REMOTE SENSING-DRIVEN MONITORING OF HUMAN DISTURBANCE AND QUANTITATIVE ECOLOGICAL RISK ASSESSMENT IN PROVINCIAL NATURE RESERVES OF HEILONGJIANG PROVINCE

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Abstract. To address the lack of systematic and objective monitoring of human disturbances in provincial-level nature reserves, this study developed an integrated remote sensing–field monitoring framework based on Landsat-8 OLI and Sentinel-2 MSI imagery from 2020 to 2023. An object-based interpretation workflow and a comprehensive Human Footprint Index were established, with accuracy calibrated using 312 field survey points. Results show that all 38 provincial-level nature reserves in Heilongjiang Province exhibit detectable human disturbance signals, though no areas with high-intensity disturbance were identified. Five reserves were classified as moderate disturbance, primarily influenced by farmland expansion, centralized settlements, and high-grade transportation corridors; eight reserves as general disturbance, dominated by scattered farmland and low-grade roads; and twenty-five reserves as mild disturbance maintaining good ecological integrity. Based on these findings, differentiated management strategies are proposed, including establishing ecological buffer zones and compensation mechanisms in moderately disturbed areas, promoting farmland-to-wetland/forest conversion and connectivity restoration in generally disturbed zones, and implementing community-based joint monitoring and early-warning systems in mildly disturbed reserves. The study demonstrates feasibility and applicability of an integrated remote sensing–field monitoring framework for large-scale ecological assessment and targeted management, providing scientific support for refined governance and sustainable use of protected areas in Heilongjiang and other cold-temperate regions.

Keywords: *human footprint index, remote sensing monitoring, reserve management, ecological risk assessment, reserve management*

Introduction

With the continuous expansion of regional economies and the intensification of human activities, development and construction, agricultural expansion, resource extraction, and recreational tourism have all shown a marked upward trend. As a result, large areas of ecologically valuable land urgently needing protection are being encroached upon, sharpening the conflict between conservation and development (Bruner et al., 2001). This pressure has driven sustained incursions across nature reserve boundaries, subjecting ecosystems to disturbance levels beyond their self-repair capacity. Consequently, habitats of rare and endangered species are becoming fragmented, key migration corridors are frequently obstructed, and the reproductive success and habitat integrity of nationally protected species are under serious threat (CBD, 2020; Chen et al., 2020). Nature reserves—key instruments for safeguarding ecological security and biodiversity—have drawn heightened public attention, underscoring the need for scientific and refined supervision (Cheng and Wang, 2016).

Heilongjiang Province, a representative cold-temperate ecological region in China, encompasses diverse habitats including high-latitude wetlands, northern forests, and mountainous systems, and ranks among the top nationwide in species diversity and

natural resource endowment (Gao et al., 2016). However, because reserves are widely distributed, difficult to access, and situated in complex terrain, traditional ground-based patrol and monitoring are labor-intensive, limited in coverage, and lacking in timeliness (Geldmann et al., 2013), making it difficult to capture real-time spatial patterns and the dynamic evolution of human disturbances. With rapid advances in aerospace engineering and digital-earth technologies, remote sensing monitoring has been widely validated and applied in ecosystem quality assessment and natural resource management (Goodchild, 2003; He et al., 2015), providing technical support to overcome the limitations of ground monitoring and to improve regulatory timeliness (Li et al., 2020). In 2016, the Satellite Environment Application Center of the Ministry of Ecology and Environment launched remote-sensing monitoring of human activities in national nature reserves, systematically revealing spatiotemporal disturbance patterns and providing important clues and decision support for central environmental inspections and routine supervision (Liu et al, 2013; Liu et al., 2013).

Although a national-level remote-sensing monitoring framework exists, regional studies with higher accuracy, more frequent updates, and indicator systems tailored to management needs remain scarce for provincial nature reserves—particularly in cold-temperate regions (Ministry of Ecology and Environment of China, 2016). To address this gap, this study uses Landsat-8 OLI and Sentinel-2 MSI imagery from 2020 to 2023 to construct an object-based interpretation workflow and a comprehensive Human Footprint Index (HFI), calibrated with 312 field-survey points. We systematically evaluate the intensity and spatial distribution of human disturbances across 38 provincial nature reserves in Heilongjiang. Based on these results, we propose differentiated regulatory and ecological-function enhancement strategies, providing a scientific basis and technical guidance for refined management and ecological-security optimization in Heilongjiang and comparable cold-temperate regions (Nagendra, 2001).

Current status of the study area

Construction status

Since the nationwide surge in the establishment of nature reserves in the 1980s, Heilongjiang Province has rapidly entered a phase of large-scale expansion in its protected area system (Naughton-Treves et al., 2005). After more than a decade of continuous development, the province has gradually established a comprehensive network of nature reserves featuring diverse resource types and distinctive regional characteristics (Ni et al., 2006). To date, 46 nature reserves have been formally established, supported by a coordinated planning framework and a hierarchical management structure covering provincial and lower-level reserves (Pettorelli et al., 2014). These protected areas play a vital role in conserving representative ecosystems, essential habitats and breeding grounds for wild flora and fauna, and valuable natural relics, forming a core ecological security barrier in northern China (Thompson, 1984).

However, compared with the national trend toward "quality and efficiency enhancement," the upgrading of nature reserves in Heilongjiang has lagged behind (Turner et al., 2003). Current reserves exhibit deficiencies in ecological coverage, spatial integrity, and functional connectivity, which constrain alignment with the province's role as a key region of natural resources and biodiversity. These structural limitations have become a major bottleneck restricting the high-quality development of regional protected areas (Venter et al., 2016).

Of the 46 established nature reserves, this study quantitatively assessed 38 sites. The remaining eight were excluded a priori based on standardized technical and data-quality criteria to ensure methodological consistency and cross-site comparability:

(i)   absence or inconsistency of authoritative boundary or zoning data (core, buffer, experimental) required for zone-weighted index computation;

(ii) insufficient cloud-free satellite imagery within the analysis period, hindering reliable land-use and land-cover classification;

(iii) attribute or administrative discrepancies, such as conflicting records of area or establishment date; and

(iv) insufficient field verification for ambiguous zones affected by industrial, mining, energy, or tourism activities.

These exclusion rules were defined ex ante and applied independent of disturbance outcomes. The eight omitted sites and their exclusion reasons are summarized in *Table 1* to ensure transparency and traceability. All 38 included reserves meet the inclusion requirements of validated boundary data, adequate imagery, and confirmed field verification.

To provide an immediate spatial perspective of anthropogenic pressure, *Figure 1* illustrates the Human Activity Impact Level (HFI) distribution across the analyzed reserves, following the classification thresholds described in Section 3. Meanwhile, *Table 1* lists each reserve's name, administrative affiliation, area, protection type, and establishment date, thereby documenting spatial heterogeneity and temporal development patterns. Together, these materials respond directly to reviewer recommendations by presenting both visual and tabular summaries of the study area, establishing a coherent foundation for subsequent analyses of human disturbance and ecological risk.
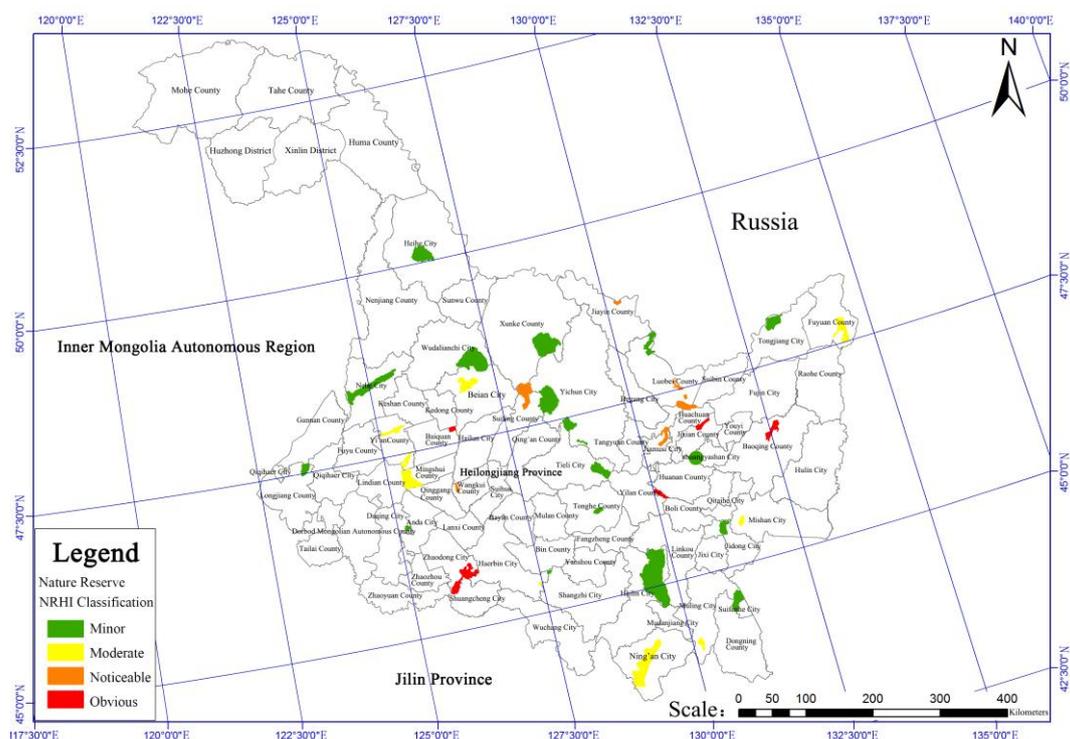

Figure 1. *Human activity impact level (HFI) across nature reserves analyzed in Heilongjiang Province*

Table 1. *Basic information of nature reserves analyzed in this study (name, administrative region, area, type, and establishment date)*

Nature reserve name	Administrative region	Area (ha)	Type	Establishment date
Anxing Wetland Nature Reserve	Yilan County	11,000	Inland Wetland	2002-03-04
Tonghe Longkou Nature Reserve	Tonghe County	10,303	Forest Ecosystem	1997-11-12
Songfeng Mountain Nature Reserve	Acheng City	1,465	Inland Wetland	1984-05-23
Heilonggong Wood Frog Nature Reserve	Shangzhi City	3,600	Wildlife	1982-04-30
Xiandong Mountain Nature Reserve	Qiqihar City	2,450	Wildlife	2009-04-07
Halahai Nature Reserve	Longjiang County	16,564	Inland Wetland	2007-08-13
Nemoer River Wetland Nature Reserve	Yi'an County	61,385	Desert Ecosystem	2007-08-13
Wuyuer River-Shuangyang River Nature Reserve	Nehe City	22,934	Inland Wetland	2007-08-06
Shuguang Tussah Nature Reserve	Jidong County	9,766	Wildlife	1992-08-01
Tiexi Nature Reserve	Mishan City	7,235	Forest Ecosystem	1996-11-13
Taipinggou Nature Reserve	Hegang City	22,199	Forest Ecosystem	2009-12-30
Shuilian Nature Reserve	Luobei County	8,952	Inland Wetland	2003-09-16
Dulu River Nature Reserve	Luobei County	19,967.33	Inland Wetland	2000-08-01
Anbang River Nature Reserve	Jixian County	10,295	Inland Wetland	1993-03-01
Qixing Lazi Amur Tiger Nature Reserve	Jixian County	23,000	Wildlife	1990-01-01
Dongsheng Nature Reserve	Baoqing County	19,244	Inland Wetland	2004-09-01
Wusuli River Nature Reserve	Raohe County	39,668	Inland Wetland	2001-01-11
Longfeng Wetland Nature Reserve	Daqing City	5,050.39	Inland Wetland	2003-03-13
Yichun River Headwater Nature Reserve	Yichun City	78,864	Forest Ecosystem	2009-01-01
Cuibei Wetland Nature Reserve	Yichun City	27,730	Inland Wetland	2001-10-15
Wuma River Sable Nature Reserve	Yichun City	20,730	Wildlife	2006-03-13
Bishui Scaly-sided Merganser Nature Reserve	Yichun City	2,535	Wildlife	1997-07-11
Langxiang Alpine Musk Deer Nature Reserve	Yichun City	31,355	Wildlife	2005-01-01
Ku'erbin Wetland Nature Reserve	Yichun City	66,964	Inland Wetland	2004-01-01
Jiayin Dinosaur Fossil Nature Reserve	Jiayin County	3,844	Paleontological Relic	1998-04-06
Jiamusi Riverside Wetland Nature Reserve	Jiamusi City	11,267	Inland Wetland	2007-08-13
Qindeli Sturgeon and Huso Sturgeon Nature Reserve	Tongjiang City	36,663	Wildlife	1998-12-04
Dongning Niaoqing Mountain Nature Reserve	Dongning County	18,002	Forest Ecosystem	2007-01-12
Hailin Lianhua Lake Nature Reserve	Hailin City	190,000	Inland Wetland	1997-12-26
Jingpo Lake Nature Reserve	Ning'an City	126,000	Inland Wetland	1980-11-01
Liufeng Lake Nature Reserve	Muling City	6,591	Inland Wetland	1996-11-13
Gongbiela River Nature Reserve	Heihe City	50,180	Inland Wetland	2005-10-18
Shankou Nature Reserve	Heihe City	99,489.90	Inland Wetland	2002-10-18
Bei'an Nature Reserve	Bei'an City	36,505	Inland Wetland	2006-10-25
Xiwa Huang Wetland Nature Reserve	Wangkui County	10,201	Inland Wetland	1990-04-01
Mingshui Wetland Nature Reserve	Mingshui County	30,840	Inland Wetland	2007-06-08
Suiling Numin River Nature Reserve	Suiling County	50,025	Inland Wetland	2007-01-12
Zhaodong Riverside Wetland Nature Reserve	Zhaodong City	36,700	Inland Wetland	2003-03-12

The map displays reserve polygons/centroids over prefecture-level administrative boundaries and major hydrographic features. HFI classes follow the thresholds defined in Section 3.3: mild (HFI ≤ 0.2), general (0.2 < HFI ≤ 0.4), moderate (0.4 < HFI ≤ 0.6), and high (HFI > 0.6); no areas with high-intensity disturbance were identified in the present analysis. Symbology and intervals are kept identical to those used in later figures. Map projection: CGCS2000/Gauss–Krüger; scale bar and north arrow included.

Management status

Heilongjiang Province has long emphasized the legal governance of nature reserves, with efforts dating back to the 1980s when it began drafting the

"Heilongjiang Province Nature Reserve Management Measures," which were officially issued in 1996. Building on this foundation, some nature reserve management agencies have developed more operational management systems tailored to their specific resource endowments and conservation targets (Wang et al., 2016). However, due to historical, institutional, financial, and perceptual constraints, there are still challenges such as insufficient funding, incomplete organizational structures, unclear law enforcement authority, outdated management tools, and a lack of skilled personnel (Wang et al., 2018). Wetland-type nature reserves in particular face issues like unauthorized excavation, grassland and wetland destruction, illegal fishing, and agricultural pollution. In some cases, development and commercial activities have been carried out without proper approval (Watson et al., 2014). Moreover, the lack of dynamic monitoring of biodiversity and ecological conditions within nature reserves hinders the timely and accurate identification of human-induced damage (Wu et al., 2011; Xu et al., 2017).

Remote sensing monitoring and evaluation

Remote sensing monitoring

This study employed multi-temporal satellite imagery (2020–2023) from resource and environmental satellites (e.g., CCD sensors) (Xi, 2021), complemented by Landsat-8 OLI and Sentinel-2 MSI scenes, to characterize human activities in Heilongjiang's provincial nature reserves. To ensure data quality and spatial comparability, we selected only images with scene-level cloud cover < 10% and no obstruction of key monitoring areas, and excluded scenes affected by extensive snow/ice or haze that would compromise land-use/land-cover (LULC) separation. All imagery was preprocessed for radiometric/atmospheric correction and georeferenced to a unified cartographic framework (CGCS2000/Gauss–Krüger). Leveraging integrated "3S" technologies (RS–GIS–GPS) (Yang et al., 2020), we overlaid interpreted human-activity layers with functional zoning (core, buffer, experimental) to derive zone-weighted disturbance metrics that are spatially consistent and temporally comparable across reserves. Feature interpretation targeted disturbance-relevant classes—farmland, residential areas, roads, tourism and energy facilities, and industrial/mining sites—and was calibrated and validated using 312 field-collected ground-truth points, thereby supporting robust computation of the Human Footprint/Activity indices and reliable mapping of disturbance patterns for the 38 reserves analyzed.

We adopted an object-based image analysis (OBIA) workflow on multi-temporal Landsat-8 OLI and Sentinel-2 MSI imagery (2020–2023; scene-level cloud < 10%) to delineate land-use and land-cover classes relevant to human-activity monitoring. Scenes were radiometrically/atmospherically corrected, co-registered in CGCS2000/Gauss–Krüger, and segmented into spectrally and texturally homogeneous image objects. For each object we derived spectral indices (e.g., NDVI for vegetation vigor, MNDWI/NDWI for water and aquaculture ponds, NDBI for built-up/bare features), band ratios, GLCM-based texture, and shape/context descriptors. Classification combined rule-based keys and visual QA, followed by zoning overlays (core/buffer/experimental) to produce zone-weighted metrics. Ambiguities were resolved using 312 field-verified points (facility status, build year, approvals, photos), and the final map was edited to remove spurious objects and enforce cartographic coherence. This procedure ensures consistent separation of the

classes listed in *Table 1* and supports robust HFI/NRHI computation across the 38 reserves.

Class-specific separation cues (examples used in the rule set):

Farmland—medium-to-high NDVI with seasonal variability (multi-temporal cues), rectilinear field blocks/row texture; proximity to irrigation ditches; MNDWI used to exclude wet meadows/shallow water.

Residential (urban/rural settlements)—high NDBI, low NDVI, rectilinear roof patterns, blocky textures, intersection with road nodes; compact morphology near farmland edges.

Industrial & mining land/quarries—very low NDVI, bright SWIR-rich reflectance (exposed soil/rock), pits/stockpiles with sharp boundaries, haul-roads and spoil-heaps; elongated extraction scars on slopes (quarries).

Energy facilities—regular arrays or point-objects with characteristic geometry and shadow signatures (e.g., turbine towers), large graveled substation pads (high NDBI, coarse texture), solar array grids (periodic structure, subdued VNIR reflectance).

Tourism facilities—mixed built-up/parking surfaces with internal paths, often near scenic water/forest edges; moderate NDBI, distinct parcel shapes.

Transportation facilities—airports/wharfs/ports identifiable by large geometric platforms and linear runways/piers; strong edges and consistent orientation.

Roads—linear, high-contrast edge features with consistent width and network connectivity; extracted via line-enhancement and confirmed by context.

Aquaculture farms/livestock facilities—rectangular ponds/levees (high MNDWI/NDWI; stable water tone) or regular farmyards (low NDVI, pens/sheds texture) within floodplains or lowland terrace.

Other artificial facilities—residual engineered surfaces not meeting the above keys; flagged for manual QC and, where possible, reassigned.

Quality controls and comparability. To ensure inter-reserve and inter-annual comparability, we (i) constrained inputs to 2020–2023, (ii) enforced < 10% cloud at each reserve footprint and excluded scenes with severe snow/ice/haze, (iii) used the same segmentation/feature stack across scenes, and (iv) clipped by reserve polygons and zoning boundaries before aggregating per-zone metrics. Field observations were used to correct mislabels (e.g., bare ground vs. early-season cropland; wet meadow vs. shallow ponds) and to confirm facility-type identity (industrial/mining, energy, tourism).

Monitoring content and evaluation indicators

Monitoring content

(1) Remote sensing monitoring

Based on the monitoring results, a human activity disturbance index was calculated using the area of land used for industry, quarries, energy facilities, tourism infrastructure, transportation infrastructure, artificial structures, farms, agricultural land, residential areas, and other man-made constructions within provincial nature reserves, as well as the length of roads. The weightings were determined according to the functional zone in which each human activity patch was located and its corresponding impact on the nature reserve. Using these monitoring outcomes, the level of human disturbance in provincial nature reserves was assessed, and spatial distribution patterns were analyzed.

(2) Field verification

Field verification campaigns were carried out during the snow-free seasons within the 2020–2023 analysis window (late spring to early autumn each year) to maximize visibility of surface features and ensure temporal consistency with the image acquisitions. For each flagged site, survey teams recorded geographic coordinates, functional zone (core/buffer/experimental), facility status, year of construction, approvals, and outstanding issues, and collected geo-tagged photographs. In total, 312 ground-truth points were used to calibrate and validate the remote-sensing interpretation across the 38 provincial-level reserves.

Evaluation indicators

(1) Classification of human activities in nature reserves

To avoid ambiguity, we distinguish the three components as follows:
- Field verification of human activities (data validation and correction).
  - Purpose: ground-truth the remote-sensing interpretation and correct mislabels.
  - Tasks: on-site checks of coordinates, zoning, facility status, construction year, approvals, issues, and photographic documentation; reconcile inconsistencies and update the interpreted vectors accordingly (312 points in total).
  - Output: a validated LULC/human-activity dataset clipped by reserve and functional zones.
- Analysis of human activities (descriptive and spatial statistics).
  - Purpose: describe the composition and pattern of human activities across reserves and zones.
  - Tasks: compute area/count/percentage by activity type and by core/buffer/experimental zones; examine spatial distribution and zonation gradients using GIS overlays.
  - Output: summary tables and maps (e.g., counts/areas by type × zone; spatial pattern figures).
- Evaluation of human activities (index-based impact assessment).
  - Purpose: quantify overall disturbance by integrating type-specific impacts and zone weights.
  - Tasks: calculate the Nature Reserve Human Activity Impact Index (NRHI/HFI) using zone weights (a_i) and activity-type weights (b_i); classify reserves into impact levels (e.g., minimal → severe) following the established thresholds.
  - Output: impact scores and classes for each reserve, with province-wide intensity maps and rankings.

The classification and definitions of human activities in nature reserves are detailed in *Table 2*.

(2) Remote sensing monitoring and evaluation indicators for human activities in nature reserves

The remote sensing monitoring and evaluation indicators for human activities in nature reserves are shown in *Table 3*.

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Table 2. Classification of human activities in nature reserves

Primary indicator	Definition	Secondary indicator
Farmland	Land used directly or indirectly for agricultural production	Paddy fields, Dry farmland
Settlements	Aggregated residential areas formed for production and daily living	Urban settlements, Rural settlements
Industrial and Mining Land	Areas with independent factories, workshops, and production sites or zones developed based on mineral resource exploitation	Factories, Mines, Oil wells, Industrial parks
Quarry	Sites used for extracting construction stones or sand	Quarries, Sand pits
Energy Facilities	Facilities used for the generation and transmission of electricity from various energy sources	Wind farms, Hydropower plants, Substations, Solar power stations
Tourism Facilities	Areas used for commercial, tourism, and recreational purposes	Tourism land, Golf courses, Resorts, Temples
Transportation Facilities	Facilities and tools used for transporting goods and passengers	Ports, Airports, Wharfs
Aquaculture Farms	Areas in tidal flats, shallow seas, riversides, or inland zones for cultivating economic animals and plants	Marine aquaculture farms, Freshwater aquaculture farms, Terrestrial livestock and poultry farms
Roads	Infrastructure for vehicle and pedestrian traffic	Railways, Expressways, Regular roads
Other Artificial Facilities	Facilities that cannot be accurately classified under the above nine categories	Other artificial facilities

Table 3. Remote sensing monitoring and evaluation indicators for human activities in nature reserves

Content	Indicator	Data source
Remote sensing interpretation of human activities in nature reserves	Area/number/percentage of each human activity	High-resolution imagery, interpreted vector data
	Area/number/percentage of each activity in different functional zones	Remote sensing imagery, interpreted vector data, functional zoning vector data
	Spatial distribution of each human activity across functional zones	Remote sensing imagery, interpreted vector data, functional zoning vector data
Field verification of human activities in nature reserves	Geographic coordinates (lat/lon) of sensitive human activities	Field survey
	Facility name	Field survey
	Year of construction	Field survey
	Current status of facility	Field survey
	Approval documents	Field survey
	Existing issues	Field survey
Analysis of human activities in nature reserves	Total area/number/percentage of human activities in reserves	Interpreted vector data, field survey
	Total area/number/percentage of human activities by functional zone	Interpreted vector data, field survey, functional zoning vector data
	Spatial distribution patterns and characteristics of different human activity types	Interpreted vector data, field survey
Evaluation of human activities in nature reserves	Number and percentage of reserves by disturbance level	Interpreted vector data
	Spatial distribution patterns of impact intensity	Interpreted vector data

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Evaluation of human activity impact

Evaluation methods and content

(1) Analytical methods

Statistical analysis and GIS spatial analysis methods were used to examine the distribution patterns and characteristics of human activities in provincial-level nature reserves.

(2) Analytical content

The analysis includes: the total area, total count, and percentage of human activities within provincial nature reserves; the total area, count, and percentage of human activities within different functional zones of the reserves; and the spatial distribution patterns and characteristics of different types of human activities across various provincial-level nature reserves.

Evaluation model and index

(1) Calculation of the human disturbance intensity index (NRHI/HFI)

To quantify the overall human pressure on each reserve by integrating (i) activity-type intensity and (ii) functional-zone sensitivity, normalized by the reserve area so results are comparable across sites.

Inputs and notation:

Let reserve R have total area $A_R (\text{ha})$.

Each mapped human-activity patch ppp belongs to type $k \in K$ (e.g., industrial/mining, energy, tourism, transportation, livestock, agriculture, residential, other artificial) and lies inside zone $z \in Z$ (core, buffer, experimental).

A_p is the patch area (ha). For linear features (e.g., roads), the length L_p (km) is converted to an *equivalent area* A_p^* by buffering with grade-specific right-of-way width w (km), i.e. $A_p^* = L_p \times w$; where grade is unknown, a documented default width is applied for consistency (see Data Records).

a_z is the zone weight (core = 0.6; buffer = 0.3; experimental = 0.1).

b_k is the activity-type weight, derived from type-specific impact intensity in *Table 3* (e.g., industrial/mining 0.21; quarry/energy 0.19; tourism 0.17; transportation 0.11; other artificial 0.07; aquaculture/farmland/residential 0.02).

Step 1—Patch scoring (zone- and type-weighted).

For each patch p of type k in zone z,

$$S_p = a_z \cdot\ b_k \cdot\ A_p^{\dagger}, \tag{Eq.1}$$

where $A_p^+ = A_p$ for areal features and $A_p^+ = A_p^*$ for linear features converted to equivalent area.

Step 2—Reserve-level aggregation.

Sum all patch scores within reserve R:

$$S_R = \sum_{p \in R} S_p = \sum_{z \in Z} \sum_{k \in K} \sum_{p \in (z,k)} a_z\ b_k A_p^{\dagger}. \tag{Eq.2}$$

Step 3—Area normalization (index formation).

Divide by the reserve area to obtain the Nature Reserve Human Activity Impact Index:

$$\text{NRHI}_R = \frac{S_R}{A_R}$$

(Eq.3)

aA dimensionless quantity on $[0,1)[0,1)[0,1)$ under this weighting scheme; in our dataset values range 0.0001–0.5649. This normalization ensures comparability across reserves of different sizes.

Optional decomposition:

Zone-specific contributions can be reported as $\text{NRHI}_{R,z} = \left(\sum_{p \in z} a_z \; b_k A_p^{\dagger} \right) / A_R$, supporting diagnostics on where pressure concentrates (core/buffer/experimental).

Reserve-level Human Disturbance Intensity Index (NRHI) values were classified into five levels based on standard-deviation thresholds calibrated from the 38-reserve dataset, consistent with *Table 4*: Minimal (0.0001–0.1323), Slight (0.1324–0.2245), Moderately Significant (0.2246–0.3758), Significant (0.3759–0.5649), and Severe (>0.5649, not observed). This classification provides a direct link between quantitative disturbance scores and management-readable categories used throughout the figures and tables. All disturbance patches were derived from object-based image analysis (OBIA) of 2020–2023 Landsat-8 OLI and Sentinel-2 MSI imagery, with 312 field-verified ground points ensuring classification accuracy. Reserve boundaries and functional zoning layers were compiled under the CGCS2000/Gauss–Krüger coordinate system. Linear features such as roads were rasterized and buffered prior to overlay to maintain consistent spatial units across datasets. The weighting coefficients for functional zones (core, buffer, experimental) and for human-activity types (e.g., industrial, agricultural, residential, energy, transportation) were determined ex ante based on their relative disturbance intensity and remained independent of analysis outcomes. The per-type intensity weights correspond to those in *Table 4,* while the threshold boundaries for NRHI classification follow *Table 5*. This integrated description clarifies the data processing, weighting principles, classification rationale, and reproducibility measures, thereby ensuring transparency and methodological rigor in the quantitative assessment of human disturbance across nature reserves.

(2) Determination of weights

① Functional zone weights

According to the Assessment Standards for Ecological and Environmental Protection Effectiveness in Nature Reserves, the impact weights of human activities in different zones are assigned as follows: core zone = 0.6, buffer zone = 0.3, and experimental zone = 0.1.

② Human activity type weights

To improve interpretability and ensure consistency with the reserve-level classification reported in Section 4.1.4, we (i) mapped the activity-type impact scores in *Table 3* to the five impact intensity levels (Severe, Significant, Moderately Significant, Slight, Minimal), and (ii) added numeric intervals to *Table 4* using the standard-deviation–based thresholds derived from the Human Activity Impact Index (NRHI/HFI) of the 38 reserves. The revised tables now allow readers to see, at a glance, how each activity type (*Table 4*) aligns with the reserve-level impact taxonomy (*Table 4*), with

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thresholds identical to those used in Section 4.1.4. No reserves fell into the Severe class in this dataset. The impact weights assigned to each type of human activity on nature reserves are shown in *Table 4*.

Table 4. Impact weights of different human activity types on nature reserves

No.	Type	Impact intensity on nature reserves	Impact weight	Impact intensity level
1	Industrial and mining land	100	0.21	Severe
2	Quarry sites	90	0.19	Significant
3	Energy facilities	90	0.19	Significant
4	Tourism land	80	0.17	Significant
5	Transportation facilities	50	0.11	Moderately significant
6	Other artificial facilities	30	0.07	Slight
7	Aquaculture farms	10	0.02	Minimal
8	Farmland	10	0.02	Minimal
9	Residential areas	10	0.02	Minimal

Mapping rule used (for clarity): Severe = 95–100; Significant = 80–94; Moderately Significant = 50–79; Slight = 20–49; Minimal = 0–19

(3) Classification of impact intensity

Based on the Human Activity Impact Index calculated for each nature reserve, the impact intensity is classified into five levels: severe, significant, moderately significant, slight, and minimal (see *Table 5*). Given the considerable differences in the types and quantities of human activities across reserves, the classification thresholds for impact intensity are determined according to the specific conditions of each reserve.

Table 5. Classification of human activity impact intensity in nature reserves

Impact intensity level	NRHI/HFI interval (this study)	Description of human activities
Severe	>0.5649	Very high number and variety of human activities; significant development and construction; strong overall impact
Significant	0.3759 – 0.5649	Relatively high number and variety of activities; noticeable development and construction; considerable impact
Moderately significant	0.2246 – 0.3758	Primarily includes farmland, settlements, roads, aquaculture farms, and artificial facilities, with limited development activities
Slight	0.1324 – 0.2245	Mainly farmland, settlements, and ordinary roads; essentially no development or construction activities
Minimal	0.0001 – 0.1323	Very few human activities present

Results and analysis

Overview of human activities

Types of human activities

Based on remote sensing monitoring and field verification results, eight categories of human activities were identified within the 38 provincial-level nature reserves in

Heilongjiang Province. These include industrial and mining land, energy facilities, tourism land, transportation infrastructure, livestock farms, agricultural land, urban residential areas, and other artificial structures and roads.

Area and quantity of human activities in different functional zones

In terms of overall distribution, human activities are primarily concentrated in the experimental zones, with some extending into buffer zones and core zones. Regarding area coverage, the extent of human activities follows the order: experimental zone > buffer zone > core zone. Similarly, in terms of activity types, the experimental zone exhibits the greatest variety, followed by the buffer zone and then the core zone. See *Table 6* for details.

Table 6. *Area statistics of human activities in different functional zones of provincial nature reserves*

Zone	Aquaculture farms (ha)	Other artificial facilities (ha)	Tourism land (ha)	Transportation facilities (ha)	Energy facilities (ha)	Farmland (ha)	Urban settlements (ha)	Industrial & mining land (ha)	Total (ha)
Protected area (general)	44.1	525.6	2.9	2.3	11.5	25,294.5	455.5	0.0	26,336.3
Core zone	0.0	208.2	18.8	0.0	9.2	33,737.9	1,769.7	0.0	35,743.7
Buffer zone	0.2	428.3	94.8	0.0	13.2	70,015.3	6,565.2	20.9	77,137.9
Experimental zone	40.1	333.2	6.2	1.0	9.2	72,712.7	4,369.4	122.2	77,594.0

Analysis of human activity distribution

Remote sensing monitoring across the 38 provincial-level nature reserves shows distinct patterns by activity type and functional zone. Industrial and mining land is not prevalent across Heilongjiang's provincial-level reserves: it occurs in 5 of 38 reserves (13.2%), totaling 16 sites and 174.44 ha, and is absent from core zones. These patches are localized and primarily confined to experimental zones (with limited occurrence in buffer zones), indicating that while the phenomenon exists, it is spatially restricted and management-contingent rather than widespread. In total, 16 industrial/mining sites were mapped, covering 174.44 ha. Energy facilities appear in 5 reserves (7 installations). Tourism facilities are present in 9 reserves and are predominantly located in buffer and experimental zones; Songfeng Mountain is the only reserve with tourism infrastructure in the core zone. Livestock farms (animal husbandry) were identified in 5 reserves (20 sites), all within experimental and buffer zones. Transportation facilities number 2 in total—one in Zhaodong Riverside Wetland and one in Xiwa Huang Wetland.

Agricultural land is the most prevalent class, with 1,563 instances overall: 628 in experimental zones, 362 in buffer zones, and 306 in core zones. Residential points total 415, with experimental zones accounting for the majority (254, 61%); core and buffer zones contain 48 and 42 sites (12% and 10%), respectively. An additional 184 other artificial facilities were recorded; Hailin Lianhua Lake exhibits the highest count (31), mainly concentrated in the experimental zone.

To ensure cross-reserve and inter-annual comparability, imagery was screened to (i) match the 2020–2023 analysis window, (ii) satisfy a <10% cloud threshold at each reserve footprint, and (iii) maintain stable geometric referencing for cross-year mosaics. Reserve polygons/centroids and functional-zoning boundaries were used to clip scenes

and aggregate per-zone metrics before classification and index computation. Field surveys documented facility status, construction year, approvals, and outstanding issues at flagged sites; these observations were used to correct ambiguous interpretations and validate the mapped distribution of human activities (*Table 7*).

Table 7. *Proportion of human activity types within provincial-level nature reserves of Heilongjiang Province (%)*

No.	Nature reserve	Agricultural land	Residential areas	Other artificial facilities	Tourism facilities	Industrial & mining land	Livestock farms	Energy facilities
1	Anbang River Wetland	88.95	0.82	0.78	0.00	0.00	0.00	0.00
2	Zhaodong Riverside Wetland	83.92	2.21	0.02	0.01	0.10	0.07	0.04
3	Anxing Wetland	82.42	2.68	0.03	0.00	0.00	0.00	0.00
4	Xiandong Mountain Sika Deer	73.20	1.11	0.00	0.00	0.00	0.00	0.00
5	Dongsheng	53.78	0.19	16.73	0.06	0.00	0.00	0.09
6	Jiayin Dinosaur Fossil	48.74	0.53	0.68	0.86	0.00	0.00	0.00
7	Jiamusi Riverside Wetland	46.80	1.31	0.48	0.00	0.00	0.00	0.00
8	Dulu River	46.74	0.95	0.03	0.00	0.00	0.00	0.00
9	Shuilian Wetland	45.66	0.45	0.00	0.00	0.00	0.00	0.00
10	Liufeng Lake	41.50	1.05	0.09	0.05	0.00	0.00	0.00
11	Xiwa Huang Wetland	38.49	0.26	2.09	0.06	0.00	0.93	0.24
12	Wuyuer–Shuangyang River	34.71	0.71	0.00	0.00	0.00	0.00	0.00
13	Mingshui Wetland	31.77	0.62	0.01	0.00	0.00	0.00	0.00
14	Wusuli River	25.71	1.37	0.00	0.00	0.00	0.00	0.00
15	Bei'an	22.56	0.88	0.03	0.00	0.00	0.00	0.00
16	Songfeng Mountain	21.09	3.97	0.00	0.46	0.00	0.00	0.00
17	Tiexi	19.24	0.54	0.00	0.01	0.00	0.00	0.00
18	Qindeli Sturgeon & Huso Sturgeon	17.30	1.69	0.03	0.00	0.00	0.02	0.00
19	Jingpo Lake	12.29	4.54	0.20	0.00	0.00	0.00	0.00
20	Shankou	11.10	0.24	0.02	0.00	0.00	0.00	0.00
21	Halahai	11.04	0.13	0.09	0.01	0.00	0.00	0.00
22	Suiling Numin River	10.88	0.19	0.06	0.00	0.00	0.00	0.00
23	Nemoer River Wetland	6.60	1.69	0.00	0.00	0.00	0.00	0.00
24	Bishui Scaly-sided Merganser	6.56	2.02	3.61	0.00	0.00	0.00	0.00
25	Dongning Niaoqing Mountain	5.20	2.04	0.00	0.18	0.36	0.00	0.00
26	Tonghe Longkou	3.79	0.39	0.25	0.00	0.00	0.00	0.00
27	Shuguang Tussah	2.89	0.38	0.02	0.00	0.00	0.00	0.00
28	Hailin Lianhua Lake	2.07	1.13	0.04	0.00	0.53	0.00	0.00
29	Ku'erbin Wetland	1.97	0.11	0.08	0.00	0.00	0.00	0.00
30	Langxiang Alpine Musk Deer	1.32	0.25	0.82	0.00	0.00	0.00	0.00
31	Gongbiela River	1.03	0.02	0.42	0.00	0.00	0.00	0.00
32	Longfeng Wetland	0.91	0.55	0.06	0.00	0.00	0.00	0.00
33	Yichun River Headwater	0.80	0.30	0.01	0.00	0.00	0.00	0.00
34	Taipinggou	0.66	0.28	0.36	0.00	0.00	0.00	0.00
35	Cuibei Wetland	0.24	0.09	0.03	0.00	0.00	0.00	0.00
36	Qixing Lazi	0.18	0.10	0.03	0.00	0.00	0.00	0.00
37	Wuma River Sable	0.04	0.03	0.02	0.00	0.00	0.00	0.00
38	Heilonggong Wood Frog	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Evaluation of human activity impact intensity

Using each provincial-level nature reserve as the evaluation unit, the extent of human activity impact was assessed for all 38 reserves. The calculated Human Activity Impact

Index for Heilongjiang's provincial-level nature reserves ranged from 0.0001 to 0.5649. The comprehensive evaluation results of human activity impact intensity across the 38 reserves are presented in *Table 8*.

Table 8. *Nature reserve human activity impact index (NRHI) of 38 provincial-level nature reserves in Heilongjiang Province*

No.	Nature reserve name	NRHI
1	Anxing Wetland	0.5649
2	Anbang River Wetland	0.5549
3	Dongsheng	0.4364
4	Zhaodong Riverside Wetland	0.4269
5	Xiandong Mountain Sika Deer	0.4118
6	Suiling Numin River	0.3375
7	Jiayin Dinosaur Fossil	0.2999
8	Xiwa Huang Wetland	0.2998
9	Jiamusi Riverside Wetland	0.2987
10	Dulu River	0.2868
11	Shuilian Wetland	0.2315
12	Liufeng Lake	0.2191
13	Wusuli River	0.1924
14	Wuyuer–Shuangyang River	0.1909
15	Bei'an	0.1669
16	Mingshui Wetland	0.1448
17	Tiexi	0.1196
18	Songfeng Mountain	0.1095
19	Jingpo Lake	0.1053
20	Qindeli Sturgeon and Huso Sturgeon	0.0635
21	Shankou	0.0604
22	Langxiang Alpine Musk Deer	0.0496
23	Dongning Niaoqing Mountain	0.0447
24	Halahai	0.0362
25	Shuguang Tussah	0.0318
26	Bishui Scaly-sided Merganser	0.0314
27	Nemoer River Wetland	0.0300
28	Tonghe Longkou	0.0233
29	Ku'erbin Wetland	0.0219
30	Taipinggou	0.0213
31	Gongbiela River	0.0151
32	Yichun River Headwater	0.0111
33	Hailin Lianhua Lake	0.0101
34	Wuma River Sable	0.0037
35	Qixing Lazi	0.0017
36	Cuibei Wetland	0.0015
37	Longfeng Wetland	0.0003
38	Heilonggong Wood Frog	0.0001

Due to significant differences in the types and quantities of human activities across nature reserves, the classification range for impact intensity needs to be determined based on the specific conditions of each reserve. Therefore, the Human Activity Impact Index for each provincial-level nature reserve was analyzed using ArcGIS statistical tools. A standard deviation classification method was applied to categorize the impact intensity according to established grading standards. The human activity impact levels were classified into five categories: severe, significant, moderate, slight, and minimal. The classification statistics for human activity impact intensity in Heilongjiang's provincial-level nature reserves are presented in *Table 9*.

Table 9. *Statistical classification of human activity impact intensity in nature reserves*

Impact intensity level	Standard deviation classification	Human activity impact index (HFI)	Number of nature reserves	Percentage
Severe	–	> 0.5649	0	0%
Significant	>1.5 std. dev.	0.3759 – 0.5649	5	13.16%
Moderately significant	0.5 – 1.5 std. dev.	0.2246 – 0.3758	5	13.16%
Slight	–0.5 – 0.5 std. dev.	0.1324 – 0.2245	8	21.05%
Minimal	<–0.5 std. dev.	0.0001 – 0.1323	20	52.63%

The remote sensing results indicate that all 38 provincial-level nature reserves in Heilongjiang exhibit detectable signals of human activity, with a pronounced gradient of disturbance. Specifically, 10 reserves (26.32%) fall within moderate disturbance categories (i.e., Significant + Moderately Significant), 8 reserves (21.05%) fall within Slight disturbance, and the remaining 20 reserves (52.63%) exhibit Mild/Minimal disturbance. Notably, no areas with high-intensity disturbance (HFI > 0.6) were identified. This pattern suggests that provincial regulatory measures have been partially effective in curbing large-scale, high-intensity development; however, the fact that more than a quarter of reserves still experience relatively elevated human pressure warrants close management attention.

By disturbance type, moderate zones are typically driven by a combination of farmland expansion, spillover of residential settlements, and major transportation corridors. Among these, the outward extension of cultivated-land boundaries is most evident in wetland–farmland transition belts of the northern low mountains and hills and the southern Songnen Plain, reflecting a direct tension between intensive land use in major grain-producing areas and conservation objectives. Co-location of residential areas with high-grade roads lowers access thresholds and increases development reach, thereby accelerating ecological fragmentation. In contrast, reserves under slight disturbance are also influenced by farmland, ordinary roads, and rural settlements but lack substantial secondary or tertiary industrial activity—indicating that dispersed, low-intensity livelihood activities remain the primary pressure source. Without targeted habitat-connectivity measures and farmland-to-wetland/forest restoration, even this "livelihood-driven" pattern could gradually evolve into a new fragmentation risk.

Mildly disturbed reserves—over half of the total—are predominantly situated in northern temperate forests and high-latitude wetland regions characterized by rugged terrain, limited accessibility, or high ecological sensitivity. Cases such as the Heilonggong Wood Frog reserve exhibit extremely low HFI values (down to 0.0001), indicating high habitat integrity. These reserves often benefit from natural barriers, strict

core-zone rules, and a cautious stance toward external development. Nevertheless, rising winter tourism and ecological sightseeing, together with growing demand for arable land in the black-soil belt under "north-to-south grain transfer," suggest that latent development pressure is emerging and may intensify.

The internal gradient across functional zones further confirms spatial heterogeneity: experimental zones experience the strongest human activity, followed by buffer zones, with core zones the least affected. Even so, isolated tourism facilities, farmland, and settlements have encroached into some core zones, indicating that "core–buffer–experimental" controls are not always rigorously enforced. Where boundaries are ambiguous or legacy land-use issues persist, both buffer and core zones remain vulnerable to incremental, "encroachment-style" pressures.

Relative to comparable national studies—some southern hilly reserves report >35% of area with HFI > 0.4—Heilongjiang's overall disturbance level lies in the lower-middle range. However, the share of moderately disturbed reserves still exceeds the average of the three northeastern provinces, reflecting the province's concentration of state-run farms, a radial-plus-ring transportation network, and historical mining/sand-extraction legacies in certain sites. This underscores the need for management strategies that address both the large-scale ecological security framework and localized high-risk nodes, so that local pressures do not propagate into broader ecological degradation.

Finally, although the integrated remote sensing–ground observation approach enables rapid and objective identification of disturbance patterns, it is constrained by the temporal cadence and spatial resolution of satellite imagery, which may miss short-term, high-intensity, or covert small-scale activities (e.g., nighttime poaching or unauthorized extraction). Moreover, as a composite indicator, HFI does not fully capture differences in ecological carrying capacity among ecosystems. Future work should integrate agile high-resolution satellites, UAVs, and IoT sensors, and overlay ecosystem-service and species-habitat thresholds, to build a more sensitive and adaptive risk-assessment framework that supports refined management and high-quality development of protected areas in Heilongjiang and other cold-temperate regions.

Strategies and recommendations

Management strategies

Scientifically plan the construction of nature reserves

For existing reserves, strengthen standardized construction and prioritize in-situ conservation (Zhang et al., 2017). Shift the development paradigm from "quantity and scale" to "quality and efficiency" (Zhu et al., 2019) by: (i) accelerating the implementation–evaluation–adjustment cycle of the integration and optimization plan; (ii) properly resolving legacy land-use issues (e.g., boundary ambiguities, historical encroachments); and (iii) optimizing spatial structure and layout to improve ecological connectivity, management feasibility, and alignment with conservation objectives.

Improve the effectiveness of reserve management

Establish a stable, multi-channel financing mechanism led by government investment and supplemented by reserve self-financing and domestic/international donations. Increase investment in critical infrastructure and facility upkeep. Build an information-networked management system that enables efficient command, timely feedback,

data/resource sharing, and public participation. Standardize operational procedures (monitoring, enforcement, emergency response), and strengthen performance evaluation to ensure that management inputs translate into measurable ecological outcomes.

Coordinate relations with surrounding communities

Because reserve–community relations directly affect construction, management, and development, management should center local residents and document/use traditional ecological knowledge to promote coexistence. Where appropriate, moderately relax restrictions on reasonable resource use to support ecologically beneficial livelihoods. Develop operational mechanisms that balance resource protection with community development (e.g., benefit-sharing, eco-compensation, alternative livelihoods), and improve co-management institutions to enhance compliance, reduce conflict, and increase stewardship.

Development recommendations

Accelerate implementation of the integration and optimization plan

Following the release of Heilongjiang's integration and optimization plan, align actions with local needs and accelerate implementation and evaluation. Optimize the spatial configuration of reserves, resolve historical issues, and enhance standardized construction so that planning translates into on-the-ground ecological gains.

Strengthen management effectiveness

Strictly enforce reserve regulations and ecological redline policies. Fully implement environmental impact assessment and approval systems; tighten project screening, approval, and supervision for any activity involving reserves; and investigate and rectify violations that damage protected areas. Couple enforcement with transparent information disclosure and public reporting channels to increase deterrence and accountability.

Establish a long-term monitoring mechanism

Develop a long-term, integrated space–air–ground monitoring system that enhances remote-sensing–based tracking of human activities. Deeply integrate satellite image interpretation with on-the-ground patrols to form a near-real-time, closed-loop monitoring–warning–response framework. This will enable timely detection of changes, targeted regulation at high-risk nodes, and continuous evaluation of management effectiveness across core, buffer, and experimental zones.

Conclusion

Based on Landsat-8 OLI and Sentinel-2 MSI imagery (2020–2023) and validated by 312 ground-truth points, this study developed a workflow for quantifying and validating the Human Footprint Index (HFI) in cold-temperate provincial regions. The results confirm the feasibility of integrating remote sensing with field-based monitoring in complex-terrain nature reserves. Monitoring results revealed that all 38 provincial-level nature reserves in Heilongjiang exhibited detectable human activity signals, although overall disturbance levels remained primarily low to moderate: 65.8% showed mild

disturbance (HFI ≤ 0.2), 21.1% moderate (0.2 < HFI ≤ 0.4), and 13.2% relatively strong (0.4 < HFI ≤ 0.6). No areas with high-intensity disturbance (HFI > 0.6) were detected.

Disturbance sources displayed pronounced spatial heterogeneity: experimental zones experienced the highest disturbance, followed by buffer zones, with the least activity in core zones. Farmland expansion, residential encroachment, and road development were the dominant drivers, while industrial, energy, and tourism facilities—though spatially limited—posed significant localized threats. Accordingly, a differentiated management framework is recommended: establish ecological buffer zones and pilot ecological-compensation and alternative-industry programs in moderately disturbed areas; implement farmland-to-wetland/forest restoration and corridor-connectivity projects in generally disturbed zones; and promote community-based monitoring and early-warning systems in mildly disturbed areas to maintain low-disturbance states and strengthen ecosystem resilience.

While the proposed monitoring framework enables rapid, objective quantification of human disturbance, limitations persist due to image-acquisition intervals and spatial resolution, potentially leading to omission of short-term, high-intensity, or small-scale covert activities. Furthermore, as a composite index, HFI does not yet capture the differing ecological carrying capacities among ecosystems. Future research should integrate agile, high-resolution satellites, unmanned aerial vehicles, and IoT-based sensor data to improve spatiotemporal granularity, and couple ecosystem-service valuation with multi-factor risk modeling. Such integration would support joint assessments of conservation effectiveness and socioeconomic dynamics, providing a robust scientific foundation for refined management and sustainable development of nature reserves in Heilongjiang and other cold-temperate regions.

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