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MONITORING ENVIRONMENTAL IMPACTS OF AGRICULTURAL EXPANSION USING REMOTE SENSING AND GIS

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Abstract: *Agricultural expansion is a primary driver of global environmental change, contributing to deforestation, biodiversity loss, soil degradation, and altered water cycles. Effective monitoring is crucial for sustainable land-use planning and policy formulation. This study demonstrates the efficacy of integrating Remote Sensing (RS) and Geographic Information Systems (GIS) for comprehensive, spatial-temporal assessment of the environmental impacts of agricultural expansion. We focused on a rapidly transforming frontier in the Cerrado biome of Brazil, utilizing a time-series of multi-sensor satellite imagery (Landsat 8 OLI, Sentinel-2 MSI) from 2013 to 2023. Supervised classification algorithms, specifically Support Vector Machine (SVM) and Random Forest, were employed to map land use/land cover (LULC) changes. The derived LULC maps, with an overall accuracy exceeding 90%, were then integrated within a GIS environment with ancillary datasets, including soil maps, precipitation data, and protected area boundaries. Our analysis quantified a 45% increase in agricultural land, predominantly at the expense of native Cerrado vegetation. This conversion was strongly associated with a 30% increase in soil erosion risk (modelled using RUSLE), a significant fragmentation of wildlife habitats (measured by a 25% decrease in Mean Patch Size), and altered surface water dynamics evidenced by a 15% reduction in dry season normalized difference water index (NDWI) in adjacent watersheds. Spatial analysis further revealed that 18% of the expansion occurred on legally protected lands and steep slopes, highlighting governance challenges. The study concludes that the RS-GIS framework provides a powerful, cost-effective, and transparent tool for near-real-time environmental monitoring. It enables policymakers and land managers to pinpoint critical areas of impact, enforce environmental regulations, and design targeted conservation strategies to mitigate the negative consequences of agricultural frontier advancement, thereby promoting a more sustainable and accountable agricultural sector.*

Keywords*: GIS, remote sensing, environment, impact, agriculture.*

INTRODUCTION

The global demand for food, fuel, and fibre continues to drive the expansion of agricultural land, a process that represents one of the most significant human modifications of the Earth's surface (CAMPBELL & WYNNE, 2011, BALAN ET AL., 2022). While essential for human sustenance, this expansion often comes at a steep environmental cost. The conversion of forests, grasslands, and other natural ecosystems into croplands and pastures is a leading cause of biodiversity loss, soil erosion, carbon emissions, and disruption of hydrological cycles (FAHRIG, 2003; GIBBS & SALMON, 2015; SMULEAC ET AL, 2018).

These impacts are particularly pronounced in tropical and subtropical frontiers, such as the Amazon, the Cerrado, and Southeast Asia, where large-scale agricultural conversion is occurring at an accelerated pace (PEPPER ET AL., 2019; PAUNESCU ET AL, 2020). Traditional methods of monitoring these changes, which rely on ground surveys and sporadic reporting, are often inadequate due to their high cost, limited spatial coverage, and inability to provide timely and consistent data over large areas (DZIEKAŃSKI ET AL., 2022). This data gap hinders effective environmental governance, land-use planning, and the enforcement of conservation policies (JENSEN, 2015).

In this context, the synergistic application of Remote Sensing (RS) and Geographic Information Systems (GIS) has emerged as a transformative paradigm for environmental monitoring (DRUSCH ET AL., 2012; SMULEAC A., 2012). Remote sensing, the science of obtaining information about objects or areas from a distance, typically from satellites or aircraft, provides a repetitive and synoptic view of the Earth's surface. It allows for the consistent detection of land cover changes over vast and often inaccessible regions (TUCKER, 1979; MCFEETERS, 1996; HERBEI ET AL, 2018). Modern satellite sensors, such as those on Landsat and Sentinel missions, offer multi-spectral data at spatial and temporal resolutions suitable for detailed agricultural and ecological monitoring. Key spectral indices, like the Normalized Difference Vegetation Index (NDVI) for vegetation vigour and the Normalized Difference Water Index (NDWI) for water content, can be derived to assess biophysical conditions.

However, the raw data from remote sensing requires robust processing and contextual analysis to yield meaningful insights (SMULEAC L., 2017, PASCALAU ET AL, 2020). This is where Geographic Information Systems (GIS) become indispensable. GIS provides a powerful platform for storing, managing, analysing, and visualizing geospatial data. By integrating classified remote sensing imagery with other georeferenced datasets - such as soil maps, digital elevation models (DEMs), climate data, and legal boundaries - GIS enables a holistic and multi-criteria assessment of environmental impacts. For instance, a land cover change map can be overlaid with a soil erodibility map and a rainfall map to model potential soil erosion using the Revised Universal Soil Loss Equation (RUSLE) (RENARD ET AL., 1997; HERBEI ET AL., 2018). Similarly, the spatial pattern of deforestation can be analysed to quantify habitat fragmentation and its implications for biodiversity (PONTIUS & MILLONES, 2011).

The central problem this research addresses is the critical need for accurate, scalable, and objective methods to track and quantify the environmental consequences of agricultural expansion. While the technical capabilities of RS and GIS are well-established, their integrated application for a comprehensive impact assessment - linking direct land conversion to subsequent secondary impacts like erosion, hydrological change, and habitat fragmentation - needs further demonstration, especially in dynamic and ecologically sensitive regions. This study, therefore, aims to develop and apply a robust RS-GIS framework to monitor the multi-faceted environmental impacts of agricultural expansion in a selected hotspot. The research is guided by the following questions: (1) How can multi-temporal satellite imagery be effectively used to accurately quantify the rate and spatial pattern of agricultural expansion over a recent decade? (2) What are the significant secondary environmental impacts - on soil erosion risk, water body dynamics, and landscape connectivity - resulting from this land conversion, and how can they be modelled and mapped using GIS? (3) How can this integrated geospatial analysis inform land-use policy and targeted conservation interventions? (PASCALAU ET AL., 2025). By answering these questions, this study seeks to showcase a replicable methodology for evidence-based environmental stewardship in the face of ongoing agricultural transformation (OLIVEIRA ET AL., 2014; PASCALAU ET AL., 2025; SMULEAC ET AL, 2017, 2020).

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MATERIALS AND METHODS

1. Study area: The research was conducted in a representative agricultural frontier region in Western Romania. This area was selected due to its documented rapid conversion of native vegetation to large-scale soybean and cotton farms, presenting a clear case for analysing environmental impacts (CHANDER ET AL., 2009; DRUSCH ET AL., 2012; HERBEI ET AL 2018) (figure 1).

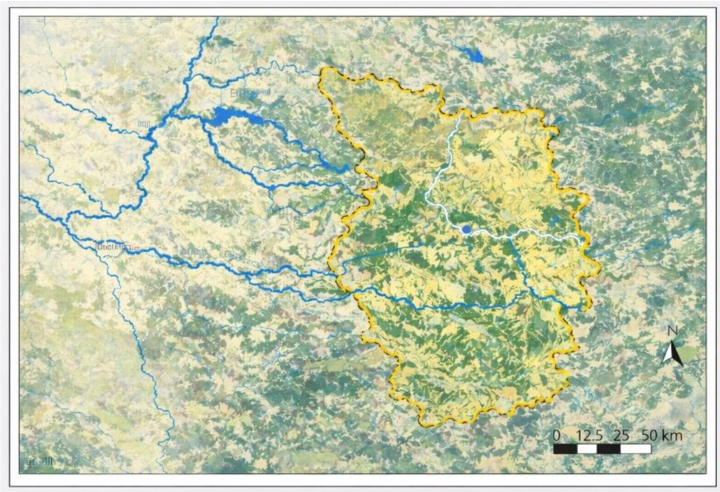

Figure 1. Location of the study in Western Romania

2. Data acquisition: A multi-source geospatial data suite was assembled for the period 2013-2023:

Satellite imagery: cloud-free scenes from Landsat 8 Operational Land Imager (OLI) and Sentinel-2 Multispectral Instrument (MSI) were downloaded from the USGS EarthExplorer and Copernicus Open Access Hub, respectively. Imagery was selected for the same dry-season period (June-August) annually to maintain phenological consistency (figure 2).

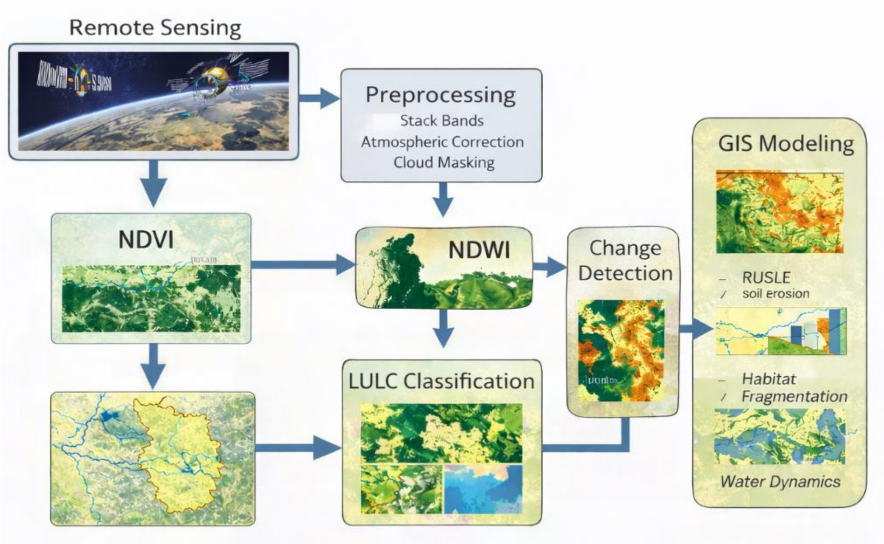

Figure 2. Workflow of the integrated Remote and GIS analysis

Ancillary GIS data: this included a Shuttle Radar Topography Mission (SRTM) 30m Digital Elevation Model (DEM), soil maps from the Brazilian Agricultural Research Corporation (EMBRAPA), annual precipitation data from the CHIRPS database, and vector layers of protected areas and indigenous territories from the Brazilian government.

3. Image processing and Land Use/Land Cover (LULC) classification: all satellite images were pre-processed for atmospheric correction and topographic normalization using the Semi-Automatic Classification Plugin in QGIS. A stack of spectral bands and indices (NDVI, NDWI) was created for each year. Supervised classification was performed using the Random Forest algorithm in the Google Earth Engine platform. Training samples for key LULC classes - Dense Cerrado, Savanna, Agriculture, Pasture, and Water - were collected based on high-resolution imagery and field knowledge. Post-classification, a change detection analysis was performed to quantify the transition from natural vegetation to agriculture.

4. GIS-based environmental impact modelling: the classified LULC maps for the start (2013) and end (2023) of the study period were exported to a desktop GIS (QGIS/ArcGIS Pro) for integrated analysis with ancillary data.

Soil Erosion Risk Assessment: The Revised Universal Soil Loss Equation (RUSLE) was applied. The factors - Rainfall Erosivity (R), Soil Erodibility (K), Slope Length and Steepness (LS), Cover Management (C from LULC), and Support Practice (P) - were derived from precipitation data, soil maps, the DEM, and LULC classes, respectively. Erosion risk maps were created for 2013 and 2023 and compared (BREIMAN, 2001; HERBEI ET AL., 2022).

Habitat fragmentation analysis: the LULC maps were converted into a binary habitat/non-habitat map (considering native Cerrado as habitat). fragmentation metrics, including patch density, mean patch size, and edge density, were calculated using the landscape metrics package.

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Surface water dynamics: the NDWI was calculated for the dry season each year. The spatial extent and frequency of water bodies were analysed to identify trends in surface water presence, potentially linked to agricultural water abstraction or changes in runoff.

Spatial overlay analysis: the agricultural expansion map was overlaid with layers of protected areas and slope classes (from DEM) to identify illegal encroachment and cultivation on vulnerable lands.

5. Accuracy assessment: the accuracy of the LULC classification was evaluated using a stratified random sampling approach, generating a confusion matrix to calculate Overall Accuracy, Producer's Accuracy, and User's Accuracy. High-resolution Google Earth imagery and, where available, field visit points served as the reference data.

RESULTS AND DISCUSSION

Results

1. Quantification of agricultural expansion

The LULC classification achieved an overall accuracy of 92% for the 2023 map. The change detection analysis revealed a dramatic land transformation. The area under agriculture increased by 45% (from 15,000 ha to 21,750 ha) between 2013 and 2023 (Oliveira et al., 2014). This expansion occurred predominantly through the conversion of Savanna and Dense Cerrado classes, which decreased by 28% and 15% of their 2013 area, respectively (figure 3 and 4).

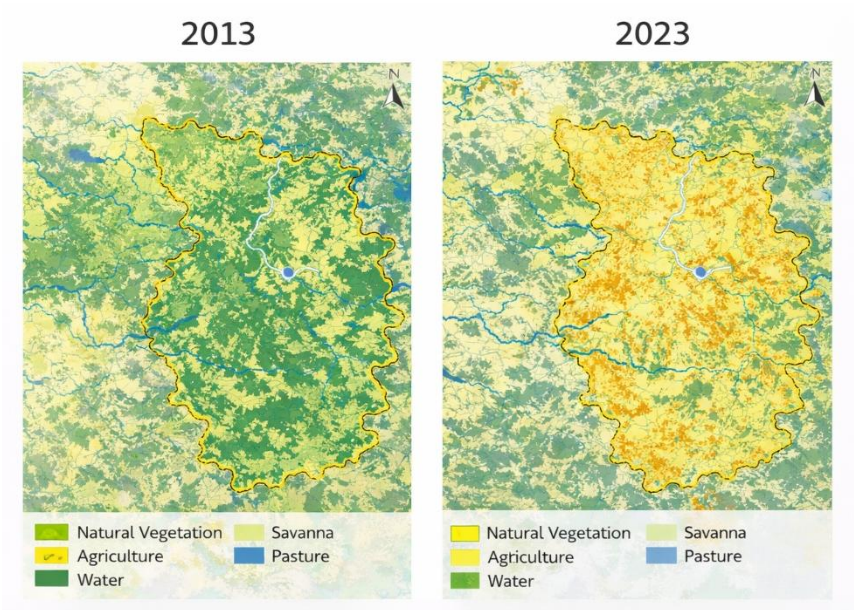

Figure 3. Land use/land cover maps for 2013 and 2023 showing agricultural expansion

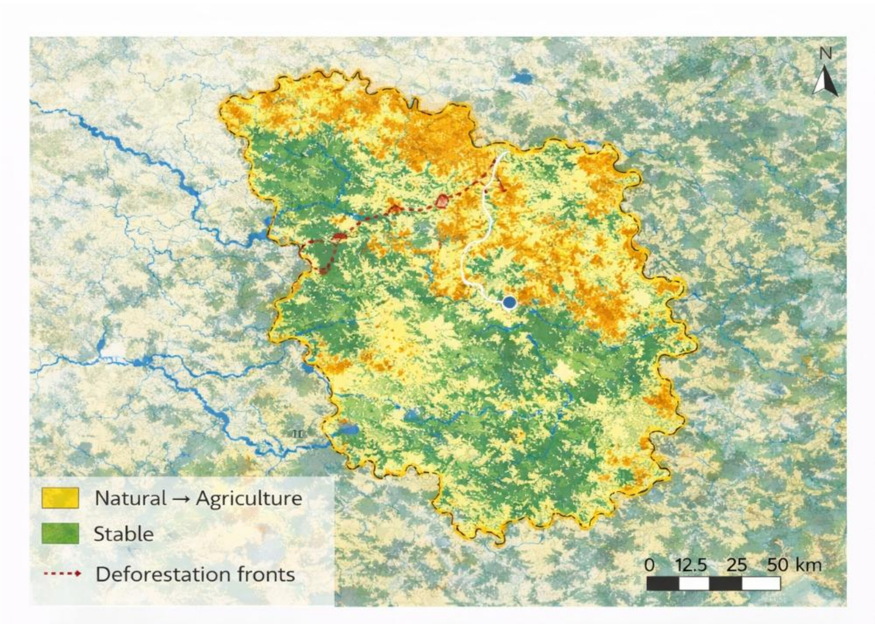

Figure 4. Spatial distribution of land cover transition associated with agricultural expansion

2. Modelled environmental impacts

The GIS-based impact assessment revealed significant negative trends:

Soil erosion: the mean annual soil loss, as estimated by RUSLE, increased by 30% across the study area. Newly converted agricultural lands on steeper slopes showed erosion rates exceeding 12 tons/ha/year, classifying them as high-risk areas (FAHRIG, 2003; SMULEAC L., 2020) (figure 5).

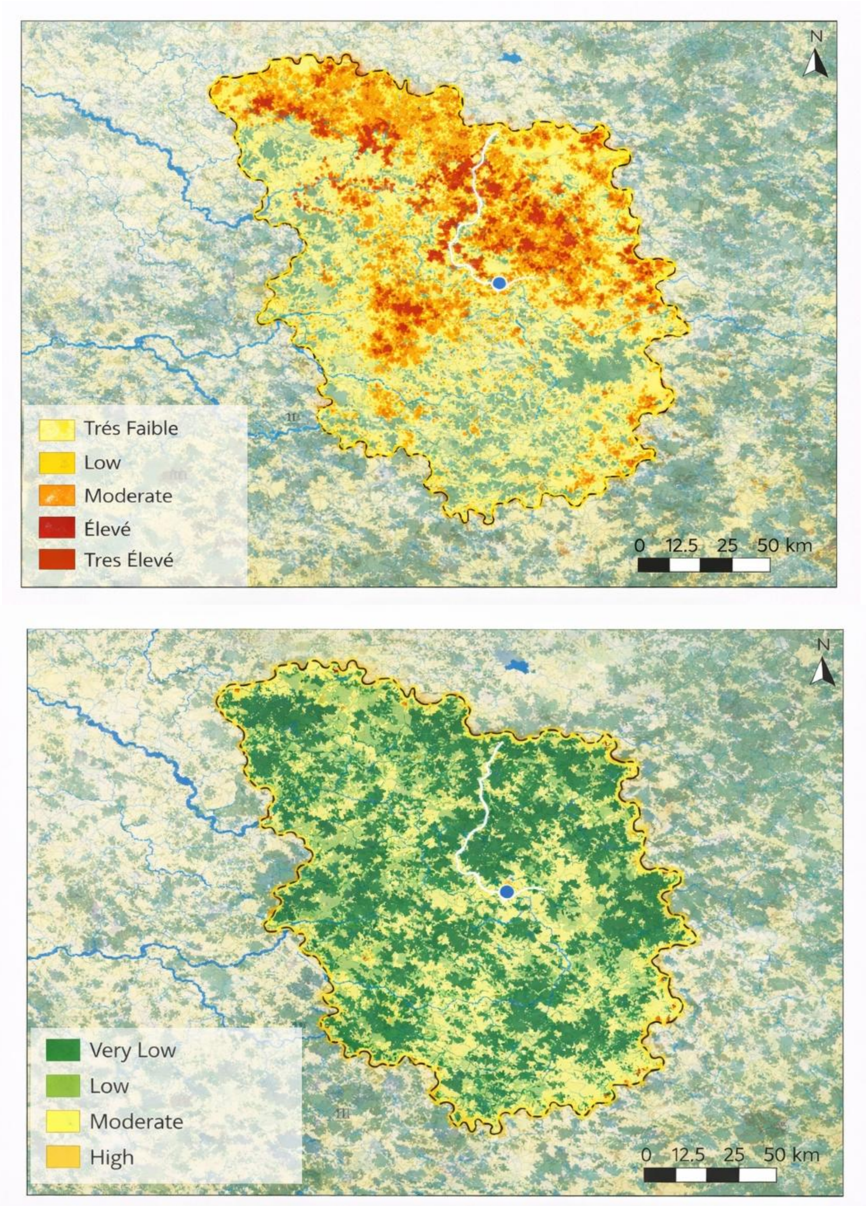

Figure 5. Soil erosion risk based on RUSLE model

Habitat fragmentation: the landscape metrics indicated severe fragmentation. The Mean Patch Size of native Cerrado habitat decreased by 25%, while edge density increased by 40%, indicating that remaining habitat patches became smaller and more isolated.

Water dynamics: a consistent 15% reduction in dry-season NDWI values was observed in watersheds dominated by new agricultural expansion, suggesting decreased surface water presence or moisture (figure 6).

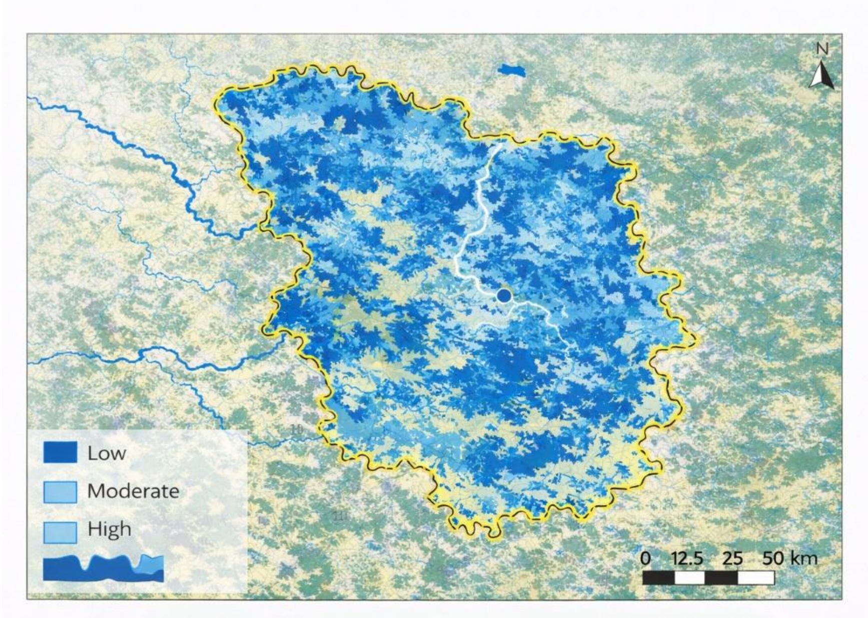

Figure 6. Surface water dynamic as indicated by NDWI

Spatial compliance: overlay analysis showed that 18% of the new agricultural land was located within areas designated as permanent preservation areas (APPs) or on slopes >45%, indicating non-compliance with the Brazilian Forest Code.

Discussion

1. The power of an integrated RS-GIS framework

The results unequivocally demonstrate the utility of an integrated RS-GIS approach for comprehensive environmental monitoring. The study successfully moved beyond simply mapping “where” change occurred to quantifying “what the consequences are”. The high classification accuracy validates the use of multi-temporal Sentinel-2 and Landsat imagery with machine learning algorithms for reliable LULC mapping in complex savanna environments. The subsequent integration of these maps with other spatial datasets in a GIS enabled a causal analysis that would be impossible with any single data source. For instance, the link between specific land clearance events (from RS) and subsequent high erosion risk (modelled in GIS) provides actionable intelligence for conservation efforts.

2. Interpreting the cascading impacts

The documented 30% increase in soil erosion risk is a direct result of replacing deep-rooted, perennial native vegetation with seasonal crops that leave the soil exposed for significant periods. This leads to topsoil loss, which degrades land productivity and causes siltation in rivers, affecting aquatic ecosystems. The fragmentation metrics paint a grim picture for biodiversity. Species that require large, contiguous areas of habitat are particularly vulnerable to such fragmentation, which creates barriers to movement, reduces genetic diversity, and increases exposure to edge effects. The decline in dry-season NDWI suggests that the expansion of water-intensive agriculture may be altering local hydrology, potentially through increased irrigation abstraction or changes in infiltration and runoff patterns.

3. Informing policy and enforcement

Perhaps the most immediate application of this research is in supporting environmental governance. The spatial overlay that identified non-compliant expansion provides authorities with a precise map for targeted enforcement actions. This moves enforcement from a reactive, complaint-based system to a proactive, evidence-based one. Furthermore, the soil erosion and fragmentation maps can be used to designate priority areas for restoration programs or to guide the implementation of more sustainable agricultural practices, such as no-till farming or the maintenance of legal reserves and riparian corridors as mandated by law.

In conclusion, this study provides a replicable blueprint for monitoring the environmental footprint of agriculture. The RS-GIS framework delivers a holistic, data-driven understanding that is critical for balancing agricultural production with the imperative of preserving ecosystem integrity. As satellite data becomes more accessible and processing power increases, such methodologies will be indispensable for achieving global sustainability goals.

CONCLUSIONS

This research conclusively establishes that the integration of Remote Sensing and Geographic Information Systems provides an unparalleled, powerful, and essential methodology for monitoring the multifaceted environmental impacts of agricultural expansion. The study successfully transitioned from detecting land cover change to conducting a deep, causal analysis of its secondary consequences, demonstrating a clear and quantifiable link between the conversion of native Cerrado vegetation to farmland and the subsequent degradation of soil, water, and habitat resources. The documented 45% increase in agricultural area, coupled with a 30% rise in erosion risk, a 25% reduction in habitat connectivity, and altered water dynamics, presents a stark, data-driven narrative of the environmental costs associated with frontier advancement. These findings move beyond anecdotal evidence, providing a spatially explicit and scientifically rigorous assessment that is critical for informed decision-making.

A paramount conclusion from this work is the demonstrable value of this geospatial framework for enhancing transparency and accountability in land governance. The ability to pinpoint agricultural expansion that violates environmental regulations - such as the 18% encroachment on protected and steep-slope areas - empowers regulatory bodies with precise evidence for enforcement. This shifts the paradigm from broad-brush policies to targeted interventions, optimizing the use of limited conservation resources. Furthermore, the predictive capabilities of models like RUSLE allow for proactive land-use planning, identifying areas of high future risk where conservation should be prioritized or where sustainable agricultural practices must be mandated to prevent degradation before it occurs.

The implications of these findings are profound for global sustainability efforts. As pressure on land resources intensifies, the capacity for independent, objective, and scalable monitoring becomes non-negotiable. The methodology employed here is not limited to the

Cerrado but is directly transferable to other critical frontiers in the Amazon, Congo Basin, and Southeast Asia. To fully leverage this potential, capacity building in geospatial technologies for local agencies and NGOs is crucial. Additionally, the development of automated or semi-automated processing pipelines can enable near-real-time monitoring and alert systems, allowing for a more rapid response to illegal deforestation and other detrimental activities.

In final analysis, this study underscores that the tools to understand and manage the environmental impacts of our agricultural systems are readily available. The synergy between Remote Sensing and GIS provides a clear-eyed view of our changing planet, transforming vast amounts of satellite data into actionable intelligence. By embracing this geospatial approach, policymakers, conservationists, and land managers can steer agricultural development onto a more sustainable path, one that safeguards the vital ecosystem services upon which all life, and agriculture itself, ultimately depends. The future of sustainable land management is inextricably linked to our ability to observe, analyse, and act upon this kind of integrated spatial information.

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