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Assessment of Spatiotemporal Variability in Desiccation Efficiency Using a Spray UA Through Vegetation Indices

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Abstract.

The adoption of unmanned aircraft (UA) for herbicide applications has increased substantially in recent years due to their operational flexibility, reduced soil compaction, and potential integration with precision agriculture technologies. Despite these advantages, evaluating vegetation response following desiccation remains a challenge, particularly under operational field conditions where traditional field assessments are often labor-intensive and time-consuming. In this context, satellite remote sensing offers an alternative approach for monitoring vegetation dynamics over time. This study aimed to evaluate the spatiotemporal variability of vegetation response to herbicide desiccation using vegetation indices derived from PlanetScope satellite imagery following an application performed by a spray drone.

The study was conducted in a commercial field of approximately 7 ha located in Ijaci, Minas Gerais, Brazil. Desiccation was carried out on February 19, 2026, using a DJI Agras T25P unmanned aircraft. The herbicide mixture included synthetic auxins (2,4-D, picloram, aminopyralid, and fluroxypyr) and glyphosate. Five PlanetScope Surface Reflectance 8 Bands images acquired by SuperDove satellites were selected for analysis, corresponding to pre-application conditions and 10, 15, 25, and 32 days after application (DAA). Twenty-one sampling points were randomly distributed throughout the experimental area, and a 10-m radius buffer was established around each point to extract mean vegetation index values. The Normalized

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Difference Vegetation Index (NDVI) and the Normalized Difference Red Edge Index (NDRE) were calculated for all evaluation dates. Descriptive statistics and Statistical Process Control (SPC) charts were used to characterize temporal trends, spatial variability, and process stability throughout the desiccation period.

Both vegetation indices showed a progressive reduction after herbicide application, indicating a decline in vegetation vigor and photosynthetic activity. NDRE demonstrated greater sensitivity during the initial stages of desiccation, exhibiting a reduction of approximately 33% at 10 DAA. This behavior is associated with the high sensitivity of the Red Edge spectral region to changes in chlorophyll content and physiological stress. In contrast, NDVI presented greater reductions during later stages of the process, reaching approximately 43% at 25 DAA, reflecting structural changes in the vegetation canopy, biomass reduction, and increased soil exposure. The coefficient of variation increased over time for both indices, indicating greater spatial heterogeneity in vegetation response. However, SPC charts showed that most observations remained within control limits, suggesting that the desiccation process remained statistically stable despite the increase in variability.

The results indicate that NDRE and NDVI provide complementary information regarding vegetation response to desiccation. NDRE was more effective in detecting early physiological changes, whereas NDVI was more suitable for monitoring later structural effects. Furthermore, the integration of PlanetScope imagery and statistical process control tools proved to be a promising approach for monitoring vegetation response to herbicide applications performed by spray drones under operational conditions.

Keywords.
PlanetScope; vegetation indices; NDVI; NDRE; spray drone; statistical process control..

Introduction

Chemical desiccation constitutes an essential practice in modern agricultural systems and is widely used for weed management, crop area uniformity, and optimization of mechanized operations. The efficiency of this process is directly related to the quality of herbicide application and the response of the treated vegetation, since failures in desiccation may compromise the establishment of subsequent crops, increase operational costs, and reduce the efficiency of agricultural management (Martins et al., 2021).

In recent years, the use of Unmanned Aircraft (UA) for spraying has grown significantly due to their high operational capacity, flexibility of use, and potential integration with precision agriculture strategies (Chen et al., 2021). In addition to enabling applications in hard-to-reach areas, these platforms allow greater operational precision compared to conventional methods under certain conditions (Cavalaris et al., 2022). However, environmental, operational, and vegetation-related factors may influence spray distribution and herbicide performance, resulting in heterogeneous vegetation responses within the same treated area.

The spatial and temporal variability of desiccation represents a challenge for evaluating application efficiency. Traditionally, monitoring of this process is carried out through visual assessments or point sampling in the field, methodologies that may present a high degree of subjectivity and limited ability to represent the spatial heterogeneity of the area. In this context, remote sensing has become an important tool for agricultural monitoring, allowing the acquisition of spatial and temporal information on vegetation conditions in an objective and continuous manner, demonstrating greater accuracy and consistency in detecting plant responses associated with herbicide action when compared to conventional visual assessments (Duddu et al., 2019).

Among remote sensing tools, vegetation indices stand out for providing information related to plant vigor, photosynthetic activity, and chlorophyll content. The Normalized Difference Vegetation Index (NDVI) is one of the most widely used indicators for monitoring vegetation cover conditions since the pioneering work of Rouse et al. (1974). In addition, indices that explore the Red Edge spectral region have also demonstrated greater sensitivity in detecting physiological changes associated with chlorophyll dynamics and plant stress (Gitelson and Merzlyak, 1994; Gitelson et al., 2003). Considering that desiccation promotes progressive changes in photosynthetic activity, canopy structure, and plant pigment dynamics, it is expected that such changes can be detected by different vegetation indices over time. In this context, indices such as NDVI and NDRE have the potential to monitor the spectral evolution of vegetation following herbicide application, enabling the assessment of the intensity and uniformity of vegetation cover response.

In addition to detecting these spectral changes, it is essential to understand how they are spatially distributed and temporally evolve after application. The advancement of satellite constellations with high spatial resolution and high revisit frequency, such as PlanetScope, expands the possibilities for continuous monitoring of agricultural areas, allowing the monitoring of desiccation dynamics at different stages of the process and on an operational scale. This capability enables more comprehensive analyses of vegetation response compared to the point-based evaluations traditionally conducted in the field.

Associated with remote sensing techniques, statistical tools can contribute to a more robust interpretation of the obtained data. Descriptive statistics make it possible to characterize the distribution and variability of vegetation indices, while control charts allow monitoring of process stability over time by identifying trends, deviations, and possible behavioral patterns. Additionally, spatial analysis techniques such as geostatistics and thematic map generation can assist in identifying distribution patterns of vegetation response within the evaluated area.

Despite advances in the use of vegetation indices for agricultural monitoring, studies using high-resolution orbital imagery associated with statistical process control tools to evaluate the spatiotemporal variability of desiccation efficiency are still limited (Yan et al., 2025). This gap hinders the understanding of process dynamics and the development of approaches that enable objective and continuous monitoring of vegetation response following herbicide application.

Therefore, this study aimed to evaluate the spatiotemporal variability of vegetation spectral response to desiccation using NDVI and NDRE vegetation indices derived from PlanetScope satellite imagery after herbicide application by an Unmanned Aircraft (UA). Furthermore, descriptive statistics and Statistical Process Control (SPC) tools were used to investigate temporal dynamics, spatial variability, and the stability of vegetation response throughout the desiccation process.

Materials and methods

The experiment was conducted in a commercial field of approximately 7 hectares located in the municipality of Ijaci, Minas Gerais, Brazil, near the geographic coordinates 21°07'41.25"S and 44°55'49.96"W, referenced to the WGS84 geodetic coordinate system.

The study area is situated at an average altitude of 850 m and is characterized by a Cwa climate according to the Köppen climate classification (Köppen, 1948). A single desiccation application was performed on February 19, 2026, using a DJI Agras T25P Unmanned Aircraft (UA). The operational flight parameters adopted during the application are presented in Table 1.

Table 1. Flight parameters adopted during the UAV herbicide application.

Flight altitude	6 m
Swath width	7 m
Flight speed	25 km h^{-1}
Application rate	15 L ha^{-1}
Droplet size (VMD)	420 μm

The operational parameters adopted during the application were defined according to technical recommendations for herbicide applications using agricultural UAVs. These parameters fall within the range commonly employed in low-volume spraying operations, aiming to balance operational capacity, deposition uniformity, and drift reduction. In particular, the use of coarse droplets contributes to minimizing drift losses, while the selected swath width and flight speed favor the maintenance of application uniformity. The herbicide products and application rates used in the desiccation operation are presented below:

Table 2. Herbicides used in the desiccation operation.

Commercial product	Active ingredient(s)	HRAC group / Mode of action	Application rate
Tordon ultra	2,4-D Aminopiralide	(Grupo O / HRAC 4)	1 L/Ha
Torban	Picloram Equivalente ácido	(Grupo O / HRAC 4)	3 L/Há
Planador Xt	Aminopiralide Picloram Fluroxipir-meptílico	(Grupo O / HRAC 4)	1 L/Há
Roundup ultra	Glifosato Equivalente ácido	Inibidor da EPSPS (Grupo G / HRAC 9)	5 L/Ha

The herbicide mixture used in the operation was formulated considering the high floristic heterogeneity of the experimental area, which consisted of broadleaf species, grasses, and perennial plants at different developmental stages. The combination of active ingredients with distinct control spectra aimed to enhance desiccation effectiveness under field conditions, enabling the simultaneous management of different groups of weeds present in the area.

To monitor the spectral response of vegetation following herbicide application, orbital images from the PlanetScope constellation (Planet Labs Inc., San Francisco, CA, USA) were used. The images corresponded to the Surface Reflectance 8 Bands product acquired by SuperDove (PSB.SD) satellites. This product provides eight spectral bands (Coastal Blue, Blue, Green I, Green, Yellow, Red, Red Edge, and Near Infrared – NIR), allowing the acquisition of information from different regions of the electromagnetic spectrum. The Red, Red Edge, and NIR bands were used to calculate the evaluated vegetation indices. NDVI was calculated using the Red and NIR bands, whereas NDRE was obtained using the Red Edge and NIR bands.

Five image acquisition dates were selected: 18/02/2026 (pre-application), 01/03/2026 (10 DAA), 06/03/2026 (15 DAA), 16/03/2026 (25 DAA), and 23/03/2026 (32 DAA), where DAA corresponds to days after herbicide application. The acquisition dates were defined according to the availability of cloud-free imagery over the study area, ensuring the quality of the spectral analyses. The image acquired on 18/02/2026 was used as the baseline reference because it represented the closest date to the application with suitable radiometric quality, since no cloud-free imagery was available on the day of application.

From the acquired images, the vegetation indices NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red Edge Index) were calculated and used to monitor physiological and structural changes in vegetation throughout the desiccation process.

For spatial sampling, 21 points were randomly distributed across the experimental area. A circular buffer with a radius of 10 m was established around each point and used as the sampling unit for spectral data extraction. The points were distributed to represent the spatial variability of the study area while avoiding overlap among sampling units.

Figure 1. Experimental area showing the spatial distribution of the 21 sampling points used for vegetation index extraction.

Subsequently, zonal statistics analyses were performed to obtain the mean vegetation index values within each buffer for every evaluation date. All image processing, vegetation index calculations, data extraction, and spatial analyses were conducted using QGIS software version 3.40.9.

Using the vegetation index data, the percentage reduction of each index was calculated to quantify the desiccation progression over time (Eq. 1).

Reduction (%) = [($Value_0$DAA − $Value_t$) / $Value_0$DAA] × 100 (Eq. 1)

where: $Value_0$DAA corresponds to the mean vegetation index value before desiccation, and $Value_t$ corresponds to the mean vegetation index value at the evaluated time.

The variability of vegetation response to desiccation following UAV application was assessed using descriptive statistics and Statistical Process Control (SPC). SPC is a statistical tool widely used for process quality monitoring. Individual and Moving Range control charts were employed to identify sources of variation and potential instability events not inherent to the process, which are considered critical for quality assessment (Montgomery, 2009). These charts include central lines (overall mean and average moving range), as well as upper and lower control limits (UCL and LCL, respectively), calculated based on the standard deviation of the variables (for UCL, the mean plus three standard deviations; for LCL, the mean minus three standard deviations, when greater than zero).

Results and Discussion

The vegetation indices showed a pronounced reduction following herbicide application, indicating progressive impairment of weed photosynthetic activity. NDRE was the most sensitive index to changes induced by desiccation during the initial stages following application. However, a progressive increase in the coefficients of variation of the spectral indices was observed over time, with the lowest CV recorded for NDVI at 15 DAA (Table 1). This behavior suggests an increase in the spatial heterogeneity of vegetation response to herbicide application, possibly associated with variations in spray deposition, canopy structural variability, and differences in plant susceptibility to desiccation. Skewness coefficients remained below 1 throughout all evaluation periods, indicating an approximately symmetrical data distribution and the absence of strong influence from extreme values on vegetation index estimates.

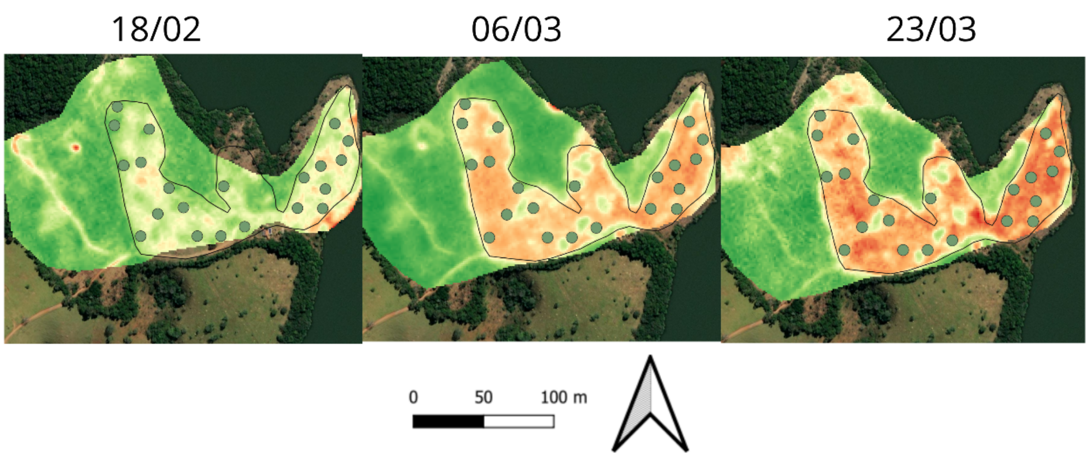

Figure 2. Spatiotemporal evolution of the Normalized Difference Vegetation Index (NDVI).

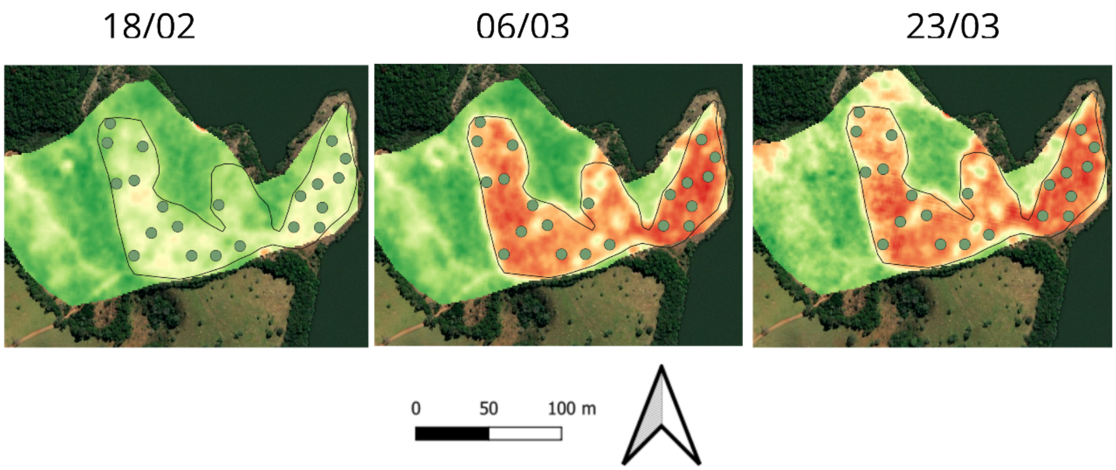

Figure 3. Spatiotemporal evolution of the Normalized Difference Red Edge Index (NDRE) throughout the desiccation period.

Table 1. Descriptive statistics of NDVI and NDRE throughout the desiccation period following herbicide application using a DJI Agras T25P UAV.

Índice	DAA	Média	EP	DP	CV (%)	Mínimo	Mediana	Máximo	Assimetria	Curtose
	0	0.77	0.00	0.04	5.73	0.69	0.77	0.86	0.01	-0.50
	10	0.54	0.01	0.05	10.80	0.45	0.53	0.65	0.42	-1.06
NDVI	15	0.54	0.01	0.04	7.85	0.47	0.54	0.62	0.21	-0.79
	25	0.43	0.01	0.07	16.54	0.33	0.42	0.58	0.58	-0.76
	32	0.43	0.01	0.08	18.34	0.32	0.41	0.61	0.67	-0.43
	0	0.53	0.01	0.03	6.95	0.47	0.53	0.60	0.23	-0.44
	10	0.35	0.01	0.04	12.08	0.29	0.34	0.43	0.45	-1.16
NDRE	15	0.34	0.01	0.04	12.44	0.28	0.33	0.43	0.60	-0.61
	25	0.31	0.01	0.05	17.27	0.24	0.31	0.42	0.56	-0.73
	32	0.32	0.01	0.05	17.24	0.24	0.31	0.45	0.65	-0.43

DAA = dias após a aplicação; EP = erro-padrão da média; DP = desvio-padrão; CV = coeficiente de variação. (n=21)

As a complement to descriptive statistics, which characterize the temporal behavior of vegetation indices, control charts enabled the assessment of the stability and spatial uniformity of vegetation response throughout the desiccation process (Figure 4).

The control chart analysis revealed marked changes in the behavior of the spectral indices following herbicide application. A pronounced reduction in the central line (mean) was observed after application, indicating a progressive decline in vegetation vigor, photosynthetic activity, and chlorophyll content, corroborating the trends identified by descriptive statistics. The lowest NDVI values were observed between 25 and 32 days after application (DAA), when the index reached relative stabilization (Figure 4). Despite this reduction, most observations remained within the established control limits, suggesting the absence of special causes of variation and indicating that vegetation response occurred in a relatively consistent manner across the treated area.

The results also indicate that the greatest changes detected by NDVI occurred during the first 10 DAA, when the index decreased by approximately 29% relative to pre-application conditions. Between 10 and 15 DAA, only minor additional reductions were observed, suggesting a temporary stabilization of the process. Subsequently, from 15 to 25 DAA, NDVI exhibited a further decline of approximately 19.8%, resulting in a total reduction of nearly 43% at 25 DAA. After this period, NDVI values remained relatively stable, indicating that the maximum effect detectable by this index had likely been reached.

This behavior is consistent with the characteristics of NDVI, which is strongly influenced by canopy structure, vegetation cover, and biomass. While herbicide-induced physiological changes occur shortly after application, substantial reductions in NDVI generally become more evident during advanced stages of desiccation, when leaf senescence, tissue necrosis, biomass reduction, and increased soil exposure alter the spectral response of the canopy.

In contrast, the moving range chart revealed an increase in variability after herbicide application, particularly during the later evaluation periods. This finding agrees with the coefficients of variation obtained through descriptive statistics and suggests increased spatial heterogeneity in vegetation response. Such variability may be associated with differences in spray deposition, canopy structural characteristics, species composition, and differential plant susceptibility to herbicides. Therefore, although desiccation promoted a substantial reduction in vegetation indices throughout the study area, the intensity of the response was not completely homogeneous, even when mean NDVI values remained relatively stable between 25 and 32 DAA.

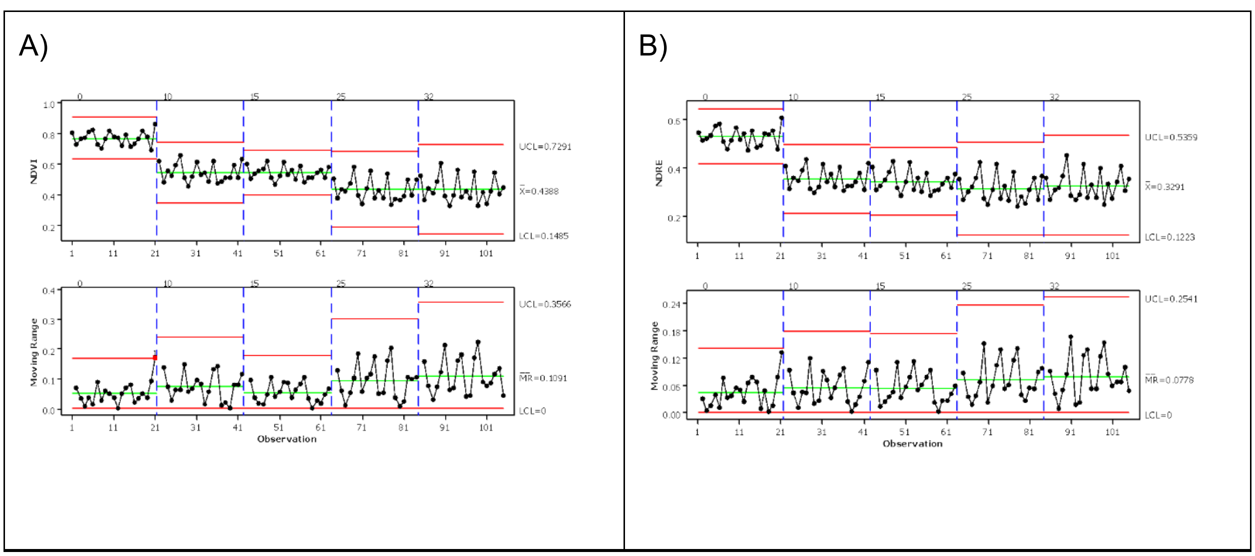

Figure 4. Individual and Moving Range Control Charts.

The NDRE exhibited greater sensitivity than NDVI for monitoring the desiccation process during the initial stages following herbicide application. The reduction of approximately 33% observed at 10 days after application demonstrates the ability of this index to detect early changes associated with vegetation physiological status. Notably, this represented the largest reduction observed among all evaluated spectral indices and assessment dates. The higher sensitivity of NDRE can be attributed to the inclusion of the Red Edge band in its formulation, which is strongly associated with chlorophyll content and photosynthetic performance. Consequently, NDRE is capable of detecting physiological changes induced by herbicides before significant structural alterations become evident in the canopy, such as chlorosis, necrosis, and biomass reduction.

This behavior may be associated with the mechanisms of action of the herbicides used during desiccation. Synthetic auxin herbicides belonging to HRAC Group 4, including 2,4-D, picloram, aminopyralid, and fluroxypyr, promote hormonal deregulation, abnormal tissue growth, and physiological disturbances that progressively impair plant metabolism. Simultaneously, glyphosate, an EPSPS inhibitor (HRAC Group 9), disrupts the shikimic acid pathway, reducing the synthesis of essential aromatic amino acids and affecting metabolic processes associated with plant growth and photosynthetic maintenance. As a result, chlorophyll degradation and reductions in photosynthetic efficiency may occur before visible symptoms become evident, favoring early detection by vegetation indices based on the Red Edge spectral region.

The reduction observed in NDRE represented the most pronounced spectral response detected during the initial phase of desiccation. Control charts further demonstrated that, despite an increase in spatial variability following herbicide application, the process remained statistically stable, with no observations exceeding the control limits. These results indicate that NDRE has strong potential for monitoring the physiological response of vegetation subjected to UAV-based desiccation, allowing both the quantification of early changes associated with reductions in photosynthetic activity and the assessment of spatial uniformity during the first stages after application.

In contrast, at 25 and 32 days after application, NDVI exhibited greater cumulative reductions than NDRE, reaching values close to 43%. This behavior suggests that NDVI is more strongly influenced by structural changes in vegetation, including reductions in green biomass, canopy cover loss, and canopy degradation. As the initial physiological effects progress into visible symptoms such as chlorosis, senescence, and tissue necrosis, greater soil exposure and reductions in canopy integrity occur, directly affecting the spectral response of the red and near-infrared bands used in NDVI calculations. Thus, while NDRE proved more sensitive for detecting the initial physiological effects induced by herbicides, NDVI was more effective in monitoring the later stages of desiccation associated with structural vegetation degradation.

Overall, the results indicate that NDRE and NDVI provide complementary information throughout the desiccation process. NDRE demonstrated greater potential for early detection of vegetation physiological responses following herbicide application, whereas NDVI was more suitable for monitoring advanced stages of desiccation characterized by more pronounced structural changes in vegetation cover.

Conclusions

The results suggest that desiccation occurred in two distinct stages. Initially, physiological changes associated with reductions in photosynthetic activity and chlorophyll degradation predominated, being detected primarily by NDRE. Subsequently, structural changes in the vegetation canopy, including reductions in green biomass and increased soil exposure, became more pronounced and were more effectively captured by NDVI. This differentiated temporal response demonstrates that the combined use of NDRE and NDVI enables the monitoring of complementary stages of the desiccation process.

Furthermore, the integration of vegetation indices with Statistical Process Control (SPC) tools proved useful for evaluating both the temporal evolution and the spatial variability of vegetation response following herbicide application by UAV. The control charts allowed the identification of changes in process behavior over time while providing information regarding the stability and uniformity of vegetation response throughout the treated area.

Although field assessments were not conducted to validate the observed spectral responses, the results demonstrate the potential of PlanetScope imagery for operational-scale spatiotemporal monitoring of herbicide desiccation. The approach presented here represents a promising alternative for remote monitoring programs aimed at evaluating vegetation response following UAV-based herbicide applications and may support future studies focused on application quality, operational performance, and precision agriculture management.

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