IMPORTANCE OF IRRADIANCE CORRECTION FOR UAV-BASED VEGETATION INDICES IN THE PREDICTION OF SHOOT BIOMASS IN WHEAT

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Abstract.

The extraction of vegetation indices from multispectral images obtained with UAV-based sensors for biomass estimation has proven to be a useful tool for designing site-specific interventions on wheat. The reflectance values from monochromatic bands collected with optical sensors for calculating vegetation indices should have high reliability and repeatability in the case of successive assessments under different illumination conditions. In this context, the objective of the study was to characterize the effect of using an irradiance sensor in the correction of spectral data and generation of vegetation indices derived from images obtained by a multispectral camera embedded on an unmanned aerial vehicle (UAV) for estimating aboveground biomass in wheat. The experiment was conducted at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul (UFRGS), located in Eldorado do Sul, Rio Grande do Sul, Southern Brazil. Treatments consisted of different nitrogen rates applied at plant emergence (no N, 15, 30, 45, and 60 kg ha^{-1}) and as topdressing (no N, 40, and 80 kg ha^{-1}) at the four-leaf growth stage (V4 stage), with four replications. Biomass was collected at the V4, stem elongation (first node visible) and flowering. Before biomass sampling, spectral data were acquired with a multispectral camera embarked on a DJI Phantom 4 drone, equipped with sensors that capture the following bands: blue (450 nm ± 16 nm), green (560 nm ± 16 nm), red (650 nm ± 16 nm), red-edge (730 nm ± 16 nm) and near-infrared - NIR (840 nm ± 26 nm), and used for the calculation of 23 vegetation indices. A total of three flights were conducted, all occurring between 10:00 a.m. and 11:00 a.m. Spectral data extraction was performed on orthomosaics subjected or not to reflectance correction using the information from the irradiance sensor (sunshine sensor) of the drone. Digital values of monochromatic bands and vegetation indices values showed a better correlation with shoot biomass and grain yield when spectral data correction by the irradiance sensor was applied. The NDRE (Normalized Difference Red Edge) and SFDVI (Spectral Feature Degree Vegetation Index) indices showed the greatest increase in correlation with the biomass when spectral data correction by incident irradiance was used. Furthermore, the absolute values of normalized

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vegetation indices, as e.g. NDRE and the Normalized Difference Vegetation Index (NDVI), indicate an increase of 15% up to 60% due to the use of the irradiance sensor. Correcting data obtained from multispectral sensors using an irradiance sensor is essential to ensure reliable and repeatable shoot biomass estimation in wheat, particularly when temporal assessments are conducted.

Keywords.
Sunshine sensor, UAV, vegetation index, radiometric correction and wheat.

Introduction

In recent years, the use of unmanned aerial vehicles (UAVs) in agriculture has increased significantly, given that traditional assessment methods for shoot biomass estimation in wheat (*Triticum aestivum*) are time-consuming, labor-intensive, and resource-demanding (Haghighattalab et al., 2016). To enable biomass assessment and grain yield estimation, a multispectral camera mounted on a UAV can be used to obtain raw spectral data. The key to accurately estimating these crop phenotypic parameters is converting the captured Digital Numbers (DN) into true surface reflectance (Zhu et al., 2024).. This reflectance data is subsequently utilized to generate vegetation indices that directly correlate with field parameters, allowing for the fast and precise identification of field areas with nutritional deficiencies.

However, despite the potential of vegetation indices, extracting spectral data throughout the crop cycle is subject to variations in solar illumination and atmospheric conditions during flights (Gilliot et al., 2018). In this context, the objective of this study was to evaluate the necessity of using UAV-mounted irradiance sensors to construct reliable and stable vegetation indices over time, highlighting the impacts caused by the lack of radiometric correction on field UAV-based spectral data.

Material and Methods

The experiment was conducted at the Agronomic Experimental Station of the Federal University of Rio Grande do Sul (EEA-UFRGS), located in Eldorado do Sul, southern Brazil (-30.11095° S, -51.68116° W). Wheat was sown on June 13, 2025, under a no-tillage system. The experimental design was a randomized complete block design, with four replications. Plots consisted of 10 rows spaced 0.17 meters apart and 6 meters long, totaling 10.2 m^2. To ensure greater variability for image collection, five nitrogen (N) doses were applied at plant emergence (0, 15, 30, 45, and 60 kg ha^{-1}) and three N doses at the V4 growth stage (0, 40, and 80 kg ha^{-1}).

To determine aboveground biomass, destructive plant sampling was performed by completely removing plants from a 0.255 m^2 area per plot at the growth stages V4, stem elongation, and flowering. The samples were dried in a forced-air oven at 60°C for subsequent weighing on a precision scale, with values expressed in kilograms of dry matter per hectare (kg ha^{-1}). Grain yield was determined by harvesting the eight central rows and standardized to 13% moisture content, with values presented in kilograms per hectare (kg ha^{-1}).

Spectral data collection for the plots was carried out at the V4, stem elongation, and flowering growth stages. The imaging flights were performed using a DJI Phantom 4 rotary-wing unmanned aerial vehicle (UAV), with autonomous flight control managed via the Pix4D application. The flight parameters included an altitude of 30 m and a 75% forward and lateral overlaps. This configuration enabled the acquisition of reflectance data at the following regions of the electromagnetic spectrum: blue (450 nm ± 16 nm), green (560 nm ± 16 nm), red (650 nm ± 16 nm), red-edge (730 nm ± 16 nm), and near-infrared (NIR, 840 nm ± 26 nm). All flights were conducted around 11:00 AM to ensure consistent illumination conditions and on the same days as the biomass sampling. An onboard irradiance sensor (“sunshine sensor”) mounted on the upper surface of the drone was used to record solar irradiance for each spectral band during image acquisition. These measurements were subsequently used for radiometric correction and reflectance calibration of the images.

The radiometric correction process was based on converting the raw digital counts from the sensor, known as Digital Numbers (DNs), into true surface reflectance (*p*). This reflectance (*p*) is defined as the ratio between the reflected radiant flux (*r*) from the canopy and the total incident solar radiant flux (*i*), as expressed in Equation 1 (Aasen et al., 2018; Zhu et al., 2024).

$$p = \frac{r}{i} \qquad (1)$$

Image processing was performed using Agisoft Metashape software to generate orthomosaics, enabling or disabling the "use sun sensor" function that converts raw radiance data (DNs) into true surface reflectance. This process yielded one corrected and one uncorrected mosaic for each flight. These mosaics were registered using eight ground control points georeferenced with GNSS-RTK for geometric correction. Spectral data extraction from the orthomosaics was performed using QGIS software and the Raster Calculator plugin to calculate different vegetation indices (Table 1).

To verify the effect of radiometric correction on the coefficient of correlation between shoot biomass and the vegetation indices calculated in this study (Table 1), Microsoft Excel was used. Thus, to identify the differences in absolute values between indices obtained with and without the irradiance sensor correction, data were initially submitted to the Shapiro-Wilk test to verify the normality of the paired differences. As the data were not normally distributed ($p < 0.05$), non-parametric analyses were performed using Wilcoxon Signed-Rank test to compare the population means under both conditions (with or without radiometric correction). All statistical analyses were performed in the R computational environment (R Core Team, 2026), adopting a 5% significance level.

TABLE 1. Vegetation indices calculated in this study.

Index	Equation*
Normalized Difference Vegetation Index	NDVI = (NIR – R) / (NIR + R)
Normalized Difference Red Edge Index	NDRE = (NIR – RE) / (NIR + RE)
Spectral Feature Degree Vegetation Index	SFDVI = [(NIR + G)/2] / [(NIR + RE)/2]

*R: Red, G: Green, RE: Red-edge, NIR: near-infrared

Results and Discussion

When comparing the vegetation indices calculated from the corrected and uncorrected data, differences in their absolute values became evident. Furthermore, some indices showed a significant increase in correlation when analyzed against shoot biomass. Notably, NDRE and SFDVI derived from the corrected spectral data exhibited expressive gains in correlation (14% and 23%, respectively) at the stem elongation stage (Table 2). This improvement occurs because, unlike the NDVI, these indices utilize the red-edge band, which is less sensitive to biomass saturation than the red band (Gitelson et al., 1996). This difference was more pronounced at stem elongation because the crop had developed a substantial amount of dry matter that covered the soil surface. This contrast was less evident in the V4 stage due to low soil coverage, and in the flowering stage, where high biomass saturation had already occurred.

TABLE 2. Coefficients of correlation between vegetation indices and wheat aboveground biomass as affected by radiometric correction.

Index	Radiometric correction	Growth Stage		
		V4	Stem elongation	Flowering
NDVI	Yes	0.47	0.77	0.78
	No	0.46	0.74	0.78
NDRE	Yes	0.39	0.79	0.76
	No	0.31	0.69	0.73
SFDVI	Yes	0.47	0.79	0.75
	No	0.44	0.64	0.73

When compared to the indices calculated without radiometric correction, the corrected indices displayed higher values across all stages and plots (Figure 1). The differences between the indices were consistent and statistically significant ($p < 0.01$). The three indices — NDRE, NDVI, and SFDVI — showed differences of 14%, 65%, and 19% in their absolute values, respectively (Table 3).

According to Zhu et al. (2024), conducting UAV campaigns under variable atmospheric conditions introduces non-systematic errors due to cloud occlusion and changes in diffuse radiation. This phenomenon explains the artificial stabilization of the uncorrected NDRE values at approximately 0.08. Without an irradiance sensor, raw spectral data is highly susceptible to flight-time illumination shifts, such as cloud shadows, which the camera misinterprets as a lack of vegetation, thereby lowering the index values during the stem elongation and flowering growth stages. Conversely, applying radiometric correction (Equation 1) mitigates these fluctuations, rendering the data reliable. Consequently, while the uncorrected index remained constant, the corrected NDRE exhibited a sharp absolute increase of 0.14 from V4 to stem elongation. This dynamic accurately reflects the real field accumulation of aboveground biomass, which increased by 1.3 t ha^{-1} from V4 to stem elongation, and reached a total gain of 4.5 t ha^{-1} by the flowering stage. These results demonstrate the necessity of incorporating an irradiance sensor for accurate data collection.

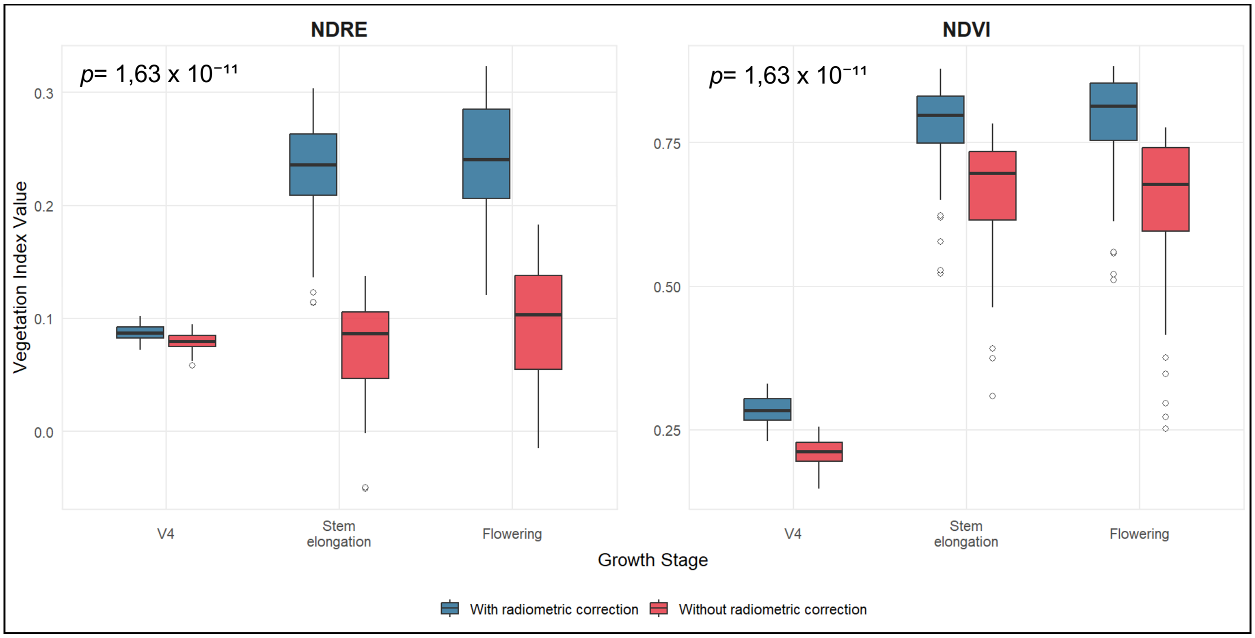

Figure 1. Boxplots of the NDRE and NDVI vegetation indices at different phenological stages of wheat (V4, stem elongation, and flowering) as affected by radiometric correction.

TABLE 3. Absolute values of vegetation indices as affected by radiometric correction.

Growth Stage	Radiometric correction	NDVI	NDRE	SFDVI
V4	Yes	0.28	0.09	0.27
	No	0.21	0.08	0.28
Stem elongation	Yes	0.77	0.23	0.41
	No	0.66	0.08	0.33
Flowering	Yes	0.79	0.24	0.42
	No	0.64	0.09	0.34

Conclusion

We concluded that applying radiometric correction based on incoming irradiance data (sunshine sensor) is essential for obtaining repeatable and comparable vegetation index values. This correction is particularly important when comparing vegetation indices across different wheat growth stages and under varying aboveground biomass conditions.

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