# Intensity of Human Activities and their Spatiotemporal Evolution in the Border Regions of Iran

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**Abstract**

The surveillance of human activities along border zones is often complicated by the inherent intricacy of geographical landscapes. As a nation possessing one of the most extensive terrestrial boundaries globally, Iran presents a vital context for this type of investigation. This research introduces a Human Activity Intensity (HAI) index, formulated by integrating land cover data, population density metrics, and nocturnal light imagery acquired from satellites. We computed the HAI at a spatial resolution of 1 km within a 50-kilometer corridor flanking Iran's entire land frontier for four distinct time points: 1992, 2000, 2010, and 2020. Our findings reveal that nearly 90 percent of this border zone is characterized by low levels of human activity. A comparative analysis shows that HAI values are consistently greater on the Iranian side relative to adjacent nations. Furthermore, within Iran's borders, there has been a marked escalation in land-use intensity over the study period. Among the neighboring countries, Iraq exhibits the highest HAI and the most rapid rate of increase. The temporal dynamics of the HAI delineate four distinct patterns: a concurrent decrease observed in both Iran and Turkey; asymmetric growth favoring Iran over Turkmenistan; a persistent, steady rise within Afghanistan; and a coupled increase shared by Iran and Afghanistan. A subsequent hotspot analysis unveiled three distinct modes of spatiotemporal progression: expansion occurring on a single side, bilateral outward growth, and the eventual merging of transboundary clusters. The analysis clearly demonstrates the presence of both "border effects" and "aggregation effects" within these areas. These fluctuations in HAI have implications that extend beyond environmental concerns, significantly impacting geopolitical relations and geo-economics strategies. Consequently, the proposed HAI index proves to be a valuable instrument for policymakers, facilitating informed decisions regarding cross-border environmental protection, regional security measures, and the regulation of commercial exchange.

## 1. Introduction

The Anthropocene is defined by the profound and pervasive transformation of terrestrial ecosystems by human actions, which fundamentally alters biogeochemical cycles (Crutzen, 2002). This anthropogenic pressure increasingly threatens planetary boundaries—specifically biosphere integrity, biogeochemical flows, and land-system change—positioning human activity as a principal catalyst of global environmental shifts (Honghu Meng et al., 2021; Steffen et al., 2015). In response, international frameworks like the United Nations 2030 Agenda and its Sustainable Development Goals (SDGs) seek to alleviate human-induced stress on ecological systems while enhancing global well-being (Cheng et al., 2021). To achieve this, accurately mapping and comprehending the spatial distribution of human influence is paramount for deciphering humanity's role in shaping Earth's surface processes (Williams et al., 2020). Furthermore, a detailed understanding of the spatiotemporal evolution of this influence is critical for effective environmental management and policy (Josa and Aguado, 2019; Nassauer and Raskin, 2014). Borderlands, as dynamic interfaces of geographical interaction, are particularly susceptible to rapid and extensive anthropogenic modifications. Since the 1990s, nearly one-fifth of global population expansion has occurred within these zones, contributing to the loss of over one-third of their forest cover (Xiao et al., 2021). The ecological significance of these regions is further underscored by the fact that more than half of the world's terrestrial bird, mammal, and amphibian species traverse international boundaries, rendering them vulnerable to threats such as deforestation, poaching, and the development of frontier infrastructure.

Spatially, anthropogenic activity in border areas tends to coalesce around transportation nodes and urban centers. Border crossings function as critical international conduits for the movement of goods and people, while adjacent cities serve as primary residential zones that reinforce national identity. The integrated development of these urban areas has, in some instances, given rise to transboundary "twin city" agglomerations (Norman et al., 2009). The resultant human activity patterns in these regions are inherently complex and heterogeneous, shaped by a confluence of geopolitical tensions, cross-border commerce, and ethnic integration. In certain contexts, heightened activity along frontiers may also be driven by strategic military or political objectives. Therefore, the intricate interplay of natural and societal factors in borderlands necessitates dedicated and nuanced analytical scrutiny. Existing research has approached the quantification of human-environment interactions from multiple angles, developing concepts such as the human footprint (Williams et al., 2020; Mu et al., 2022), human pressure (Mammides, 2020), environmental footprint (Vanham et al., 2019), and human disturbance (Martinez-Ramos et al., 2016). These assessments typically rely on global and regional indicators, including population distribution, land-use change, infrastructure density, and accessibility. For instance, Williams and colleagues mapped the global human footprint, revealing that approximately 1.9 million square kilometers of previously undisturbed land underwent significant modification between 2000 and 2013 (Williams et al., 2020). Similarly, Venter et al. quantified cumulative human pressures worldwide from 1993 to 2009 using data on infrastructure, land cover, and accessibility, concluding that the expansion of the human footprint did not keep pace with the rapid rates of population and economic growth (Venter et al., 2016). At regional and urban scales, numerous studies have employed adapted methodologies and localized data to refine our understanding of the human footprint (Li et al., 2018).

Despite these advances, comprehensive quantitative assessments focused specifically on border regions are conspicuously absent. The prevailing body of border scholarship tends to concentrate on localized, activity-specific phenomena. These include the construction of infrastructure and buildings (Rutt and Coleman, 2005), the dynamics of cross-border trade and economic cooperation (McCallum, 1995), agricultural and pastoral practices (Ziegler et al., 2009), migration flows (Payan and Cruz, 2020), and the incidence of armed conflict (Mueller et al., 2016). While much of this work examines the ecological and biodiversity consequences of border activities, it seldom addresses the overarching patterns of human activity themselves. Consequently, large-scale modeling efforts that characterize anthropogenic signatures across borderlands have been largely overlooked. Moreover, existing global datasets on human activity frequently suffer from insufficient spatial resolution, limited temporal coverage, or inconsistent cross-border calibration, which restricts their utility for dedicated frontier studies. This reveals a significant research gap: a dearth of longitudinal, large-scale investigations into human activity dynamics within the world's border regions. Research within Asia has provided some insights into these dynamics. For example, Liu et al. (2016) documented land-use and land-cover changes in Laos's Luong Namath Province over two decades. Wang et al. (2017) observed an increasing trend in vegetation greenness on the Chinese side of its borders with North Korea and South Asian nations. Song et al. (2020) chronicled the evolution of a minor border town into a significant hub for Sino-Myanmar cooperation. However, these inquiries remain geographically confined and are often reliant on census or survey data, limiting their broader applicability.

The borderlands of Iran, spanning over 6,000 kilometers and adjoining seven distinct nations, present a critical and underexplored case for such analysis. This region is geopolitically sensitive and has historically been a theater for local conflicts influenced by extra-regional powers. Recent tensions, such as cross-border disputes with Afghanistan, alongside the development of economic corridors under initiatives like the Belt and Road Initiative, have focused considerable international attention on the area (Dai, 2019; Murton and Lord, 2020; Holslag, 2009; Maxwell, 2003). In response to the increased accessibility of these frontiers, the Iranian government has implemented policies to stimulate border development through cross-border cooperation, leading to rapid agricultural expansion, urbanization, and industrialization in specific locales. These regions have also become integral to the Belt and Road Initiative, particularly in the establishment of cross-border economic corridors (Liu et al., 2018). Consequently, compounded by recent global health crises and regional military tensions, Iran's border areas are undergoing a period of accelerated transformation. This study aims to bridge the identified research gap by quantitatively characterizing the patterns of human activity within Iran's border zones. To achieve this, we propose a Human Activity Intensity (HAI) index, calculated at a 1 km resolution for a 50 km buffer zone along both sides of Iran's land borders for the period 1992–2020. This index is constructed by integrating three key datasets: land cover, population density, and satellite-derived nighttime light imagery. We analyze HAI variations at national, country-pair, and regional scales. By identifying spatial hotspots of HAI, we delineate three distinct spatiotemporal evolutionary patterns of high-activity zones. Finally, we discuss the multifaceted implications of these HAI dynamics, encompassing ecological consequences, geopolitical shifts, and geo-economics developments in these strategically vital borderlands.

## 2. Data and Methodology

### 2.1 Study Area

For the purposes of this investigation, the designated study area was defined as a 50-kilometer corridor extending on both sides of Iran's terrestrial boundaries (Figure 1). Encompassing a frontier of roughly 6,000 kilometers, this zone exhibits a diverse array of landscapes, including undisturbed forested areas, arid deserts, and elevated plateaus. The temporal scope of the analysis commences in 1992, a pivotal year marking the full accessibility of Iran's borders following prior restrictions. Leveraging the availability of consistent datasets, four distinct time steps were chosen for examination—1992, 2000, 2010, and 2020—establishing approximately decadal intervals to capture medium-term environmental and anthropogenic changes.

### 2.2 Data Sources and Preprocessing

**2.2.1 Land Cover:** Alterations in land use serve as a primary indicator of anthropogenic influence, with landscape modifications driven by agricultural encroachment and deforestation offering critical insights into the evolving characteristics of border zones (Xiao et al., 2021). To capture these dynamics, land cover information was sourced from the Global Land Cover database (accessible via https://cds.climate.copernicus.eu/), covering the period from 1992 to 2020 at an initial spatial resolution of 300 meters. To standardize the analysis with other datasets, a majority resampling technique was employed to aggregate this data to a 1 km grid. The classification scheme adheres to the UN FAO Land Cover Classification System (LCCS), which delineates the landscape into 22 distinct categories. To quantify the degree of human influence associated with each category, a Human Activity Score was assigned, drawing on established methodologies from prior research (Xu and Xu, 2016; Li et al., 2019; Zhao et al., 2015). This scoring system operates on a scale from 0 to 10, where 0 denotes a complete absence of human activity and 10 represents the maximum level of anthropogenic modification. Consequently, urban and settlement areas were assigned the highest score (10), followed sequentially by agricultural lands, grasslands, and water bodies. Conversely, land cover types that remain largely untouched by direct human intervention received a baseline score of 0.

**2.2.2 Population Density:** Data pertaining to population distribution were acquired from the Socioeconomic Data and Applications Center, administered by NASA. Addressing the limited availability of data for the initial time point, the 1990 iteration of the Gridded Population of the World (GPW) dataset, originally provided at a 2.5 arc-minute resolution, was utilized as a proxy for 1992. This dataset was subsequently resampled to align with the study's target 1 km (approximately 30 arc-seconds) grid. For the subsequent temporal intervals of 2000, 2010, and 2020, population data were sourced from the United Nations World Population Prospects (WPP), which were already available at the desired 1 km spatial resolution. To ensure comparability across all time steps and integration with other indices, the population density values were normalized using the following equation:


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Figure 1. Study Area Map

$$Popu_{nor}(n,t) = (popu(n,t)/max(popu(n',t'))) \times 10 \quad (1)$$

where $Popu_{nor}$ (n,t) is the normalized population intensity for raster n in year t, ranging from 0 to 10; popu(n,t) is the raw population density; and max (popu (n′,t′))is the maximum raster value across all four years (1992, 2000, 2010, 2020).

**2.2.3 Nighttime Lights:** Nighttime light imagery has become an indispensable tool for capturing spatial disparities in economic performance, urban expansion, infrastructure distribution, and carbon emissions, serving as a reliable indicator of anthropogenic presence (Wang et al., 2020; Wu et al., 2018; Mellander et al., 2015). These satellite-derived datasets detect low-level luminosity originating from urban settlements, combustion sources, and vehicular networks. In the present study, nighttime lights are employed as a surrogate for socio-economic activity and development levels, following established approaches in the literature (Singhal et al., 2020). The raw data are provided at a 1 km spatial resolution, with pixel values ranging from 0 to 63. Owing to the lack of available data for the final time point, the 2020 analysis utilizes nighttime light observations from 2018 as a representative substitute. To ensure consistency with other indices, the nighttime light values were normalized using the following equation:

$$Light_{nor}(n,t) = (light(n,t)/max(light(n',t'))) \times 10 \quad (2)$$

where $Light_{nor}$ (n,t) is the normalized nighttime light intensity for raster n in year t, ranging from 0 to 10; light (n′,t′) is the raw light intensity; and max(light (n′,t′)) is the maximum value among the four years.

## 2.3 Methodology

Drawing upon prior scholarly work and constrained by the availability of consistent temporal data, three core indicators—land cover, population density, and nighttime light intensity—were ultimately selected to formulate the Human Activity Intensity (HAI) index. The methodological framework and sequential steps employed in deriving this composite index are systematically illustrated in Figure 2.

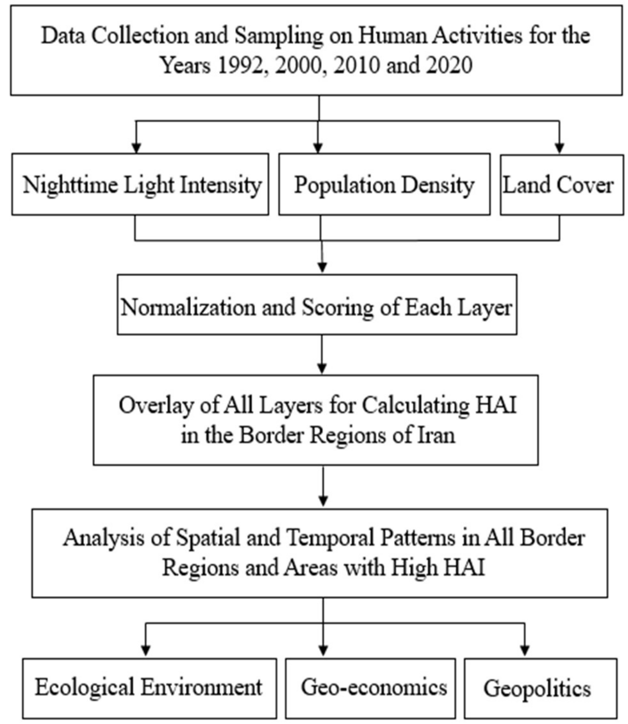


Figure 2. HAI Calculation Workflow

As an initial preprocessing step, all input datasets were harmonized to a consistent spatial resolution of 1 km × 1 km through resampling. Subsequently, the population density and nighttime light layers were normalized to a 0–10 scale using the transformations specified in Equations (1) and (2), respectively. For the land cover component, each grid cell was assigned a human activity score based on its land type, following the established scoring framework derived from previous research. The final Human Activity Intensity (HAI) index was then computed for each cell as the arithmetic mean of these three standardized components. The formal expression of this calculation is as follows:

$$HAI(n,t) = (Land(n,t) + Popu_{nor}(n,t) + Light_{nor}(n,t))/3 \quad (3)$$

where HAI(n,t) is the human activity intensity for raster n in year t, ranging from 0 to 10; Land(n,t) is the land cover score; $Popu_{nor}$ (n,t) is the normalized population intensity; and $Light_{nor}$(n,t) is the normalized nighttime light intensity.

To facilitate interpretation, the continuous HAI values were stratified into five distinct ordinal categories—very low, low, moderate, relatively high, and high. It is important to note that these categories denote relative levels of activity intensity within the study area and are not intended for absolute comparison across different regions or contexts. Building upon this classification, a series of analyses were conducted to examine spatiotemporal dynamics, first at the scale of the entire border zone and subsequently focusing on localized areas exhibiting notable patterns. The broader ecological, geopolitical, and geoeconomic implications derived from the observed HAI variations were then synthesized and discussed. All cartographic visualizations and spatial analyses presented in this study were generated using ArcGIS software (version 10.8).

# 3. Results

## 3.1 Evolution of HAI Across the Entire Border Region

An analysis of the mean Human Activity Intensity (HAI) on the Iranian side of the border reveals a gradual but consistent upward trend over the study period. The average values recorded for 1992, 2000, 2010, and 2020 were 0.31, 0.32, 0.35, and 0.38, respectively (Figure 3). The spatial distribution of HAI across Iran's border regions exhibited considerable range. The minimum value of 0 was consistently observed in the forested areas of the north, areas characterized by challenging topography. Conversely, the maximum value of 9.97 was recorded in 2020 within an urban center located in the eastern part of the country. A notable finding is the predominance of low-intensity areas; approximately 93% of all raster cells registered an HAI of less than 1, and 60% of cells fell below the calculated mean. This distribution underscores that, despite localized increases, human activity throughout Iran's border zones remained generally subdued between 1992 and 2020. This pattern is largely attributable to the prevalence of high-altitude terrain and severe environmental conditions across substantial portions of the buffer zone, which naturally constrain anthropogenic development.

On the opposing side of the frontier, encompassing the territories of Iran's neighboring countries, the mean HAI values for the same time points—1992, 2000, 2010, and 2020—were 0.23, 0.31, 0.31, and 0.33 (Figure 3). The spatial extremes on this side ranged from a minimum of 0, found in the desert regions of Iraq, to a maximum of 6.78, observed in an urban area of Afghanistan in 2020. Mirroring the pattern on the Iranian side, the vast majority of the landscape (roughly 91% of raster cells) exhibited HAI values below 1, indicating a similarly low baseline of activity across most of the neighboring territories. A direct comparison of the two sides reveals a consistent disparity: throughout the entire observation period, the mean HAI values on the Iranian side were persistently higher than those recorded across its combined international boundaries.

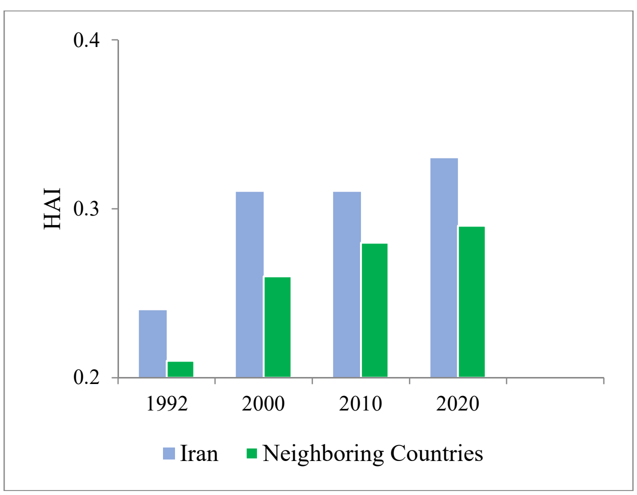


Figure 3. Overall changes in the study area between Iran and its neighboring countries.

The border regions of Iran have experienced pronounced transformations in land use over recent decades. A key driver of this change has been a series of national policy initiatives implemented since 1992, including the establishment of Free Trade Zones, "Border Development and Opening Trial Zones," and "Border Economic Cooperation Zones." These designations have served as catalysts for accelerated urbanization and industrial expansion along the periphery. Iran's accession to the World Trade Organization (WTO) as an observer in 2001 further stimulated this trend, prompting substantial investment in border ports and urban centers designed to facilitate cross-border trade.

These developmental policies have manifested in distinct spatial patterns of HAI. Elevated intensity values were observed along several frontier segments, notably those adjoining Iraq, Afghanistan, and Turkmenistan. In these areas, the combination of relatively fertile land and concentrated anthropogenic activity has produced sustained HAI hotspots. A similar pattern emerged along the Iran-Pakistan border, where Pakistan's own infrastructure development initiatives, beginning around 2016, spurred settlement growth and generated locally elevated HAI values. International dynamics have also played a significant role. Since 2013, Turkey has emerged as a pivotal transit corridor, particularly through two major border crossings with Iran, thereby intensifying activity in those zones (Notteboom et al., 2022). More broadly, large-scale transnational initiatives such as the Belt and Road Initiative (BRI) have contributed to accelerated HAI growth across multiple border segments by enhancing connectivity and economic integration. Conversely, not all border areas have followed this trajectory of increasing intensity. The northern frontiers shared with Azerbaijan and Armenia exhibited persistently low HAI values throughout the study period. These high-latitude border regions, characterized by mountainous terrain and more limited economic integration, have remained comparatively insulated from the developmental pressures observed elsewhere along Iran's periphery.

## 3.2 Cross-Country Comparison Along the Border

A comparative assessment of Iran's neighboring countries reveals substantial disparities in both the magnitude and trajectory of human activity. Among all adjacent nations, Iraq recorded the highest mean HAI values alongside the most rapid rate of increase throughout the study period. In stark contrast, Armenia exhibited the lowest HAI and the slowest growth, a pattern largely attributable to its inhospitable mountainous terrain and limited development capacity. The temporal dynamics of HAI across the borderlands can be delineated into two distinct phases. During the initial period from 1992 to 2010, HAI values remained relatively stable across most neighboring territories, with Turkey representing the sole exception where a modest decline was observed. However, the post-2010 era marked a significant shift, characterized by accelerated HAI growth in Iraq, Afghanistan, and Turkmenistan. Conversely, this same period witnessed a slight contraction in HAI values for Azerbaijan and Armenia. Notably, synchronous growth patterns emerged along multiple frontier segments, with HAI increasing concurrently on both sides of the Iran-Afghanistan, Iran-Pakistan, and Iran-Iraq borders.

When comparing absolute HAI levels between Iran and its neighbors, a nuanced picture emerges. For the majority of border dyads—specifically those involving Turkey, Azerbaijan, and Pakistan—HAI values on the Iranian side consistently exceeded those recorded across the frontier. Only two nations, Afghanistan and Iraq, registered higher mean HAI values than their adjacent Iranian border areas. The relative balance of activity between certain country pairs has shifted markedly over time. The contrast along the Iran-Turkmenistan border, for instance, has been significantly altered by Turkmenistan's targeted border development programs in its Far East region. Meanwhile, the corresponding areas on the Iranian side experienced comparatively sluggish growth, hampered by economic underdevelopment, population outmigration, and resource limitations. Similar dynamics were observed along the northern frontiers; Azerbaijan's limited external connectivity constrained human activity, while Armenia's highland regions experienced accelerated HAI decline after 2010, driven in part by unsustainable land management practices such as overgrazing.

### 3.3 Regional Analysis

An analysis of the net change in HAI between 2020 and 1992 reveals that the majority of the landscape remained relatively stable over the nearly three-decade period. Approximately 80% of all raster cells exhibited HAI differences within the narrow range of -1 to 1, underscoring the persistence of low-intensity conditions across most of the study area. To investigate the more significant deviations from this baseline, four border segments exhibiting notable changes were selected for detailed examination: the frontiers with Turkey, Iraq, Pakistan, and Afghanistan.

The northwestern border shared with Turkey displayed a distinctive pattern of declining HAI over the study period. This contrasts sharply with the western, eastern, and southeastern frontiers, where substantial increases were concentrated, particularly in and around border cities and ports along the Iraq and Afghanistan interfaces. From these observations, four primary spatiotemporal patterns of HAI evolution were delineated: (1) a bilateral decrease characterizing the Iran-Turkey border; (2) asymmetric, or unilateral, growth favoring the Iraqi side of the Iran-Iraq frontier; (3) sustained, continuous growth on the Pakistani side of the Iran-Pakistan border; and (4) concurrent, simultaneous growth along the Iran-Afghanistan boundary.

The declining trend observed in the northwest requires further contextualization. Despite ongoing development activities in sectors such as energy, mining, agriculture, forestry, and machinery along the Iran-Turkey corridor, the region has experienced sluggish overall growth. This stagnation is largely attributed to historical patterns of population outmigration and sustained economic underdevelopment on the Iranian side, which have counteracted the potential simulative effects of cross-border commerce. Along the eastern frontier with Pakistan, a pronounced asymmetry in growth rates was observed. The mean HAI increase on the Iranian side was 0.09, while the Pakistani side recorded a more substantial increase of 0.34. This disparity likely reflects fundamental differences in natural environmental conditions and carrying capacity between the two adjacent territories. In contrast, the southeastern border with Afghanistan exhibited a pattern of concurrent growth. Mean HAI increases of 0.14 on the Iranian side and 0.12 on the Afghan side were recorded. This synchronized intensification has been facilitated by a combination of favorable climatic conditions, robust bilateral trade relations, and the prevalence of frequent cross-border social and economic interactions.

### 3.4 Hotspot Analysis

Hotspots of high human activity intensity, defined as areas with HAI values exceeding 4, were predominantly localized within border cities that have undergone substantial urban expansion. Examining the spatiotemporal evolution of these hotspots from 1992 to 2020 revealed three distinct modes of spatial development: unilateral expansion, bilateral expansion, and cross-border integration.

Unilateral expansion describes a pattern in which elevated HAI develops predominantly on one side of an international boundary, forming a single-centered agglomeration with limited transboundary interaction. These centers frequently exhibit directional growth toward the frontier line, evolving into international transport nodes while simultaneously generating disparities in local welfare between the two sides. Historical legacies and geopolitical circumstances play a significant role in shaping this asymmetrical development trajectory.

Bilateral expansion occurs when high HAI zones emerge in proximity to the border on both sides simultaneously. This pattern is typically facilitated by active cross-border trade relationships and reinforced by supportive national policies on each side of the frontier, creating twin centers of activity that develop in parallel.

Cross-border integration represents the most advanced stage of spatial coalescence, wherein high-activity zones extend across the international boundary to form functionally connected "twin cities" characterized by strong social and economic linkages (Okunev and Tislenko, 2017; Mikhailova, 2013). This pattern tends to emerge in areas endowed with favorable natural conditions, such as flat and unobstructed terrain, and is further reinforced by historical trade routes and established transport networks that predate or transcend the political boundary.

## 4. Discussion

### 4.1 Comparison with Previous Studies

Prior investigations of border regions have predominantly relied upon demographic and land-use datasets as their primary analytical lenses. For instance, You and colleagues conducted an analysis of population dynamics within a 200-kilometer buffer zone encircling China's international boundaries (You et al., 2017). Their findings revealed that population densities on the neighboring side were approximately twice those observed on the Chinese side—a pattern consistent with the population density disparities identified in the present study. However, an important nuance emerged when comparing these results with our HAI findings: despite lower population densities, the Chinese side exhibited higher overall HAI values. This discrepancy underscores a critical methodological insight: population data alone, in isolation from other indicators, cannot fully capture the multifaceted nature of human activity intensity in borderland contexts.

In a complementary study, Huang et al. employed census data to examine population distribution patterns across 131 border counties in China over the period from 1982 to 2010 (Huang et al., 2020). Their research demonstrated that border populations tended to concentrate in plains areas and along transportation corridors. However, the analysis also revealed substantial spatial heterogeneity when examined at the administrative unit level, suggesting that single-source datasets may yield incomplete or potentially biased representations of borderland dynamics. This limitation was further articulated by Stokes and Seto, who demonstrated in the context of urban infrastructure research that integrating multiple data sources—specifically population, land-use, and nighttime light imagery—provides a more nuanced and comprehensive characterization of human activity heterogeneity (Stokes and Seto, 2019).

Building upon these insights, the present study adopts an integrated multi-indicator approach, combining land cover, population density, and nighttime light data to construct a more holistic representation of human activity intensity across Iran's border regions. The methodological design incorporates several novel elements. First, the deliberate selection of a 50-kilometer buffer zone flanking the international boundary represents a departure from conventional administrative unit-based analyses. This spatial delineation is grounded in the premise that the border's influence on human activity is most pronounced within this proximate distance, an effect that may be diluted when using larger or administratively defined units. Second, the study addresses a gap in existing literature concerning spatial scale. Prior research has predominantly focused on administrative aggregates such as provinces (Liu et al., 2016) or cities (Song et al., 2020), with limited attention to multi-scale comparisons enabled by raster-based data structures. By employing a gridded analytical framework, this research facilitates systematic comparison across multiple spatial scales, offering a more granular understanding of how human activity evolves on both sides of the frontier. Finally, the temporal scope of this investigation extends beyond the relatively short-term horizons characteristic of many previous studies (e.g., You et al., 2017). Spanning nearly three decades from 1990 to 2020, this longitudinal assessment captures the long-term dynamics of HAI evolution, providing deeper insights into the spatiotemporal trajectories that have shaped Iran's borderlands over a period of significant geopolitical and economic transformation.

### 4.2 Geopolitical and Geo-Economic Implications of HAI Changes

The intensity and spatial distribution of human activities along international boundaries carry profound geopolitical consequences. The character of these activities—whether cooperative or conflictual in nature—constitutes a fundamental determinant of broader geopolitical dynamics in border regions. Areas characterized by contested sovereignty or unresolved territorial disputes present a particular concern. In such contexts, accelerated growth in human activity intensity can act as a catalyst for heightened cross-border friction. When one party perceives rapid development on the opposing side as a strategic challenge, bilateral relations may become ensnared in what political scientists term "security dilemmas," wherein actions taken by one state to enhance its own security are interpreted as threatening by the other, prompting countermeasures and escalating tensions. Conversely, the institutionalization of cross-border cooperation presents an alternative trajectory. The deliberate establishment of transboundary economic cooperation zones serves to channel human activity into productive channels that stabilize rather than destabilize bilateral relationships. These designated areas prioritize collaborative ventures in industrial development and logistics infrastructure, transforming the border from a potential flashpoint into a shared platform for economic integration. This process enhances what may be termed border geo-economics—the strategic management of cross-border economic space—by aligning the interests of neighboring states around mutual material benefits rather than zero-sum security calculations. Thus, the trajectory of human activity intensity in border regions is not merely a passive outcome of underlying conditions but an active force that shapes the geopolitical character of the frontier itself.

### 4.3 HAI Implications for Ecosystem Services and Biodiversity

The accelerated proliferation of anthropogenic activities along Iran's frontier zones—encompassing both urban expansion and agricultural intensification—exerts considerable pressure on local habitats and biodiversity (Fang et al., 2021; Liu et al., 2022). Within this context, systematic monitoring of both ecological and economic dimensions of land-use intensity becomes imperative (Shen et al., 2021). To investigate the environmental correlates of rising HAI, this study incorporated monthly Normalized Difference Vegetation Index (NDVI) data acquired from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) (Ji et al., 2021). These data, provided at a spatial resolution of 1 kilometer, enabled a spatiotemporal comparison with HAI values over the period from 2000 to 2020. The analysis revealed a generally negative correlation between HAI changes and NDVI values in areas characterized by higher population density, suggesting that intensified human activity is associated with diminished vegetation cover in these zones. The implications for biodiversity are particularly concerning. Several critical junctures within the study area—identified as biodiversity hotspots in prior research (Mi et al., 2021)—have experienced substantial HAI increases over the study period. This convergence of ecological sensitivity and anthropogenic intensification places local species and ecosystems at heightened risk, underscoring the need for targeted conservation interventions in these vulnerable borderland environments.

### 4.4 Limitations and Future Research Directions

Notwithstanding the contributions of this study, several uncertainties and limitations warrant acknowledgment. First, the construction of the Human Activity Intensity index was necessarily constrained by the availability of consistent historical datasets spanning the entire study period. Certain potentially valuable indicators—most notably, road network density and transportation infrastructure—could not be incorporated due to the absence of temporally compatible data. This omission may result in an underestimation of human influence in areas where infrastructure extends beyond concentrated population centers, such as remote transit corridors or resource extraction sites. Second, the current HAI formulation, while integrating multiple data sources, remains an empirical approximation based primarily on static or coarsely temporal land-use information. The availability of more granular data in the future—including daily or monthly population dynamics, seasonal tourist flows, and migrant population movements—would enable a more nuanced characterization of intra-annual HAI variability. Such high-frequency data could reveal temporal patterns of human activity that are obscured in the decadal time steps employed in this study.

Beyond these methodological considerations, the substantive findings of this research point to important avenues for future inquiry. Human activities within border buffer zones generate spillover effects that transcend political boundaries, including transboundary air and water pollution that propagate across frontiers with little regard for national jurisdiction (Liu et al., 2020). These phenomena exemplify what has been conceptualized as "tele coupling"—socioeconomic and environmental interactions over distance (Hull and Liu, 2018). Future research should prioritize investigation of these cross-border connectivity mechanisms and explore the institutional architectures that might support effective transboundary environmental governance and cooperation. Such efforts would not only advance scientific understanding but also inform policy responses to the shared environmental challenges that increasingly characterize the world's borderlands.

## 5. Conclusions

This study provides a comprehensive assessment of human activity intensity along Iran's border regions over a three-decade period. The findings reveal that approximately 90 percent of the study area maintains low HAI values, indicating that anthropogenic influence remains minimal across the majority of the landscape. A consistent asymmetry characterizes the cross-border comparison, with HAI values on the Iranian side generally exceeding those recorded on the territories of neighboring countries. Notably, while land-use intensity has increased substantially within Iran, population densities remain lower than those observed across several adjacent frontiers. Among Iran's land-border neighbors, Iraq exhibits the highest HAI coupled with rapid growth, whereas Armenia registers the lowest intensity throughout the study period.

The evolution of Iran's geostrategic relationships with its neighbors has manifested in four distinct regional HAI trajectories: a bilateral decline along the Iran-Turkey frontier, unilateral growth favoring the Turkmenistan side, sustained increases within Afghanistan, and synchronized growth along the Iran-Afghanistan border. At the local scale, hotspot analysis revealed three spatial development patterns—unilateral expansion, bilateral expansion, and cross-border integration—which collectively illustrate the complex spatial logic of borderland intensification. These patterns reflect the coexistence of two paradoxical forces: the "border effect" that artificially separates contiguous regions, and the "aggregation effect" that concentrates human activity precisely along this dividing line.

The implications of these patterns extend beyond academic observation. Internationally, the concentration of populations and industrialization in border zones—expressed through migration flows, urbanization processes, cross-border economic cooperation zones, and transport infrastructure development—carries significant environmental consequences. Simultaneously, human activity intensity in these areas exerts substantial influence on geopolitical dynamics and geoeconomic strategies. Governments frequently relocate populations to contested frontier areas as a means of asserting control, while the natural aggregation of populations in border cities stimulates cross-border economic cooperation, which in turn attracts further settlement in a self-reinforcing cycle.

Given the limited body of research systematically examining human activities in international border regions, this study positions Iran as an instructive case for addressing this knowledge gap. By integrating three complementary datasets into a unified HAI framework, the research illuminates the evolution of human activity along Iran's borders over the past thirty years. The resulting insights offer a valuable reference for border scholarship and provide actionable intelligence to support decision-making in critical areas of Iran's cooperation with its neighbors, including environmental protection, border security management, and the facilitation of cross-border trade.

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