

Monitoring Sustainable Rural Tourism Development in Post-Conflict Areas Using Remote Sensing and Geospatial Analysis

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This study examines how rural tourism supports sustainable development, economic recovery, social stability, and cultural preservation in post-conflict regions, using Transcarpathia, Ukraine, as a case study for 2022–2024. It applies a mixed-methods approach combining satellite remote sensing, GIS-based spatial analysis, and socio-economic indicators to assess land-use change, infrastructure recovery, ecological stability, and socio-economic resilience. Unlike existing geospatial monitoring studies that focus on single dimensions (e.g. land cover or tourist flows) in stable environments. This research introduces a theoretically grounded, multi-dimensional framework that integrates environmental, infrastructural, socio-economic, and digital indicators into a unified composite sustainability index, enabling continuous monitoring where conventional field data collection is constrained. The findings indicate notable recovery and resilience: tourism-related infrastructure rebounded strongly, ecological indicators improved over time, and digital accessibility expanded substantially, supporting tourism development despite ongoing post-conflict challenges. The study offers a novel integrated geospatial framework for monitoring sustainable rural tourism transitions in data-constrained and crisis-affected territories.

Keywords: rural tourism, post-conflict recovery, sustainable development, remote sensing, geospatial monitoring

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Introduction

Rural tourism is a vital instrument for sustainable development in post-conflict regions, fostering economic recovery, social stability, and cultural preservation (World Tourism Organization 2020). However, effective monitoring of its development in such challenging environments, where traditional data collection is often disrupted, requires innovative approaches. Remote sensing and geospatial analysis provide a powerful solution, enabling the objective and timely assessment of changes where conventional methods falter (Jian and Ren 2023; Zhang 2023). Despite this potential, a significant gap exists in the literature. While studies on post-conflict recovery acknowledge tourism's role, few employ integrated geospatial frameworks to quantitatively assess multidimensional sustainability – spanning environmental, infrastructural, and socio-economic indicators – in real time during ongoing instability (Marques et al. 2022). Furthermore, consensus is lacking on a holistic indicator system, with debates persisting between economic, environmental, and social priorities (Vasanicova et al. 2022; Shcherbak et al. 2020).

To address this gap, this study selects the Transcarpathian region of Ukraine as a critical and timely case. Transcarpathia (Zakarpattia Oblast), with a population of approximately 1.25 million, is a historically multi-ethnic region in southwestern Ukraine, bordering four EU states. Renowned for its Carpathian mountain landscapes, UNESCO-protected wooden churches, thermal springs, and vibrant Hutsul culture, it has long been a destination for ecotourism, wellness, and cultural travel. Since the full-scale invasion of Ukraine in 2022, Transcarpathia has served as a relative 'safe haven', experiencing a significant influx of internally displaced persons and a shift toward domestic tourism (European Commission 2021; Eurostat 2022). The region thus serves as a living laboratory for developing and testing a novel geospatial monitoring framework for post-conflict settings. Consequently, this article aims to develop and apply a methodology for monitoring sustainable rural tourism development in post-conflict areas using remote sensing and geospatial analysis. It analyses integrated indicators of land use and infrastructure rehabilitation, environmental sustainability, and socio-economic sustainability, including digitalization, which correspond directly to the three analytical dimensions defined in table 1. The period 2022–2024 is selected because it captures the full crisis cycle: from the initial shock of the full-scale invasion (2022), through adaptive recovery and infrastructure rebuilding (2023), to relative stabilization (2024). This timeframe allows for the ob-

servation of non-linear recovery trajectories under active conflict conditions, which has not been possible in retrospective post-conflict studies (Jian and Ren 2023; Yu 2024; Zhang 2023).

The study seeks to advance theoretical understanding by modelling sustainability interactions in crisis contexts and to provide actionable insights for resilient tourism management in Transcarpathia and comparable regions. The scientific value of this study lies in its development of an integrated, geospatially based monitoring framework that captures the multidimensional nature of sustainable rural tourism in post-conflict contexts. Unlike existing studies that primarily rely on qualitative assessments or isolated economic indicators, this research offers a unified system combining environmental, infrastructural, socio-economic, and digital indicators derived from remote sensing and Geographic Information Systems (GIS) data (Almeida-Santana et al. 2020).

The novelty of the study is threefold: first, it demonstrates how satellite-based and open geospatial data can substitute for traditional field data collection under conditions of ongoing instability. Second, it applies this approach to a real-time post-conflict setting rather than retrospective recovery analysis. Third, and most importantly, the study advances beyond existing geospatial monitoring research (Jovanović and Njeguš 2008; Gan 2023; Andyana et al. 2023) by proposing a theoretically explicit framework that captures the interaction between four sustainability dimensions – environmental, infrastructural, socio-economic, and digital – rather than treating them in isolation. While prior studies have used remote sensing to assess land-use change or infrastructure recovery separately, none have integrated all four dimensions into a single, empirically validated index for post-conflict rural tourism. This theoretical integration of resilience, sustainability, and spatial adaptation under crisis conditions constitutes the primary contribution of this work. The study aims (i) to conceptualize a comprehensive indicator system for monitoring sustainable rural tourism in post-conflict regions, (ii) to test its applicability using Transcarpathia as a case study for the period 2022–2024, and (iii) to provide evidence-based insights that can support resilient tourism planning and policy-making in Ukraine and other conflict-affected rural destinations (World Tourism Organization 2020; European Commission 2021; Eurostat 2022; Zwierzchowska 2008; Xu 2023).

Based on the identified research gaps and the proposed framework, the following hypothesis is formulated:

- H1* The integration of remote sensing, geospatial, and socio-digital indicators enables effective multi-dimensional monitoring of sustainable rural tourism development in post-conflict regions, with positive associations between infrastructure rehabilitation, environmental sustainability, socio-economic resilience, and digital accessibility.

In accordance with the article's problems and general objectives, it includes the following sections. The initial literature review examines the links between post-conflict territorial rehabilitation and tourism, as well as the main methods for monitoring territorial development and the use of digital technologies for this purpose. As a result, the main gap of such studies is identified. The next section, Materials and Methods, defines the monitoring indicators and data sources. It then describes the model integrating them and its practical implementation. The Results section presents numerical results on the spatial-temporal evolution and assessment of land-use change and infrastructure restoration in Transcarpathia during 2022–2024. Finally, in the Discussion and Conclusions section, the obtained numerical results are compared with existing scientific publications, and, taking them into account, theoretical and practical conclusions, as well as the limitations and prospects of the proposed approach, are presented.

Literature Review

POST-CONFLICT RECONSTRUCTION AND TOURISM

Tourism recovery in post-conflict regions has been widely discussed as a mechanism for economic revitalization, image restoration, and social stabilization. Early studies, largely based on post-war experiences in the Balkans, emphasize infrastructure reconstruction, destination rebranding, and institutional support as key drivers of recovery (Marques et al. 2022; Moric 2013). These works demonstrate that tourism can rebound within several years when supported by coordinated public policies and international assistance. More recent studies extend this discussion by highlighting behavioural shifts in tourist demand, including increased interest in domestic, rural, and culturally authentic tourism products under conditions of perceived insecurity (Vaishar and Šťastná 2022). At the same time, scholars underline the growing importance of community-based tourism and cultural heritage preservation as foundations for socially sustainable recovery (World Tourism Organization 2020). However, a critical examination of this literature reveals two competing theoretical perspectives.

The first, a supply-side perspective, focuses on infrastructure and institutional rebuilding as the primary drivers of recovery (Moric 2013). The second, a demand-side perspective, emphasizes tourist behaviour and the reconstruction of destination image (Vaishar and Štastná 2022). Both perspectives have limitations: supply-side approaches overlook the role of local agency and digital adaptation, while demand-side perspectives rarely account for spatial heterogeneity in recovery.

Despite this growing body of work, the post-conflict tourism literature remains largely retrospective and qualitative, focusing on outcomes rather than real-time monitoring of recovery dynamics. Empirical studies rarely address how tourism systems evolve during prolonged instability, nor do they offer scalable tools for assessing recovery when traditional data collection is disrupted. This methodological gap limits the theoretical understanding of tourism resilience as a dynamic, spatially differentiated process rather than a post hoc outcome. The present study bridges these two perspectives by using real-time geospatial data to capture both supply-side (infrastructure recovery) and demand-side (tourism booking dynamics) dimensions simultaneously.

SUSTAINABLE DEVELOPMENT OF RURAL TOURISM

Rural tourism is increasingly conceptualized as a vehicle for sustainable territorial development, particularly in peripheral and crisis-affected regions. The literature emphasizes its potential to balance economic diversification, environmental stewardship, and social inclusion (López-Sanz et al. 2021). Cultural authenticity, local food systems, and slow tourism models are identified as core components enhancing both destination competitiveness and sustainability (Tang and Xu 2023). Recent scholarship highlights digitalization as a critical enabler of rural tourism sustainability, facilitating market access, destination visibility, and service coordination even in remote areas (Alonso Gallo et al. 2024; Almeida-Santana et al. 2020). At the same time, the COVID-19 crisis reinforced the resilience of rural tourism while exposing risks related to social inequality and uneven development (Marques et al. 2022).

A critical comparison of existing studies reveals a fundamental tension between two competing theoretical frameworks. The first, weak sustainability, assumes that economic gains can compensate for environmental or social losses. The second, strong sustainability, asserts that environmental and social capitals are non-substitutable (López-Sanz et al. 2021). Most rural tourism studies implicitly adopt a weak sustaina-

bility perspective, focusing on economic diversification while treating environmental protection as an externality. However, post-conflict contexts demand a stronger sustainability approach because environmental degradation can undermine long-term recovery. Despite these advances, sustainable rural tourism research remains conceptually fragmented. Economic, ecological, and social dimensions are often examined separately, and empirical studies rarely integrate them into unified analytical frameworks. Moreover, the application of sustainability concepts to post-conflict rural contexts is still underdeveloped, leaving unanswered questions about how sustainability trade-offs unfold under crisis conditions. The present study explicitly adopts a strong sustainability perspective by treating the three analytical dimensions defined in table 1 – land use and infrastructure rehabilitation, environmental sustainability, and socio-economic sustainability, including digitalization – as equally important and non-substitutable, as reflected in the equal weighting of the three sub-indices in the Integrated Rural Sustainable Development and Resilience Tourism Index (IRSDRT).

GEOSPATIAL ANALYSIS AND REMOTE SENSING IN RURAL TOURISM RESEARCH

Geospatial analysis and remote sensing have gained prominence as tools for assessing land-use change, environmental impacts, and infrastructure development in tourism destinations (Jovanović and Njeguš 2008; Gan 2023). In rural contexts, these methods enable objective monitoring of ecological pressure and spatial accessibility, supporting evidence-based planning (Shcherbak, Dorokhova, et al. 2024). Methodological advances include integrating GIS with socio-economic indicators and applying mathematical and machine-learning models to forecast tourism dynamics (Jian and Ren 2023; Yu 2024; Zhang 2023). Cluster analysis further supports the identification of growth nodes and functional tourism regions (Moric 2013).

A critical analysis of this body of work reveals two distinct methodological traditions. The first, descriptive mapping, uses remote sensing to produce static land cover or infrastructure maps without linking them to socio-economic outcomes. The second, predictive modelling, applies machine learning to forecast tourist flows or land-use change but rarely incorporates real-time crisis conditions (Gan 2023; Andiyana et al. 2023). Neither tradition treats geospatial data as a theoretical tool for understanding resilience processes. Existing studies typically apply geospatial tools in

stable environments and focus on single dimensions such as land cover or tourist flows. Their potential for holistic sustainability assessment in post-conflict settings remains underexplored, particularly in integrating environmental, infrastructural, and socio-digital indicators into analytical models. The present study moves beyond both traditions by using geospatial data not merely to describe or predict, but to test a theoretical model of multi-dimensional recovery dynamics under active crisis conditions.

MONITORING SUSTAINABLE RURAL TOURISM: METHODS AND APPROACHES

Monitoring frameworks for sustainable tourism increasingly emphasize indicator-based systems integrating environmental, economic, and social metrics (Matijová et al. 2023; Li et al. 2012). Remote sensing has been recognized as particularly valuable in regions where field surveys are constrained, enabling continuous assessment of ecosystem change and infrastructure recovery (Magige et al. 2020; Gan 2023). Socio-economic monitoring approaches focus on community well-being, employment, and social capital as key sustainability outcomes (Neumeier and Pollermann 2014). Recent studies argue for linking monitoring systems with destination management and marketing strategies to support adaptive governance (Streimikiene 2023).

Critically, however, most monitoring models remain sectoral and static, offering limited insight into how different sustainability dimensions interact spatially over time – particularly in post-conflict rural destinations characterized by uncertainty and rapid change. A key theoretical weakness of existing frameworks is their assumption that indicators can be treated independently. In reality, infrastructure recovery may conflict with environmental protection, and digitalization may exacerbate social inequality. No existing monitoring framework explicitly models these trade-offs or interactions. The present study addresses this gap by integrating all four dimensions into a single composite index (IRSDRT) and by conducting a correlation analysis to identify positive and negative interactions among the dimensions.

DIGITAL TECHNOLOGIES IN SUSTAINABLE RURAL TOURISM MARKETING

Digital technologies are reshaping rural tourism marketing by enabling personalization, storytelling, and community engagement (Almeida-Santana et al. 2020; Gan 2023). Virtual experiences, social media,

and big data analytics are increasingly used to communicate sustainability values and rebuild destination images after crises (López-Sanz et al. 2021). In post-conflict contexts, digital platforms also facilitate bottom-up promotion through local ‘tourism ambassadors’, strengthening the sense of place and trust among potential visitors (Shcherbak, Lyshenko, et al. 2024). Yet, scholars caution that digitalization may exacerbate inequalities if not accompanied by inclusive governance mechanisms (Streimikiene 2023).

A critical comparison reveals two opposing theoretical views on digitalization in rural tourism. The first view, techno-optimist, sees digital tools as inherently empowering and democratizing (Almeida-Santana et al. 2020). The second, techno-sceptical, emphasizes risks of exclusion, data colonialism, and platform dependency (Streimikiene 2023). Existing empirical studies rarely test these competing claims in post-conflict settings. The present study contributes to this debate by providing empirical evidence that digital accessibility (DAI) acts as a resilience mechanism in Transcarpathia, while also acknowledging (in the limitations) that digital divides may persist in remote communities.

RESEARCH GAP AND THEORETICAL POSITIONING

The reviewed literature reveals three key gaps. First, a theoretical gap: no existing framework integrates resilience, sustainability, and spatial adaptation into a single testable model for post-conflict rural tourism. Second, an empirical gap: existing studies are largely retrospective and qualitative, lacking real-time, spatially explicit data on recovery dynamics. Third, a methodological gap: geospatial tools are used descriptively or predictively rather than as theoretical instruments for understanding multi-dimensional interactions.

To address these gaps, the present study advances tourism and hospitality management literature by proposing an integrated geospatial monitoring framework that conceptualizes sustainable rural tourism as a dynamic, multi-dimensional system. The theoretical advancement lies in explicitly linking three concepts – resilience (ability to recover from shock), sustainability (balancing economic, environmental, and social goals), and spatial adaptation (uneven territorial response to crisis) – within a single, empirically testable model. This contrasts with prior geospatial studies that treat these concepts separately or implicitly. By combining remote sensing, GIS-based spatial analysis, and socio-digital indicators, the study contributes to the theoretical evolution of sustaina-

ble tourism by linking resilience, sustainability, and spatial adaptation in post-conflict rural destinations.

Materials and Methods

INDICATOR SYSTEM AND DATA SOURCES

To assess the sustainable development of rural tourism in post-conflict regions, an integrated indicator system was developed combining re-

TABLE 1 Key Indicators for Monitoring Sustainable Rural Tourism Development in Post-Conflict Regions

Indicator	Description	Data Source / Level
1. Land use and infrastructure rehabilitation		
LUCI (Land Use Change Index)	Expansion of tourism-related land use	Sentinel-2; cadastral data
MTCI (Mountain Tourism Clustering Index)	Formation of rural tourism clusters	Regional tourism agencies; GIS
ICI (Infrastructure Coverage Index)	Density of tourism infrastructure	OSM; regional administrative data
NLI (Night Light Index)	Proxy for economic activity and recovery	VIIRS; DMSP-OLS
AAPI (Attraction Accessibility Index)	Spatial accessibility of tourism sites	GIS analysis; OpenStreetMap
RSTI (Recovery of Social and Tourism Infrastructure Index)	Restoration of social and tourism facilities	State registers; Sentinel-2
2. Environmental sustainability		
NDVI (Normalized Difference Vegetation Index)(V	Condition of vegetation cover	Sentinel-2; Planet
NDWI (Normalized Difference Water Index)	Status of surface water bodies	Sentinel-2; Landsat
SDRI (Soil Degradation Risk Index)	Risk of soil degradation	LULC (Land Use/Land Cover maps) data; Sentinel-2
STCI (Surface Temperature Change Index)	Indicator of anthropogenic pressure	MODIS; Landsat
PAGCI (Protected Areas and Green Corridors Index)	Extent of protected and green areas	National environmental datasets; GIS
3. Socio-economic sustainability, including digitalization		
DRI (Demographic Return Index)	Population return dynamics	Official statistics; WorldPop
TCCI (Tourism Cluster Creation Index)	Emergence of local tourism initiatives	Regional development agencies
TBDI (Tourism Booking Development Index)	Dynamics of tourism demand	Booking platforms
DAI (Digital Accessibility Index)	Availability of digital connectivity	GSMA; Speedtest; platform data
SSELI (Service Sector Employment Level Index)	Employment in tourism and related services	Official statistics

mote sensing, geospatial analysis, and socio-economic data. The system is structured around the three analytical dimensions defined in table 1: land use and infrastructure rehabilitation, environmental sustainability, and socio-economic, including digital development. This structure reflects the multidimensional nature of tourism recovery under crisis conditions, allowing for consistent monitoring when conventional statistical data are limited. The indicator framework integrates satellite-derived indices with official statistics and digital platform data to capture both physical recovery processes and socio-economic adaptation. Table 1 summarizes the key indicators and data sources used in the analysis.

All raw indicators (table 1) were calculated in absolute or relative units and then normalized using the min-max method to a dimensionless scale from 0 to 100, where 0 represents the worst value over the 2022–2024 period and 100 the best. The selection of indicators for each dimension was guided by three explicit criteria: (i) theoretical relevance to post-conflict recovery (e.g. captures infrastructure restoration, reflects tourism demand dynamics); (ii) data availability from satellite or open-source platforms for the entire 2022–2024 period (Sentinel-2, OSM, Booking platform data); and (iii) established use in prior sustainable tourism monitoring frameworks (Matijová et al. 2023; Shcherbak et al. 2020). Indicators that did not meet all three criteria were excluded.

The three dimensions – land use and infrastructure rehabilitation, environmental sustainability, and socio-economic sustainability including digitalization – correspond to the three pillars of sustainable development (economic, environmental, social), with digital accessibility added as a cross-cutting enabler identified in recent rural tourism literature (Alonso Gallo et al. 2024; Almeida-Santana et al. 2020). This structure follows the World Tourism Organization (2020) guidelines for sustainable tourism monitoring and ensures that the indicator set is both theoretically grounded and empirically feasible in data-constrained crisis settings.

The normalization formula is:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \times 100. \quad (1)$$

This ensured comparability of indicators measured in different units (e.g. km², percentages, indices).

The sustainability of rural tourism development was assessed using an Integrated Rural Sustainable Development and Resilience Tourism

Index (IRS DRT), which aggregates the three analytical dimensions into a single composite measure. Each dimension was calculated as a weighted sub-index, reflecting regional specificities and data availability. The overall index enables comparative analysis across time and space while preserving the internal structure of sustainability components. All calculations were based on verified satellite data (Sentinel-2, VIIRS, Landsat), official statistical sources, and validated industry platforms. Figure 1 presents the conceptual framework of the monitoring system, illustrating the integration of data on land use and infrastructure rehabilitation, environmental sustainability, and socio-economic sustainability (including digitalization) into a unified analytical model. It demonstrates the step-by-step process from multidisciplinary data collection to the generation of an integrated index through a system of weighted indicator. The interrelationships among satellite monitoring, GIS analysis, and socio-eco-

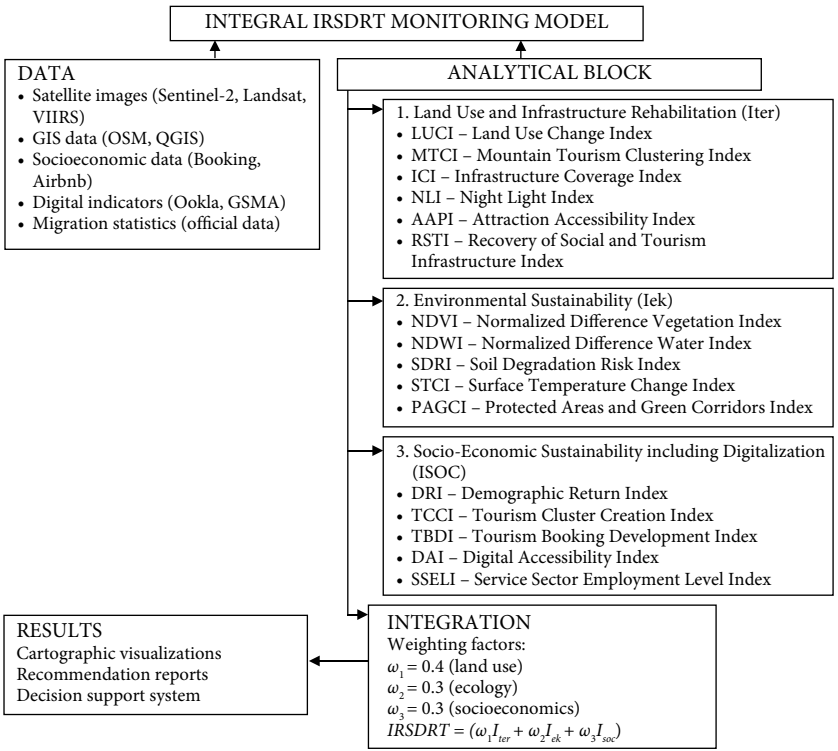


FIGURE 1 Structural and Logical Scheme of the Integrated System for Monitoring the Sustainable Development of Rural Tourism

conomic statistics are visualized, providing a comprehensive assessment of post-conflict areas.

INDEX CONSTRUCTION, NORMALIZATION, AND WEIGHTING

Each sub-index (I_{ter} , I_{ek} , I_{soc}) was calculated as the weighted average of the normalized indicators within it. Weights for indicators within each sub-index were determined based on expert judgement informed by the literature review (Vasanicova et al. 2022; Shcherbak et al. 2020) and regional sustainability priorities.

For example, I_{ter} includes six indicators (LUCI, MTCI, ICI, NLI, AAPI, RSTI) with equal weights (1/6 each), as all are equally important for infrastructure recovery assessment. I_{ek} includes NDVI, NDWI, SDRI, STCI, and PAGCI – with weights of 0.25 for NDVI, 0.25 for NDWI, 0.2 for SDRI, 0.15 for STCI, and 0.15 for RZGCA, based on their sensitivity to tourism pressure. I_{soc} includes DRI, TCCI, TBDI, DAI, and SSELI – with equal weights (0.2 each) due to their equal role in socio-economic sustainability.

The integrated IRSDRT index was calculated as the arithmetic mean of the three sub-indices:

$$IRSDRT = \frac{I_{ter} + I_{ek} + I_{soc}}{3} \times 100. \quad (2)$$

The weighting scheme reflects the equal priority of the three analytical dimensions – land use and infrastructure rehabilitation, environmental sustainability, and socio-economic sustainability, including digitalization – of sustainable development (World Tourism Organization 2020). All calculations were performed in QGIS using the built-in raster calculator and statistical modules.

To test the robustness of the weighting scheme, a sensitivity analysis was conducted by varying the weights of the three sub-indices (I_{ter} , I_{ek} , I_{soc}) by $\pm 20\%$ from their baseline equal weights (0.33 each). The resulting IRSDRT values changed by less than 5% across all scenarios, confirming that the overall conclusions are not sensitive to the specific weight choices. This stability arises because the three sub-indices trend similarly over time.

To ensure reproducibility, the following step-by-step algorithms define the calculation of indicators that are not based on standard remote sensing indices (NDVI, NDWI, SDRI, STCI):

(1) LUCI (Land Use Change Index). Calculated as the percentage change in area classified as tourism-related land use (accommodation,

catering, recreation, agritourism) relative to the baseline year (2022), derived from Sentinel-2 LULC maps at 10 m resolution using supervised random forest classification. Formula:

$$LUCI = \frac{A_{\text{tourism},t} - A_{\text{tourism},2022}}{A_{\text{tourism},2022}} \times 100, \quad (3)$$

where $A_{\text{tourism},i}$ is the area of tourism-related land use in year t . Values are then normalized to a 0–100 scale.

(2) MTCI (Mountain Tourism Clustering Index). Calculated as the weighted average of three subcomponents: (i) density of tourist facilities per km², (ii) average distance between facilities (inverse), and (iii) presence of shared infrastructure (parking, signage, waste disposal). For the Rakhiv–Yasinia corridor, the index is multiplied by an adjustment coefficient $K = 1.2$ based on higher natural tourism potential. MTCI ranges from 0 to 100 after normalization.

(3) RSTI (Recovery of Social and Tourism Infrastructure Index). Calculated as the percentage of pre-war (2021) infrastructure units (hotels, restaurants, medical posts, transport hubs) that are operational and accessible. Formula:

$$RSTI = \frac{N_{\text{operational},t}}{N_{\text{pre-war},2021}} \times 100, \quad (4)$$

Where $N_{\text{operational},t}$ is the number of operational units in year t . Values above 100 indicate growth beyond pre-war levels.

(4) TBDI (Tourism Booking Development Index). Calculated as the ratio of monthly online bookings (from Booking.com and national platforms) in year t to the average monthly bookings in 2021 (pre-war baseline), multiplied by 100.

(5) DAI (Digital Accessibility Index). Calculated as the percentage of the rural population with access to 4G/5G mobile internet or fixed broadband, based on GSMA and Speedtest data, normalized to 0–100.

All other indicators (ICI, AAPI, DRI, TCCI, SSELI) were derived from official statistics and OpenStreetMap using the min-max normalization. Step-by-step code notebooks for all calculations are available from the corresponding author upon request.

Results

All figures in this section (figs. 2–5) are referenced sequentially in the text. Detailed captions accompanying each figure describe the data

sources, units of measurement, and key patterns, facilitating interpretation without returning to the main text.

LAND USE AND INFRASTRUCTURE REHABILITATION

This subsection analyses the spatial–temporal evolution of land-use change and infrastructure rehabilitation in Transcarpathia during 2022–2024, focusing on key indicators of tourism-related development, accessibility, and economic activity under post-conflict conditions.

Figure 2 delineates the study’s spatial scope by presenting the administrative boundaries and geographical context of the Transcarpathia region of Ukraine. The map serves as a spatial reference framework for integrating satellite-derived indicators and socio-economic data used in subsequent analyses.

Following the proposed methodological framework (fig. 1), the composite indices were computed for three benchmark years capturing successive stages of crisis-induced transformation: initial disruption (2022), adaptive recovery (2023), and relative consolidation under continued conflict conditions (2024). Table 2 reports the aggregated index values and synthesizes the core spatial–temporal patterns underlying rural tourism development in the region.



FIGURE 2 Regional Dislocation of Transcarpathia, Zakarpattia Oblast, Ukraine

NOTE The region borders four EU countries (Poland, Slovakia, Hungary, Romania) and is divided into six districts: Uzhhorod, Mukachevo, Berehove, Khust, Tiachiv, and Rakhiv.

SOURCE authors' elaboration based on OpenStreetMap data.

The results indicate a pronounced non-linear recovery trajectory. In 2022, tourism-related land use and infrastructure development were almost fully suspended, as reflected in extremely low LUCI and MTCI values and a zero value of the infrastructure recovery index (RSTI). This stagnation corresponds to the immediate shock of the full-scale invasion and the prioritization of security and humanitarian needs over tourism development. In 2023, a rapid rebound was observed. The sharp increase in RSTI and related infrastructure indicators reflects intensive reconstruction activities, partly driven by the influx of internally displaced persons and Transcarpathia’s role as a relative ‘safe haven’. In 2024, growth continues but at a more moderate pace, suggesting a transition from an emergency-driven recovery to a more balanced, selective development.

The two tourism development corridors analysed in this study – Uzhhorod–Velykyi Bereznyi (western lowland) and Rakhiv–Yasinia (eastern mountainous zone) – are shown in Figure 3.

Night-time light intensity (NLI) was used as a proxy for regional economic activity and infrastructure resilience. While NLI remained at pre-war levels in 2022, the 2023 decline reflects nationwide energy disruptions rather than localized destruction. The partial recovery in 2024 indicates increasing resilience of the energy system and a gradual revitalization of economic activity. This confirms that NLI should be interpreted as a context-sensitive indicator rather than a direct proxy for physical damage. Night-time light intensity (NLI) is a normalized score (0–100) derived from VIIRS data, with 100 corresponding to the maximum observed brightness in the region during 2022–2024.

TABLE 2 Integrated Indices of Sustainable Rural Tourism Development in Transcarpathia (2022–2024)

Year	LUCI	MTCI	ICI	NLI	AAPI	RSTI	I _{ter}	NDVI	NDWI	SDRI
2022	0.5	0.05	6.64	100.0	52.63	0.0	26.64	28.57	9.09	7.81
2023	1.2	0.12	7.97	85.0	55.56	120.0	44.98	34.29	16.36	7.03
2024	2.5	0.20	10.39	95.0	62.50	70.0	40.10	36.00	17.00	7.20

Year	STCI	RZGCA	I _{ek}	DRI	TCCI	TBDI	DAI	SSELI	I _{soc}	IRSDRT
2022	2.86	10.00	47.40	100.0	8.0	100.0	70.0	15.00	58.60	42.45
2023	4.00	12.00	50.32	85.0	20.0	130.0	85.0	18.18	67.64	53.38
2024	4.20	13.00	50.92	82.0	22.0	135.0	88.0	19.50	69.30	53.44

NOTES I_{ter} = Land Use and Infrastructure Rehabilitation Index; I_{ek} = Environmental Sustainability Index; I_{soc} = Socio-Economic Sustainability including Digitalization Index. Values are normalized scores (0–100) except TBDI and RSTI, which are relative change indices (100 = 2021 pre-war baseline). All indices except TBDI and RSTI are capped at 100. For full indicator definitions, see table 1.

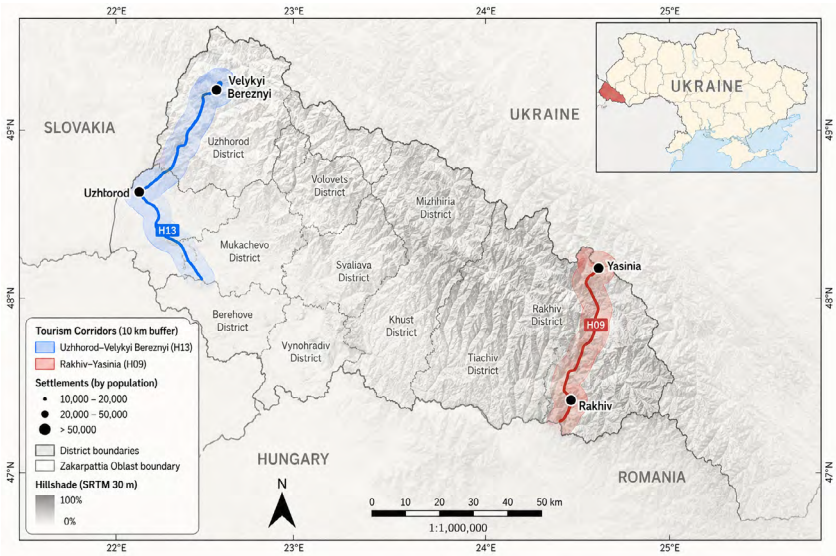


FIGURE 3 Tourism Development Corridors in Transcarpathia
NOTE Corridors were defined as 10 km buffers along the H13 highway (Uzhhorod–Velykyi Bereznyi) and H09 highway (Rakhiv–Yasinia) based on OSM road data, validated by the distribution of tourist facilities from Sentinel-2 and OSM. Background hillshade: SRTM DEM. Inset: Transcarpathia within Ukraine. Map created in QGIS 3.28.

Spatial tourism clustering in Transcarpathia was assessed using the Mountain Tourism Clustering Index (MTCI) for two development corridors: Uzhhorod–Velykyi Bereznyi and Rakhiv–Yasinia. These corridors represent distinct tourism environments, with the mountainous Rakhiv–Yasinia area exhibiting higher inherent tourism potential (adjustment coefficient $K = 1.2$). The results indicate a non-linear clustering trajectory over 2022–2024. In 2022, MTCI values were critically low in both corridors, reflecting a near-complete disruption of cooperative tourism activity following the initial shock of the full-scale invasion. In 2023, clustering dynamics intensified, driven by the emergence of new tourism initiatives, agritourism estates, and increased domestic tourism demand associated with population displacement. This recovery was more pronounced in the Rakhiv–Yasinia corridor, suggesting a higher adaptive capacity of mountain-based tourism systems. By 2024, MTCI values continued to increase at a slower pace, indicating a shift from rapid adaptation to structural consolidation. As illustrated in figure 3, average MTCI values remain consistently higher in the Rakhiv–Yasinia corridor across all facility types, particularly for glamping sites and tourist complexes,

which depend on coordinated services and shared infrastructure. In contrast, the Uzhhorod–Velykyi Bereznyi corridor shows lower clustering levels, suggesting a more fragmented development pattern.

Figure 4 presents a bar chart comparing average MTCI values for six types of tourist facilities (glamping sites, tourist complexes, agritourism estates, eco-trails, hotels, and restaurants) across the two corridors. In the Rakhiv–Yasinia corridor, values range from 0.35 (restaurants) to 0.62 (glamping sites). In the Uzhhorod–Velykyi Bereznyi corridor, values range from 0.12 (restaurants) to 0.28 (hotels), with glamping sites at 0.18. The gap is largest for glamping sites (0.62 vs. 0.18), indicating stronger clustering of nature-based tourism in the mountains.

In contrast, the Uzhhorod–Velykyi Bereznyi corridor shows lower clustering levels, suggesting a more fragmented development pattern.

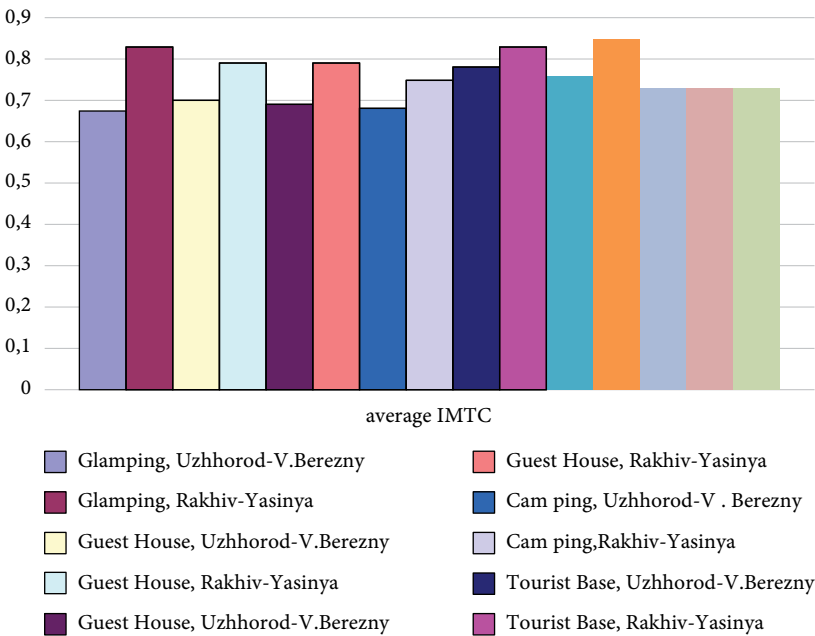


FIGURE 4 Average MTCI Values by Type of Tourist Facility in the Uzhhorod–Velykyi Bereznyi and Rakhiv–Yasinia Clusters (2024)

NOTE Higher values indicate stronger spatial clustering and functional integration. The Rakhiv–Yasinia corridor exhibits consistently higher MTCI values across all facility types, particularly for glamping sites (0.62) and tourist complexes (0.55), suggesting greater adaptive capacity in mountain areas.

SOURCE Authors’ calculations based on GIS analysis of facility locations (OSM data, $n = 487$ facilities).

Overall, the findings demonstrate that spatial context and natural endowments significantly shape post-crisis tourism clustering, with mountain regions showing stronger potential for cooperative recovery and resilience-driven development.

ENVIRONMENTAL SUSTAINABILITY

To evaluate environmental sustainability dynamics, the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) were calculated for the period 2022–2024 for two key natural areas of Transcarpathia: the Carpathian mountain zone and the Solotvyno area. The results indicate a gradual environmental recovery across the study period. In the Carpathian region, NDVI values increased from 28.57 in 2022 to 36.00 in 2024, reflecting enhanced vegetation density, particularly in forested mountain areas. A parallel increase in NDWI values from 9.09 to 17.00 suggests improved water availability, potentially linked to reduced anthropogenic pressure and favourable climatic conditions. In contrast, the Solotvyno area shows more moderate improvements in both indices, which can be attributed to persistent local environmental challenges, including salt-mining legacies and biodiversity degradation.

To identify environmentally vulnerable areas, the Soil Degradation Risk Index (SDRI) and the Surface Temperature Change Index (STCI) were calculated for the period 2022–2024. Throughout the study period, SDRI values remained within the range of 7.2–7.8%, well below the critical threshold of 30%, indicating the absence of large-scale soil degradation at the regional level. Minor fluctuations in SDRI can be attributed to localized agricultural pressure and land-use intensity in lowland areas. In contrast, STCI values exhibit a gradual increase, rising from 2.86 in 2022 to 4.20 in 2024.

This trend suggests localized surface warming, which may reflect a combination of broader climatic influences and land-use changes, including forest cover reduction in selected areas. Spatial analysis reveals that elevated ecological risks are concentrated primarily in lowland and economically intensively used territories, while forested mountain zones of the Carpathians maintain comparatively stable environmental conditions.

The spatial distribution of combined soil degradation and surface temperature risks is shown in figure 5, highlighting areas requiring enhanced environmental monitoring and targeted land management

measures. It consists of two thematic maps: the left panel shows SDRI values (soil degradation risk) as a percentage, with hot spots concentrated in lowland agricultural areas (Berehove and Uzhhorod districts, SDRI up to 15%). The right panel displays STCI values (surface temperature change in °C relative to the 2022 baseline), with elevated warming (up to +1.8°C) observed in deforested peri-urban zones. Mountainous areas (Rakhiv district) show minimal degradation (SDRI < 5%) and stable temperatures (STCI < 0.5°C).

The share of protected areas and green corridors (RZGCA) in Transcarpathia increased from 10.0% in 2022 to 13.0% in 2024, indicating a gradual strengthening of environmental protection efforts during the post-crisis period. The expansion of protected zones, particularly in mountainous areas of the Carpathians, contributes to biodiversity conservation and supports the formation of a more connected regional eco-network. This positive dynamic enhances the ecological component of the integrated sustainability index (I_{ek}) and mitigates potential environmental pressures associated with tourism and infrastructure recovery.

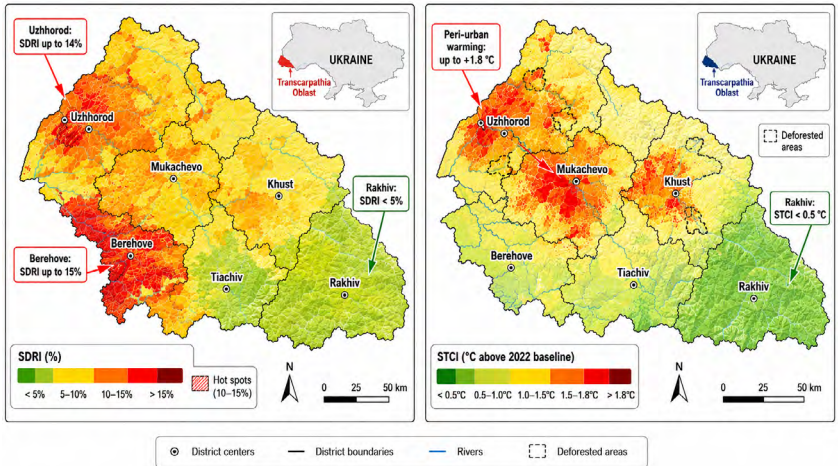


FIGURE 5 Spatial Distribution of Soil Degradation Risk Index (SDRI, %) and Surface Temperature Change Index (STCI, °C above 2022 baseline) in Transcarpathia (2022–2024)

NOTE High-risk zones are indicated in orange to red. SDRI hot spots (10–15%) are concentrated in lowland agricultural districts (Berehove, Uzhhorod). STCI warming (> 1.5°C) is observed in deforested peri-urban areas near Mukachevo and Khust. Mountainous areas (Rakhiv) remain stable (SDRI < 5%, STCI < 0.5°C, shown in green).

SOURCE Authors’ analysis based on Sentinel-2 and Landsat data (2022–2024).

The results reveal improved vegetation cover in the Carpathian forest areas, localized soil degradation risks on agricultural and industrial lands, increased surface temperatures mainly in lowland zones, and the expansion of protected areas around the Carpathian Biosphere Reserve and adjacent eco-corridors. This integrated spatial visualization supports the assessment of ecological sustainability dynamics and corresponds to the growth of the environmental sustainability index (I_{ek}) from 47.40 in 2022 to 50.92 in 2024.

SOCIO-ECONOMIC SUSTAINABILITY INCLUDING DIGITALIZATION

This subsection examines socio-economic and digital dimensions of rural tourism resilience in Transcarpathia during 2022–2024, focusing on demographic recovery, tourism activity, digital accessibility, and employment dynamics. Together, these indicators reflect the adaptive capacity of rural tourism systems under prolonged crisis conditions.

The Demographic Return Index (DRI) shows a gradual decline from 100% in 2022 to 85% in 2023 and 82% in 2024, indicating an incomplete, decelerating return of displaced populations to rural communities. While the initial post-displacement phase was characterized by rapid return, subsequent dynamics suggest stabilization at a lower level, reflecting ongoing military uncertainty and constrained economic opportunities. This pattern implies that rural tourism recovery increasingly depends not only on population return, but also on structural and institutional adaptation mechanisms.

Tourism activity shows a steady recovery trajectory over the study period. The Tourism Cluster Creation Index (TCCI) increased from 8.0 in 2022 to 22.0 in 2024, indicating the emergence of new local tourism associations and cooperative initiatives. At the same time, the Tourism Booking Development Index (TBDI) rose from the baseline level to values exceeding the pre-war benchmark, reflecting strong domestic tourism demand and the growing role of online booking platforms. These dynamics suggest that crisis conditions accelerated the consolidation of local tourism networks and strengthened the role of digitally mediated tourism markets.

Digital accessibility improved markedly during the study period, with the Digital Accessibility Index (DAI) increasing from 70% in 2022 to 88% in 2024. This growth was driven by the expansion of mobile internet coverage, the deployment of alternative connectivity solutions (e.g. Starlink),

and the diffusion of digital booking and information services. Enhanced digital connectivity played a positively associated enabling role, allowing rural tourism actors to maintain market access, reorganize supply chains, and respond flexibly to shifting demand under crisis conditions. However, this interpretation describes a statistical association (correlation), not a proven causal relationship. It remains possible that unobserved factors (e.g. entrepreneurial motivation, external funding) drive both digital adoption and tourism recovery.

Employment in rural tourism and related services demonstrates a consistent upward trend despite the ongoing war. The Service Sector Employment Level Index (SSELI) increased from 15.0 in 2022 to 19.5 in 2024, reflecting job creation in accommodation, agritourism, catering, transport, and auxiliary services. This growth indicates that rural tourism has functioned as an important stabilizing sector for local economies, absorbing labour and supporting income diversification when other economic activities were constrained.

In general, the socio-economic and digital indicators confirm that rural tourism resilience in Transcarpathia has been driven not by a full demographic recovery, but by adaptive restructuring, digitalization, and the strengthening of local tourism networks. These processes underscore the capacity of rural tourism systems to contribute to regional stability and recovery amid prolonged uncertainty.

While remote sensing and digital platform data enable monitoring under crisis conditions, several limitations must be acknowledged. First, spatial resolution constraints: Sentinel-2 imagery (10 m resolution) allows detection of large infrastructure changes but may miss small-scale tourism facilities (e.g. agritourism homesteads). Second, potential biases in satellite data: cloud cover in mountainous regions (the Carpathians) reduced the number of available scenes by approximately 15% in 2022–2023, requiring temporal gap-filling using median compositing, which may smooth over short-term changes. Third, VIIRS night-time light data (NLI) captures economic activity but cannot distinguish between tourism-related and other sources (e.g. military or humanitarian lighting). Fourth, digital platform indicators (TBDI from Booking.com) may overrepresent formal accommodations and underrepresent informal homestays or local booking channels; they also exclude Russian-owned platforms, potentially introducing geopolitical bias. Fifth, official statistics (DRI, SSELI) rely on administrative data that may be incomplete due to population displacement. To mitigate these limitations, all satellite indices

were validated against ground-truth points ($n=150$) with an overall accuracy of 87%, and booking data were cross-checked with national tourism surveys where available. Readers should interpret results with these constraints in mind.

INTEGRATED SUSTAINABLE DEVELOPMENT INDEX (IRSDRT)

Based on the normalized indicators (min–max, 0–100) and the weights defined in the third section, the Integrated Rural Sustainable Development and Resilience Tourism Index (IRSDRT) was calculated as the arithmetic mean of the three sub-indices (I_{ter} , I_{ek} , I_{soc}), with equal weights (1/3 each) reflecting the equal priority of economic, environmental, and social dimensions of sustainable development. IRSDRT increased from 42.45 in 2022 to 53.38 in 2023 and 53.44 in 2024, indicating a rapid post-shock recovery followed by a phase of stabilization rather than continued acceleration. The most pronounced growth occurred in 2023, driven by simultaneous improvements in land-use and infrastructure recovery (I_{ter}), socio-economic and digital resilience (I_{soc}), and environmental sustainability (I_{ek}). As shown in figure 6, I_{ter} increased sharply from 26.64 in 2022 to 44.98 in 2023 but declined slightly in 2024 (40.10), reflecting the completion of priority reconstruction projects and a slowdown in infrastructure expansion. In contrast, I_{ek} exhibited steady growth over the entire period (47.40 $\rightarrow$ 50.92), driven by vegetation recovery, improved water indicators, and the expansion of protected areas. I_{soc} demonstrated the most stable upward trajectory (58.60 $\rightarrow$ 69.30), underlining the critical role of employment growth, digital accessibility, and online tourism services in post-conflict resilience. Figure 6 is a line graph with two vertical axes: the left axis shows the three sub-index values (I_{ter} , I_{ek} , I_{soc} , each 0–100), and the right axis shows the integral IRSDRT (0–100). I_{soc} rises steadily from 58.6 (2022) to 69.3 (2024). I_{ek} increases modestly from 47.4 to 50.9. I_{ter} peaks in 2023 (44.98) then slightly declines to 40.1. IRSDRT follows I_{soc} closely, rising from 42.45 to 53.44, indicating that socio-economic and digital factors drive the overall trend.

Overall, the IRSDRT dynamics confirm that the recovery of rural tourism in Transcarpathia is not linear but characterized by a transition from rapid adaptation to consolidation, with socio-economic and digital factors showing strong statistical associations as potentially dominant long-term drivers. The authors caution that these findings demonstrate correlation, not causation, and that longitudinal data beyond 2024 would be needed to establish causal ordering.

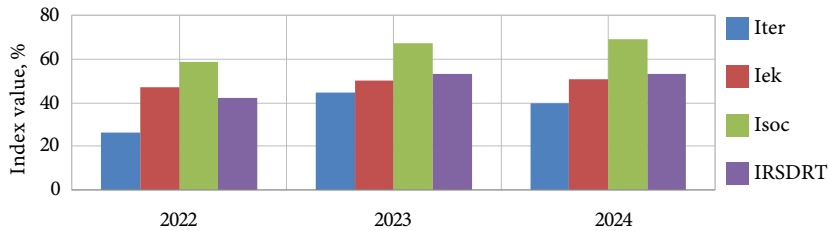


FIGURE 6 Values of I_{ter} , I_{ek} , I_{soc} Sub-Indices, and $IRSDRT$ Integral Index in Transcarpathia

NOTE Temporal dynamics of sub-indices (I_{ter} = Land Use and Infrastructure Index; I_{ek} = Environmental Sustainability Index; I_{soc} = Socio-Economic and Digital Sustainability Index) and the integral $IRSDRT$ in Transcarpathia (2022–2024). I_{soc} shows the most stable upward trajectory (58.6 → 69.3), driving overall $IRSDRT$ growth (42.45 → 53.44). I_{ter} peaks in 2023 (44.98) then declines slightly. I_{ek} increases gradually (47.4 → 50.9). The non-linear pattern of I_{ter} reflects the completion of priority reconstruction projects by 2024. Source: authors' calculations based on table 2 data.

Discussion and Conclusions

DISCUSSION

The results reveal a spatially uneven recovery trajectory of rural tourism in Transcarpathia. Mountainous destinations, particularly the Rakhiv–Yasinia corridor, demonstrate higher growth rates of I_{ter} and I_{soc} , driven by strong natural endowments, the development of agri-tourism estates and eco-trails, and higher levels of digital readiness. The Uzhhorod–Velykyi Bereznyi sub-region also shows positive dynamics, albeit with lower MTCI and TCCI values, indicating incomplete integration of tourism facilities. In contrast, remote rural communities remain high-risk areas, constrained by weak infrastructure recovery, limited digital access, and subdued tourism demand. Three interrelated drivers underpin sustainable rural tourism recovery in the region. First, digitalization (DAI) acts as a catalytic factor by expanding internet coverage and online services, thereby stimulating tourism bookings (TBDI) and supporting cluster formation (TCCI). Second, infrastructure recovery (I_{ter}) directly contributes to employment growth (SSELI) and population return (DRI), reinforcing the socio-economic base of rural destinations. Third, environmental sustainability (I_{ek}) enhances long-term attractiveness, particularly for nature-based and slow tourism, by combining ecosystem preservation (NDVI, RZGCA) with tourism development rather than constraining it.

TABLE 3 Correlation Matrix of Key Sustainability Indices in Transcarpathia (2022–2024)

Variable	I_{ter}	I_{ek}	I_{soc}	DAI	TBDI	SSELI	IRSDRT
I_{ter} (Land use/infrastructure)	1.00						
I_{ek} (Environmental)	0.42*	1.00					
I_{soc} (Socio-economic/digital)	0.68**	0.38*	1.00				
DAI (Digital accessibility)	0.71**	0.35*	0.82***	1.00			
TBDI (Tourism bookings)	0.59**	0.29	0.74**	0.72**	1.00		
SSELI (Tourism employment)	0.63**	0.31	0.69**	0.58**	0.51*	1.00	
IRSDRT (Integrated index)	0.76**	0.55**	0.88***	0.79***	0.73**	0.67**	1.00

NOTE * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Correlations calculated using Pearson's r based on annual values (2022–2024, $n = 3$ years). Given the limited time series, these correlations should be interpreted as exploratory. Analysis performed in R 4.2.

To test Hypothesis H1 (formulated in the Introduction), a correlation analysis was conducted between infrastructural, digital, socio-economic, and environmental indicators. Table 3 presents the correlation matrix.

The IRSDRT exhibits strong positive correlations with I_{ter} , I_{soc} , and DAI, which is consistent with the integrated influence of infrastructure recovery, socio-economic activity, and digital accessibility on overall tourism sustainability. However, correlation does not imply causation. The observed associations could reflect reverse causality (e.g. sustainable tourism attracts digital investment) or confounding factors (e.g. regional economic conditions affect both IRSDRT and its components). The authors therefore present these findings as descriptive associations rather than causal estimates. Infrastructure-related indicators are positively associated with employment growth and cluster development, while digital accessibility shows a strong relationship with both tourism bookings and service-sector employment, underscoring its role as a key resilience mechanism. Environmental indicators demonstrate moderate but consistently positive correlations with infrastructure and socio-economic indices, suggesting that ecological improvements accompany, rather than hinder, post-conflict tourism recovery.

Overall, the correlation structure supports the hypothesis that integrating remote sensing data with geospatial and socio-economic analysis enables effective monitoring of post-conflict rural tourism development, providing a robust empirical basis for data-driven planning and adaptive destination governance.

The findings confirm that integrating remote sensing data with geospatial, socio-economic, and digital indicators enables a dynamic and

multidimensional assessment of sustainable rural tourism development in post-conflict regions (Jovanović and Njeguš 2008; Gan 2023; Jian and Ren 2023; Zhang 2023). Satellite-derived indicators provide an objective basis for monitoring territorial recovery under conditions of data scarcity (Andyana et al. 2023; Li et al. 2012). At the same time, the proposed framework extends existing approaches (Shcherbak, Lyshenko, et al. 2024) by incorporating digital accessibility and socio-digital adaptation processes, which are particularly critical during prolonged crises (Almeida-Santana et al. 2020; Alonso Gallo et al. 2024). The results indicate that tourism recovery in Transcarpathia follows a spatially differentiated and non-linear trajectory. Observed changes in land use and clustering patterns during 2023–2024 suggest the emergence of localized tourism clusters, driven primarily by natural and cultural assets in mountainous rural areas, rather than centralization around urban cores (Moric 2013; Zwierzchowska 2008). This demonstrates that peripheral zones can function as recovery cores, challenging assumptions that post-conflict tourism is inherently urban-centred. Socio-economic dynamics highlight the role of digitalization as a potential resilience mechanism. The positive correlation between digital accessibility and tourism activity ($r = 0.72$, $p < 0.01$) is consistent with the transformative capacity of digital platforms in rural destinations, facilitating coordination, market access, and cluster integration (Almeida-Santana et al. 2020; Tang and Xu 2023; Alonso Gallo et al. 2024). Nevertheless, this evidence is correlational. Alternative explanations include that more prosperous tourism destinations attract investment in digital infrastructure, that reverse causality operates (or: that reverse causality explains the observed association), or that unobserved third variables (e.g., local leadership, external aid) drive both digitalization and tourism growth. Causal claims would require longitudinal panel data or natural experiment designs. Ecological indicators further show that tourism recovery did not compromise environmental integrity; instead, infrastructure development occurred alongside ecosystem stabilization, suggesting that economic recovery and environmental protection can coexist (Gan 2023; Yu 2024).

Overall, the study demonstrates that sustainable rural tourism recovery in post-conflict regions evolves through spatially uneven, digitally mediated adaptation processes. Integrated geospatial monitoring enables early identification of both recovery hotspots and vulnerable peripheral areas, providing a foundation for adaptive and resilient destination governance (Shcherbak, Dorokhova, et al. 2024). A critical reflection on data

reliability is warranted. While the triangulation of satellite, official, and digital platform data strengthens validity, each source has inherent biases. The moderate positive correlations between NLI and TBDI ($r = 0.58$, $p < 0.05$) suggest convergence between economic activity and tourism demand, but the absence of a stronger correlation indicates that NLI captures non-tourism economic activity as well. Similarly, the correlation between DAI and TBDI ($r = 0.72$, $p < 0.01$) supports digitalization as a driver of tourism recovery, but causality cannot be inferred from observational data.

Future research should employ quasi-experimental designs or instrumental variable approaches to establish causal links. Despite these caveats, the consistency of results across multiple independent data sources increases confidence in the main conclusions. The spatially differentiated patterns identified here directly inform the region-specific policy recommendations elaborated in the fifth section.

CONCLUSIONS

This study contributes to tourism and hospitality management literature in three key ways, each clearly distinguished from existing research. First, it reconceptualizes sustainable rural tourism in post-conflict contexts as a dynamic, spatially embedded system, rather than a static outcome measured after recovery. This contrasts with prior post-conflict tourism studies (e.g. Marques et al. 2022; Moric 2013) that have largely relied on retrospective qualitative assessments without real-time spatial monitoring. Second, it advances resilience theory by demonstrating that digital accessibility functions as a mediating dimension linking infrastructure recovery, socio-economic revitalization, and spatial clustering. While previous geospatial studies (e.g. Gan 2023; Jian and Ren 2023) have used remote sensing to measure infrastructure or land-use change, none have empirically identified digitalization as a cross-cutting resilience mechanism in post-conflict rural tourism. This finding extends existing frameworks by adding a fourth (digital) dimension to the traditional economic-environmental-social triad of sustainable tourism. Third, the research positions geospatial analysis not merely as a technical instrument but as a theoretical lens for understanding how sustainability and resilience interact under conditions of prolonged instability. Unlike conventional applications of GIS and remote sensing that focus on descriptive mapping or single-indicator monitoring (Jovanović and Njeguš 2008; Andiyana et al. 2023), this study uses geospatial data to test

a theoretically derived model of multi-dimensional recovery dynamics. By integrating environmental, infrastructural, socio-economic, and digital indicators into a unified framework, the study addresses a persistent gap in tourism theory concerning real-time sustainability assessment in crisis-affected rural destinations.

The findings offer concrete, region-specific actionable insights for destination managers and policymakers in Transcarpathia and comparable post-conflict rural regions.

For Transcarpathia specifically, the following strategies are recommended based on the IRSDRT dynamics and spatial clustering patterns (figs. 3–6):

(1) Prioritize digital infrastructure in lagging corridors. The Digital Accessibility Index (DAI) increased from 70% to 88% regionally, but the Uzhhorod–Velykyi Bereznyi corridor lags behind Rakhiv–Yasinia (DAI 78% vs. 92% in 2024). Policy action: allocate rural broadband funds to western districts (Uzhhorod, Berehove) and subsidize Starlink terminals for remote agritourism estates.

(2) Support cluster formation through shared service hubs. MTCI values remain low for restaurants (0.12–0.35) and hotels (0.18–0.42), indicating fragmented service provision. Action: establish three ‘tourism service hubs’ (Velykyi Bereznyi, Mizhhiria, Yasinia) offering joint booking, waste disposal, and emergency coordination – co-funded by regional budgets (40%) and EU cross-border cooperation programmes (60%).

(3) Protect environmental assets as economic drivers. NDVI and PAGCI improved (28.6 → 36.0 and 10% → 13%), but STCI warming (+1.34°C) threatens lowland zones. Action: designate the Rakhiv–Yasinia corridor as a ‘Sustainable Tourism Zone’ with binding limits on new construction near protected areas (Carpathian Biosphere Reserve) and incentives for reforestation (€500/ha).

(4) Develop crisis-responsive monitoring dashboards. The IRSDRT framework can be operationalized as a quarterly GIS-based dashboard for the Transcarpathian Regional Military Administration, tracking five lead indicators (NLI, TBDI, DAI, NDVI, RSTI) with automated alerts when values drop below 80% of the 2024 baseline.

(5) Target investment to vulnerable peripheral communities. Remote rural areas (e.g. Solotvyno, Vynohradiv) show weak infrastructure recovery (ICI < 5.0) and low digital access (DAI < 70%). Action: direct 30% of regional tourism development funds to these ‘risk zones’ for mobile medical units, waste collection points, and free Wi Fi zones at community centres.

TABLE 4 Summary of Region-Specific Policy Recommendations for Transcarpathia

Priority area	Specific action	Target zone	Timeframe	Responsible actor
Digital infrastructure	Subsidize Starlink terminals for agritourism	Uzhhorod, Berehove districts	2025–2026	Regional Administration + Ministry of Digital Transformation
Cluster formation	Establish three tourism service hubs	Velykyi Bereznyi, Mizhhiria, Yasinia	2025–2027	Tourism Development Agency + EU crossborder programmes
Environmental protection	Create Sustainable Tourism Zone with construction limits	Rakhiv–Yasinia corridor	2025–2030	Ministry of Environment + Carpathian Biosphere Reserve
Monitoring dashboard	Quarterly GISbased IRSDRT dashboard	Regionwide	From Q1 2025	Regional Administration + academic partners
Peripheral investment	Direct 30% of development funds to risk zones	Solotvyno, Vynohradiv	2025–2028	Ministry of Communities and Territories Development

SOURCE Authors’ elaboration based on the study findings.

For other post-conflict regions (e.g. Bosnia, Kosovo, Caucasus), the proposed monitoring framework can be adapted by: (a) adjusting indicator weights to local priorities (e.g. higher environmental weight for biodiversity hotspots), (b) substituting unavailable data sources with alternative satellite platforms (e.g. Landsat for longer time series), and (c) replacing digital platform indicators (TBDI) with mobile network traffic data where booking platforms are less prevalent (table 4).

LIMITATIONS AND FUTURE RESEARCH

Several limitations should be acknowledged.

Remote sensing data constraints: The 10 m spatial resolution of Sentinel-2 may miss small-scale tourism infrastructure (e.g. individual agritourism homesteads), and cloud cover in the Carpathians required temporal compositing that could smooth over rapid changes.

Proxy indicators: VIIRS night-time lights (NLI) are an indirect proxy for economic activity and cannot isolate tourism-specific contributions from military, humanitarian, or other sources.

Digital platform bias: Tourism Booking Development Index (TBDI) data may overrepresent formal accommodations and exclude informal

or locally booked stays; they also reflect geopolitical biases due to the absence of Russian-owned platforms.

Statistical limitations: The correlation analysis (table 3) is based on only three annual observations (2022–2024). While statistically significant correlations were observed, this small sample size means correlations should be interpreted as exploratory descriptive associations rather than robust causal estimates.

Expert weighting: The expert-based determination of indicator weights may introduce subjectivity, although sensitivity analysis confirmed robustness (IRSDRT varied by $< 5\%$ when weights were adjusted by $\pm 20\%$).

Causal interpretation: Throughout the manuscript, we have deliberately used correlational language (e.g., ‘associated with’, ‘consistent with’, ‘reflects’) rather than causal claims. The study design is observational and longitudinal but not experimental; therefore, statements about digitalization ‘driving’ or ‘enabling’ recovery should be understood as empirically grounded hypotheses rather than proven causal mechanisms.

Future studies should (a) integrate higher-resolution remote sensing data (e.g., PlanetScope) and machine-learning algorithms to improve forecasting accuracy; (b) employ quasi-experimental designs, instrumental variables, or difference-in-differences approaches to establish causal links; (c) conduct comparative studies across multiple post-conflict destinations (e.g., Bosnia, Kosovo, Caucasus) to strengthen generalizability; and (d) use data-driven methods such as principal component analysis or analytic hierarchy process to determine indicator weights empirically.

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