Nitrogen fertilization for wheat following soybean and interfering factors on spectral reflectance readings

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Abstract

A field experiment examined the wheat response following soybean due to urea-N fertilization at sowing (0, 20, 40, and 60 kg N ha⁻¹) and top dressing (0, 30, 60, and 90 kg N ha⁻¹). Normalized difference vegetation index (NDVI) measurements using a GreenSeeker active sensor were taken at different growth stages, at various sensor heights above the canopy, and at different times of day. Both the shoot dry matter yield and the grain yield were not affected by N fertilization at sowing and increased with increasing N rates at top dressing. A maximum economic yield was obtained at 55 kg N ha⁻¹ in top dressing, causing a 33% increase in grain yield and an economic return of US\$ 189.50 ha⁻¹. Differences in NDVI were found before and after top-dressing N fertilization, indicating that GreenSeeker was efficient in monitoring wheat N nutrition. NDVI varied depending on the measurement distance, stabilizing from 0.30 to 1.20 m above the canopy. Because of the influence of incident radiation, higher NDVI values were obtained at the beginning and end of the day. The results suggest that for the wheat cultivar Quartzo following soybean under minimum soil disturbance, while there is no need to apply N at sowing, an important increase in grain yield can be obtained with top-dressing N fertilization. In addition, to improve the accuracy in developing N fertilizer recommendation models using GreenSeeker, a consistent protocol for spectral reflectance readings, mainly regarding the time of day, is required.

Keywords Remote sensing · GreenSeeker · Timing of sensing · Measurement distance · NDVI

1 Introduction

Wheat is grown in nearly every region of the world and represents a main source of food and income for millions of farmers. Wheat-based foods are critical for food security and nutritional security worldwide. The main world producers of wheat are the European Union, China, India, Russia, and the USA (USDA 2019). Although Brazilian wheat production is only around 6.0 million Mg, wheat is the main winter crop grown following soybean in southern Brazil.

Wheat has a high nitrogen (N) requirement, and most of the N is required over a short period, during an exponential growth phase [25]. Usually, the soil supplies a certain

amount of N that depends on the soil organic matter mineralization, but this is not enough to provide all the needs of the plant and additional N fertilization is required to achieve highest yields [5]. An advantage under the soybean–wheat system is the contribution of the previous legume to reduce the need of N fertilizer application, since higher rates of decomposition and mineralization of N can be recycled and recovered by the crop in succession due mainly to the lower residue C/N ratio (about 20:1). Anyway, fertilizer N use is expanding globally to satisfy food demand of a growing world population. However, more than half of the N added for crop fertilization is currently lost into the environment [15, 30]. The development of

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management practices in agriculture aimed at increasing the N use efficiency is a worldwide need.

Readings from optical sensors can be associated with important indicators of agricultural crops, such as leaf area index [35], biomass production [18], and grain yield [9]. Thus, the proper use of optical sensors has been useful to improve the production and nutrient use efficiency [10]. Several studies have focused on the development of models for converting indices obtained by reflectance sensors into N fertilizer rates [16, 26, 32], without much concern with the development of a consistent protocol for spectral reflectance readings related to interfering factors.

An intended advantage of active optical sensors is that they can take measures at any time of day regardless of variations in solar radiance [8, 13]. However, sensor readings can be affected directly or indirectly by several factors. Combining light source and measurement distance can result in different spectral reflectance readings [33]. Depending on the measurement distance, the sensor can result in different viewing angles and a chance of footprint size, automatically changing the monitored area [13, 36]. Factors like weather conditions and time of day [19, 20], photosynthetically active radiation [24], air temperature [13], and daily variations in chlorophyll fluorescence [40] have been highlighted with the possibility of affecting sensor readings. Reflectance patterns can also be strongly affected by factors related to the different stages of plant growth and levels of N fertilization [23, 27].

This study reports a field experiment that examined the effects of N fertilization at sowing and top dressing on spectral reflectance measurements and shoot dry matter and grain yields of wheat in succession to soybean. During wheat development, spectral reflectance readings using a GreenSeeker sensor were taken at different crop growth stages, at various sensor heights above the canopy, and at different times of day. We hypothesized that N fertilization causes significant increases in wheat grain yield, even under a soybean–wheat system, and that, although remote sensing can be used to monitor the wheat development to differentiate N nutrition, the performance of the GreenSeeker active sensor may be compromised if factors like the sensor–plant distance and the time of day for taking readings are not adequately standardized.

2 Material and methods

2.1 Site description and soil

The experiment was conducted on an Oxisol (clayey, kaolinitic thermic Typic Hapludox) in Palmeira, PR, Brazil (25°23'S, 50°00'W). Table 1 shows the results of chemical analyses of topsoil (0–0.20 m) in May 2014 before

Table 1 Results of chemical analyses of the topsoil (0–0.20 m) in May 2014 before the establishment of the experiment on an Oxisol in Palmeira, PR, southern Brazil

Attributes	Results
pH (1:2.5 soil:0.01 m CaCl ₂ suspension)	5.2
Total acidity pH 7.0 (H + Al) (mmol _c dm ⁻³)	43
Organic matter (g dm ⁻³)	35
P (Mehlich-1) (mg dm ⁻³)	3.5
Exchangeable cations (mmol _c dm ⁻³)	–
Ca ²⁺	58
Mg ²⁺	28
K ⁺	1.3
Al ³⁺	0
ECEC (mmol _c dm ⁻³) ^a	87.3
CEC pH 7.0 (mmol _c dm ⁻³) ^b	130.3
Base saturation (%) ^c	67

^aEffective cation exchange capacity (ECEC) = Al³⁺ + Ca²⁺ + Mg²⁺ + K⁺

^bCation exchange capacity (CEC) pH 7.0 = Ca²⁺ + Mg²⁺ + K⁺ + total acidity (H + Al)

^cBase saturation = 100 (Ca²⁺ + Mg²⁺ + K⁺/CEC pH 7.0)

the establishment of the experiment. According to Köppen–Geiger system, the climate at the site is categorized as a Cfb type (mesothermal, humid, subtropical), with mild summer and frequent frosts during the winter. The average altitude is 920 m, and the annual rainfall is about 1550 mm. The experiment site had been used for 2 years in a livestock–soybean system using black oat during the winter and with a soybean–wheat system under minimum soil disturbance for the past 5 years.

3 Experimental design, treatments, and evaluations

A randomized complete block design was used, with 3 replications in a split-plot arrangement. Four levels of N fertilization were applied to the plots (24 m × 6 m) at sowing (0, 20, 40, and 60 kg ha⁻¹), and 4 levels of N fertilization were applied in top dressing (0, 30, 60, and 90 kg ha⁻¹) to the subplots (6 m × 6 m), totaling 48 experimental units. Nitrogen was applied as urea.

Wheat (*Triticum aestivum* L.), cultivar Quartzo, was sown on June 26, 2014, at a density of 350 plants m⁻² and row spacing of 0.17 m. Quartzo is a medium-cycle wheat cultivar used for bread-making and indicated for cultivation in the Brazil southern region [14]. Fertilizers at rates of 26 kg ha⁻¹ P and 50 kg ha⁻¹ K were applied at sowing. Nitrogen fertilization in top dressing was performed at wheat tillering, at growth stage Z₂₄ (main stem and four tillers) on the decimal growth scale of Zadoks

et al. [39]. The rainfall data registered and the events occurring during the execution of the experiment are presented in Fig. 1. Rainfall was well distributed, and there was no water limitation throughout the development period of the wheat crop. Total rainfall during the wheat cycle amounted to 358 mm. Pest, disease, and weed controls were performed as needed, so as to allow adequate plant development.

The influence of sensor height on spectral reflectance measurements was evaluated by performing readings between 0.10 and 1.20 m from the plant canopy. A total of 12 height measurements were performed every 0.10 m. Spectral reflectance measurements at the different tested heights were performed at the time of N application in top dressing (stage Z_{24}), within a delimited area of 1.0 m² (2.0 m × 0.5 m). Since the N fertilization in top dressing had not yet been applied at that time, the subplots consisted of different measuring heights, and the treatments with different N levels in top dressing were considered as replications.

The influence of the wheat development on spectral reflectance measurements was evaluated by performing readings at the following wheat growth stages, on the decimal growth scale of Zadoks et al. [39]: (1) Z_{17} —seven leaves emerged; (2) Z_{20} —main stem only; (3) Z_{24} —main stem and four tillers; (4) Z_{31} —stem elongation, first node detectable; (5) Z_{34} —stem elongation, fourth node detectable; and (6) Z_{45} —boots swollen. The measurements were performed at 0.90 m from the plant canopy within a 3.0 m² (3.0 m × 1.0 m) central area of each subplot. Since N fertilization in top dressing was only applied on Z_{24} , measurements performed on Z_{17} , Z_{20} , and Z_{24} were considered subplots, and treatments with different N levels in top dressing were considered as replications. After N rates application in top dressing, subplots consisted of different N levels in top dressing,

and measurements performed at Z_{31} , Z_{34} , and Z_{45} were considered sub-subplots.

The influence of the time of day on spectral reflectance measurements was evaluated by performing readings at three different times: (1) from 7:30 to 8:30 am (early morning), (2) from 1 to 2 pm (early afternoon), and (3) from 7 to 8 pm (night). The measurements were performed at 0.90 m from the plant canopy, on growth stage Z_{50} [first spikelet of inflorescence just visible (Zadoks et. al. 1974)] on an almost cloudless day within a 3.0 m² (3.0 m × 1.0 m) central area of each subplot. The different times of day by the early morning, early afternoon, and night were considered sub-subplots. Photosynthetically active radiation was also measured at the same time as the early morning and early afternoon using an AccuPar LP-80 sensor, which has an approximately 0.86-m-long probe containing 80 sensors that perform measurements in quanta [34], with a 1 $\mu\text{mol m}^{-2} \text{s}^{-1}$ resolution.

At 120 days after sowing, the plant aerial part was collected in three continuous rows of 4 m (2.04 m²), and the dry biomass was evaluated to determine shoot dry matter yield. Grain wheat was harvested after crop physiological maturation from a 13.6 m² area (middle 20 rows by 4.0 m in length). Grain yield was expressed at 130 g kg⁻¹ moisture content. An economic analysis of N fertilization was conducted using global average prices of the products over the last 10 years [3]. The average price of N as urea, based on CIF (Cost, Insurance, and Freight) payment, was estimated at US\$ 1150.00 Mg⁻¹ N. The average price of wheat was estimated at US\$ 240.00 Mg⁻¹ grain. Based on average prices of the products, the ratio of unit cost between kg of N and kg of grain was 4.8.

3.1 Active sensor used

A GreenSeeker 505 Hand Held Optical Sensor was used in our study. This active sensor uses light-emitting

Fig. 1 Weekly rainfall and main events during the wheat development period in the experimental field in 2014

diodes (LEDs) as light source and measures reflectance in the visible (VIS) (650 ± 10 nm) and near-infrared (NIR) (770 ± 15 nm) regions [6]. The LEDs alternate their pulses, with each emitting 40 light pulses in 1 ms ($= 40$ kHz) before pausing for the other LED. A single silicon photodiode detector captures the reflected light of both LEDs. The amount of VIS and NIR light reflected by the plant canopy is measured by the sensor and sent to the coupled computer. Angular field of view for the GreenSeeker sensor is not reported by the manufacturer, which indicates that optical masking and position of the sensor LEDs allow the sensor to view a 0.60-m-wide strip regardless of the sensor height; however, a sensor height of at least 0.80 m above the target is also recommended. The spectral reflectance measurements are converted to normalized difference vegetation index (NDVI) by the GreenSeeker sensor system [29].

3.2 Statistical analysis

Data from the spectral reflectance measurements converted to NDVI and shoot dry matter and grain yields were analyzed through an analysis of variance and regression methods using a randomized complete block design in split-plot or split-split-plot arrangements, depending on the factors and times evaluated. For wheat shoot dry matter and grain yields, the interaction effect of N rates applied at sowing and top dressing was evaluated. For spectral reflectance measurements, the following interaction effects were evaluated: N rates at sowing $\times$ sensor height, N rates at sowing $\times$ Z₁₇, Z₂₀, and Z₂₄ growth stages, N rates at sowing $\times$ N rates in top dressing $\times$ Z₃₁, Z₃₄, and Z₄₅ growth stages with their combinations (N rates at sowing $\times$ N rates in top dressing, N rates at sowing $\times$ Z₃₁, Z₃₄, and Z₄₅ growth stages, and N rates in top dressing $\times$ Z₃₁, Z₃₄, and Z₄₅ growth stages), and N rates at sowing $\times$ N rates in top dressing $\times$ time of day with their combinations (N rates at sowing $\times$ N rates in top dressing, N rates at sowing $\times$ time of day, and N rates in top dressing $\times$ time of day). In the absence of a significant interaction effect on the variables studied, the data analysis was conducted using the means of the observations. Nitrogen rates applied at sowing and top dressing were analyzed by regression methods, and when the effect was significant at $P < 0.05$, the magnitude of the determination coefficients was used as a criterion for choosing the model. The effects of sensor height, plant growth stage, and time of day were compared by the Tukey test at $P = 0.05$. Statistical analyses were performed using the R software.

4 Results and discussion

4.1 Effect of N fertilization on wheat shoot dry matter and grain yields

Wheat shoot dry matter and grain yields were not significantly influenced by either different N fertilization levels at sowing, or by interaction of N rates applied at sowing and top dressing. Increasing N rates in top dressing linearly increased ($P < 0.01$) shoot dry matter yield (Fig. 2a) and quadratically increased ($P < 0.01$) wheat grain yield (Fig. 2b). Based on the regression equation for grain yield (Fig. 2b), the maximum wheat grain yield (4280 kg ha^{-1}) would be reached by applying 65 kg N ha^{-1} in top dressing, and considering the ratio of unit cost between kg of N and kg of grain of 4.8, the N rate in top dressing for maximum economic yield (4250 kg ha^{-1}) was estimated at 55 kg ha^{-1} . Based on average price of wheat of US\$ 240.00 per Mg of grain and the average price of N as urea of US\$ 1150.00 Mg^{-1} N, the economic return would be US\$ 189.50 ha^{-1} with the N application rate in top dressing for maximum economic yield (55 kg N ha^{-1}).

Fig. 2 Wheat shoot dry matter (a) and grain (b) yields as affected by nitrogen rates applied in top dressing at wheat tillering. $^{**}P < 0.01$. The vertical bars indicate the standard error of the mean

Since the soil N availability is dependent on mineralization of organic matter [5] and due to the essential role of N in high-yield systems [7], positive effects of N fertilization on wheat yields have been frequently observed in studies conducted on Brazilian soils [11, 17, 28]. In our study conducted on an Oxisol with 35 g dm^{-3} of organic matter in the topsoil (Table 1), a rate of 55 kg N ha^{-1} for wheat cultivar Quartzo following soybean provided a maximum economic return to obtain grain yield of 4250 kg ha^{-1} . Similar results under a soybean–wheat system were found in other studies, with wheat responding economically to the rate of 35 kg N ha^{-1} for yield around 3100 kg ha^{-1} [38], and to the rate of $61.5 \text{ kg N ha}^{-1}$ for yield around 4000 kg ha^{-1} [17]. It is true that to provide more appropriate N recommendations for wheat, our study should have comprised more cultivars, soils, locations, and years. However, the N rate for maximum economic yield found in our study was consistent with the recommendation of N fertilization in top dressing for wheat following soybean [22] under high-yield systems ($3600\text{--}4500 \text{ kg ha}^{-1}$) in Parana State, Brazil ($51\text{--}80 \text{ kg N ha}^{-1}$). Although for wheat following soybean, it is recommended to apply $10\text{--}30 \text{ kg N ha}^{-1}$ at sowing [22], in our study, there was no need to apply N at sowing certainly because the soil had a high organic matter content. This result is relevant because the Brazil southern region soils often have higher levels of organic matter due to the predominance of cropping systems with minimum soil disturbance [31].

4.2 Effect of sensor height on wheat spectral reflectance measurements

NDVI, obtained from spectral reflectance measurements in wheat, was not significantly influenced by the interaction of sensor heights and N rates applied at sowing. NDVI, calculated based on reflectance measurements performed when the fourth tiller was emitted (time of N application in top dressing), linearly increased ($P < 0.01$) with increasing N rates at sowing (Fig. 3). NDVI variations depending on the level of N fertilization are usually fitted by linear or quadratic equations [1, 11]. Although wheat shoot dry matter and grain yields at physiological maturation were not affected by the level of N fertilization at sowing, the NDVI values showed that N fertilization at sowing favored the early growth of wheat plants. These results might be related to the better initial development that N rates at sowing provide wheat plants. In a study by Da Ros et al. [4], it was found that the application of N in pre-sowing or sowing in a clayey Oxisol increased the availability of N in the early stages of wheat development, but there were also no effects of this application on the dry above-ground mass and grain yields.

Fig. 3 Mean values of NDVI obtained in the wheat crop at the time of nitrogen fertilization in top dressing (Z_{24} stage by Zadoks growth scale) as affected by nitrogen rates applied at sowing. $**P < 0.01$. The vertical bars indicate the standard error of the mean

Table 2 Mean values of NDVI depending on the measuring distance of the GreenSeeker sensor to the wheat plant canopy

Measuring height of the sensor relative to the wheat plant canopy (m)	NDVI
0.10	0.82230 a
0.20	0.76896 a
0.30	0.59832 b
0.40	0.56001 b
0.50	0.56403 b
0.60	0.56711 b
0.70	0.57801 b
0.80	0.56843 b
0.90	0.57684 b
1.00	0.58966 b
1.10	0.59636 b
1.20	0.58652 b

*Different letters indicate significant difference by the Tukey test at $P = 0.05$

NDVI was also significantly affected by the sensor height from the plant canopy (Table 2). The GreenSeeker manufacturer states that the sensor should be used between 0.80 and 1.20 m above the canopy. In our study, the closest heights from the canopy resulted in higher NDVI values, causing worsening in the detection of differences in plant development. The NDVI values obtained at 0.10 and 0.20 m from the plant canopy were not significantly different, but they were higher than the values obtained from 0.30 to 1.20 m to the canopy. No significant differences in NDVI values were observed for sensor heights from 0.30 to 1.20 m from the plant canopy. This allows a safety margin for measuring height oscillations.

Table 3 NDVI values at different wheat growth stages before nitrogen fertilization in top dressing

Wheat development stage (Zadoks growth scale)	NDVI
Z ₁₇ —seven leaves emerged	0.214 c
Z ₂₀ —main stem only	0.331 b
Z ₂₄ —main stem and four tillers	0.553 a

*Different letters indicate significant difference by the Tukey test at $P=0.05$

Table 4 NDVI values at different wheat growth stages after nitrogen fertilization in top dressing

Wheat development stage (Zadoks growth scale)	NDVI
Z ₃₁ —stem elongation, first node detectable	0.718 b
Z ₃₄ —stem elongation, fourth node detectable	0.734 b
Z ₄₅ —boots swollen	0.782 a

*Different letters indicate significant difference by the Tukey test at $P=0.05$

Fig. 4 Mean values of NDVI obtained in the wheat crop at Z₁₇, Z₂₀, and Z₂₄ stages (Zadoks growth scale), before nitrogen fertilization in top dressing, as affected by nitrogen rates applied at sowing. ** $P < 0.01$. The vertical bars indicate the standard error of the mean

Fig. 5 Mean values of NDVI obtained in the wheat crop at Z₃₁, Z₃₄, and Z₄₅ stages (Zadoks growth scale), after applications of nitrogen rates in top dressing. * $P < 0.05$. The vertical bars indicate the standard error of the mean

For example, if the sensor is placed at 1.00 m from the canopy and it oscillates ± 0.20 m during the displacement of the agricultural machinery, the sensor efficiency would not be negatively affected by resulting variations in NDVI. Similar results were found by Kipp et al. [13], who observed no variations in NDVI values measured between 0.70 and 1.40 m from the plant canopy. For cotton, the GreenSeeker NDVI predicted an economically optimal N rate acceptable at the middle of the recommended range (1.00 m), but performed as well or better at 0.50 m height [21]. Our results showed that, even with an oscillation of ± 0.20 m (up or down), the sensor could still be placed at 0.50 m above the canopy of wheat plants, without significantly affecting NDVI values.

4.3 Effect of wheat growth stage on spectral reflectance measurements

For NDVI measurements performed before N fertilization at top dressing in wheat (growth stages Z₁₇, Z₂₀, and Z₂₄), no significant interaction between different measurement times and N rates applied at sowing was

observed. However, NDVI increased as the plant growth stages advanced (Table 3) and N rates applied at sowing increased (Fig. 4).

After applying N rates at top dressing in wheat (growth stages Z₃₁, Z₃₄, and Z₄₅), NDVI was also not affected by the interactions of different measurement times and levels of N fertilization. Spectral reflectance measurements were not affected by N rates applied at sowing. However, NDVI was significantly influenced by the plant growth stage (Table 4), and by the levels of N fertilization at top dressing (Fig. 5). At Z₄₅ stage, NDVI was significantly higher than Z₃₁ and Z₃₄ stages (Table 4). NDVI was also raised with the application of N rates in top dressing ($P < 0.05$), exhibiting a quadratic response (Fig. 5). The adjusted regression equation showed that the highest mean value of NDVI at Z₃₁, Z₃₄, and Z₄₅ stages would be reached with N fertilization in top dressing at 50 kg N ha⁻¹, whose rate was close to that obtained for maximum economic yield (55 kg N ha⁻¹). Similar results related to changes in NDVI depending on the level of N fertilization and plant development stage were found by Rissini et al. [27].

4.4 Influence of the time of day on wheat spectral reflectance measurements

Increasing N rates in top dressing linearly increased NDVI ($P < 0.01$) measured on growth stage Z_{50} (first spikelet of inflorescence just visible) (Fig. 6).

Photosynthetically active radiation increased approximately $6 \mu\text{mol m}^{-2} \text{s}^{-1}$ per minute during the early morning, varying from $540 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 7:30 am to $900 \mu\text{mol m}^{-2} \text{s}^{-1}$ at approximately 8:30 am (Fig. 7a). During the early afternoon, photosynthetically active radiation was measured when it was already decreasing, at approximately $2.15 \mu\text{mol m}^{-2} \text{s}^{-1}$ per minute, going from $1750 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 1 pm to $1620 \mu\text{mol m}^{-2} \text{s}^{-1}$ at approximately 2 pm (Fig. 7b). Photosynthetically active radiation can reach approximately $2000 \mu\text{mol m}^{-2} \text{s}^{-1}$ on a sunny day and be greater at higher altitudes [34]. No photosynthetically active radiation incidence was measured at night (from 7 to 8 pm).

Significant differences in NDVI were observed at different times of day, in the following descending order: from 7 to 8 pm > from 7:30 to 8:30 am > from 1 to 2 pm (Table 5). Our results indicate that NDVI was highest when photosynthetically active radiation was lowest, which closely agree with observations by Allen et al. [2], who demonstrated that short-term reductions in solar radiation due to a cloud covering the sun were repeatedly associated with an immediate increase in GreenSeeker NDVI. Kim et al. [12] also found a slight decrease in GreenSeeker NDVI as ambient light level increased in a controlled environment. Allen et al. [2] measured GreenSeeker NDVI from cotton nine times during the course of a day and found that the average NDVI values were about 4% higher 4 h before and

Fig. 6 NDVI values obtained in the wheat crop at Z_{50} stage (first spikelet of inflorescence just visible by Zadoks growth scale) as affected by nitrogen rates applied in top dressing. $**P < 0.01$. The vertical bars indicate the standard error of the mean

Fig. 7 Photosynthetically active radiation during the early morning (a) and early afternoon (b) in wheat experiment

after noon than at noon. In a study by Oliveira and Scharf [20], the highest NDVI values from cotton using the GreenSeeker sensor were also measured early and late in the day. In our study, GreenSeeker NDVI values were 3 and 5% higher from 7:30 to 8:30 am and from 7 to 8 pm than from 1 to 2 pm, respectively. Oliveira and Scharf [20] suggest that GreenSeeker sensor is the source of this variation and the behavior of the sensor is influenced by environmental conditions. Because photosynthetically active radiation indirectly affects NDVI due to its natural relationship with

Table 5 NDVI readings from wheat canopy according to timing of sensing within a day

Period	Timing of sensing (h)	NDVI
Early morning	7:30 to 08:30 am	0.813 b
Early afternoon	1 to 2 pm	0.788 c
Night	7 to 8 pm	0.830 a

*Different letters indicate significant difference by the Tukey test at $P = 0.05$

Fig. 8 Wheat shoot dry matter yield as affected by NDVI values obtained during the early morning (7:30 to 8:30 am), early afternoon (1 to 2 pm), and at night (7 to 8 pm). *** $P < 0.01$ and * $P < 0.05$

ambient temperature [24], GreenSeeker NDVI may not have been directly affected by photosynthetically active radiation through its effect on spectral reflectance [13]. In addition, the ambient temperature can affect device temperature and it influences the quality of the different light-emitting diodes affecting sensor readings [13].

Wheat shoot dry matter yield was linearly correlated to NDVI (Fig. 8), with coefficients of determination (R^2) of 0.99 ($P < 0.01$), 0.98 ($P < 0.01$), and 0.97 ($P < 0.05$) for measurements performed from 7 to 8 pm, from 7:30 to 8:30 am, and from 1 to 2 pm, respectively. Because all measurements were performed within the same area and at the same height from the plant canopy, differences were likely due to different times of sensing within a day. Unlike previous studies with wheat reporting that canopy reflectance measurements were not affected by the time of day and solar radiation [8, 13], in our study we found that, in view of the influence of incident radiation, the time of day could cause distortions in GreenSeeker NDVI values. Such reading distortions could result in large differences in the practical situations of using this technology. For example, if the sensor is used for N fertilization recommendation, as in Raun et al. [26], the lack of care with the timing of sensing, depending on the incident radiation, could distort the spectral reflectance readings and, consequently, the NDVI, resulting in over- or underestimation of the optimal N rate to be applied to the wheat crop.

5 Conclusion

Under a soybean–wheat system established on an Oxisol with 35 g dm^{-3} of organic matter in the topsoil, both the shoot dry matter yield and the wheat grain yield cultivar Quartzo were not affected by N fertilization at

sowing, although they were increased with N fertilization in top dressing. The maximum yield (4280 kg ha^{-1}) and the maximum economic yield (4250 kg ha^{-1}) of wheat were achieved when applying N in top dressing at 65 and 55 kg ha^{-1} , respectively. An increase by 33% in grain yield and an economic return of US\$ 189.50 ha^{-1} were obtained applying N in top dressing at the rate of maximum economic yield. GreenSeeker NDVI measurements varied depending on the sensor height, stabilizing from 0.30 to 1.20 m above the canopy. So, even with an oscillation of $\pm 0.20 \text{ m}$ during the displacement of the agricultural machinery, the sensor could be placed at least 0.5 m above the wheat canopy, without significantly affecting its performance. Different NDVI values were observed for different wheat growth stages, before and after N fertilization in top dressing, indicating that GreenSeeker was efficient in monitoring wheat development to differentiate N nutrition. However, higher NDVI values were measured at times of day with lower incident radiation (from 7 to 8 pm > from 7:30 to 8:30 am > from 1 to 2 pm). Thus, to improve the accuracy in developing N fertilizer recommendation models using GreenSeeker, a consistent protocol for spectral reflectance readings, mainly regarding the time of day, is required.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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