91. Using satellite remote sensing for evaluating herbicide efficacy in maize (*Zea mays*)

S. Aharon[1,2,*], R. Lati[2], H. Eizenberg[2] and Y. Cohen[3]
[1]*The Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, The Hebrew University of Jerusalem, Jerusalem, Israel; * Shlomiaharon123@gmail.com*
[2]*Department of Phytopathology and Weed Research, Newe Ya'ar Research Center, Agricultural Research Organization, Ramat Yishay, Israel*
[3]*Agricultural and Biosystems Engineering, Agricultural Research Organization, Volcani Center, Rishon LeZion, Israel*

Abstract

Early detection of herbicide efficacy via satellite remote sensing can enhance weed management. However, their spatial resolution limits weed suppression assessment. This study integrates spatial, spectral, and temporal metrics to estimate weed control efficacy in maize using PlanetScope imagery. A field experiment with four treatments (two herbicides, no weeds intervention, and without weeds) was analyzed using grey level co-occurrence matrix (GLCM). Results show that variance in GLCM features, mainly based near infra-red (NIR) and green bands, was most sensitive to detecting weed suppression over time. These results offer a potential new tool for assessing weed control using satellite data.

Keywords: herbicide efficacy, maize, satellite imagery, spectral diversity

Introduction

Crop yield losses due to weeds, which compete with crops for nutrients, water, space and sunlight, have been widely documented globally across various crops. As a result, effective weed management is a crucial component of agricultural production (Oerke, 2006)especially weeds, pathogens and animal pests. Crop losses due to these harmful organisms can be substantial and may be prevented, or reduced, by crop protection measures. An overview is given on different types of crop losses as well as on various methods of pest control developed during the last century.Estimates on potential and actual losses despite the current crop protection practices are given for wheat, rice, maize, potatoes, soybeans, and cotton for the period 2001–03 on a regional basis (19 regions. Globally, herbicide application is preferred over other weed management options in most agricultural regions to achieve optimum weed control and higher yields with the lowest economic cost (Parven *et al.*, 2024). However, the future of this weed management program is currently uncertain. The excessive use of herbicides has resulted in the development of herbicide-resistant weed populations, which risks the overall efficacy of current management (Heap, 2014). In addition, this trend may also be affected by climatic changes, influencing plant detoxification and intensifying the risk of non-target site herbicide resistance evolution (Matzrafi *et al.*, 2016). Accordingly, evaluating and monitoring historical and real-time herbicide efficacy using empirical tools is crucial. Understanding the dynamics of herbicide efficacy will enable farmers to make data-driven decisions, optimize herbicide application, and ensure the long-term sustainability of weed management programs. The last development of remote sensing platforms, such as unmanned aerial vehicles (UAVs) and high-resolution satellite imagery, have significantly advanced weed mapping and precision herbicide application (de Villiers *et al.*, 2023). However, an area that remains less explored is the evaluation of herbicide efficacy using satellite remote sensing, specifically, estimating the weed damage status after herbicide application in crop fields using satellite imagery analysis. A key challenge in this goal is based on satellite imagery's relatively low spatial resolution compared to UAV data. While UAVs provide high-resolution images (approx. 1 cm) that can capture fine details, such as individual weeds or small patches, Planetscope satellite imagery, the most available high-resolution satellite for farmers today often lacks the detail required for weed detection (approx. 300 cm) (Rösch *et al.*, 2022). Due to this lower resolution, spectral signals from healthy weeds, damaged weeds, crops, and soil mix make it challenging to separate these components and estimate the weed damage/healthy status. Addressing this limitation involves drawing inspiration from field scenarios, where the effects of herbicide application change over time. In areas where herbicide application effectively suppresses weeds, biodiversity decreases due to the removal of weeds and establishment of the crops, resulting in greater homogeneity and uniformity across the field during a defined time series. In contrast, in areas with low herbicide efficacy, weeds and crops lead to reduced homogeneity over the same period. This spatial variability is hypothesized to be quantifiable through the Gray Level Co-occurrence Matrix (GLCM), a well-established method in remote sensing for analyzing image texture in agriculture fields (Romano *et al.*, 2021). Texture analysis enhances imagery with additional information that reflects these spatial patterns by capturing vegetation structure and composition variations (Kupidura, 2019). Considering these motivations, a new approach was proposed for describing herbicide efficacy zones using satellite spectral indices. The study aimed to identify a methodology based on a time series of high-resolution observations from satellites of eight spectral bands and eight textural features to estimate the herbicide effects in maize fields.

Materials and methods

Study site and experimental design

A field experiment was carried out to describe the scenario differences of weed control. The experiment was held at the Newe Ya'ar research station, the northern branch of the Israel Agricultural Research Organization (ARO). Two hectares of silage maize were divided into four treatments using a randomized block design with five replicates (Figure 1). Maize seeds were sown at a density of nine plants per 5-meter row. Weed infestation was based on the natural seed bank. Control treatments were classified into positive and negative controls. The positive control consisted of a weed-free treatment, achieved by applying preemergence herbicides – Metolachlor-S (1195 g a.i./ha) and Atrazine (400 g a.i./ha) immediately after sowing on 30 July 2023 to prevent weed emergence. The negative control represented an untreated scenario, where maize and weeds were allowed to establish without weed management, simulating complete weed control failure. Postemergence herbicide treatments included two distinct modes of action. The first targeted the acetolactate synthase (ALS) enzyme, with foramsulfuron applied at a rate of 45 g a.i./ha. The second mode of action involved the inhibition of 4-hydroxyphenylpyruvate dioxygenase (HPPD), an enzyme essential for carotenoid biosynthesis, using tembotrione at a rate of 94.5 g a.i./ha. All postemergence herbicides were applied at the V2–V4 maize growth stage using a tractor-mounted commercial sprayer. The maize variety used in the study was resistant to both herbicides.

Satellite data

Five cloud-free PlanetScope image datasets were acquired in the summer of 2023 (21 August, 24 August, 30 August, 4 September and 15 September). They were correlated to the day of herbicide application (time 0) and days after the spraying (DASp) herbicide: 3, 10, 14 and 25 DASp. PlanetScope is a satellite constellation of over 200 CubeSats (Doves) flying in a near-polar orbit at 475 km altitude. The imagery used in this study was acquired by the SuperDove (Dove-R) satellites, which provide eight spectral bands. PlanetScope imagery is acquired at a spatial resolution of 3.7 m and eight bands (costal blue, wavelength λ=431–452 nm, Blue λ=455–515 nm, Green λ=513–549 nm, Green2 λ=547–583 nm, Yellow λ=600–620 nm, Red λ=650-680 nm, Red edge λ=697–713 nm and near-infrared (NIR) λ=845–885 nm). All images were obtained from the Planet web platform and were radiometric, orthorectified, and atmospherically corrected using the "Analytic Ortho Scene" surface reflectance product (resampled to 3 m).

Texture analysis

All band maps obtained from the time series were processed to calculate the GLCM indices developed by Haralick *et al.* (1973) to characterize heterogeneous surface samples and the inhomogeneity of digital images. GLCM evaluates the spatial relationship between pixel intensity values by computing the frequency of specific gray-level pairs within a defined window (batch pixels, can be 3 by 3, 5 by 5, etc.), distance, and angular relationship. The resulting metrics quantify spatial-spectral patterns, providing insights into the texture and composition of the imagery. The adjacency of the pixels is defined as an angle of 45 degrees. Windows size was empirically set to 3 by 3 pixels. Eight GLCM indices were selected and presented in Table 1. The GLCM calculations for this analysis were performed using the glcm package in R Studio (Zvoleff, 2015)

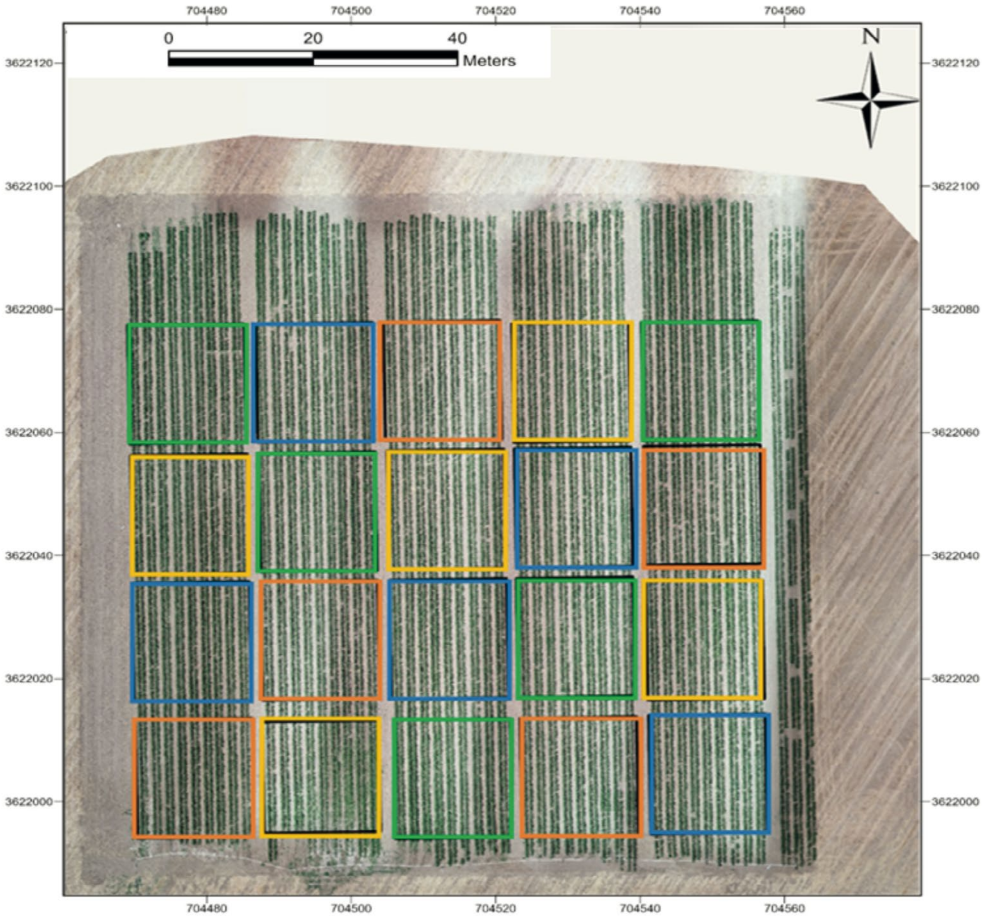

Figure 1. The crop field experiment. Each replicate is marked with a polygon, and each treatment is described using a coloured polygon. Blue is ALS herbicide, Yellow is HPPD herbicide, orange is maize without weeds, and green is maize and weeds without any weed control treatment. Each replicate was 20 m×25 m with an area of approx. 0.05 ha. The sowing directions and the size of the replicates were designed to fit the orientation of the PlanetScope satellite image.

Table 1. A list of GLCM texture features extracted from eight planetscope bands and used in this analysis.

Feature	Description
Contrast	Measures the intensity contrast between a pixel and its neighbor over the entire image.
Correlation	Evaluates the correlation between pixel pairs in the image.
Entropy	Quantifies the randomness in the image texture, with higher values indicating higher randomness.
Homogeneity	Assesses the similarity of pixel values, with higher values for more homogeneous images.
Variance	Measures the dispersion of pixel intensities around the mean value.
Mean	Indicates the average pixel value in the image.
Dissimilarity	Measures the variation in pixel pairs, representing the average difference between pixel pairs.
Autocorrelation	Evaluates the strength of the linear relationship between pixel pairs.

Derived from Haralick *et al.* (1973).

Ground truth assessment

Ground truth data were collected using an unmanned aerial vehicle (UAV) equipped with a dual MicaSense multispectral sensor to validate the weed status changes. Using the UAV Matrice 300 RTK, flights were conducted at an altitude of 30 m, capturing high-resolution multispectral imagery (0.015 m) on three separate dates to monitor changes in weed damage over time (0, 3, and 10 days after herbicide spraying). The imagery was processed using Pix4D software to create orthomosaics for each flight, including radiometric and spatial corrects. The reflectance values based on each orthomosaic were classified in ArcGIS Pro using a support vector machine (SVM) model. The model categorized pixels into four distinct classes: healthy weeds, damaged weeds, soil, and maize. The classified weed coverage data (healthy and damaged) were captured for further analysis. Boxplots were generated to evaluate differences between treatments and within treatments.

Statistical analysis

A one-way analysis of variance (ANOVA) was performed to evaluate differences between treatments for textural features derived from the GLCM across multiple spectral bands. The analysis was conducted separately for each spectral band and textural feature combination to determine whether the treatments significantly affected the computed textural features. The test did not include the maize with free weed treatment. Following the ANOVA, textural features displaying the highest differences between treatments were selected for further analysis. Dynamic curves were generated for these features to examine temporal patterns across treatments. The curves were modelled using a Generalized linear model (GLM) to capture the temporal dynamics and assess trends over time.

Results

GLCM features reveals changes in weed suppression detection

Figure 2 highlights differences in textural features across various spectral bands when comparing herbicide-treated areas to untreated (no weed control) pixels in 10 DASp. Among these features, only three band-feature combinations showed statistically significant differences (p<0.05): the mean and variance in the NIR and green bands. These findings suggest that integrating spectral and textural features from specific bands can effectively distinguish between herbicide-treated and untreated areas.

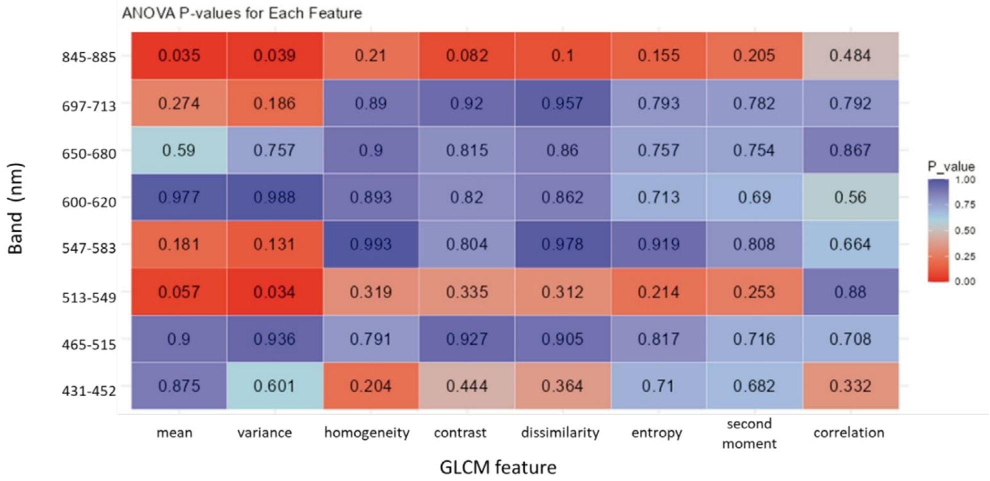

Figure 2. ANOVA for GLCM features across different spectral bands to differentiate between with and without herbicide's application treatments.

How does satellite pixel behaviour change over time following herbicide application?

Over time, satellite pixel behaviour analysis revealed trends across different metrics, including GLCM variance based green and NIR band, and GLCM mean based NIR band. In the green band, both herbicide-treated curves show initially increased variance, particularly during the first 7 days after application. However, a decrease in variance values was observed after this initial period, indicating reduced spatial heterogeneity and improved uniformity, indicating the effect of the herbicide. In contrast, the control plots exhibited a steady increase in variance values over time, reflecting growing spatial variability due to the establishment and spread of weeds. In the NIR band, variance values in herbicide-treated plots remained relatively stable throughout the observation period, indicating consistent pixel intensity and spatial uniformity. Conversely, variance values in the control plots increased over time, reflecting growing spatial variability caused by weed establishment and spread. Similarly, the GLCM mean features for the NIR band in herbicide-treated plots remained steady and closely aligned, reflecting minimal treatment differences and consistent spatial patterns, while the GLCM mean features of control plots increased over time, highlighting growing heterogeneity associated with uncontrolled weed growth. Temporal analysis of Normalized Difference Vegetation Index (NDVI) values revealed no significant differences between treatments, suggesting that NDVI alone may not sufficiently capture herbicide application's spatial and temporal effects.

Weed coverage in different treatments from UAV imagery

Figure 4 shows the dynamics of healthy weed coverage across treatments and observation dates based on pixel classification from a multispectral data-based UAV. On the day of spraying (day 0), ANOVA test showed no significant differences between the treatments (p=0.37). However, the HPPD treatment exhibited higher weed coverage compared to the ALS treatment and the control (Figure 4a). At 3 DASp, significant differences were shown (p<0.0.001). The ALS-treated plots showed lower healthy weed coverage compared to the HPPD-treated plots. The control plots displayed a slight reduction in weed coverage but remained comparable to 0 DASp levels (Figure 3b). At 10 DASp, healthy weed coverage in both herbicide-treated plots dropped close to zero, reflecting total weed suppression. In contrast, the control plots continued to maintain high levels of healthy weed coverage, similar to 0 DASp, indicating no weed management effects (Figure 4c). all classifications achieved an accuracy of over 0.95, underscoring the reliability of the UAV multispectral sensor-based ground truth data.

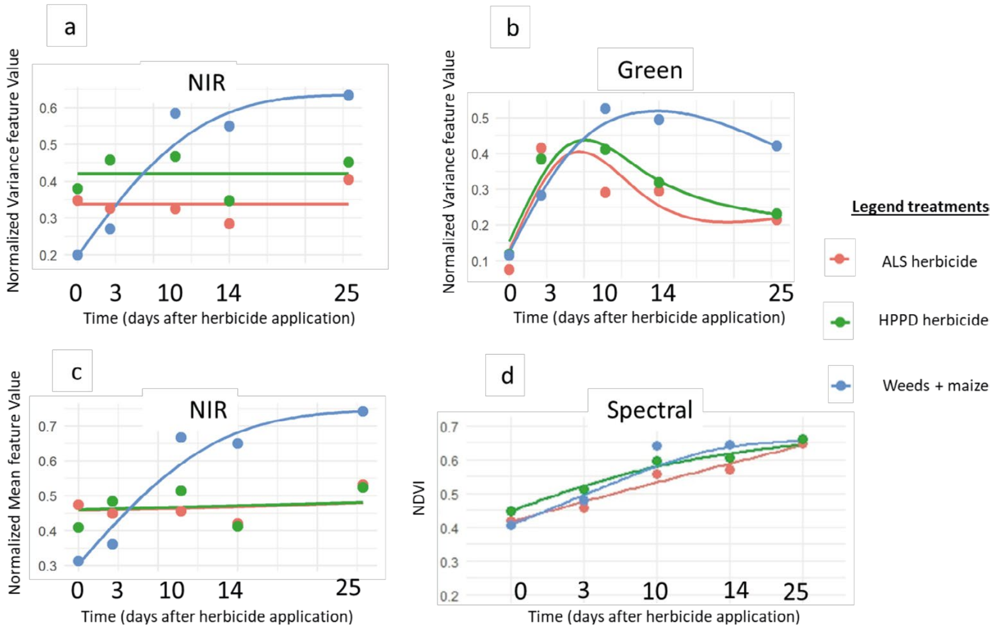

Figure 3. GLCM features values of treated and untreated areas in different days after herbicide application: (a) GLCM variance feature values of the NIR band; (b) GLCM variance feature values based green band; (c) GLCM variance feature values based NIR band, (c) mean GLCM feature values based NIR band and (d) NDVI values for reference. The x-axis represents the days after herbicide application.

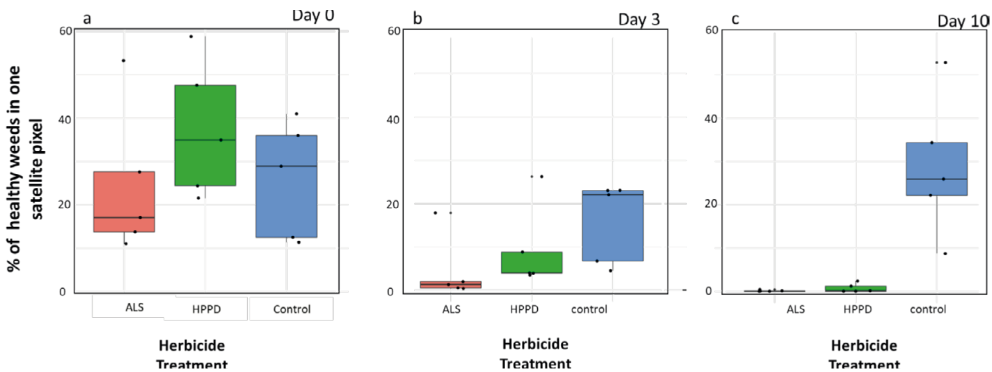

Figure 4. Weed relative coverage (% of satellite pixel area) in different treatments derived from three UAV multi-spectral images. (a), herbicide application day, (b) 3 day after herbicide application and (c) 10 days after herbicide application.

Discussion

This study demonstrated the effectiveness of using satellite imagery to evaluate the effects of herbicide treatments on weed suppression in maize fields. The methods presented here expand the capabilities of herbicide efficacy assessment by providing spectral-spatial-temporal monitoring for weed damage estimation dynamics after herbicide application. The variance GLCM feature, which derives from the green band, shows the dynamic that confirms our research hypothesis. The curve decreases over time after 7 days from the herbicide application for both herbicide treatments (Figure 3b), expressing a reduction of biodiversity in the field, fewer weeds, and establishment of the maize, while the control treatment shows opposite trends. The initial increase observed in the curve during the first 7 days can be explained by the herbicide's reaction time in affecting the weeds. The herbicides used in this study require a few days to be absorbed, translocated within the plant, and disrupt their target pathways. This delay explains the time needed before visible symptoms of weed death become apparent, as shown in Figure 4b, where 30% of weeds under the HPPD treatment are still classified as healthy. Another possible explanation is the increased diversity caused by a mix of damaged weeds, which continue to reflect light due to partial degradation combined with maize. Over time, as damaged weeds deteriorate further and their chlorophyll content decreases, light absorption by leaves is reduced, leading to weaker reflectance, a decrease observed after seven days, and an overall increase in field diversity. Overall, this ability to detect changes involving spectral, spatial, and temporal data aligns with the study of Romano *et al.* (2021), which demonstrated the utility of satellite-derived spectral-spatial and temporal for estimating wheat yield maps. These researchers report that the addition of analysis performed with the GLCM method allowed for the further improvement of the estimate's accuracy and better definition of homogeneous productivity zones of durum wheat fields. Another study reported that including GLCM features with spectral data significantly improved the accuracy of classification mapping mountain pine stands using PlanetScope satellite imagery (Rösch *et al.* 2022).

Conclusions

This study highlights the potential of using remote sensing satellites to monitor herbicide efficacy, offering practical benefits for farmers and researchers. Farmers can utilize this approach to assess the effectiveness of their herbicide applications. If areas of low efficacy are detected, they can take targeted actions to address specific problem zones, optimizing their weed management strategies. Additionally, farmers can leverage historical field data to analyze trends in herbicide efficacy, enabling data-driven decisions regarding future herbicide applications. From a research perspective, this tool provides a means to analyze historical field data to identify factors influencing herbicide efficacy in crop systems, such as crop, herbicide, and tillage rotation. These insights can contribute to improved weed management practices and sustainable agricultural systems. This study represents an initial result. Future work will validate this methodology in commercial fields to ensure its practical applicability in real-world farming scenarios.

References

de Villiers, C., Munghemezulu, C., Chirima, G.J., Tesfamichael, S.G., & Mashaba-Munghemezulu, Z. (2023). Crop classification and weed detection in rainfed maize crops using UAV and PlanetScope imagery. Abstracts of the ICA, 6, 1–1. https://doi.org/10.5194/ica-abs-6-50-2023

Haralick, R.M., Shanmugam, K., & Dinstein, I.H. (1973). Textural features for hyperspectral pixel classification. Lecture Notes in Computer Science, 5524, 208–216. https://doi.org/10.1007/978-3-642-02172-5_28

Heap, I. (2014). Global perspective of herbicide-resistant weeds. Pest Management Science, 70(9), 1306–1315. https://doi.org/10.1002/ps.3696

Kupidura, P. (2019). The comparison of different methods of texture analysis for their efficacy for land use classification in satellite imagery. Remote Sensing, 11(10), 1233. https://doi.org/10.3390/rs11101233

Matzrafi, M., Seiwert, B., Reemtsma, T., Rubin, B., & Peleg, Z. (2016). Climate change increases the risk of herbicide-resistant weeds due to enhanced detoxification. Planta, 244(6), 1217–1227. https://doi.org/10.1007/s00425-016-2577-4

Oerke, E.C. (2006). Crop losses to pests. Journal of Agricultural Science, 144(1), 31–43. https://doi.org/10.1017/S0021859605005708

Parven, A., Meftaul, I.M., Venkateswarlu, K., & Megharaj, M. (2024). Herbicides in modern sustainable agriculture: environmental fate, ecological implications, and human health concerns. International Journal of Environmental Science and Technology, 22, 1181–1202. https://doi.org/10.1007/s13762-024-05818-y

Romano, E., Bergonzoli, S., Pecorella, I., Bisaglia, C., & de Vita, P. (2021). Methodology for the definition of durum wheat yield homogeneous zones by using satellite spectral indices. Remote Sensing, 13(11) 2036.

Rösch, M., Sonnenschein, R., Buchelt, S., & Ullmann, T. (2022). Comparing planetscope and sentinel-2 imagery for mapping mountain pines in the Sarntal Alps, Italy. Remote Sensing, 14(13), 1–24. https://doi.org/10.3390/rs14133190

Zvoleff, A. (2015). Calculate textures from grey-level co-occurrence matrices (glcms) in R, R Package Version 0.3.1. Available online at http://cran.r-project.org/src/contrib/Archive/glmc (accessed February 2025)