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INTEGRATING OPEN-SOURCE SATELLITE DATA AND ARTIFICIAL INTELLIGENCE FOR GRASSLAND MONITORING. A CASE STUDY

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Abstract. *Monitoring and assessing pasture condition represent a fundamental element in the sustainable management of agrosilvopastoral resources, having direct implications for productivity, livestock carrying capacity, and biodiversity conservation. In the current context of the transition towards smart agriculture, developing accessible and scalable methods for the spatio-temporal analysis of vegetation has become a priority. This paper proposes a pasture evaluation approach based exclusively on visible spectrum (RGB) imagery, demonstrating that, through the use of open-source data and deep learning algorithms, results comparable to those obtained with traditional multispectral methods can be achieved. The main objective of the study is to highlight the potential of RGB data, with a spatial resolution of 20–30 m, for determining vegetation indices and classifying pasture conditions. The analysis was conducted on grasslands located in Timiș County, Romania, using both annual and multi-annual time series derived from the Copernicus program. The methodology integrated the computation of vegetation indices specific to the visible spectrum and the application of a classification model based on convolutional neural networks (CNN). The model was trained and validated on labeled datasets, achieving an accuracy of over 95% on the test set. The results revealed a significant correlation between seasonal variations of vegetation indices, precipitation patterns, and the specific phenology of the studied grasslands. The multi-annual analysis enabled the identification of degradation and regeneration trends in the grass cover, contributing to a better understanding of ecological dynamics and the impact of climatic factors on green biomass. Furthermore, the study introduces a Python-based application that integrates the entire workflow: satellite data acquisition, vegetation index computation, and CNN-based classification. Through its open, reproducible, and scalable nature, this technological solution provides a modern tool to support farmers, agronomists, and decision-makers involved in the sustainable management of pastures and the adaptation of agricultural practices to climate change.*

Keywords: *vegetation indices; RGB imagery; CNN; grasslands monitoring; smart agriculture.*

INTRODUCTION

Monitoring the condition of grasslands and pastures represents a key component in the sustainable management of agrosilvopastoral ecosystems (EMANUELSSON, 2009; HOPKINS, 2011; CALUSERU ET AL., 2013). These areas are not only essential sources of fodder for livestock but also play a crucial role in carbon sequestration, soil protection, and biodiversity conservation (VÎNTU ET AL., 2011; KIZEKOVÁ ET AL., 2018; SAMUIL ET AL., 2018; NITA ET AL., 2019; VAIDA ET AL., 2021). Consequently, the ability to assess vegetation dynamics with high spatial and temporal resolution is indispensable for understanding ecological processes and optimizing agricultural productivity. Traditional field-based monitoring methods, although accurate, are often time-consuming, expensive, and spatially limited, creating the need for efficient remote sensing approaches that can provide large-scale, repeatable, and objective assessments.

In recent years, the transition towards smart and data-driven agriculture has accelerated the integration of remote sensing technologies and artificial intelligence into

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agronomic research and management (DENG ET AL., 2018; COPACEAN ET AL., 2020; LI ET AL., 2021; SIMON ET AL., 2021; SOUBRY ET AL., 2021; COJOCARIU ET AL., 2024). Satellite imagery, particularly from programs such as Copernicus (Sentinel-2), has enabled continuous and large-area monitoring of vegetation cover (FRANTZ, 2019; KHALIQ ET AL., 2019; PARVEEN ET AL., 2022; LIU ET AL., 2023). Historically, such analyses have relied heavily on multispectral or hyperspectral data, which provide rich spectral information suitable for computing well-established vegetation indices (e.g., NDVI, EVI) (XUE, SU, 2017; LORANTY ET AL., 2018; HUANG ET AL, 2020). However, the cost, complexity, and data volume associated with multispectral sensors can limit their accessibility and practical implementation, especially in small and medium-scale agricultural contexts.

Recent advances in deep learning and computer vision have opened new opportunities for exploiting visible spectrum (RGB) imagery in vegetation monitoring. Despite its spectral limitations, RGB data are widely available, easy to process, and compatible with most open-source platforms. Studies have shown that, when combined with appropriate algorithms, RGB images can reveal meaningful patterns in vegetation dynamics and serve as proxies for biophysical parameters such as canopy greenness, biomass, or vegetation density (LUSSEM ET AL, 2018; MARCIAL-PABLO ET AL, 2018; BERRA ET AL., 2019; KIOR ET AL,2024). Thus, developing methods that leverage RGB information for pasture evaluation represents an important step towards democratizing access to remote sensing–based monitoring.

The current study builds upon this premise, proposing an RGB-based approach for assessing pasture condition using openly available satellite imagery and convolutional neural networks (CNNs). The methodology integrates three main components: (i) the acquisition and preprocessing of RGB satellite data from the Copernicus Sentinel-2 program, (ii) the computation of vegetation indices derived exclusively from the visible spectrum, and (iii) the classification of pasture condition using a CNN model trained on labeled datasets. The case study focuses on grasslands located in Timiș County, Romania, a region characterized by mixed agricultural and pastoral systems with pronounced interannual climatic variability.

The main objective of the research is to demonstrate the potential of RGB data—with a spatial resolution of 20–30 meters, for obtaining reliable vegetation indices and performing accurate pasture classification. Through a systematic comparison of annual and multi-annual time series, the study aims to identify degradation and regeneration trends in the grass cover, correlate vegetation dynamics with climatic factors such as precipitation and temperature, and provide insights into local ecological processes. The CNN-based model achieved an accuracy exceeding 95% on the test set, confirming the robustness of the proposed approach (SIMION, 2025).

Beyond its analytical contribution, the study also presents a Python-based open-source application that integrates the entire workflow—from data acquisition and preprocessing to vegetation index computation and classification (SIMION 2025; TAZRIAN ET AL., 2025). By offering a reproducible and scalable tool, this research contributes to the broader framework of digital and sustainable agriculture, supporting farmers, agronomists, and policy-makers in making informed decisions regarding pasture management and adaptation strategies under changing climatic conditions.

MATERIALS AND METHOD

Study Area

Timiș County is the largest county in Romania by area, spanning approximately 8,697 km^2 and located in the western part of the country, forming the central area of the historical region of Banat (RUSU, 2007). Due to its geographic location, it shares extensive international borders with Hungary to the northwest and Serbia to the southwest, positioning it as a major regional and European gateway.

The county's relief is predominantly characterized by the Banat Plain, which covers over 77% of the territory and is highly favorable for agriculture (BORDEAN ET AL., 2013), particularly for cereal crops. The relief gently rises towards the east, transitioning into the pre-mountain hills of Buziaș and Lipova, which are noted for viticulture and fruit orchards, before culminating in the easternmost sector with the Poiana Ruscă Mountains, where the highest altitude is 1,374 m (POSEA, BADEA, 1984).

Dataset

The dataset utilized for this study is comprised of Level-2A Red-Green-Blue (RGB) satellite imagery acquired from the Sentinel-2 mission via the Copernicus Browser. The Level-2A products inherently include atmospheric and radiometric corrections, meaning no further manual preprocessing was required for this research.

The temporal framework of the research was established to facilitate both multiannual and annual analyses, enabling a comprehensive assessment of changes across different agricultural and semi-natural environments.

- Multiannual Analysis: This component was designed to capture long-term trends and variations over a seven-year period. The analysis utilized imagery from 2019 to 2025. To ensure temporal consistency for comparing annual vegetation states during the key growth period, all images were strictly selected to fall around the 1st of May of each respective year. This selection criterion provides a comparable snapshot of surface conditions at the onset of the main growing season.
- Annual Analysis: A focused annual analysis was conducted to evaluate high-resolution, short-term changes. This involved selecting a time series of images spanning from June 2024 to June 2025. This period was chosen to capture the full cycle of the vegetation growing season, allowing for a detailed examination of seasonal changes within a single year.

All selected images across both temporal scopes were subject to a rigorous screening process to ensure minimal cloud coverage and maintain high spatial and temporal consistency throughout the dataset.

RGB Indices Used

This study focused on leveraging the non-NIR spectral information from the Sentinel-2 RGB bands to quantify and monitor **vegetation dynamics** and changes in surface cover. To this end, a total of seven different vegetation indices were computed and evaluated (Tabel 1).

Table 1.

Vegetation Indices Computed (KIOR ET AL., 2024)

Index Acronym	Full Name	Formula
ExG	Excess Green Index	2*G-R-B
ExGR	Excess Green minus Red Index	3*G-2.4*R-B
GLI	Green Leaf Index	(2*G-R-B) / (2*G+R+B)
NGRDI	Normalized Green Red Difference Index	(G-R) / (G+R)
Pseudo-NDVI	Pseudo-Normalized Difference Vegetation Index	(B-R) / (B+R)
TGI	Triangular Greenness Index	G - 0.37 * R - 0.63 * B
VARI	Visible Atmospherically Resistant Index	(G - R) / (G + R - B)

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The use of these indices is critical for enhancing the contrast between vegetated and non-vegetated areas, thereby facilitating the quantitative assessment of surface change from the visible spectrum data.

Following the computation and comparative analysis of all seven indices across the study area and time series (Figure 1), the **Excess Green minus Red Index (ExGR)** was ultimately selected as the primary metric for the final analysis (SIMION 2025). Specifically, the ExGR index successfully provided the **highest contrast** for the multi-annual and annual change detection analysis (SIMION, 2025).

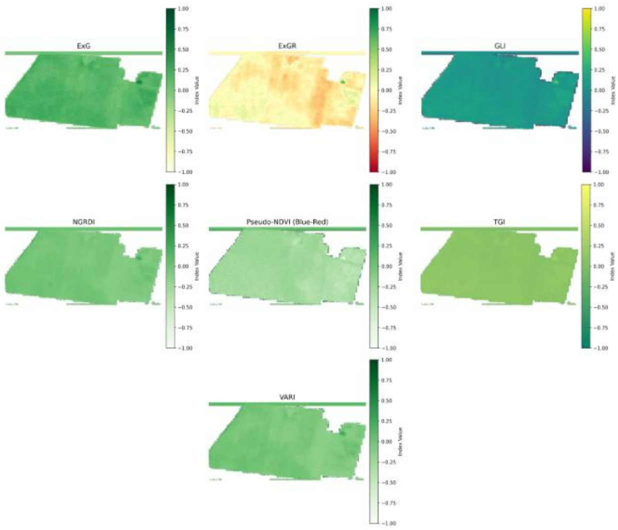

Figure 1. A plot processed in turn with ExG, ExGR, GLI, NGRDI, Pseudo-NDVI, TGI and VARI indices

CNN Classification

The classification of land surface condition was performed using a convolutional neural network (CNN) trained exclusively on RGB satellite imagery. The model was developed and optimized on a labeled dataset derived from the EuroSat-RGB collection (HELBER ET AL., 2019), ensuring adequate representation of different vegetation states. The CNN architecture, based on multiple convolutional and pooling layers followed by fully connected layers, was designed to automatically extract spatial and spectral features relevant to vegetation cover (MORAIS ET AL., 2024; VAWDA ET AL., 2024). During training, the model achieved a high level of stability and generalization, obtaining an overall classification accuracy of 95% on the independent test dataset (SIMION, 2025).

To evaluate the performance and reliability of the model, a confusion matrix was generated(Tabel 2), providing a detailed comparison between predicted and actual classes. The matrix confirmed the model's robustness, with the highest precision recorded for ”Forest” and ”SeaLake” areas and the lowest misclassification rate between intermediate vegetation states. This distribution highlights the network's capacity to differentiate subtle spectral variations in RGB data (SIMION, 2025).

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Table 2.

Confussion matrix

	AnnualCrop	Forest	HerbaceousVegetation	Highway	Industrial	Pasture	PermanentCrop	Residential	River	SeaLake	Total
AnnualCrop	-	1	3	4	0	1	2	0	3	1	15
Forest	0	-	0	0	0	1	0	0	0	0	1
HerbaceousVegetation	0	0	-	2	0	0	10	2	1	0	15
Highway	1	0	0	-	3	0	1	0	1	0	6
Industrial	0	0	0	3	-	0	0	3	0	0	6
Pasture	2	0	4	1	2	-	0	0	3	0	12
PermanentCrop	5	0	11	5	3	1	-	0	0	0	25
Residential	0	0	1	0	10	0	0	-	0	0	11
River	2	0	1	13	1	1	0	0	-	1	19
SeaLake	0	0	0	0	0	1	0	0	0	-	1

Python-Based Application

A dedicated Python application was developed to automate and integrate the entire workflow of the study, from satellite data acquisition to vegetation index computation and CNN-based classification. The application was designed to ensure reproducibility, scalability, and ease of use, enabling rapid processing of multi-temporal RGB imagery.

The software architecture follows a modular design, consisting of three main components:

1. Data Acquisition Module, which automatically downloads and organizes Sentinel-2 RGB scenes through the Copernicus Browser.
2. Processing Module, responsible for computation of vegetation indices specific to the visible spectrum, such as the Excess Green (ExG), Visible Atmospherically Resistant Index (VARI), Excess Green minus Red (ExGR), computation of indices means.
3. Classification Module, which loads the trained CNN model and applies it to the processed images, generating labels for each land coverage.

The application was implemented using Python 3.10, employing open-source libraries such as NumPy, Rasterio, Tkinter, and PyTorch. Outputs were exported in PNG format for further analysis and visualization. This open and modular structure facilitates future extensions, including multi-sensor data integration or web-based deployment for real-time pasture monitoring.

RESULTS AND DISCUSSION

Seasonal Variability (June 2024 – June 2025)

The seasonal assessment performed between June 2024 and June 2025 revealed distinct intra-annual fluctuations in the ExGR (Excess Green Ratio) index (Figure 2), closely aligned with short-term variations in precipitation and temperature. The vegetation signal reached its lowest values during late summer (August–September 2024), when ExGR declined to –0.336, corresponding to high temperatures (26–27 °C) and limited rainfall (<10 mm) (Tabel

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3). These conditions indicate a pronounced drought-induced stress and partial senescence of the grass canopy, typical of Mediterranean-type summer dry spells.

A subsequent recovery phase was observed in October 2024, when increased rainfall (67.3 mm) and milder temperatures (15.4 °C) promoted rapid regrowth, raising ExGR to 0.232. Vegetation remained active through early winter, although lower temperatures in December–February suppressed green biomass. From March 2025 onward, greenness gradually increased, culminating in a maximum ExGR of 0.266 in early May, reflecting optimal moisture and thermal conditions for growth (Tabel 3).

Statistical analysis revealed a positive correlation between ExGR and precipitation (r ≈ 0.69) and a negative correlation with temperature (r ≈ –0.55). These relationships confirm that water availability is the primary driver of short-term vegetation vigor, while elevated temperatures tend to amplify evapotranspiration stress. The overall pattern highlights the seasonal resilience of the grassland ecosystem, characterized by cyclic degradation during summer droughts and regeneration following autumn and spring rainfall. This emphasizes the capability of RGB-based indices to capture fine-scale phenological transitions within a single growing season, providing relevant indicators for adaptive pasture management.

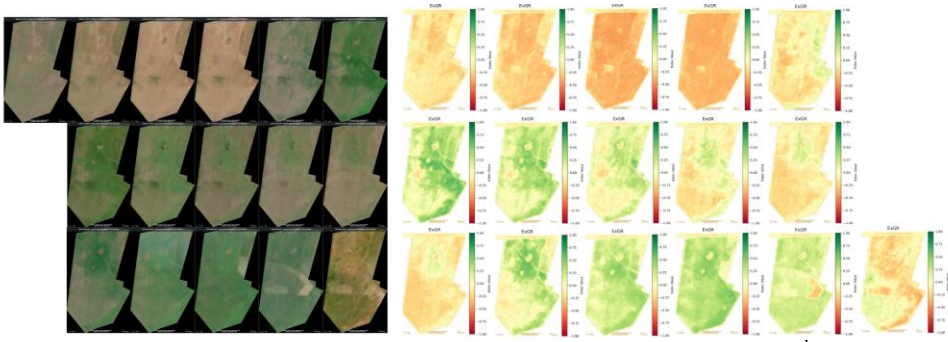

Figure 2 – Left – Copernicus browser raw images; Right – ExGR processed images (7th of July 2024 top left corner to 12th of June 2025 bottom right corner)

Table 3.

ExGR mean through a season 2024 – 2025

Date	ExGR means	Temperature means 30 days before[1] (°C)	Precipitation 30 days before[2] (mm)
July 7	-0.145	23.9	60
July 27	-0.24	26.9	29.2
August 18	-0.336	26.1	7.3
September 5	-0.328	27.3	3.5
September 27	-0.080	20.9	45.9
October 15	0.232	15.4	67.3
November 4	0.192	12.1	6.1
November 21	0.083	7.1	16
December 26	-0.045	3.2	31.7
January 28	-0.098	1.4	24.2
February 22	-0.126	2.2	29.5
March 19	0.144	5.7	29.9
April 13	0.203	8.7	56.4
May 3	0.266	12.4	32
May 28	0.143	14.5	82.2
June 12	-0.102	17.6*	49.9*
[1]Averages taken from the website: https://meteostat.net. The Sânnicolau Mare			

weather station is the closest one
[2]Values taken from the website: https://meteostat.net. The Sânnicolau Mare weather station is the closest one

Multi-Annual Variability (2019–2025)

The multi-annual assessment of the ExGR index for a plot between 2019 and 2025 revealed significant interannual variability reflecting both climatic influences and ecological dynamics (Figure 3). Mean ExGR values ranged between 0.032 (2020) and 0.351 (2023), with the lowest greenness recorded during dry years and the highest during wet years. The exceptional ExGR in 2023 coincided with the maximum 30-day cumulative precipitation (58.6 mm), while the 2020 minimum aligned with a marked rainfall deficit (4.3 mm) (Tabel 4).

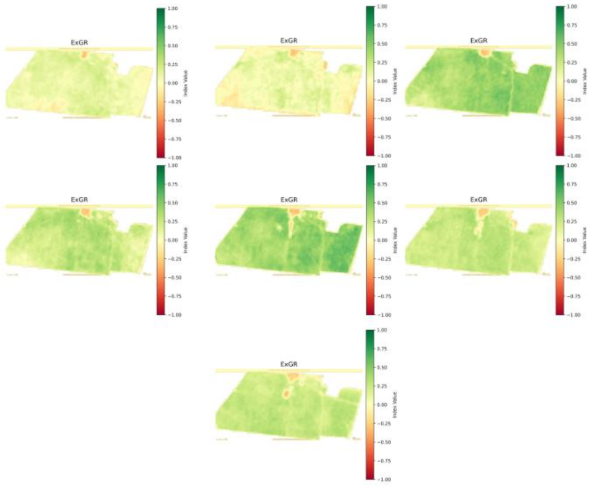

Figure 3. ExGR index from 2019 (top left) to 2025 (bottom)

Table 4.

ExGR mean from 2019 to 2025

Year	ExGR means	Precipitation 30 days before[1] (mm)	Temperature means 30 days before[2] (°C)
2019	0.073	12.7*	13
2020	0.032	4.3	10.3
2021	0.337	22.2*	9.3
2022	0.210	32.6*	10.6
2023	0.351	58.6	9.3
2024	0.209	23.4	13.8
2025	0.210	16.8	12.8

[1]Averages taken from the website: https://meteostat.net, Timișoara weather station.
[2]Averages taken from the website: https://meteostat.net. Timișoara weather station.

The Pearson correlation coefficient between ExGR and precipitation (r = 0.78) confirmed a strong positive relationship, indicating that short-term moisture availability substantially influences canopy vigor and photosynthetic activity. Conversely, the correlation with mean temperature was weakly negative (r = –0.29), suggesting that elevated thermal

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conditions did not necessarily promote greenness and may, in some cases, have accelerated senescence under water stress.

These interannual patterns underscore the dominant role of precipitation in controlling pasture condition in the study area. The consistent response of ExGR to climatic variability demonstrates the robustness of RGB-derived vegetation indices in capturing long-term dynamics. Moreover, the integration of CNN-based classification validated that RGB satellite imagery can effectively substitute for multispectral data in monitoring grassland health.

Overall, both the seasonal and multi-annual analyses confirm that the ExGR index, computed from visible-spectrum satellite imagery, provides a reliable and sensitive indicator of vegetation status. Its capacity to mirror climatic fluctuations and phenological cycles supports its use as a cost-effective, open-source tool for sustainable pasture management and for tracking ecosystem responses to ongoing climate variability.

For future research, several directions are recommended: (i) extending the methodology to include higher temporal resolution data and additional machine learning techniques on RGB spectral bands for improved sensitivity to vegetation stress, (ii) integrating ancillary environmental datasets, such as soil properties and grazing patterns, to refine predictive models, and (iii) adapting the workflow to different agro-ecological regions to evaluate the generalizability and robustness of RGB-based monitoring approaches. Furthermore, continuous development of lightweight and efficient deep learning architectures could facilitate near-real-time pasture assessment, enhancing the responsiveness of smart agricultural systems to climatic variability and ecological changes.

CONCLUSIONS

This study demonstrates that high-resolution RGB imagery, combined with deep learning techniques, offers a reliable and scalable method for monitoring and assessing pasture conditions. By integrating vegetation index computation with convolutional neural network (CNN) classification, the proposed approach provides accurate identification of pasture status, capturing seasonal dynamics and multi-annual trends in grass cover. The results confirm that RGB-based analysis can serve as a cost-effective alternative to traditional multispectral methods, particularly when open-source satellite data are leveraged.

The multi-annual assessment highlights the strong influence of climatic factors, such as precipitation, on pasture phenology, enabling the detection of both degradation and regeneration patterns. This capability is crucial for adaptive management strategies in agrosilvopastoral systems, where timely interventions can enhance productivity, biodiversity conservation, and sustainable use of natural resources.

From a practical standpoint, the Python-based application developed in this study consolidates the entire workflow, including satellite data acquisition, index computation, and CNN classification. Its open-source, reproducible, and scalable design makes it a valuable tool for farmers, agronomists, and policymakers seeking to implement data-driven decisions in pasture management.

Overall, this study underscores the potential of RGB imagery and machine learning as practical, efficient, and scalable tools for sustainable pasture management, contributing to the ongoing transition towards precision and climate-adaptive agriculture.

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