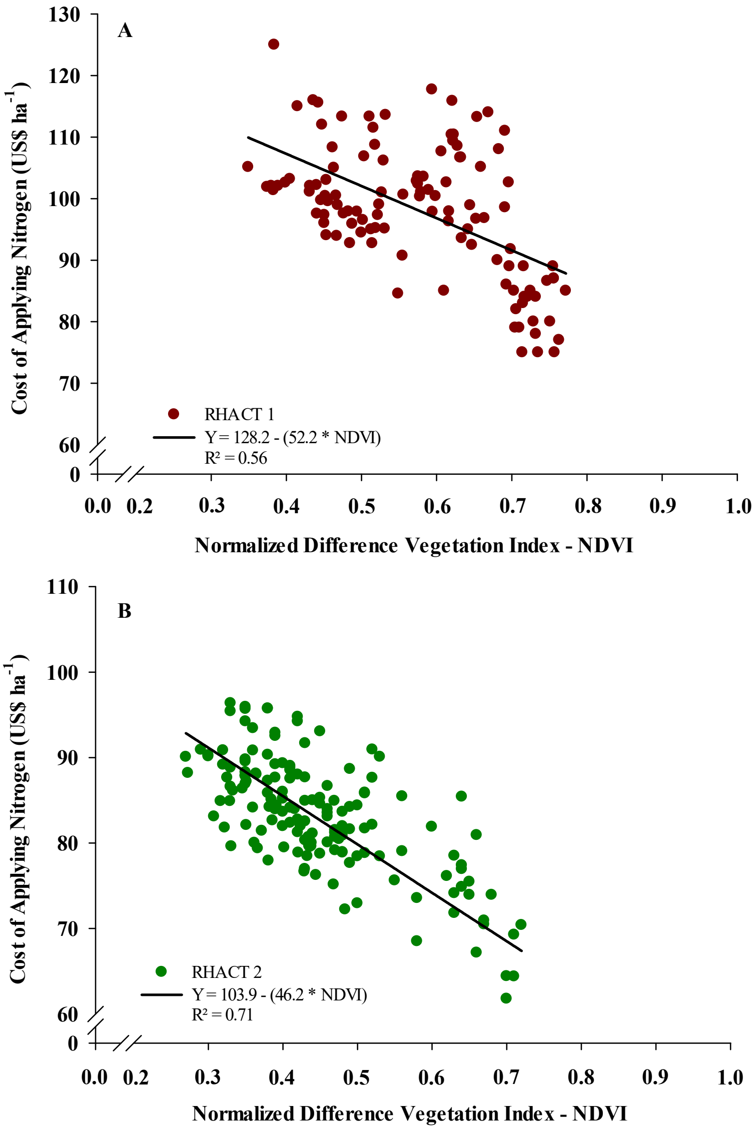

FIGURE 7. Estimated costs in dollars (US\$) for the nitrogen use as a function of the proposed model for the management of topdressing nitrogen fertilization in wheat at the stage of six fully expanded leaves in the South of Brazil (RHACT 1 – A and RHACT 2 – B).

CONCLUSIONS

The analysis of the relationship between the amounts of N accumulated in the shoot and NDVI values allows establishing a single model for different cultivars.

The proposed model is sensitive to capturing regional edaphoclimatic differences and variability in the N dynamics in cultivated areas.

The spectral response of wheat from NDVI values for estimating the amount of N accumulated in the tissue shows that the generation of a model based on data relating to the amount of accumulated N and NDVI has high precision and allows its use in the field to estimate this parameter.

The proposed model has the potential to improve the topdressing nitrogen fertilization indication, as it allows a more adequate variation of the N dose in the area than the use of a fixed dose.

The proposed model is easy to implement due to the relationship between the amount of N in the shoot and NDVI values, providing a simple model for N indication for a variable rate in wheat, using an active vegetation sensor.

ACKNOWLEDGMENTS

Thanks to the Agrisus Foundation for financial support of the research through project 2222/17 and the Secretariat of Agriculture, Livestock, and Rural Development of RS (SEAPDR) for providing the area for the tests in Vacaria, RS.

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