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Spatial modeling of tourism environmental load on communities using the example of Ivano-Frankivsk region of Ukraine

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ABSTRACT

This study aims to assess the spatial intensity and structural characteristics of tourism-related environmental impacts in Ivano-Frankivsk region, with particular attention to mountain communities of the Carpathian region. The research integrates the Tourism Satellite Account (TSA) methodology with geospatial analysis and environmental statistics in order to ensure consistency between economic indicators of tourism development and ecological pressure metrics.The empirical framework is based on data from tourist tax reporting, environmental tax statistics, regional accounts, and the Unified State Register of business entities for the period 2019–2024, with detailed analysis conducted for 2024. Tourism demand intensity is measured using tourist-days normalised per square kilometre, while environmental pressure is evaluated through area-based indicators of water consumption, atmospheric emissions, discharges into water bodies, and municipal solid waste generation. In addition, the share of tourism enterprises in the formation of each environmental indicator is calculated to identify the structural role of the tourism sector within territorial communities.The results reveal a pronounced spatial concentration of tourism demand in mountain communities, where compact territorial size and recreational specialisation lead to exceptionally high levels of tourism intensity. Industrial and energy-oriented communities dominate in absolute and specific environmental pressure indicators, whereas tourism-oriented territories exhibit a high sectoral share of tourism enterprises in water use and wastewater discharges, despite lower total volumes. Municipal solid waste generation demonstrates extreme spatial concentration linked primarily to industrial infrastructure, while the contribution of tourism enterprises remains relatively limited even in highly recreational areas.

Keywords: tourism development, spatial analysis, territorial communities, Ivano-Frankivsk region, sustainable tourism.

INTRODUCTION

Sustainable development of tourism destinations represents a strategic priority of contemporary environmental, economic and regional policy, reflecting the rapidly growing contribution of tourism to global and national economies alongside its increasing environmental externalities (European Environment Agency, 2025; UN Tourism, 2024). While tourism functions as an important driver of regional development, employment and investment, its expansion is simultaneously associated with intensified pressures on ecosystems through higher energy demand, water use, waste generation, atmospheric emissions and land-use change. This inherent duality has placed tourism at the core of academic and policy debates on balancing economic competitiveness with long-term ecological integrity (Matiyiv et al., 2022).

Conceptual and empirical research demonstrates that tourism-related environmental impacts are spatially differentiated and strongly dependent on destination type, scale and underlying economic structure (Arkhypova et al., 2022). Tourism growth often reinforces existing patterns of resource consumption and pollution, particularly in regions with limited environmental

carrying capacity or insufficient infrastructure development (Gössling et al., 2015). In addition, tourism acts as an indirect driver of environmental change by stimulating transport flows, construction activity and service-sector energy use, thereby amplifying cumulative and cross-sectoral pressures on natural systems (Lopes et al., 2021). These interlinkages underscore the need to integrate principles of resource efficiency, pollution prevention and ecosystem protection into tourism governance at both national and subnational levels (Guzii et al., 2021).

Recent literature highlights a shift toward multidimensional sustainability assessment frameworks that combine environmental, economic and social indicators, increasingly supported by spatially explicit analytical tools (Papečkys & Jasinskas, 2024). However, their application remains uneven, especially in regions characterised by fragmented governance, limited statistical capacity and exposure to external shocks such as climate change, public health crises and geopolitical instability. In the European context, mountain regions are widely recognised as particularly vulnerable due to limited carrying capacity, strong seasonality and fragile natural systems. Empirical evidence confirms that rapid growth of tourist flows without adequate regulation and spatial planning leads to habitat degradation, water and soil pollution, waste accumulation and loss of landscape value, frequently exceeding ecological thresholds and generating tensions between short-term economic benefits and long-term environmental sustainability (Schirpke et al., 2021).

Research provides robust quantitative evidence of the sensitivity of mountain environments to tourism-induced pressures. Spatial analyses in the Carpathian Mountains demonstrate statistically significant relationships between the expansion of tourism infrastructure, increased recreational load and changes in vegetation cover, landscape fragmentation and ecosystem functioning, indicating a limited capacity of mountain ecosystems to absorb additional anthropogenic stress without irreversible change (Kasiyanchuk, 2025). In parallel, contemporary studies on regional tourism systems emphasise the growing importance of adaptive governance models that integrate environmental monitoring, spatial analysis and digital decision-support tools, particularly in regions exposed to geopolitical, economic and climate-related uncertainty. Such sustainability-oriented governance frameworks are considered essential for balancing tourism development with ecological resilience (Holovchuk et al., 2025). Complementary insights are provided by empirical research on tourism-related waste generation: a monthly panel analysis of 160 coastal municipalities in Croatia reveals that the elasticity of municipal solid waste generation with respect to tourist overnight stays significantly exceeds that associated with the resident population, with tourists contributing at least 22% more to waste generation and up to 55% under certain model specifications (Mance, Vilke, & Debelić, 2020).

From an analytical standpoint, literature highlights the value of combining advanced panel techniques—such as two-way fixed effects, PCSE-corrected standard errors and dynamic GMM estimators—to mitigate biases related to unobserved heterogeneity and temporal inertia in environmental indicators, while also acknowledging limitations linked to data frequency, omission of same-day visitors and seasonal shocks that constrain direct transferability of results across regions (Mance, Vilke, & Debelić, 2020). At the global scale, Su and Lee (2022) provide robust evidence of a statistically significant inverse relationship between air quality deterioration and international tourism demand, demonstrating pronounced spatial heterogeneity whereby destinations with more developed tourism markets and higher environmental standards exhibit stronger sensitivity to pollution. Together, these findings reinforce the interpretation that tourism demand is structurally conditioned by environmental quality, functioning not only as a background factor but also as a competitive attribute of destinations. Within a subnational analytical framework, such as that applied in the present study, global results serve as an external benchmark, supporting the conclusion that spatially differentiated patterns of tourism pressure and environmental burdens—whether in air quality or waste generation—reflect common underlying mechanisms, despite differences in scale, data structure and methodological approach.

Balli et al. (2023) provide a comprehensive cross-country investigation of the environmental implications of tourism development based on a panel of twelve European economies with developing and middle-income characteristics over the period 1999–2020. Their analysis explicitly links tourism expansion to renewable energy consumption (REN), research and development (R&D) expenditures and CO_2 emissions, thereby offering

an integrated perspective on the economic and environmental dimensions of tourism-led growth. Methodologically, the authors combine panel autoregressive distributed lag (panel-ARDL) models with the Driscoll–Kraay estimator, ensuring robustness to key econometric challenges such as autocorrelation, heteroskedasticity and cross-sectional dependence.

A central contribution of the study lies in testing the environmental Kuznets curve (EKC) hypothesis. Contrary to the conventional inverted-U interpretation, the results reveal a U-shaped relationship between economic growth and CO_2 emissions, indicating that, beyond a certain threshold, further economic expansion may again intensify environmental pressure in the absence of structural transformation. At the same time, higher levels of renewable energy consumption and increased R&D investment are consistently associated with reductions in emissions, underscoring their role as critical moderating factors in achieving environmentally sustainable development paths.

The relationship between tourism activity and CO_2 emissions emerges as method-sensitive. Within the panel-ARDL framework, tourism development is linked to a reduction in emissions, suggesting potential efficiency gains or structural shifts in the long run. In contrast, specifications based on Driscoll–Kraay fixed- and random-effects estimators indicate a positive association between tourism growth and emissions, reflecting short-term or contemporaneous pressures related to transport, accommodation and service provision. Causality analysis using the Dumitrescu–Hurlin test further reveals bidirectional feedback between R&D expenditures and CO_2 emissions, alongside unidirectional causality from economic growth—including its nonlinear component—and tourist arrivals to emissions.

Taken together, the findings of Balli et al. (2023) highlight that the environmental consequences of tourism are contingent on broader structural conditions and policy choices. In particular, the expansion of renewable energy systems and strengthening of innovation capacity appear capable of offsetting or moderating the environmental footprint of tourism even in contexts of high tourism intensity. This conclusion provides an important conceptual parallel for subnational studies, reinforcing the argument that tourism-related environmental pressures cannot be assessed in isolation from energy structure, technological development and long-term growth dynamics.

The literature demonstrates substantial progress in quantifying the environmental consequences of tourism development through panel, spatial and micro-level approaches, including assessments of waste generation, air pollution, water use and carbon emissions. At the same time, existing studies predominantly operate either at the national or cross-country scale, or focus on individual environmental dimensions in isolation, while subnational, territorially differentiated assessments integrating tourism intensity with multiple environmental pressure indicators remain comparatively underdeveloped. This gap is particularly pronounced for regions characterised by pronounced spatial heterogeneity of tourism activity, limited institutional capacity, and heightened exposure to external shocks. Consequently, there is a clear need for regionally grounded empirical analyses that combine spatial normalisation of indicators, sectoral attribution of environmental pressures and comparative assessment across territorial communities. Addressing this gap, the present study focuses on Ivano-Frankivsk region as a representative case of a tourism, aiming to provide an integrated, data-driven evaluation of tourism-related environmental pressures and to contribute to the methodological advancement of sustainable tourism assessment at the subnational level.

MATERIAL AND METHODS

Tourism is understood as a complex socio-economic phenomenon that spans multiple sectors of material and immaterial production and produces a multiplicative effect on regional and national development. In the framework of national accounts, tourism is not recognised as a standalone industry, which creates methodological challenges for accurately measuring its contribution to gross domestic product and related macroeconomic indicators.

To address this issue, international statistical practice applies the Tourism Satellite Account (TSA) methodology developed by UNWTO, OECD, Eurostat and the United Nations Statistical Commission. TSA combines demand-side information on visitor expenditure with supply-side data on the production of tourism-related goods and services and is fully harmonised with the System of National Accounts (SNA 2008) and international classifications of activities and products

(ISIC, CPC), thereby enabling cross-country and interregional comparability and estimation of tourism value added and tourism direct GDP (UNWTO, 2010).

In Ukraine, economic activities are classified under KVED-2010, aligned with NACE Rev.2 (State Statistics Service of Ukraine, 2020). Tourism activities are dispersed across several sections, primarily accommodation and food services (Section I) and travel agency and reservation services (Section N). As noted by Kulyniak I.Ya. (Kulyniak, 2024), tourism in Ukraine exhibits a pronounced intersectoral character, encompassing agriculture, manufacturing, transport, trade, culture, education, healthcare and information services. This sectoral dispersion allows functional linkages between tourism types and economic activities to be identified and used for selecting tourism-related enterprises in regional analyses. Adaptation of the TSA methodology to the regional level therefore provides a basis for assessing tourism's contribution to gross regional product and employment, which is particularly relevant for Ivano-Frankivsk region with its diversified tourism profile. Integration of TSA with a KVED-based classification, adapted from Kulyniak's approach, forms a coherent methodological framework for evaluating the scale and structure of the regional tourism economy.

Empirical application of this approach is supported by the work of Zabaldina et al., (2021), who propose procedures for compiling core TSA tables at the regional level and calculating GVA-TI, TDGVA and Tourism Direct GDP using official statistics. Their findings show that tourism accounts for 10.34% of the gross regional product of Ivano-Frankivsk region (excluding the shadow economy), substantially exceeding the national average. Building on these results, the present study employs data from the Unified State Register of Legal Entities and Individual Entrepreneurs (YouControl, n.d.) to construct the structure of tourism-related economic activities and analyse the spatial distribution and dynamics of tourism enterprises in the region (Fig. 1).

RESULTS

As of the beginning of 2025, the tourism sector of Ivano-Frankivsk region comprised 6,510 officially registered business entities whose primary economic activity corresponds to tourism-related KVED codes. The internal structure of this sector is characterised by a clear predominance of small-scale organisational forms: 1,641 entities operate as legal persons, while 4,869 are registered as individual entrepreneurs. Such a configuration reflects the entrepreneurial profile of the regional tourism economy, in which micro- and small enterprises play a decisive role in service provision, accommodation, catering, excursion activities and auxiliary tourism services. The dominance of individual entrepreneurs also indicates relatively low entry barriers and a high degree of flexibility, which are typical features of tourism-oriented local economies.

An analysis of temporal dynamics reveals a stable upward trend in the registration of tourism-related enterprises since 2019, pointing to the

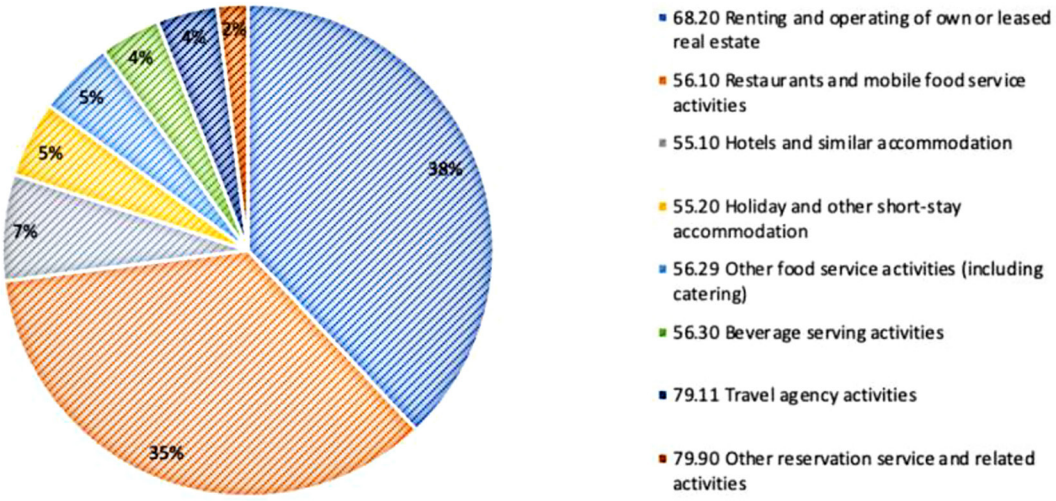

Figure 1. Structure of tourism-related economic activities in Ivano-Frankivsk region by type of economic activity (KVED), %

gradual institutionalisation of tourism as an important component of regional economic development. This growth trajectory, however, has not been linear. Two major exogenous shocks caused marked disruptions in business activity. The COVID-19 pandemic in 2020 led to an abrupt contraction of tourism demand, travel restrictions and temporary closure of accommodation and catering facilities, resulting in a slowdown of new enterprise registrations and, in some cases, business exits. A second structural shock emerged in 2022 with the onset of Russia's full-scale invasion of Ukraine, which introduced heightened security risks, damage to infrastructure, labour market dislocation and increased uncertainty for investment and entrepreneurial decision-making.

Despite these adverse conditions, post-2022 dynamics demonstrate a gradual recovery in the number of registered tourism enterprises. This rebound suggests a relatively high level of adaptive capacity and resilience within the regional tourism sector. Factors contributing to this resilience include diversification of tourism products, reorientation toward domestic tourism, increased demand for recreational and nature-based destinations, and the flexibility of small and self-employed business models. The observed recovery also indicates that tourism continues to be perceived by local entrepreneurs as a viable economic activity even under conditions of heightened uncertainty.

The spatial distribution of tourism enterprises across territorial communities was examined using geospatial analysis and visualised with Python (matplotlib), allowing identification of spatial concentration patterns and intra-regional disparities (Fig. 2). The results reveal a pronounced concentration of tourism-related business activity within the Ivano-Frankivsk territorial community, where 2,812 enterprises are registered. This clustering reflects the multifunctional role of the regional centre as a hub of transport connectivity, administrative and business services, accommodation capacity and diversified demand. At the same time, such spatial concentration points to uneven development of tourism entrepreneurship

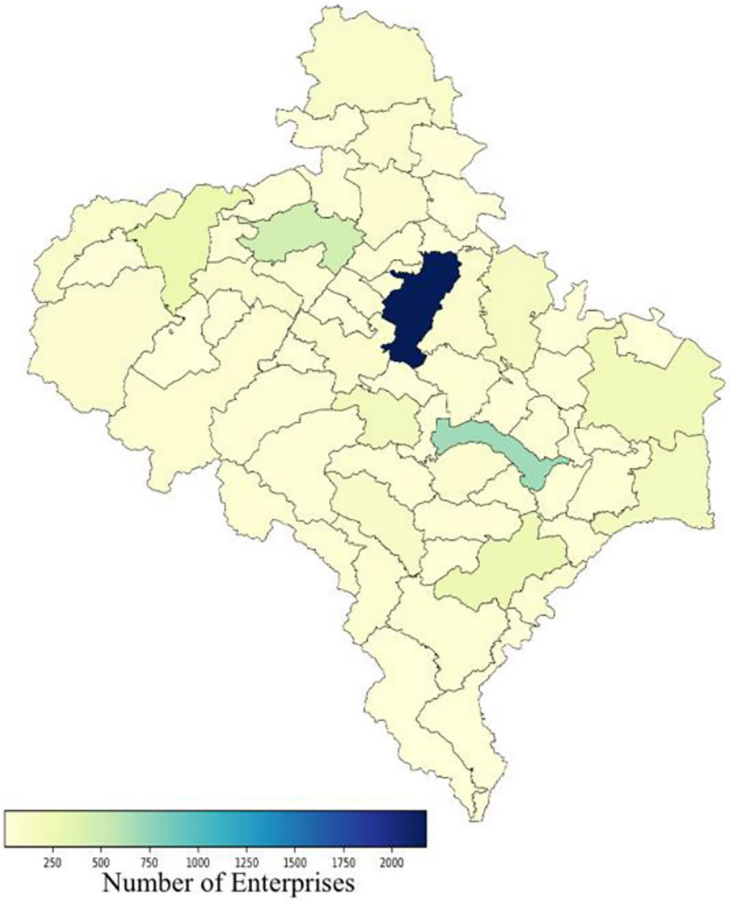

Figure 2. Visualization of the distribution of tourism enterprises (related types of tourism activities) by territorial communities of Ivano-Frankivsk region (by place of registration)

across the oblast, with peripheral and rural communities hosting significantly fewer registered entities. This imbalance underscores the importance of territorially differentiated development strategies aimed at enhancing local tourism entrepreneurship beyond the regional centre, while mitigating excessive concentration pressures on urban infrastructure and services.

The spatial distribution and concentration of tourist facilities within territorial communities is shown in Figure 3. The visualization demonstrates significant unevenness in the territorial distribution of tourism resources: individual communities form highly concentrated cores (over 700–800 facilities), while most territories are characterized by a low density of tourist locations.

Figures 4–9 present choropleth maps of tourism demand intensity (tourist-days per km²) and environmental metrics across territorial communities, including water use and emissions to the atmosphere, discharges into water bodies, and disposal of municipal solid waste (hereinafter MSW) (all enterprises) calculated per km², as well as the share of tourism enterprises in the corresponding total volumes. This layout enables simultaneous observation of the intensity of territorial pressure (through area-based normalization) and the structure of pressure sources (specifically, the contribution of tourism-related entities).

To ensure comparability of indicators across territorial communities, a unified data processing methodology was applied, based on two key principles.

First, all indicators (tourism demand, water resource use, emissions of pollutants to the atmosphere, discharges into water bodies, and generation of municipal solid waste) were normalized by the area of the community. The intensity of pressure was determined per 1 km² of territory according to the following formula:

$$I_X = \frac{X_{tot}}{S} \quad (1)$$

where: I_X – denotes the intensity of the indicator per 1 km², X_{tot} – represents the total value of the indicator for a territorial community (number of tourist-days, cubic metres of water, or tonnes of emissions or waste), S – denotes the area of the community in km².

This approach made it possible to compare pressure levels across territorial communities of different spatial sizes.

Second, the share of the tourism sector in the formation of each indicator was determined. For

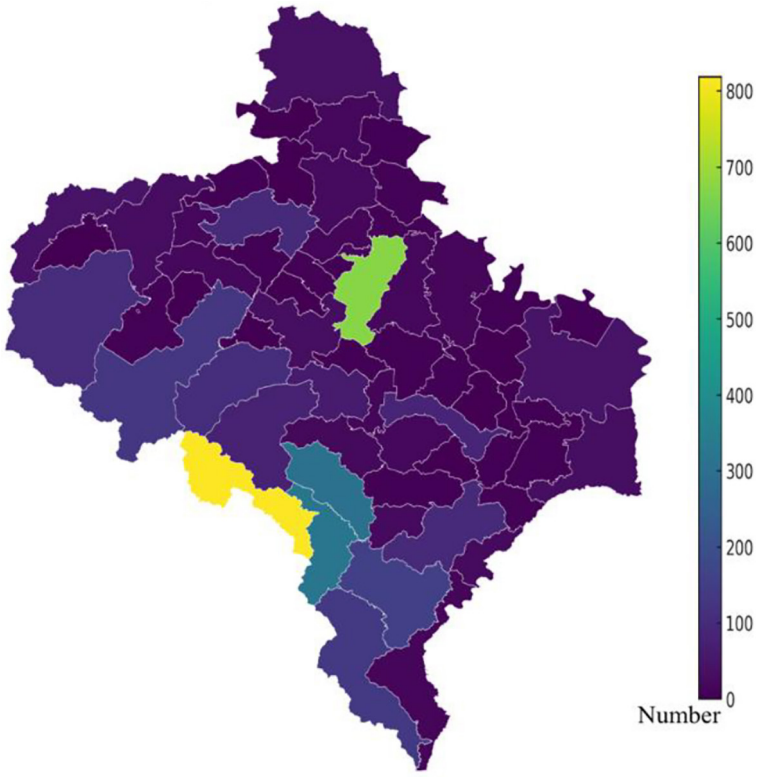

Figure 3. Spatial distribution and concentration of tourist facilities within territorial communities

this purpose, data on business entities paying the tourist tax were used, which made it possible to identify enterprises belonging to the tourism industry. The share of the tourism sector was calculated using the following formula:

$$Share_X = \frac{X_{tour}}{X_{tot}} \quad (2)$$

where: $Share_X$ – denotes the share of the tourism sector, X_{tour} – represents the value of the indicator generated by tourism enterprises, X_{tot} – denotes the total value of the indicator for the territorial community.

Analysis of empirical data for 2024 reveals a pronounced spatial concentration of tourism pressure in the mountain territorial communities of the Carpathian region. The highest intensity values are recorded in Polianytsia rural territorial community (1,709.5 tourist-days per km²), where a relatively compact area is characterised by a high concentration of visitors. Substantial values are also observed in Yaremche urban territorial community (522.7 tourist-days per km²) and Vorokhta settlement territorial community (328.6 tourist-days per km²).

The Ivano-Frankivsk urban territorial community, despite a lower relative intensity indicator (78.4 tourist-days per km²), demonstrates a significant absolute volume of overnight stays, which can be attributed to the multifunctional nature of the urban environment and a diversified structure of tourism demand. Low indicator values or the absence of statistical data in many territorial communities (visualised by hatching in the cartographic materials) reflect an insufficient level of development of formalised tourism infrastructure.

The identified spatial concentration of recreational demand within limited areas of mountain territorial communities creates preconditions for the formation of seasonal peaks of anthropogenic pressure on ecosystems and engineering infrastructure of local territories, thereby necessitating the implementation of adaptive mechanisms for managing tourism flows.

The highest spatial intensity of tourist flows is concentrated in the mountain communities of the Carpathian region. Polyanytsya rural community accumulates 2,387.9 t/d per km², Yaremche urban – 624.6, Vorokhtya settlement – 408.2. In Ivano-Frankivsk urban community the indicator is lower (395.7), however the absolute volume of overnight stays is significant, which is explained by the larger area of the territory and the multifunctionality of the urban environment (Fig. 4).

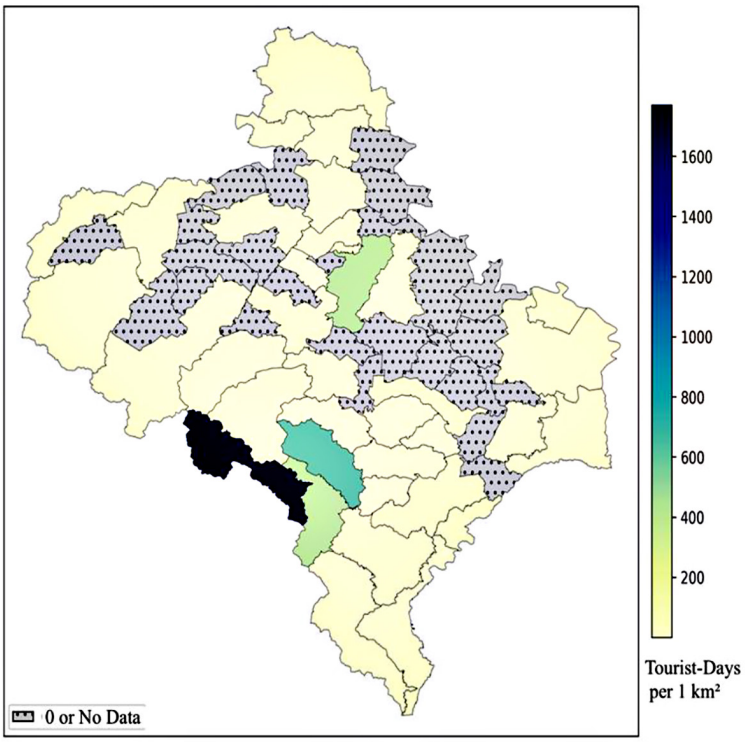

Figure 4. Tourist load (tourist daily stays per 1 km²) in territorial communities of Ivano-Frankivsk region, 2024. Sources: data from reporting on the tourist fee 2019–2024; author's calculations

Analysis of specific water consumption (m³/km²) for 2024 indicates a clearly expressed spatial differentiation of anthropogenic pressure across territorial communities, with pronounced concentration in industrial and highly urbanised centres of the region. The maximum intensity is recorded in the Yamnytsia rural territorial community (2,078.4 m³/km²), which reflects the structural dominance of large-scale industrial facilities characterised by high water intensity of production processes. In this case, water use is largely decoupled from population size or tourism activity and is instead driven by industrial technological cycles, continuous operation regimes, and limited possibilities for short-term demand regulation.

Elevated levels of water consumption are also observed in the Kalush (945.7 m³/km²) and Dolyna (820.3 m³/km²) urban territorial communities. Here, water use patterns result from a cumulative interaction between industrial water demand and municipal-household consumption associated with relatively dense settlement structures. The coexistence of industrial facilities, residential areas, and service infrastructure generates sustained baseline pressure on water resources, leading to persistently high spatial intensity values even outside peak seasonal periods.

In contrast, structural analysis of water consumption reveals a fundamentally different configuration in communities with pronounced recreational specialisation, where the tourism sector constitutes a dominant component of total water use. The highest tourism-related shares are recorded in Polianytsia rural territorial community (0.834), Yaremche urban territorial community (0.615), and Vorokhta settlement territorial community (0.542). In these administrative units, water consumption is primarily shaped by the functioning of tourism infrastructure, including accommodation facilities, catering establishments, recreational complexes, transport-related services, and auxiliary tourist-oriented activities.

This pattern reflects the service-intensive nature of tourism, where water demand is closely linked to accommodation density, service quality standards, and visitor behaviour. Unlike industrial centres, tourism-oriented communities are characterised by strong seasonal variability in water consumption, with sharp increases during peak tourism periods. As a result, even relatively moderate absolute volumes of water use translate into high spatial intensity when normalised by community area, amplifying localised pressure on water resources.

The observed territorial differentiation underscores the existence of two distinct water-use regimes within the region: an industrial–urban regime driven by production and household needs, and a tourism-driven regime associated with service provision and recreational demand. From a sustainability perspective, tourism-oriented communities exhibit heightened vulnerability of water management systems to seasonal demand shocks, limited reserve capacity, and climatic variability. This highlights the necessity of adaptive water-use governance mechanisms, including demand-side management, efficiency standards for accommodation facilities, deployment of smart metering technologies, and integration of water-saving measures into tourism development strategies (Fig. 5).

The identified structural specificity of water consumption in tourism-oriented communities indicates increased vulnerability of their water management systems to seasonal fluctuations in recreational demand. This creates preconditions for peak loads on water resources and water infrastructure during periods of maximum tourism activity, thereby necessitating the implementation of adaptive water-use management mechanisms that account for seasonal dynamics.

Analysis of the spatial distribution of specific atmospheric emissions (t/km²) demonstrates a pronounced differentiation of territorial communities according to the intensity and structural composition of anthropogenic pressure. The observed pattern reflects the combined effects of industrial specialisation, energy infrastructure concentration, settlement structure, and functional roles of territories within the regional economic system.

The Burshtyn urban territorial community exhibits an exceptionally high level of emission intensity (24,206.4 t/km²), which significantly exceeds all other territorial units in the region. This extreme value is directly attributable to the operation of a large-scale power-generating facility—the Burshtyn Thermal Power Plant, which functions as a key node of regional and transboundary electricity production. The spatial normalisation of emissions per unit area highlights the disproportionate environmental burden borne by this relatively compact territory, where stationary combustion processes dominate the emission structure and largely determine the overall atmospheric load.

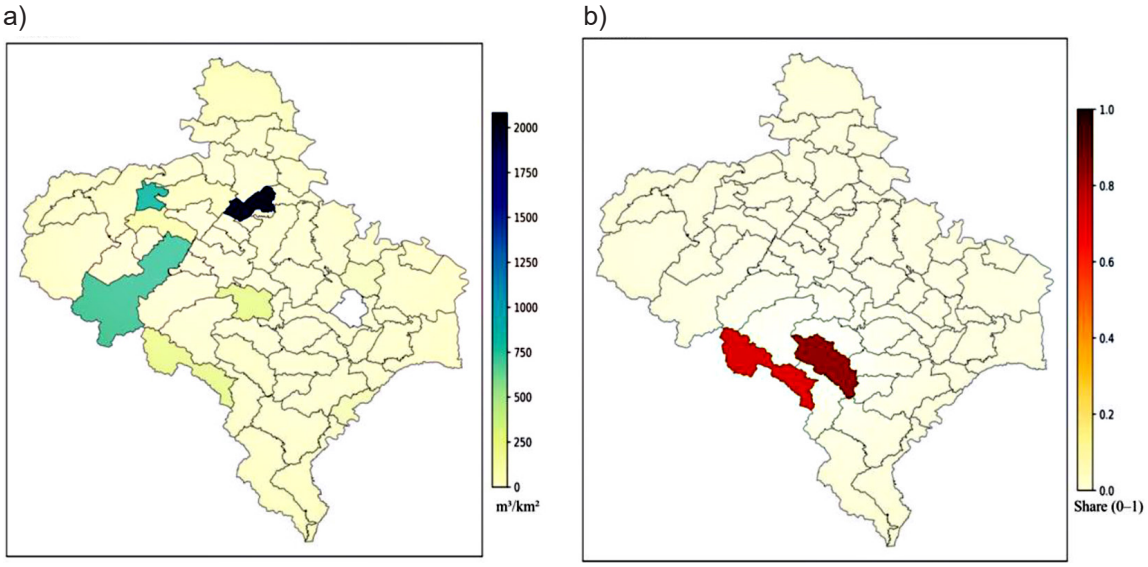

Figure 5. Water consumption intensity (m³/km²) (a) and the share of tourism enterprises (b) in the total water consumption of territorial communities of Ivano-Frankivsk region, 2024 (author's calculations)

A substantially lower, yet still considerable, level of emission intensity is recorded in the Kalush urban territorial community (1,268.7 t/km²). Unlike Burshtyn, where emissions are dominated by energy generation, Kalush represents a diversified industrial-emission profile, shaped primarily by chemical manufacturing and associated auxiliary processes. The order-of-magnitude difference between Burshtyn and Kalush underscores the decisive role of energy-sector facilities in shaping regional emission hierarchies, even when compared with traditionally pollution-intensive industrial centres.

An intermediate emission zone is formed by the Dolyna urban territorial community (306.2 t/km²) and the Solotvyn settlement territorial community (88.1 t/km²). These territories combine moderate industrial activity with transport-related and municipal emission sources, resulting in emission intensities that are markedly lower than those of major industrial hubs but still exceed the background levels observed in predominantly rural or recreational communities. Their intermediate position reflects a mixed economic structure, where neither heavy industry nor tourism-related activity exerts exclusive dominance over the emission profile.

In contrast, the majority of territorial communities within the region demonstrate comparatively low levels of specific atmospheric emissions, indicating the absence of large stationary pollution sources and confirming a strong spatial concentration of atmospheric pressure within a limited number of industrial and energy-oriented centres. This pattern supports the interpretation of regional emissions as structurally polarised, with a small number of high-intensity nodes and a broad periphery characterised by low-intensity, diffuse emission sources.

Beyond absolute emission levels, the analysis of sectoral composition reveals a distinct and systematic pattern. The share of the tourism sector in total atmospheric emissions reaches its highest values in communities with a limited industrial base, where emissions associated with recreational activity become structurally visible. The highest tourism-sector coefficients are observed in the Vorokhta settlement territorial community (0.966), Bohorodchany settlement territorial community (0.773), Nadvirna urban territorial community (0.526), and Solotvyn settlement territorial community (0.418).

In these territorial units, the absence of large industrial emitters means that transport-related emissions, space heating of accommodation facilities, catering establishments, and auxiliary tourism infrastructure constitute a dominant share of total atmospheric pollution. Consequently, even relatively modest absolute emission volumes translate into a high proportional contribution of tourism-related activities. This structural effect explains why tourism-sector shares peak precisely in low-industrialised communities, rather than in territories with the highest absolute emission intensities.

Taken together, the results provide empirical confirmation of the hypothesis that the role of tourism in atmospheric emissions is strongly conditioned by the underlying industrial structure of territories. In highly industrialised and energy-oriented communities, tourism-related emissions are statistically and structurally overshadowed by stationary industrial sources. Conversely, in communities with limited industrial activity, emissions associated with recreational mobility and heat generation become a central component of the local atmospheric burden. This duality highlights the importance of analysing both emission intensity and sectoral composition when interpreting spatial patterns of environmental pressure (Fig. 6).

Analysis of the intensity of discharges into water bodies, expressed per square kilometre of territorial area, reveals a pronounced spatial concentration of anthropogenic pressure within the principal industrial and municipal centres of the region. The highest discharge intensities are recorded in the Burshtyn urban territorial community (28.7 t/km²) and the Halych urban territorial community (16.3 t/km²), both of which host energy-generating and municipal infrastructure facilities that serve not only local populations but also wider functional zones. In these communities, wastewater discharges are predominantly associated with stationary sources, including energy production processes, municipal wastewater treatment systems, and supporting industrial operations, resulting in elevated area-normalised pressure on aquatic ecosystems.

Additional concentrations of discharge intensity are observed in the Kalush and Dolyna urban territorial communities, where a stable industrial base contributes to sustained levels of wastewater generation. Although discharge intensities in these territories are lower than those recorded in Burshtyn and Halych, they nevertheless exceed regional background levels, reflecting the cumulative effects of industrial effluents, municipal sewage, and associated infrastructural networks. The spatial configuration of these discharge hotspots indicates that point-source pollution remains a dominant factor shaping the regional pattern of impacts on surface water bodies.

In contrast, the majority of territorial communities exhibit substantially lower discharge intensities per km², confirming that significant pressures on aquatic environments are concentrated within a limited number of industrial–municipal hubs rather than being evenly distributed across the region. This spatial asymmetry underscores the role of economic specialisation and infrastructure localisation in structuring regional water quality risks (Smyk & Arkhypova, 2025).

Beyond absolute discharge volumes, analysis of the sectoral composition of discharges reveals a markedly different pattern in tourism-oriented territories. The share of tourism enterprises in total discharge volumes reaches its highest values

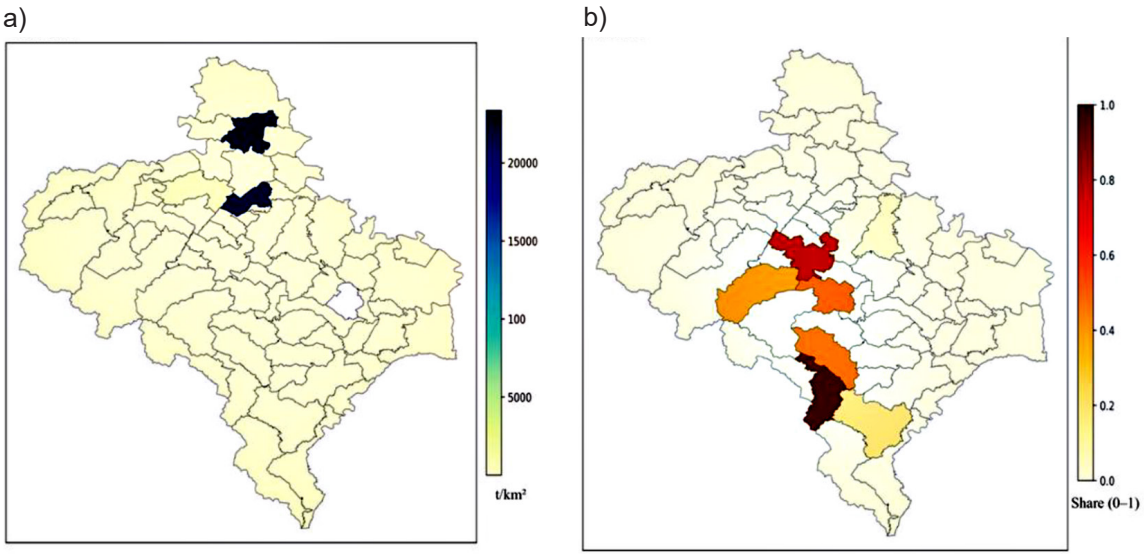

Figure 6. The intensity of pollutant emissions into the atmosphere in territorial communities of Ivano-Frankivsk region in 2024, calculated per 1 km² of community area (tons/km²) (a), and the share of the tourism sector is determined based on data from entities that paid the tourist tax (b) (data from environmental tax reporting for 2019–2024 – author's calculations)

in the Yaremche urban territorial community (0.962) and the Polianytsia rural territorial community (0.885). In these communities, industrial activity is minimal, and the discharge structure is dominated by effluents generated by tourism infrastructure, including accommodation facilities, catering establishments, wellness and leisure complexes, and auxiliary service facilities.

The high proportional contribution of tourism enterprises in these recreational territories reflects a structural effect rather than exceptionally large absolute discharge volumes. In the absence of heavy industry, even moderate levels of wastewater generated by tourism-related services become the principal source of pressure on local water bodies. This is further reinforced by the spatial concentration of tourism facilities and by seasonal peaks in occupancy, which amplify discharge volumes during periods of high recreational demand.

Overall, the juxtaposition of absolute discharge intensity and sectoral contribution highlights two distinct regimes of impact on aquatic environments within the region. In industrial and municipal centres, water bodies are primarily affected by stationary point sources linked to energy production and industrial processes. In tourism-oriented communities, by contrast, the pressure on aquatic systems is structurally shaped by the service sector, with tourism infrastructure constituting the dominant source of wastewater discharges. This differentiation demonstrates the analytical importance of simultaneously considering area-normalised discharge intensity and sectoral composition when interpreting spatial patterns of impacts on water resources (Fig. 7).

Analysis of the spatial distribution of the specific indicator of municipal solid waste (MSW) generation, expressed per square kilometre of territorial area, reveals a highly asymmetric and polarised pattern across the region. An exceptionally high concentration of MSW generation is observed in the Yamnytsia rural territorial community, where the recorded value reaches 7.4×10^{12} t/km², vastly exceeding all other territorial units. This extreme magnitude reflects not only the scale of waste generation but, more importantly, the spatial concentration of waste-related infrastructure within a territorially compact area (Fig. 8).

The observed phenomenon is primarily driven by the localisation of a significant number of industrial facilities and waste management installations, including landfill sites and associated logistics infrastructure, within the boundaries of the Yamnytsia community. The normalisation of waste volumes per unit area amplifies this effect, revealing the disproportionate environmental burden borne by territories that function as regional waste accumulation and processing nodes. Adjacent administrative units display substantially lower, yet still perceptible, levels of specific MSW generation, indicating the presence of secondary spillover effects related to waste transport corridors and auxiliary industrial activity.

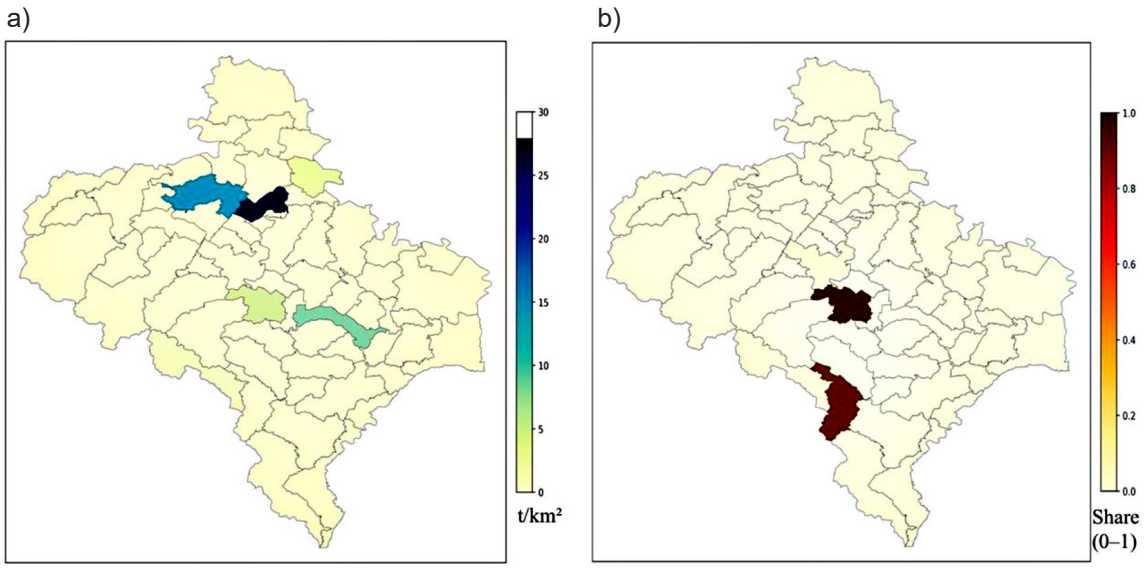

Figure 7. Intensity of discharges into water bodies (t/km²) (a), and the share of tourist enterprises (b) in their structure by territorial communities of Ivano-Frankivsk region, 2024 (author's calculations)

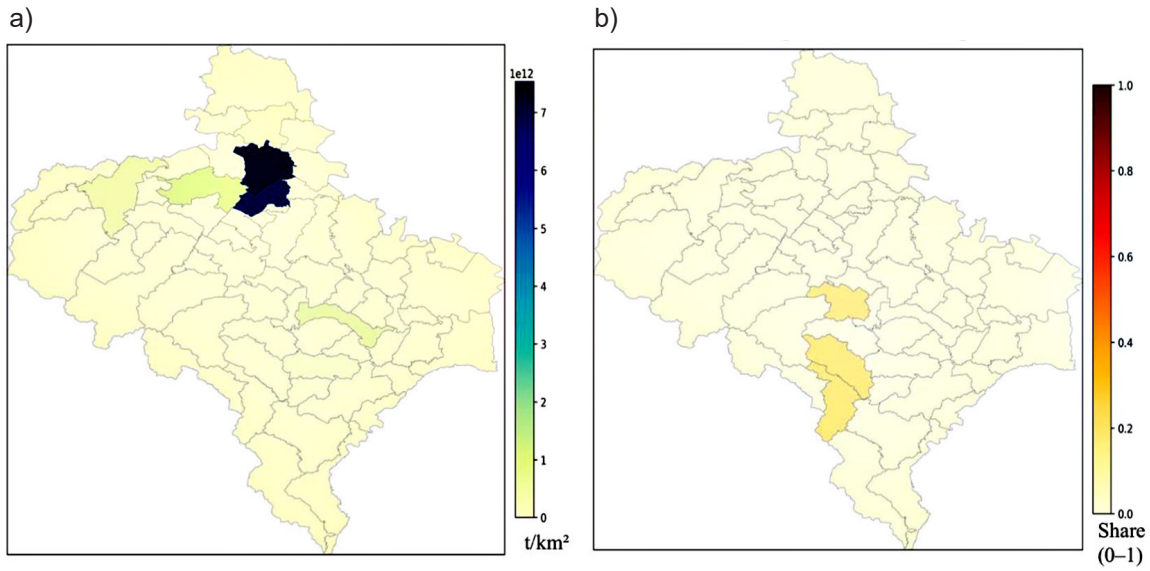

Figure 8. Intensity of solid waste disposal (tons per km²) (a), and the share of tourist enterprises (b) in their volumes by communities of Ivano-Frankivsk region, 2024

In contrast, the majority of territorial communities in the region are characterised by low levels of specific MSW generation, which confirms a highly uneven spatial distribution of waste generation sources. This pattern suggests that MSW-related environmental pressure is not diffusely generated across the region but instead concentrated within a small number of structurally specialised territories. Such spatial polarisation reflects the combined influence of economic specialisation, infrastructural localisation, and administrative allocation of waste management functions.

Beyond absolute intensity, structural analysis of MSW generation by economic sectors reveals a distinctly different configuration in tourism-oriented communities. Even in territories with pronounced recreational specialisation, the contribution of tourism enterprises to total MSW volumes remains relatively limited. The highest sectoral shares are recorded in the Vorokhta rural territorial community (0.242) and the Polianytsia rural territorial community (0.214), values that, while notable, remain substantially lower than the contributions associated with industrial and municipal–household waste streams in structurally different territories.

The comparatively modest role of the tourism sector in MSW generation can be attributed to a combination of interrelated factors. First, the pronounced seasonality of tourism activity constrains the cumulative annual volume of waste produced by recreational facilities. Peaks in waste generation during high tourist seasons are offset by extended periods of low activity, resulting in a limited contribution when aggregated over a full year. Second, the dominance of industrial and municipal–household sources in the overall MSW structure leads to a statistical overshadowing of tourism-related waste, as these sectors generate substantially higher absolute volumes of solid waste on a continuous basis.

Taken together, the results demonstrate that municipal solid waste generation exhibits the strongest degree of spatial concentration among the analysed environmental indicators, with extreme values determined by infrastructural and industrial localisation rather than by tourism intensity. At the same time, the sectoral contribution analysis confirms that tourism plays a secondary role in shaping regional MSW patterns, even in highly recreational communities. This combination of spatial polarisation and sectoral differentiation highlights the analytical importance of interpreting MSW indicators within their broader economic and infrastructural context, rather than attributing waste-related pressures primarily to tourism activity.

The empirical design applied in this study demonstrates that a combined use of the TSA framework, business register data and environmental statistics allows for a consistent identification of tourism-related economic actors and for a spatially explicit assessment of their ecological footprint. For further refinement of the experimental set-up, several methodological enhancements are recommended (Table 1).

Table 1. Methodological directions for refining the experimental framework of tourism–environment analysis

Analytical dimension	Identified limitation in the current design	Recommended methodological enhancement	Expected analytical effect
Integration of economic and environmental data	Partial separation between TSA indicators and environmental statistics	Regular updating of regional TSA and harmonisation with environmental accounts (water use, emissions, discharges, MSW) through stable correspondence between KVED classes and tourism-characteristic activities	Improved consistency between economic contribution measures (GVATI, TDGVA, Tourism Direct GDP) and environmental pressure metrics
Identification of tourism-related enterprises	Ambiguity in classifying enterprises with mixed economic activities	Refinement of KVED-to-tourism mapping and use of auxiliary criteria (tourist tax payment, service specialisation) for enterprise attribution	Increased robustness of sectoral attribution and reduction of classification bias
Temporal resolution of tourism pressure	Annual aggregation masks seasonal and short-term peaks	Integration of monthly or quarterly data on tourist tax, water abstraction, energy use and waste generation	Enhanced detection of intra-annual seasonality and episodic overloads of local systems
Coverage of informal and day-visit tourism	Underrepresentation of same-day visitors and informal accommodation	Supplementation of official statistics with anonymised mobile positioning data and accommodation platform records	More accurate estimation of actual tourism pressure, especially in high-intensity destinations
Indicator structure	Dominance of extensive, volume-based indicators	Expansion toward quality-oriented indicators: hazard-weighted emissions, wastewater treatment efficiency, MSW recycling rates, eco-certification of tourism facilities	Improved differentiation between communities with similar pressure volumes but different environmental management performance
Spatial analytical comparability	Limited transferability of results beyond the case region	Standardisation of formulas, data processing workflows and cartographic visualisation templates	Enhanced interregional comparability and scalability of the analytical framework
Replicability of the approach	Case-specific design	Application of the developed framework to other regions and aggregation to the national level	Formation of a unified evidence base for benchmarking tourism-related environmental pressure

First, the regional TSA should be updated on a regular basis and harmonised with environmental accounts in order to ensure full compatibility between economic indicators (GVATI, TDGVA, Tourism Direct GDP) and environmental pressure metrics (water use, emissions, discharges, MSW generation). Establishing a stable correspondence between KVED classes and tourism-characteristic activities would improve the robustness of enterprise selection, particularly in borderline cases where firms operate multiple types of activities.

Second, the spatial analysis of tourism pressure would benefit from the integration of higher-frequency and more disaggregated data. Use of monthly or quarterly records on tourist tax payments, water abstraction, energy consumption and waste generation, combined with GIS-based territorial units, would make it possible to capture intra-annual seasonality and short-term peaks of anthropogenic load. Incorporation of mobile positioning data or anonymised accommodation platform statistics could provide an additional control for day visitors and informal accommodation, which are only partially reflected in conventional reporting.

Third, the system of environmental indicators should be expanded towards quality-oriented metrics. Alongside extensive indicators normalised per km², it is advisable to include hazard-weighted emissions indices, indicators of wastewater treatment efficiency and MSW recycling rates, as well as tourism-related eco-certifications of facilities. Such enrichment of the indicator set would support a more nuanced differentiation between communities with similar volumes of pressure but different levels of environmental management performance.

Finally, the analytical framework developed for Ivano-Frankivsk region can be replicated for other regions and scaled up to the national level. Standardisation of data processing procedures, visualisation templates and formulae for intensity and sectoral shares would facilitate interregional comparison and benchmarking, while also providing an evidence base for designing targeted policy instruments aimed at balancing tourism development with environmental safety.

DISCUSSION

Research increasingly relies on spatially explicit, indicator-driven methodologies to analyse the links between tourism development and

environmental sustainability, providing a relevant comparative backdrop for the findings of this study (Rogowski et al, 2024). Such approaches emphasise territorial differentiation, normalisation of pressure indicators and visual analytics as key instruments for identifying imbalances between tourism intensity and environmental capacity (Prykhodko et al, 2023).

A representative example is the spatial suitability assessment proposed by Luo and Peng, (2024), who employ quantitative spatial analysis and multi-criteria mapping to delineate areas appropriate for tourism expansion and zones exposed to potential environmental overload. Their results illustrate the analytical value of area-normalised indicators and cartographic techniques for revealing spatial heterogeneity in tourism pressure. The methodological logic of the present study is aligned with this approach through the normalisation of tourism demand and environmental pressures per km² and their subregional visualisation. At the same time, an important distinction exists: while Luo and Peng (2024) focus on a forward-looking, planning-oriented evaluation of suitability, the present analysis adopts a retrospective perspective, identifying already established hotspots of tourism concentration and associated environmental stress. This difference in analytical orientation explains variations in emphasis, while confirming the robustness of spatial normalisation as a tool for detecting territorial imbalances in tourism–environment interactions (Pulido-Fernández et al, 2024).

At the macroeconomic scale, Cui, (2025) investigates the relationship between tourism development, energy consumption and CO_2 emissions in developing countries using ARDL modelling techniques. The results indicate a statistically significant association between tourism expansion and atmospheric pollution, mediated by energy intensity and economic growth dynamics. Although Cui's (2025) study is based on cross-country time-series econometrics, whereas the present research operates at a subnational level and applies spatial identification, both analyses converge in identifying tourism-related transport and service infrastructure as non-negligible contributors to emissions, particularly in areas with a limited industrial base. Methodological differences account for the fact that Cui (2025) captures long-run equilibrium relationships, while the present study highlights sectoral composition and spatial concentration of environmental pressure.

Long-term perspectives on tourism sustainability are provided by Bayramoğlu et l., (2025), who analyse tourist arrivals, overnight stays and length of visits over the period 2000–2024. Their findings demonstrate that sustainability performance cannot be inferred solely from aggregate growth indicators, as pressure intensity depends on spatial distribution and infrastructure capacity. This conclusion is corroborated by the present results, where urban communities exhibit high absolute tourism volumes but relatively moderate intensity per km², whereas compact recreational communities experience disproportionately high pressure levels. In this respect, the present study extends the insights of Bayramoğlu et al. by adding a spatially explicit dimension to the interpretation of long-term tourism dynamics.

Further evidence on the interaction between environmental policy and tourism demand is provided by Boto-García et al. (2024), who examine the effects of carbon price shocks on tourism demand in 26 European countries. Using panel models with two-way fixed effects to isolate exogenous shocks within the EU Emissions Trading System, the authors show that higher carbon prices exert a statistically significant dampening effect on tourist arrivals and length of stay, with substantial cross-country heterogeneity driven by mobility patterns, energy mixes and reliance on air transport. These findings underline the sensitivity of tourism demand to environmental cost signals and reinforce the relevance of integrating environmental policy variables into tourism sustainability assessments.

The role of information transparency is highlighted by Wang et al., (2023), who apply a difference-in-differences approach to a panel of 297 cities and demonstrate that the introduction of public air-quality monitoring systems leads to measurable increases in international arrivals and average length of stay. The magnitude of this effect varies with baseline pollution levels, suggesting that reduced information asymmetry enhances destination credibility and shifts demand toward areas with better environmental performance. At a more granular operational level, Padrón-Fumero et al. (2025) show, using micro-panel data from 213 accommodation facilities in the Canary Islands, that digital monitoring and feedback mechanisms—such as smart water meters—produce statistically significant reductions in resource consumption, illustrating the effectiveness of object-level environmental management tools.

Finally, the environmental implications of overtourism are examined by Sun et al., (2025), who demonstrate that excessive tourism intensity is associated with higher CO_2 emissions and pollution due to infrastructure expansion and inefficient waste management. While their analysis is conducted at a broader spatial scale, the present study identifies comparable mechanisms at the community level, where extreme tourism intensity per km² coincides with increased vulnerability of local water systems and infrastructure. At the same time, the relatively modest contribution of tourism enterprises to total municipal solid waste generation observed in this research indicates that the environmental expression of overtourism is highly context-specific and strongly conditioned by the underlying economic structure of territories.

Overall, comparison with recent international literature confirms that the results of this study are consistent with current analytical trends in tourism sustainability research, while offering additional evidence on the spatial and sectoral differentiation of tourism-related environmental pressure at the subregional level.

CONCLUSIONS

The conducted analysis makes it possible to draw a set of empirically grounded conclusions regarding the spatial organisation of tourism activity and its environmental implications in Ivano-Frankivsk region. Integration of the Tourism Satellite Account methodology with geospatial analysis and environmental statistics ensured consistency between economic and ecological dimensions of tourism development and enabled identification of both intensity and structure of anthropogenic pressure at the level of territorial communities.

The results confirm a pronounced spatial concentration of tourism demand in mountain communities of the Carpathian region, where high visitor density within relatively compact areas leads to elevated levels of tourism intensity per km². In contrast, urban communities demonstrate lower relative intensity values combined with substantial absolute volumes of tourist stays, reflecting the multifunctional character of urban space and diversification of tourism demand. This differentiation indicates the coexistence of distinct territorial models of tourism development within the region.

Environmental indicators reveal strong spatial heterogeneity driven primarily by the economic profile of communities. Industrial and energy-oriented centres dominate in terms of absolute and specific levels of water consumption, atmospheric emissions and discharges into water bodies. At the same time, in tourism-oriented communities with a limited industrial base, the tourism sector accounts for a significant share of environmental pressure indicators, particularly in water use and wastewater discharges. Such a pattern confirms the structural importance of tourism infrastructure as a dominant source of local environmental load in recreational territories.

The analysis of municipal solid waste generation demonstrates extreme spatial concentration associated with industrial facilities and waste management infrastructure, while the contribution of tourism enterprises to total MSW volumes remains comparatively low, even in communities with pronounced recreational specialisation. This result reflects the combined effect of tourism seasonality and the predominance of industrial and municipal–household waste streams in the overall waste structure.

Overall, the findings indicate that tourism-related environmental pressure is spatially selective and structurally heterogeneous, requiring interpretation within the specific territorial and economic context of each community. The applied combination of area-normalised indicators and sectoral decomposition proved effective for distinguishing tourism-driven impacts from those generated by industrial and municipal activities, thereby enhancing the analytical validity of regional environmental assessments.

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