

INTEGRATED UAV AND GIS-BASED TECHNOLOGIES FOR EARLY DETECTION AND SITE-SPECIFIC MANAGEMENT OF WEEDS IN ARABLE CROPS UNDER CLIMATE CHANGE CONDITIONS

Claudiu-Daniel UTOIU¹, Bogdan DRAGANCEA², Elena UTOIU², Mihai GÎDEA¹

¹University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd,
District 1, Bucharest, Romania

²National Institute of Research & Development For Food Bioresources,
6 Dinu Vintila Street, District 2, Bucharest, Romania

Corresponding author email: claudiu.utoiu@gmail.com

Abstract

Climate change and increasing environmental constraints require more precise and adaptive approaches to crop protection. This study investigates the use of integrated unmanned aerial vehicle (UAV) imagery and Geographic Information Systems (GIS) for early weed detection and site-specific management in arable crops. Multispectral UAV data were collected during key crop development stages and processed to produce high-resolution RGB, NIR and vegetation index-based orthophotoplans. Spatial analysis techniques were applied to distinguish crop rows from weed-infested areas and to evaluate the intensity and distribution of infestations. The results show that combining UAV-derived data with GIS analysis allows accurate identification of weed patterns at field level and supports targeted management decisions. Field observations were used to validate remote sensing outputs and to improve interpretation accuracy. The proposed approach contributes to reducing unnecessary agrochemical applications while maintaining effective weed control. Overall, the study demonstrates that UAV-GIS integration can provide a reliable decision-support tool for sustainable weed management and climate-resilient arable farming systems.

Key words: precision agriculture, UAV, GIS, weed detection, climate change.

INTRODUCTION

Climate change, rising input costs, and tightening environmental constraints are increasing the need for weed-management strategies that are both agronomically effective and more selective in their use of herbicides. In arable farming systems, weeds remain one of the principal biological constraints to crop establishment and productivity because they compete with crops for light, water, nutrients, and space. In this context, precision weed management is increasingly regarded as an operational extension of integrated weed management, since it combines monitoring, spatial targeting, and reduced-input intervention while maintaining weed-control effectiveness (Monteiro & Santos, 2022; Gerhards et al., 2022).

Recent advances in unmanned aerial vehicle technology, multispectral sensing, and GIS-based spatial analysis have made it possible to detect within-field heterogeneity at a much finer scale than conventional whole-field scouting.

UAV-derived orthomosaics can reveal crop-row continuity, canopy gaps, border effects, and anomalous vegetation patches at centimeter-level resolution, while GIS provides the framework needed to organize, compare, and translate those raster products into management-oriented spatial layers. Recent studies show that UAV imagery can support both vegetation-index-based interpretation and AI-assisted weed classification, although performance still depends strongly on crop stage, image resolution, and the degree of spectral similarity between the crop and the weeds (Yu et al., 2022; Shahi et al., 2023; Alirezazadeh et al., 2024). The scientific rationale for this approach lies in the fact that weeds are rarely distributed uniformly across a field. Instead, infestations tend to form spatially explicit patches influenced by field margins, traffic lines, emergence variability, and local soil conditions. In such circumstances, uniform herbicide application may be less efficient than an approach that first identifies anomaly zones and only then applies targeted intervention. This logic is central to

site-specific weed management and has been repeatedly emphasized in recent reviews dealing with sustainable weed control and precision agriculture (Monteiro & Santos, 2022; Gerhards et al., 2022).

The present study evaluates an integrated UAV-GIS workflow for early weed screening and site-specific management in experimental arable plots under climate-variability conditions. The final update focuses on the Hârşova orthophotoplan set acquired in the Topzon-supported campaign and interpreted within the broader research context of INSAC-AGRI and ADER 2.1.4. The objective was to assess whether high-resolution orthomosaics, multispectral layers, and zonation products could reliably delineate probable weed-prone sectors, describe their spatial distribution at plot level, and support more precise intervention decisions than a uniform parcel-wide approach.

MATERIALS AND METHODS

The study was carried out in experimental arable plots from Romania, with the detailed image-based update referring to the Hârşova parcel (Figure 1). For the final interpretation, the image set included RGB orthomosaics dated 1 April 2024 and 29 September 2024, grayscale multispectral orthomosaics representing the green, red, red-edge, and near-infrared bands, as well as derivative products including TGI, VARI, and a parcel zonation map. The Hârşova orthophotoplans were acquired at approximately 20 m above ground level using nadir image capture, which provided sufficient spatial resolution to observe plot boundaries, canopy continuity, and localized anomaly patches at the scale required for experimental weed screening. UAV-based weed-detection studies similarly rely on high-resolution orthomosaics to separate crop, soil, and anomalous vegetation before or around early canopy development stages (Yu et al., 2022; Nikolić et al., 2021).

The image-processing workflow followed the logic of a Pix4D-GIS pipeline. Orthomosaics and spectral layers were generated and exported as georeferenced plot-level products, after which the raster layers were interpreted in a GIS environment together with experimental plot boundaries. RGB imagery was used to assess visible canopy continuity, parcel-edge effects,

and the geometry of the experimental strips. The multispectral layers and derived TGI, VARI, and zonation products were then compared in order to identify sectors with persistent canopy heterogeneity or abnormal vegetation signatures. This procedure follows the broader recommendation from recent precision-weed-management literature that spectral indices should be interpreted together with spatial structure and agronomic context rather than as stand-alone evidence of weed occurrence (Monteiro & Santos, 2022; Gerhards et al., 2022; Alirezazadeh et al., 2024).

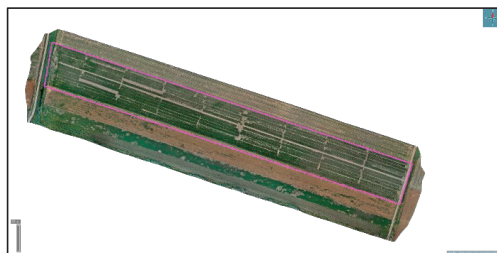


Figure 1. Experimental layout of the Hârşova parcel derived from UAV orthomosaic imagery, showing the delineated plots used for parcel-level interpretation and zonation

In the present update, weed analysis was performed as image-based anomaly mapping. Accordingly, low-vigour and heterogeneous zones were interpreted as probable weed-pressure areas only when comparable spatial signals were visible across several outputs, namely the dated RGB orthomosaics, the TGI/VARI layers, and the final zonation raster. Species-level weed identification was not inferred directly from the images alone. Instead, the workflow was designed as a screening and prioritization step for site-specific field inspection, which is consistent with both rule-based and AI-assisted weed-mapping studies that emphasize the importance of verification under real field conditions (Shahi et al., 2023; Alirezazadeh et al., 2024). For the zonation product, the 20 delineated experimental plots were treated as the basic analytical units. Pixel shares of the main vigour classes were summarized at parcel level to distinguish the more homogeneous sectors from the more heterogeneous ones. A conservative hotspot threshold was defined as the low-to-poor classes, while a broader scouting threshold also

included the moderate class. This classification logic is appropriate for site-specific weed management because image-derived maps are used first to direct scouting and then, if agronomically confirmed, to support localized mechanical or chemical intervention instead of blanket treatment (Gerhards et al., 2022; Monteiro & Santos, 2022; Nikolić et al., 2021).

RESULTS AND DISCUSSIONS

The uploaded orthophotoplans indicate that vegetation heterogeneity in the Hârşova parcel was spatially concentrated rather than uniformly distributed (Figures 2, 3). The dated RGB orthomosaics show stronger non-crop vegetation pressure on the north-western and western side of the experimental strip than along the opposite border. Inside the experimental layout, the central and lower sections of the parcel appeared visually more uniform, whereas the upper headland block and the transition zone between the narrow upper strips and the main plot sequence displayed the clearest canopy irregularities, border effects, and probable reinfestation pressure from adjacent unmanaged areas.

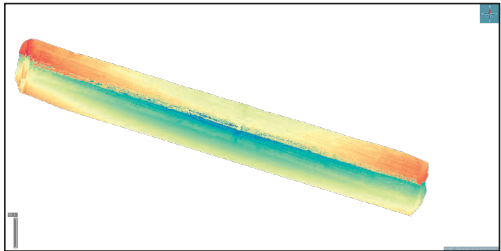


Figure 2. TGI-based visualization of canopy heterogeneity and border-related anomaly zones in the Hârşova experimental parcel

The parcel-based zonation provided the clearest quantitative summary of this pattern. Across the 20 delineated plot interiors, 45.4% of pixels were assigned to the high-vigour class and 32.5% to the good-vigour class. The moderate class represented 17.5% of the mapped interior, while the conservative hotspot classes (low, very low, poor, and very poor) summed to 4.6%. Under a strict interpretation, therefore, only a small fraction of the parcel behaved as a strong anomaly hotspot; under a scouting-oriented interpretation that also includes the moderate

class, 22.1% of the parcel should be treated as a priority zone for field checking.

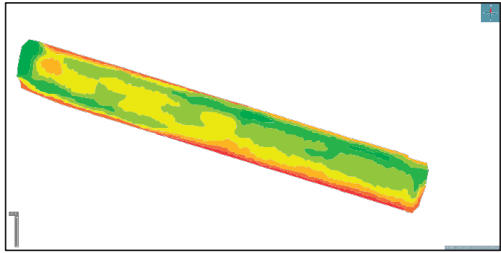


Figure 3. Parcel zonation derived from UAV imagery, highlighting high-, moderate-, and low-vigour sectors used to prioritize scouting and localized weed-management decisions

Table 1. Image-based zonation summary of the Hârşova experimental parcel

Indicator	Value	Interpretation
Delineated experimental plots	20	Parcel-level units used in the zonation analysis
High-vigour class	45.4%	Stable canopy sectors
Good-vigour class	32.5%	Generally acceptable crop performance
Moderate class	17.5%	Parcels/sectors that should be prioritized for scouting if a broader screening threshold is used
Low-to-poor classes	4.6%	Conservative hotspot estimate for probable weed/stress anomalies
High + good classes	77.9%	Majority of the parcel does not support blanket treatment logic
Plots with >80% high + good classes	11/20	Predominantly uniform plots
Plots with >5% low-to-poor share	7/20	Localized heterogeneity requiring closer field checking
Upper block high + good / moderate / low-to-poor	60.0% / 33.8% / 6.2%	More heterogeneous sector, likely influenced by headland and border effects
Main block high + good / moderate / low-to-poor	82.0% / 13.8% / 4.2%	More stable sector with fewer strong anomaly zones

The internal distribution of anomaly classes was also informative. The upper five plots were notably more heterogeneous than the remaining fifteen plots. In the upper block, the combined high-to-good classes accounted for 60.0% of the mapped interior, the moderate class accounted for 33.8%, and the low-to-poor classes accounted for 6.2%. In the main plot block, by contrast, the high-to-good classes reached 82.0%, the moderate class decreased to 13.8%, and the low-to-poor classes accounted for 4.2%(Table 1). At whole-plot level, 11 of the 20

plots were dominated by more than 80% high-to-good classes, and only one plot exceeded 10% low-to-poor classes. This indicates that the principal weed- or stress-prone sectors were concentrated in the upper headland and transition areas rather than across the entire parcel. The TGI, VARI, and zonation outputs supported the same agronomic interpretation. TGI emphasized stronger contrast along parcel borders and around the north-western external vegetation source. The zonation image showed that red-to-orange anomaly classes were concentrated mainly outside the parcel or immediately adjacent to parcel margins, while green classes dominated the interior of most plots. This is consistent with the broader literature showing that UAV-based weed screening performs best when crop–weed and crop–soil contrast remains visible and becomes more uncertain when crop and weed signatures start to overlap or when other stress factors produce similar spectral responses (Yu et al., 2022; Shahi et al., 2023; Alirezadeh et al., 2024).

An important consequence for interpretation is that the mapped anomaly classes should not be equated automatically with botanical weed identity. Some discontinuities visible in the uploaded products may also reflect local emergence variability, traffic-induced compaction, moisture gradients, or border competition. Even so, the orthophotoplans clearly support a site-specific management logic, because they show that the parcel does not require uniform treatment. The image evidence instead prioritizes the upper parcel sector, the border-adjacent strips, and the transition zone as the most likely targets for intensified scouting and, if field confirmation supports it, localized intervention. This conclusion is fully aligned with the recent literature on precision weed management, which links spatial targeting to lower input consumption and more sustainable weed control (Monteiro & Santos, 2022; Gerhards et al., 2022).

The practical relevance of this interpretation is strengthened by comparable UAV-based studies that have moved from weed detection to prescription-map generation. In maize, for example, Nikolić et al. (2021) combined UAV imagery with VARI- and ANN-based classification and reported sprayed-area

reductions ranging from 42.43% to 87.82% for ANN and from 65.29% to 93.35% for VARI, depending on decision threshold. Although the present Hârşova dataset was interpreted conservatively and without claiming species-level classification, it points in the same direction: localized anomaly mapping can support targeted scouting and potentially reduce the need for blanket herbicide application.

The agronomic significance of these findings lies in the potential to support site-specific weed management rather than uniform field-wide spraying. By identifying where intervention is needed, the proposed workflow can reduce unnecessary agrochemical use, lower operational costs, and improve the environmental performance of crop protection strategies. This direction is consistent with both recent scientific literature and the goals of current precision agriculture demonstrative projects. At the same time, the results emphasize that vegetation indices should be interpreted within a broader agronomic and spatial framework, because weed pressure is only one of several drivers of spectral variability in arable fields. For that reason, the most robust decision-support strategy combines UAV imagery, GIS, and field validation in an iterative workflow.

CONCLUSIONS

The updated orthophotoplan analysis substantially strengthens the article because it replaces generic statements with parcel-specific evidence. In the Hârşova experimental parcel, image-based zonation showed that 77.9% of plot interiors belonged to high-to-good vigour classes, while the conservative low-to-poor hotspot classes represented only 4.6% of the mapped area. The strongest anomalies were concentrated in the upper headland block, the transition zone between plot groups, and the external parcel margins. Under these conditions, UAV-GIS integration clearly supports a site-specific management strategy rather than a uniform parcel-wide intervention.

The results also confirm that UAV products are most valuable when used as a first-line decision-support tool. The orthophotoplans, multispectral layers, and zonation output made it possible to rank sectors by probable weed or canopy-stress risk, thereby improving the efficiency of field

scouting. At the same time, the image evidence should be interpreted conservatively, because canopy anomalies may also arise from emergence variability, compaction, or local moisture effects. For that reason, the strongest scientific formulation is that the workflow identifies probable weed-prone zones and supports targeted agronomic verification, not that it alone provides definitive botanical diagnosis.

From an applied perspective, the present update supports the broader conclusion that UAV–GIS workflows can contribute to climate-resilient and lower-input crop protection. By concentrating attention on a relatively small proportion of the parcel, the method creates the basis for patch treatment, variable-rate application, or intensified local monitoring, all of which are central objectives of precision weed management and sustainable weed-control systems (Monteiro & Santos, 2022; Gerhards et al., 2022; Nikolić et al., 2021).

ACKNOWLEDGEMENTS

This research was carried out with the support of National Institute of Research & Development for Food Bioresources and within the framework of research activities related to INSAC-AGRIS and ADER 2.1.4. The final update also integrated the Hârșova UAV campaign conducted with EIT Food/ Topzon voucher support, including orthophotoplan interpretation, multispectral layer comparison, and parcel-level zonation. The official INSAC-AGRIS project pages describe these activities within a wider integrated system for remote sensing, experimental field management, and differentiated input application.

USE OF GENERATIVE ARTIFICIAL INTELLIGENCE (GenAI)

The authors declare the use of Generative Artificial Intelligence (GenAI) tools in the preparation of this manuscript. GenAI was used exclusively for language editing and text refinement in the Introduction and Conclusions sections. All scientific content, data analysis, and interpretations were developed and verified by the authors.

REFERENCES

- Alirezazadeh, P., Schirrmann, M., & Stolzenburg, F. (2024). A comparative analysis of deep learning methods for weed classification of high-resolution UAV images. *Journal of Plant Diseases and Protection*, 131, 227–236. <https://doi.org/10.1007/s41348-023-00814-9>
- Gerhards, R., Andújar Sanchez, D., Hamouz, P., Peteinatos, G. G., Christensen, S., & Fernandez-Quintanilla, C. (2022). Advances in site-specific weed management in agriculture: A review. *Weed Research*, 62(2), 123–133. <https://doi.org/10.1111/wre.12526>
- Monteiro, A., & Santos, S. (2022). Sustainable approach to weed management: The role of precision weed management. *Agronomy*, 12(1), 118. <https://doi.org/10.3390/agronomy12010118>
- Nikolić, N., Rizzo, D., Marraccini, E., Ayerdi Gotor, A., Mattivi, P., Saulet, P., Persichetti, A., & Masin, R. (2021). Site- and time-specific early weed control is able to reduce herbicide use in maize: A case study. *Italian Journal of Agronomy*, 16, 1780. <https://doi.org/10.4081/ija.2021.1780>
- Shahi, T. B., Dahal, S., Sitaula, C., Neupane, A., & Guo, W. (2023). Deep learning-based weed detection using UAV images: A comparative study. *Drones*, 7(10), 624. <https://doi.org/10.3390/drones7100624>
- Yu, F., Jin, Z., Guo, S., Guo, Z., Zhang, H., Xu, T., & Chen, C. (2022). Research on weed identification method in rice fields based on UAV remote sensing. *Frontiers in Plant Science*, 13, 1037760. <https://doi.org/10.3389/fpls.2022.1037760>
- INCDA Fundulea. (2024). ADER 2.1.4 – Phase 2: Establishment of demonstration plots and generation of multispectral maps for reducing the consumption of plant protection products by using drones and advanced digital technologies. Retrieved April 30, 2026.
- INSAC-AGRIS. (2023). Abstract – Project Eureka 217/2020. Retrieved April 30, 2026.
- INSAC-AGRIS. (2023). Romania phase 1 – Physico-chemical and imaging characterization of experimental plots. Retrieved April 30, 2026.
- Peña, J. M., Torres-Sánchez, J., Serrano-Pérez, A., de Castro, A. I., & López-Granados, F. (2013). Quantifying efficacy and limits of unmanned aerial vehicle technology for weed seedling detection as affected by sensor resolution. *Precision Agriculture*, 14(6), 593–608.
- Shahi, T. B., Dahal, S., Sitaula, C., Neupane, A., & Guo, W. (2023). Deep learning-based weed detection using UAV images: A comparative study. *Drones*, 7(10), 624.
- Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture*, 13(6), 693–712.