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Research Article

Poleward expansion of human activities exacerbates Arctic ecological crisis

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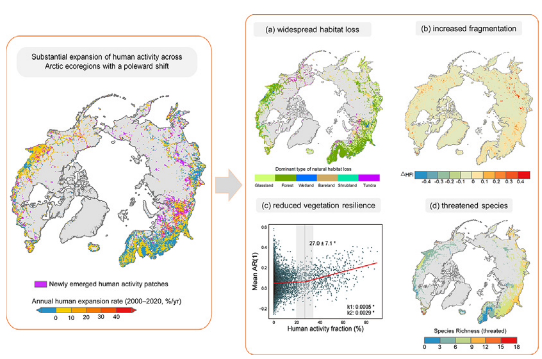
HIGHLIGHTS

- Human activity expanded by 3.7 % across Arctic ecoregions from 2000 to 2020.
- Artificial surfaces drove 77.2 % of the expansion.
- The expansion caused habitat loss and fragmentation, varying greatly by region.
- The expansion was accompanied by overall vegetation resilience decline.
- Human activity expansion heightens Arctic ecological risks beyond climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

The Arctic has experienced rapid and profound changes due to its heightened sensitivity to global warming and growing regional human pressures. While past research has advanced our understanding of these transformations, a comprehensive assessment within a unified analytical framework is still needed to quantify the ecological impacts of human activity across this fragile region. In this study, we systematically assessed the expansion of human activity and its ecological effects across Arctic and sub-Arctic regions from 2000 to 2020. We combined satellite-based land-cover datasets, vegetation resilience indicator (i.e., lag-1 month temporal autocorrelation of remotely sensed greenness), and species distribution data to track and analyze these changes and impacts. Our findings show that areas affected by human activity—mainly cultivated lands and artificial surfaces—expanded

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by nearly 13,000 km^2, equivalent to a rate of 1.8 % per decade. This growth was largely driven by the increase in artificial surfaces (~77.2 %) and extended to higher latitude. As a result, natural habitats became increasingly fragmented, vegetation resilience declined, and risks of ecological tipping points rose. These impacts threatened the habitats of approximately 97.5 % of Arctic species, including 111 species listed as vulnerable or endangered. Our results highlight that, beyond the effects of climate change, the continued expansion of human activity is intensifying ecological risks in the Arctic. This underscores an urgent need for enhanced ecological protection and transformative social strategies to safeguard the region's future.

1. Introduction

Rapid and widespread socio-ecological changes have become a defining feature of the Arctic, drawing growing global attention (Carson and Peterson, 2016). Over recent decades, many studies have explored both natural and societal transformations in the region, using diverse methods such as in-situ observations, remote sensing, modelling, social surveys, and statistical analysis (Carson and Peterson, 2016; IPCC, 2019; Rocha et al., 2022). These efforts have shown that the Arctic is experiencing serious ecological and societal challenges, including widespread cryosphere loss, major shifts in the water cycle, biogeochemical dynamics, and ecosystem processes. These changes are affecting human systems such as subsistence activities, tourism, infrastructure, and public health (IPCC, 2019; You et al., 2021).

A key driver of these changes is the amplified Arctic warming relative to the global average (England et al., 2021; Serreze et al., 2009; Zhou et al., 2024), largely caused by anthropogenic greenhouse gas emissions from outside the region (Najafi et al., 2015), as well as feedback mechanisms operating both within and outside the regions (You et al., 2021). In addition to climate change, various local human activities—including agricultural and urban expansion (Altdorff et al., 2021; Miles et al., 2023; Weber et al., 2017), resource extraction (Haddaway et al., 2022; Kruse et al., 2021; Kumpula et al., 2011; Müller-Wille, 1987), and public transport or infrastructure developments (Bartsch et al., 2021; Povoroznyuk et al., 2023)—have increasingly altered Arctic ecosystems (Carson and Peterson, 2016; Ehrich et al., 2019; Huntington et al., 2007; IPCC, 2019; Liu et al., 2023). These disturbances have led to observable habitat loss and fragmentation, reduced vegetation resilience (Zhang et al., 2024) and posing serious threats to biodiversity. However, most existing studies on human activity in the Arctic have relied on limited local data or have focused on individual types of activity (e.g., mining, shipping) or specific ecological impacts (e.g., habitat loss, changes in precipitation). As a result, they fall short of capturing the full spatial and temporal dynamics of human activity and its ecological consequences across the entire region. This lack of a unified, region-wide perspective hampers our understanding of the complex drivers, processes, and outcomes of ongoing Arctic change.

To fill this gap, this study aims to present a comprehensive assessment of human activity expansion and its ecological impacts across Arctic and sub-Arctic ecoregions from 2000 to 2020. We use a high-resolution (30 m) satellite-derived land-cover dataset to identify the extent and nature of human activity, specifically the expansion of cultivated land and artificial surfaces (Chen et al., 2021, 2015). Our analysis quantifies spatiotemporal patterns at multiple scales, including 17 Arctic bioregions and 8 biological subrealms (grouped into broader geographical clusters) defined by the One Earth framework (Dinerstein et al., 2017). We also include definitions from the Arctic Monitoring and Assessment Programme (AMAP) and Arctic Human Development Report (AHDR) (Einarsson et al., 2004) (Fig. 1 (a)). We then assess the direct ecological impacts of this expansion across three key dimensions: ecological structure, function, and biodiversity. Specifically, we analyze habitat loss and fragmentation, changes in vegetation resilience, and impacts on species richness, including threatened species. This integrated approach offers a clearer picture of the socio-ecological dynamics at play and supports more informed conservation strategies for a sustainable and resilient Arctic future.

2. Materials and methods

2.1. Study area description

There are different definitions regarding the Arctic region from various perspectives such as climatology, biodiversity, and politics (Nanni et al., 2024). Here we take Arctic and sub-Arctic bioregions as our study area to explore human activity expansion and ecological effects, by following the One Earth biogeographical framework called Bioregions 2023 (https://www.oneearth.org/bioregions-2023/). The One Earth defined 185 unique bioregions globally based on an updated map of the world's terrestrial ecoregions released by (Dinerstein et al., 2017), which helps reveal the underlying ecological fabric on the Earth, and promotes collective action to protect our planet. Regarding the Arctic region, there is a total of 17 bioregions (Fig. 1; Fig. S1 in the Supplementary materials): the 9 of them are located in the Arctic and Subarctic America (i.e., the Greenland (NA1), Canadian Tundra (NA2), North Alaskan Tundra (NA3), Greater Alaska Taiga & Tundra (NA4), Far Northern Pacific Coast (NA5), Greater Yukon (NA6), Northwest Canadian Taiga, Lakes, & Wetlands (NA7), Mid-Canada Boreal Plains & Foothill Forests (NA8), Canadian Shield & Coastal Taiga-Forests (NA9)); the others are in the Arctic and Subarctic Eurasia (including the Russian Arctic Desert Islands (PA1), Iceland (PA2), Scandinavian Birch & Coastal Conifer Forests (PA3), Greater Eurasian Tundra (PA4), East Eurasian Coastal Tundra (PA5), Sea of Okhotsk Coastal Taiga, Meadows & Tundra (PA6), Siberian Boreal Forests & Mountain Tundra (PA7), and Ural Mountains & West Eurasian Taiga Forests (PA8)). The 17 Arctic and sub-Arctic bioregions can be further clustered into 8 subrealms that cluster bioregions into a more familiar geographical taxonomy, i.e., Greenland, Canadian Tundra, Alaska, Canadian Boreal Forests, Palearctic Tundra, Scandinavia & Western Boreal Forests, Siberia & Eastern Boreal Forests, and Sea of Okhotsk & Bering Tundra/Taiga. In addition, the Arctic Monitoring and Assessment Program (AMAP) and Arctic Human Development Report (AHDR) both defined the boundary of the Arctic region (Einarsson et al., 2004; Reiersen et al., 2020), and these definitions have been widely used in Arctic research. Therefore, we also paid special attention to human activity expansion and its ecological impacts across both the AMAP and AHDR Arctic regions.

The Arctic region has more than four million inhabitants (Emelyanova, 2022; Ramage et al., 2021), with a large number of indigenous peoples, including the Athabaskan, Inuit, and Gwich'in Canada; the Sámi in Finland, Norway, and Sweden; the Inuit in Greenland; the Aleut, Alutiiq, Yup'ik, Iñupiaq, Athabaskan, Tlingit, and Haida in Alaska; and up to 40 indigenous groups (e.g., Dolgan, Nganasan, Nenets, Sámi, Khanty, Chukchi, and Evenk) in Russia. The Arctic Council was constituted in 1996 by these eight Arctic states, including Canada, Finland, Iceland, Norway, Sweden, Russian Federation, the Kingdom of Denmark (Greenland), and the United States (Alaska), and performs the primary role in stewardship of the region (Carson and Peterson, 2016).

2.2. Definition of satellite-based human activity

Patches of cultivated land and artificial surfaces (e.g., land given over to industry, transportation, and human settlement) from satellite-based land-cover products have been widely applied to represent large-scale human activity and its changes in previous research (Yang et al., 2023, 2022). In this study, we used high-resolution Globeland30 data products

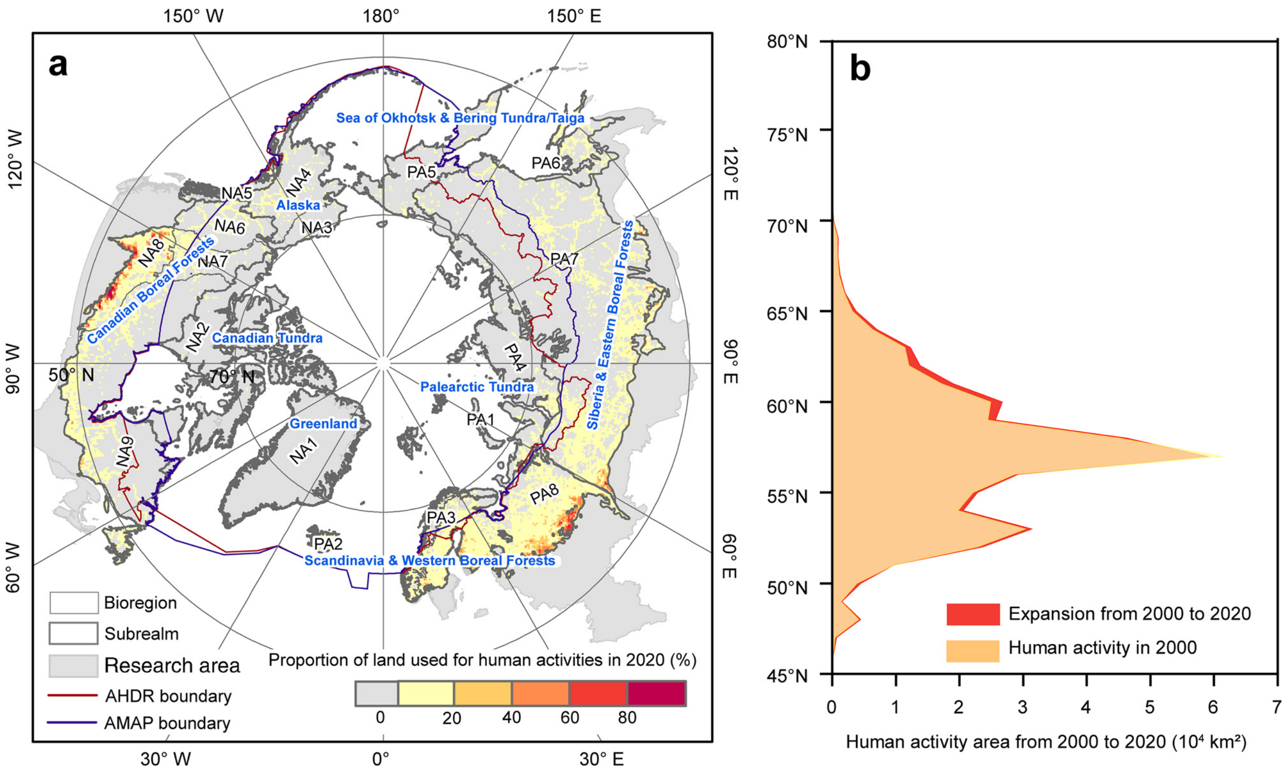

Fig. 1. Spatial distribution of human activity across Arctic and sub-Arctic bioregions between 2000 and 2020. (a) Spatial distribution of human activity proportion in each 25 km × 25 km tile scale in 2020, presented using a North Pole-centered Lambert Azimuthal Equal Area projection. The red and blue lines represent the Arctic area boundaries defined by the Arctic Human Development Report (AHDR) and the Arctic Monitoring and Assessment Program (AMAP), respectively. (b) Human activity expansion along latitude gradients. Human activity coverage is defined as all cultivated land and artificial surface expansion patches.

from 2000 and 2020 (with a spatial resolution of 30 m) as land-cover data with which to extract human activity and quantify human activity expansion and its impacts on natural habitats over the Arctic region. The Globeland30 datasets were developed by the National Geomatics Center of China (NGCC) based on the same coordinate and projection systems, and combine multispectral images, such as the Landsat TM/ETM+ images, Chinese HJ-1 satellite images, and 16 m Gaofen (GF-1) multispectral images in 2020 version (Chen et al., 2021, 2015). The classification system of the dataset consists of 10 land-cover types, namely cultivated land, artificial surfaces, forest, grassland, shrubland, wetland, water bodies, tundra, bare land, and permanent snow and ice. Among these, cultivated land refers to land used for agriculture, horticulture, and gardens, including paddy fields, irrigated and dry farmland, and vegetable and fruit gardens. Artificial surfaces represent land modified by human activity, including all types of habitation, industrial and mining areas, transportation facilities, and interior urban green zones and water bodies. The classification was performed using a split-and-merge strategy, with the Pixel–Object–Knowledge (POK) approach applied to classify each land-cover type, and a knowledge-based interactive verification procedure applied to improve mapping accuracy (Chen et al., 2015). The accuracy of Globeland30 was assessed using the landscape shape index-based sampling model and > 230,000 samples; the overall accuracy and kappa coefficient were 85.7 % and 0.82, respectively, for the 2020 version, and approximately 83.5 % and 0.78, respectively, for previous versions, which meets the accuracy requirement of large-scale land-cover change analysis (Chen et al., 2021; Ramage et al., 2021), and has been extensively used in previous studies (Yang et al., 2023; Zhu et al., 2022). Notably, Liang et al. (2019) conducted an accuracy evaluation for four commonly used global land-cover products in the Arctic region, namely the Climate Change Initiative Land Cover (CCI-LC), Global Land Cover by the National Mapping Organization (GLCNMO), Moderate Resolution Imaging Spectroradiometer Land Cover (MODIS-LC), and Globeland30. They concluded that GlobeLand30 has a high overall accuracy and is the best choice for analyzing finely divided and unevenly distributed surface features such as water bodies, urban areas, and cropland in the Arctic region.

The characteristics of human activity expansion across Arctic bioregions between 2000 and 2020 were assessed using two indicators: absolute expansion area and annual expansion rate. We quantified the characteristics of human activity expansion for both cultivated land and artificial surfaces at multiple scales, that is, a 25 km × 25 km tile scale, 17 Arctic bioregions and 8 biological subrealms, as well as both AMAP and AHDR Arctic regions. We aggregated the 30 m human activity map (including cultivated land and artificial surfaces) into 25 km cell using bilinear interpolation method and a North Pole-centered Lambert Azimuthal Equal Area projection. The zonal statistics analysis was conducted based on original human activity map with an original spatial resolution of 30 m. In addition, the trajectory of human activity area centroid movement from 2000 to 2020 was further analyzed (Dong et al., 2016).

2.3. Discrimination of natural habitat loss and fragmentation

Natural habitats refer to places where organisms make their home. Following the habitat classification scheme of the International Union for Conservation of Nature (IUCN), natural habitats were defined as any non-artificial vegetation, namely fundamental ecological land, including forests, grassland, shrubland, wetland, and unused land (Salafsky et al., 2008). Tundra, along with permanent snow and ice, also provide habitats for diverse polar organisms in the Arctic (Su et al., 2019; Xiao et al., 2015). In this study, natural habitat was therefore calculated as the sum of non-artificial vegetation (including forests, grassland, wetland, and shrubland) and other natural land (e.g., permanent snow and ice) over the Arctic region. Natural habitat loss induced by human activity expansion was measured as the area of natural habitat at time 2000 that was transformed into cultivated land or artificial surfaces at time 2020 (Yang et al., 2022). We aggregated the 30 m natural habitat data into 25 km cell to conduct human activity impact analysis.

We calculated the habitat fragmentation degree caused by human activity and its expansion between 2000 and 2020 by employing static and dynamic habitat fragmentation indices (HFIs). Following Ma et al. (2023), the static HFI was synthesized using three landscape pattern metrics, i.e., edge density (ED), patch density (PD), and mean patch area (MPA), which represent the three most important features of habitat fragmentation, i.e., the edge effect, isolation effect, and patch size effect, respectively. These metrics were calculated as follows:

$$\mathrm{ED} = \frac{\sum_{k=1}^{m} e_{ik}}{A} \times 10,000 \quad (1)$$

$$\mathrm{PD} = \frac{n_i}{A} \times 10,000 \times 100 \quad (2)$$

$$\mathrm{MPA} = \mathrm{mean}\left(\mathrm{AREA}\left[\mathrm{patch}_{ij}\right]\right) \quad (3)$$

where, e_{ik} is the total edge length (m), A is the total landscape (a grid cell was regarded as a landscape) area (m^2), n_i is the number of patches, and AREA [patch_{ij}] is the area of each patch (ha). We calculated these three pattern metrics for both 2000 and 2020 at the class level (class 0: non-habitat; class 1: habitat), and then normalized them by considering the comparability of the HFI in different years and the features of the three metrics in reflecting habitat fragmentation (Ma et al., 2023). The synthesized HFI was calculated as follows:

$$\mathrm{HFI}_k = \frac{\mathrm{ED}_{\mathrm{nor}} + \mathrm{PD}_{\mathrm{nor}} + \left(1 - \mathrm{MPA}_{\mathrm{nor}}\right)}{3} \quad (4)$$

where, HFI_k is the static habitat fragmentation index in a specific year k. The range of the HFI value is [0,1]. When the value is 0, it indicates no habitat fragmentation, whereas a value of 1 implies complete habitat fragmentation. A value closer to 1 indicates a high degree of habitat fragmentation and a drastic impact caused by human activity, and vice versa.

To reflect changes in the degree of habitat fragmentation caused by human activity expansion between 2000 and 2020, the difference in the HFI between 2020 and 2000 was taken as the dynamic habitat fragmentation index (ΔHFI):

$$\Delta\mathrm{HFI} = \mathrm{HFI}_{2020} - \mathrm{HFI}_{2000} \quad (5)$$

where, the ΔHFI value has a range of [-1,1]; a positive value implies increased fragmentation, and vice versa.

2.4. Quantification of vegetation resilience

We characterize the condition and variation of vegetation resilience based on remotely sensed 1-month Enhanced Vegetation Index (EVI), collected from MODIS13C2 product, and covered the period 2001 to 2020 at a spatial resolution of 1 km. Although the Normalized Difference Vegetation Index (NDVI) and Vegetation Optical Depth (VOD) was also widely used in previous studies (Wang et al., 2024; Xu et al., 2024; Yao et al., 2024), adopting EVI here is due to: 1) EVI integrates atmospheric corrections, and can effectively reduce canopy background noises, especially it is less sensitive to saturation in boreal forests than NDVI (Jiang et al., 2008); 2) MODIS EVI is consistent among long time series, but VOD merges records from multiple instruments to obtain a sufficient record (Smith et al., 2023; Zhang et al., 2024). We also eliminated the areas with any EVI missing data (caused by snow, ice, cloud cover, or wintertime dark day across the polar region) across the whole record from the analyses to further reduce the noise signal.

The gain and losses of vegetation resilience can be generally detected from the increased and decreased temporal autocorrelation of vegetation condition, respectively (Boulton et al., 2022; Forzieri et al., 2022; Yao et al., 2024). Theoretically, the gain of resilience is conducive to persist the structural and functional stability of ecosystems, but resilience loss would increase the risk of crossing catastrophic tipping points (Brand and Jax, 2007; Dakos et al., 2008; Smith et al., 2022). The vegetation resilience can be quantified by calculating the lag-1month temporal autocorrelation (AR(1)) of deseasonalized and detrended EVI, which has been widely used in previous studies (Zhang et al., 2024). First, we harmonized to the same spatial resolution (25 km) as the presentation of human activity expansion through bilinear interpolation method. Then, we further removed the seasonal cycles and long-term linear trends of the monthly EVI series to obtain vegetation anomalies. Finally, AR(1) was calculated by fitting an autoregressive model at lag-1 month on EVI anomalies within 5 years (60 months) sliding window (Boulton et al., 2022; Dakos et al., 2008). We evaluated the trends of AR(1) between 2000 and 2020 using Kendall-Tau (Kendall's τ) method, which can make resilience trends comparable across different regions (Feng et al., 2021; Wang et al., 2023). Increased trends in AR(1) indicates declined resilience, and vice versa. Additionally, to explore the impacts of human activity disturbance on vegetation resilience, we separated vegetation into human-disturbed and intact vegetation by overlapping the distribution of human activity in 2020. In doing so, the mean AR(1) and AR(1) trends of human-disturbed and intact vegetation were calculated and compared. We also applied piecewise-regression method (Pilgrim, 2021) to detect the impact of human activity fraction (%) on mean AR (1) before and after the turning point.

2.5. Identification of threatened species

The loss of natural habitat can reduce the living space available for species, which can in turn cause biodiversity loss and species extinction, especially for vulnerable and endangered species. Therefore, the impacts of human activity expansion on terrestrial vertebrates (mammals, amphibians, birds, and reptiles) and plant species (including threatened species) across the Arctic region were analyzed herein. The range polygons data of terrestrial vertebrate and plant species were extracted from the IUCN Red List database (version 6.2, updated in January 2019; "The IUCN Red List of Threatened Species" (IUCN, 2021)), while bird range polygons species data were obtained from the Birdlife International website (version 2020.1; http://datazone.birdlife.org/home). For threatened species data, we collectively selected vulnerable (VU), endangered (EN), and critically endangered (CR) species as threatened species, but excluded data-deficient, least concern, extinct in the wild, and extinct species (Ren et al., 2022; IUCN, 2021; Yang et al., 2023). In addition, Species Richness and Rarity-Weighted Richness maps are used to assess regional species richness and ecological importance of certain areas.

To assess the potential impacts of human activity expansion on biodiversity, we mainly focus on the direct and visible impacts of human activity on various species' habitats. We first calculated the number and distribution area of human activity affected species, by filtering intersecting data between the range polygons of all (and threatened) species and the expansion boundaries of cultivated land and artificial surfaces (i.e., natural habitat loss) from 2000 to 2020 at a same 25 km × 25 km tile scale (Seto et al., 2012); then we further calculated the change in habitat area for each affected species by comparing its original area before the human activity expansion.

3. Results

3.1. Human activity expansion across the Arctic region between 2000 and 2020

Substantial expansion of human activity was observed across Arctic ecoregions from 2000 to 2020, with marked spatial variability and a distinct poleward shift. In 2000, cultivated land and artificial surfaces covered approximately 31.6×10^4 km^2 (1.1 %) and 3.8×10^4 km^2 (0.1 %), respectively, of the studied Arctic region. Over the two-decade period,

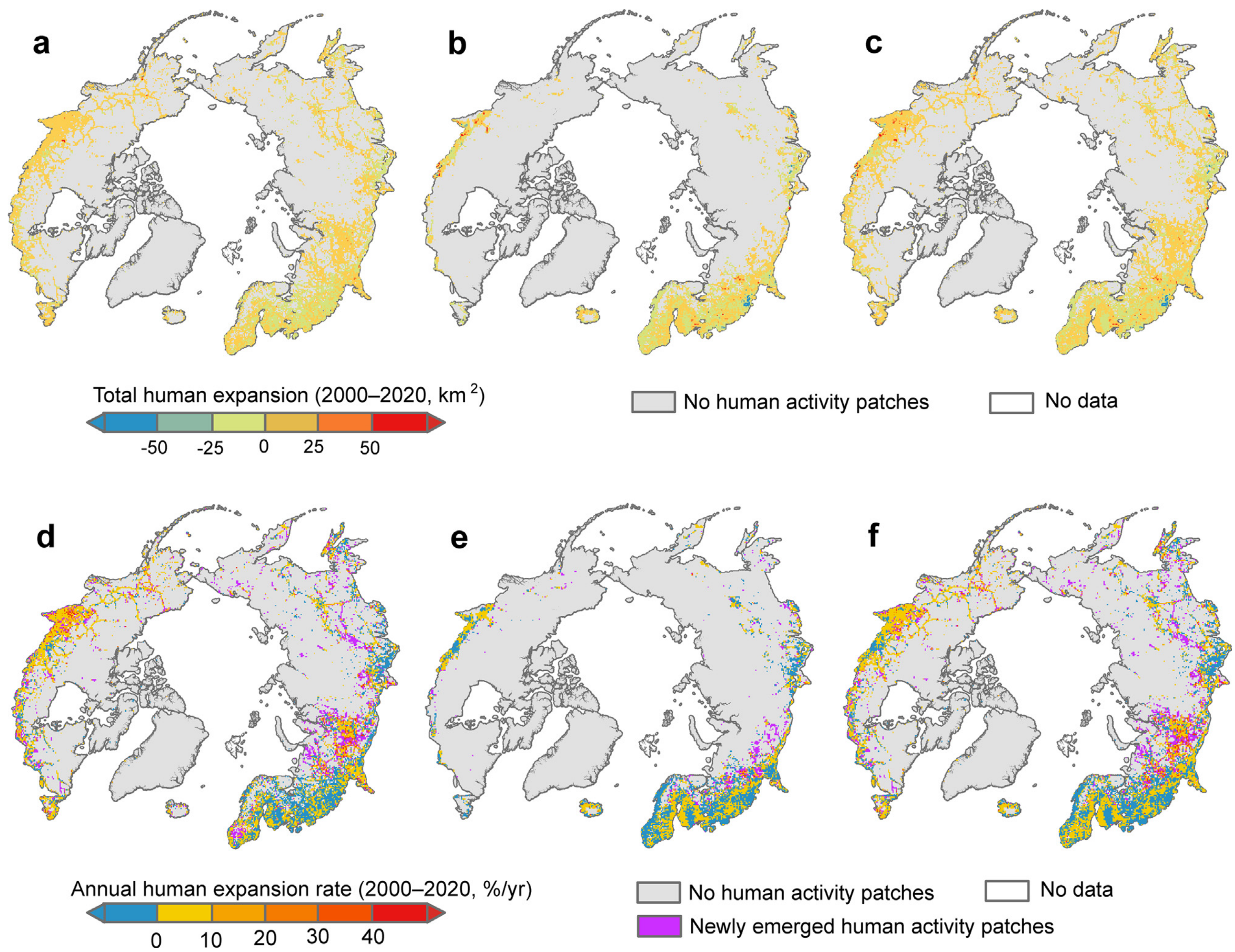

Fig. 2. Patterns of human activity expansion across the Arctic and sub-Arctic bioregions between 2000 and 2020. (a–c) Expansion area and (d–f) expansion rate in terms of artificial surfaces (first column), cultivated land (second column), and combined human activity land-cover types (third column) at a 25 km × 25 km tile scale.

the total area affected by human activity increased by 3.7 %, amounting to an additional 1.3×10^4 km^2. The majority of this expansion (77.2 %) was attributed to artificial surfaces, while cultivated land accounted for the remaining 22.8 %.

The annual expansion rate of artificial surfaces reached 1.3 %, whereas cultivated land expanded at a much slower rate of 0.05 % per year. Human activity patches were mainly concentrated in southern Canada and southwestern Eurasia (Fig. 1a). However, higher-latitude regions exhibited faster expansion rates for both artificial surfaces and cultivated land, and they accounted for the majority of newly emerged human activity areas between 2000 and 2020 (Fig. 2). We conducted a trajectory analysis to quantify latitudinal shifts in human activity in the region. The results showed that the human activity area centroid moved northward from 57.81°N to 57.90°N during 2000 to 2020, highlighting a slight poleward trend (Fig. 1b). In addition, certain areas experienced a decline in human activity, with significant shrinkage observed in parts of the Canadian, West Eurasian, and Siberian forest bioregions (Fig. 2).

Within the AMAP and AHDR-defined Arctic regions, annual expansion rates of human activity patches were 1.5 % and 1.1 %, respectively—substantially higher than the overall Arctic average. The total expansion areas were 0.23×10^4 km^2 and 0.25×10^4 km^2, respectively. Artificial surfaces in these regions grew by nearly 50 % during 2000–2020, with annual growth rates of 2.6 % and 2.3 %. Similarly, the annual expansion rates of cultivated land in the AMAP and AHDR regions (0.5 % and 0.3 %, respectively) were also notably higher than the Arctic-wide average.

Human activity expanded across all biological subrealms between 2000 and 2020, though with marked spatial differences in expansion characteristics (Table 1). The Canadian Boreal Forests subrealm experienced the largest total expansion—3,520 km^2 for artificial surfaces and 3,250 km^2 for cultivated land—followed by the Siberia & East Boreal Forests subrealm, where artificial surfaces expanded by 4,100 km^2, while cultivated land declined by 270 km^2. The Scandinavia & Western Boreal Forests subrealm had the largest area of existing human activity in 2000, with 2.0×10^4 km^2 of artificial surfaces and 17.4×10^4 km^2 of cultivated land, accounting for 54.6% of the total human-affected area in the investigated Arctic region. However, it showed limited expansion over the study period (only 400 km^2), ranking third, with artificial surfaces increasing slightly (0.01%/yr), while cultivated land decreased (-0.01 %/yr). The Okhotsk Sea & Bering Tundra/Taiga subrealm also experienced notable expansion—520 km^2 for artificial surfaces and 170 km^2 for cultivated land—corresponding to an annual human activity expansion rate of 1.5 %. No cultivated land patches were observed in the Canadian Tundra or Greenland subrealms in either 2000 or 2020; however, artificial surfaces expanded rapidly in both, at 5.9 %/yr and 1.8 %/yr, respectively (with total expansions of 69.3 km^2 and 2.9 km^2). The Alaska and Palearctic Tundra subrealms also showed rapid expansion of artificial surfaces (3.3 %/yr and 1.5 %/yr), while cultivated land increased only marginally.

Table 1

Human activity expansion in terms of cultivated and artificial surface land-cover types among Arctic regions (2000–2020). The regions include 8 biological subrealms based on the One Earth bioregions framework and the Arctic regions defined by Arctic Monitoring and Assessment Program (AMAP) and Arctic Human Development Report (AHDR).

Region	Artificial surface area in 2000 (km^2)	Cultivated land area in 2000 (km^2)	Artificial surface expansion 2000–2020 (km^2)	Cultivated land expansion 2000–2020 (km^2)	Expansion rate of artificial surfaces (%/yr)	Expansion rate of cultivated land (%/yr)	Human activity expansion rate (%/yr)
Alaska	946.4	490.4	868.3	83.3	4.6	0.9	3.3
Canadian Boreal Forests	6,056.1	96,806.1	3,527.3	3,251.2	2.9	0.2	0.3
Canadian Tundra	59.1	0	69.3	0	5.9	0	5.7
Greenland	8.0	0	2.9	0	1.8	0	1.8
Palearctic Tundra	887.8	47.6	269.8	4.6	1.5	0.5	1.5
Scandinavia & Western Boreal Forests	19,609.5	173,870.4	669.9	-269.1	0.2	-0.01	0.01
Sea of Okhotsk & Bering Tundra/Taiga	1,094.7	1,157.9	520.9	169.5	2.4	0.7	1.5
Siberia & East Boreal Forests	9,638.2	43,696.4	4,104.3	-272.5	2.1	-0.03	0.4
Above total	38,299.7	316,068.7	10,032.6	2,966.9	1.3	0.05	0.2
AMAP boundary	3,500.4	4,548.6	1,845.4	487.7	2.6	0.5	1.5
AHDR boundary	4,492.1	6,696.4	2,036.5	433.7	2.3	0.3	1.1

At the bioregion scales (Table S1 in the Supplementary materials), artificial surfaces expanded across all regions between 2000 and 2020, except for the Russian Arctic Desert Islands. The largest expansions occurred in the Siberian Boreal Forests & Mountain Tundra, followed by the Mid-Canada Boreal Plains & Foothill Forests, the Canadian Shield & Coastal Taiga-Forests, and the Greater Alaska Taiga & Tundra. However, the highest expansion rates were primarily observed in high-latitude tundra bioregions. Cultivated land patches expanded in 8 bioregions, most notably in the Mid-Canada Boreal Plains & Foothill Forests, which gained 5,400 km^2. Conversely, cultivated land declined in 4 bioregions and was absent in the remaining 5 throughout the 2000–2020 period. Regions where cultivated land decreased include the Ural Mountains & West Eurasian Taiga Forests (−480 km^2), Siberian Boreal Forests & Mountain Tundra (−270 km^2), Scandinavian Birch & Coastal Conifer Forests (−140 km^2), and Canadian Shield & Coastal Taiga-Forests (−9 km^2).

3.2. Human activity-induced natural habitat loss and fragmentation

The expansion of human activity across the Arctic has inevitably led to substantial loss and fragmentation of natural habitats. The impacts varied considerably by region (Tables S2 and S3 in the Supplementary materials). As shown in Fig. 3a, most human activity expansion occurred at the expense of forests (55.5 %) and grasslands (29.5 %). Other land-cover types—such as shrubland, tundra, wetlands, and bare land—together accounted for only 15.0 % of the total area affected (Fig. S2 in the Supplementary materials).

Forests were particularly affected in the Ural Mountains & West Eurasian Taiga Forests (15,083.8 km^2), the Siberian Boreal Forests & Mountain Tundra (7,252.2 km^2), the Mid-Canada Boreal Plains & Foothill Forests (5,053.4 km^2), and the Canadian Shield & Coastal Taiga-Forests (1,336.4 km^2). Grassland loss was also substantial in several subrealms, including the Ural Mountains & West Eurasian Taiga Forests (5,490.3 km^2), the Mid-Canada Boreal Plains & Foothill Forests (5,224.5 km^2), and the Siberian Boreal Forests & Mountain Tundra (4,993.5 km^2). Human activity, mainly in the form of artificial surface expansion, also encroached on tundra ecosystems surrounding the Arctic Ocean. Notable encroachment occurred in the Greater Eurasian Tundra (462.0 km^2), Iceland (439.2 km^2), and the Greater Alaska Taiga & Tundra (287.6 km^2). Within the AMAP and AHDR Arctic regions, forest loss accounted for 46 % and 50 % of all habitat loss, respectively, followed by tundra loss, which made up 37 % and 31 %. In addition, substantial hotspots of habitat loss were scattered across various Arctic bioregions, as shown in Fig. 3b.

To assess the impact of human activity on natural habitat fragmentation across the Arctic region between 2000 and 2020, we used a synthetic Habitat Fragmentation Index (HFI), which integrates key characteristics of fragmentation including edge effects, isolation, and patch size (see Methods). As shown in Fig. 3c, the spatial distribution of HFI values in 2000 largely reflects the existing human activity patterns, with higher fragmentation in lower-latitude regions and a decreasing trend toward higher latitudes, where human influence is relatively limited. However, the change in HFI between 2020 and 2000 (ΔHFI) reveals that most Arctic regions experienced varying degrees of increased habitat fragmentation over the two decades (Fig. 3d). This increase closely mirrors the spatial pattern of relative human activity expansion. Notably, areas with pronounced increases in fragmentation were primarily located in mid-latitude zones of the Arctic, forming a spatial pattern that diverges significantly from the static distribution of HFI in 2000.

3.3. Human activity expansion exacerbates vegetation resilience loss

Vegetation resilience is critical for maintaining the structural and functional stability of ecosystems and for preventing abrupt regime shifts in response to external disturbances (Smith et al., 2022; Wang et al., 2024). To further evaluate the ecological consequences of human activity expansion, we examined its impact on vegetation resilience across Arctic bioregions. Vegetation resilience was quantified using the Enhanced Vegetation Index (EVI) derived from remote sensing, combined with a commonly used ecological resilience indicator: the lag-1 autocorrelation (AR(1)) of deseasonalized and detrended monthly EVI time series (see Methods).

Fig. 4a–b shows the spatial pattern of mean AR(1) values and their trends from 2001 to 2020 across the Arctic. Human-disturbed bioregions exhibited significantly higher AR(1) values compared to relatively intact regions (0.06 vs. 0.04), indicating lower resilience in areas affected by human activity (Fig. 4c). This suggests that human disturbances generally reduce vegetation resilience and elevate the risk of ecosystems approaching critical tipping points. In addition to reducing average resilience levels, human activity appears to drive continued resilience loss over time. Our results show that AR(1) trends increased in human-disturbed regions but decreased in intact regions during 2001–2020 (Fig. 4d), indicating a declining trend in resilience where human activity is present, in contrast to improvements in more pristine areas.

Moreover, we identified the relationship between the fraction of human activity and vegetation resilience. Overall, AR(1) values increased gradually with increasing human activity fraction across the Arctic re-

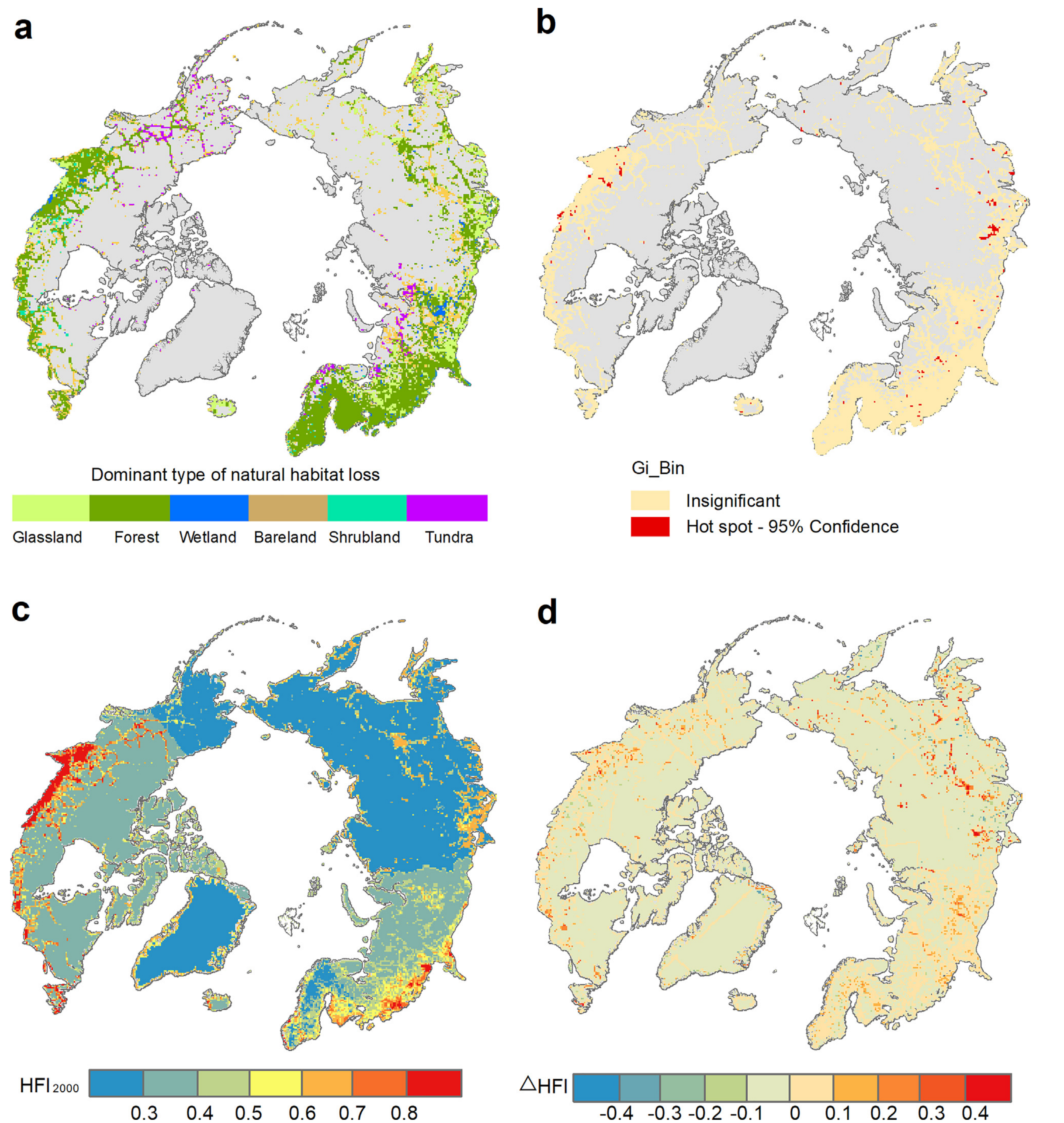

Fig. 3. Human activity expansion-induced natural habitat loss and fragmentation across the Arctic region between 2000 and 2020 at a 25 km × 25 km tile scale. (a) Dominant type of natural habitat loss induced by human activity expansion. (b) Hot spots of habitat loss as identified by Gi_Bin. Statistical significance was based on the p-value and z-score (two-sided). (c) Static habitat fragmentation index (HFI) in 2000. (d) Difference in HFI between 2020 and 2000 (ΔHFI).

gion, but beyond a threshold—when the human activity fraction exceeded 27.0 % ± 7.1 % at a 25 km × 25 km spatial scale—resilience declined at an accelerated rate (Fig. 4e). This threshold effect suggests that once a critical level of disturbance is surpassed, Arctic ecosystems may face a substantially higher risk of resilience loss and potential regime shifts. The AR(1) values significantly increased with rising human activity fractions at the biological subrealm scale. However, the susceptibility of vegetation resilience in response to human activity varies, and no clear threshold was identified (Fig. S3 in the Supplementary materials).

3.4. Potential impacts of human activity expansion on biodiversity

Natural habitat loss, fragmentation, and declining vegetation resilience pose serious threats to the living environments of native Arctic species and may lead to biodiversity loss and even species extinction—particularly among those already considered threatened. According to current estimates, the investigated Arctic bioregions are home to approximately 1,650 terrestrial species, including 848 bird, 317 mammal, 409 plant, 47 amphibian, and 29 reptile species (Table S4 in the Supplementary materials). Of these, 7.0 %—comprising 58 bird, 26

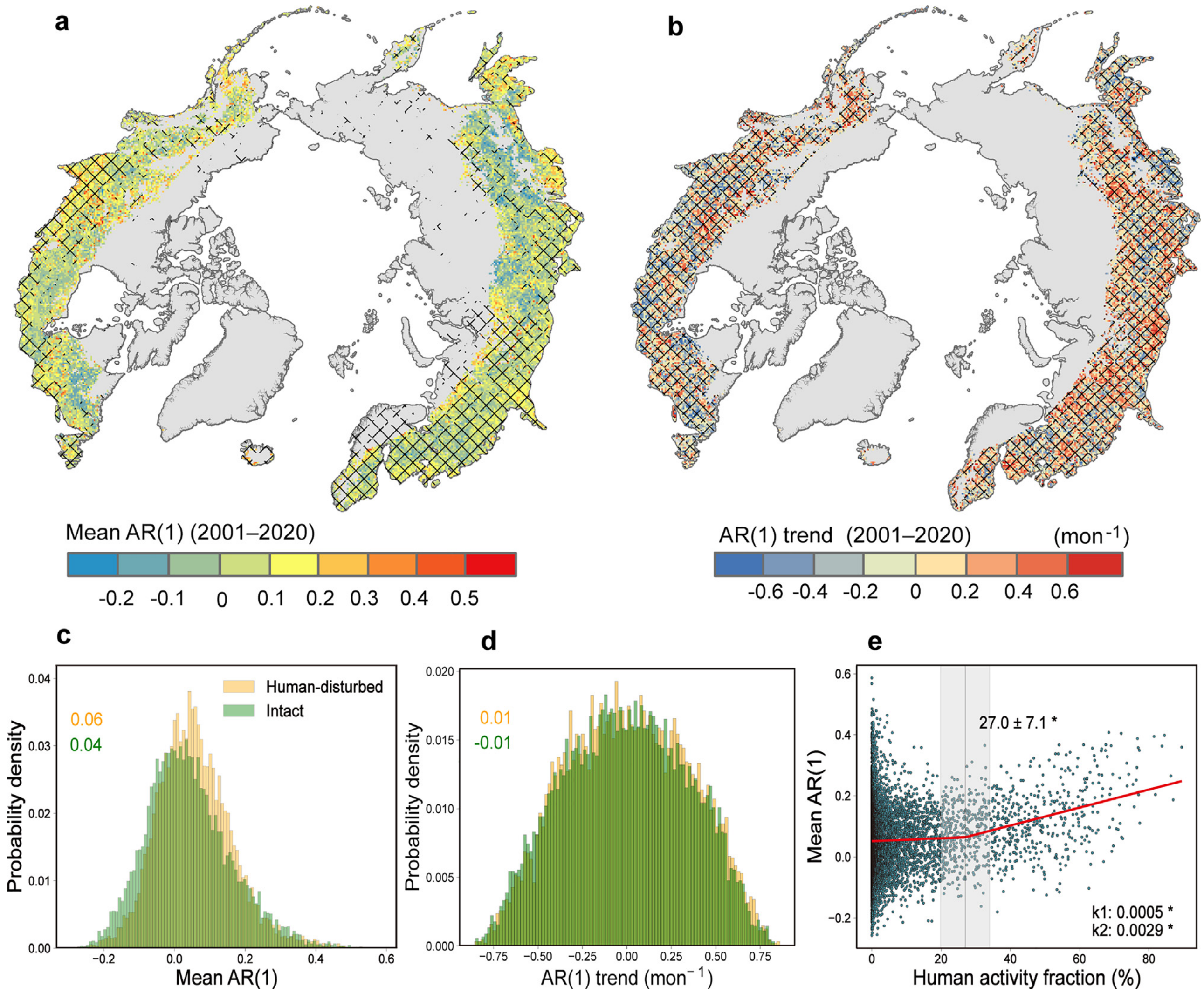

Fig. 4. Impact of human activity expansion on vegetation resilience over the Arctic region. (a) Spatial pattern of time-averaged AR(1) of depersonalized and detrended EVI. Black **crosshatches** indicate human-disturbed grid cells. (b) Spatial distribution of AR (1) trend. Black crosshatches indicate statistically significant trends at the 0.05 significance level based on the non-parametric Kendall-Tau test. (c) Probability density for time-averaged AR (1) over human-disturbed and intact ecosystems. (d) Probability density for AR(1) slope values over human-disturbed and intact ecosystems. The colored numbers in (c) and (d) denote the respective mean values. (e) Relationship between mean AR(1) and human activity fraction (%). The vertical black dashed lines and shading in represent turning points and uncertainty range identified based on a piecewise-regression method. The numbers denote the turning points and uncertainty range, with asterisks indicating statistically significance ($p < 0.05$). The k1 and k2 represent linear regression slopes before and after the turning points.

mammal, 26 plant, and 5 reptile species—are classified as threatened (i.e., critically endangered, endangered, or vulnerable) under the IUCN Red List (Table S5 in the Supplementary materials). Within the AMAP and AHDR Arctic regions, the total number of terrestrial species is 976 and 990, respectively, with 56 and 58 threatened species, predominantly birds and mammals (Tables S4 and S5).

We primarily focus on the direct and visible impacts of human activity on various species' habitats to evaluate the potential threats posed by the expansion of human activity to biodiversity. This is achieved by overlaying habitat loss with species distribution maps. The analysis reveals that the habitats of 97.5 % of all species in the Arctic bioregions were directly affected—human activity expansion has encroached upon the natural habitats of 1,609 species (835 birds, 305 mammals, 396 plants, 46 amphibians, and 27 reptiles) (Table S6 in the Supplementary materials), including 111 threatened species (57 birds, 25 mammals, 24 plants, and 5 reptiles) (Table S7 in the Supplementary materials). The extent of impact on species varied considerably across different subrealms (Fig. 5). The Ural Mountains & West Eurasian Taiga Forests (PA8) subrealm experienced the most severe effects, with human activity affecting the habitats of 722 species, including 46 threatened species. This was followed by the Siberian Boreal Forests & Mountain Tundra (PA7), where habitat encroachment affected 709 species, 45 of which are classified as threatened.

Birds, mammals, and plants account for the majority of species affected by human activity expansion, reflecting the regional structure of biodiversity (Fig. 5c, f). However, there are substantial differences across bioregions (Tables S6, S7). From 2000 to 2020, a total of 406 species (176 birds, 71 mammals, 15 amphibians, 137 plants, and 7 reptiles) lost at least 1 % of their Arctic habitat due to expanding human activity. Among these, 24 species lost more than 5 % of their habitat—specifically, 15 birds, 5 mammals, 2 plants, 1 amphibian, and 1 reptile. Notably, six bird species (i.e., *Setophaga fusca, Meleagris gallopavo, Buteo regalis, Leiothlypis ruficapilla, Passerculus bairdii*, and *Serinus serinus*) experienced habitat loss of over 10 % (Table S8 in the Supplementary materials). In total, 24 threatened species (10 birds, 7 mammals, and 7 plants) lost at least 1 % of their habitat, with the vulnerable bird species Calcarius ornatus losing about 5.2 % of its Arctic habitat (Table S8).

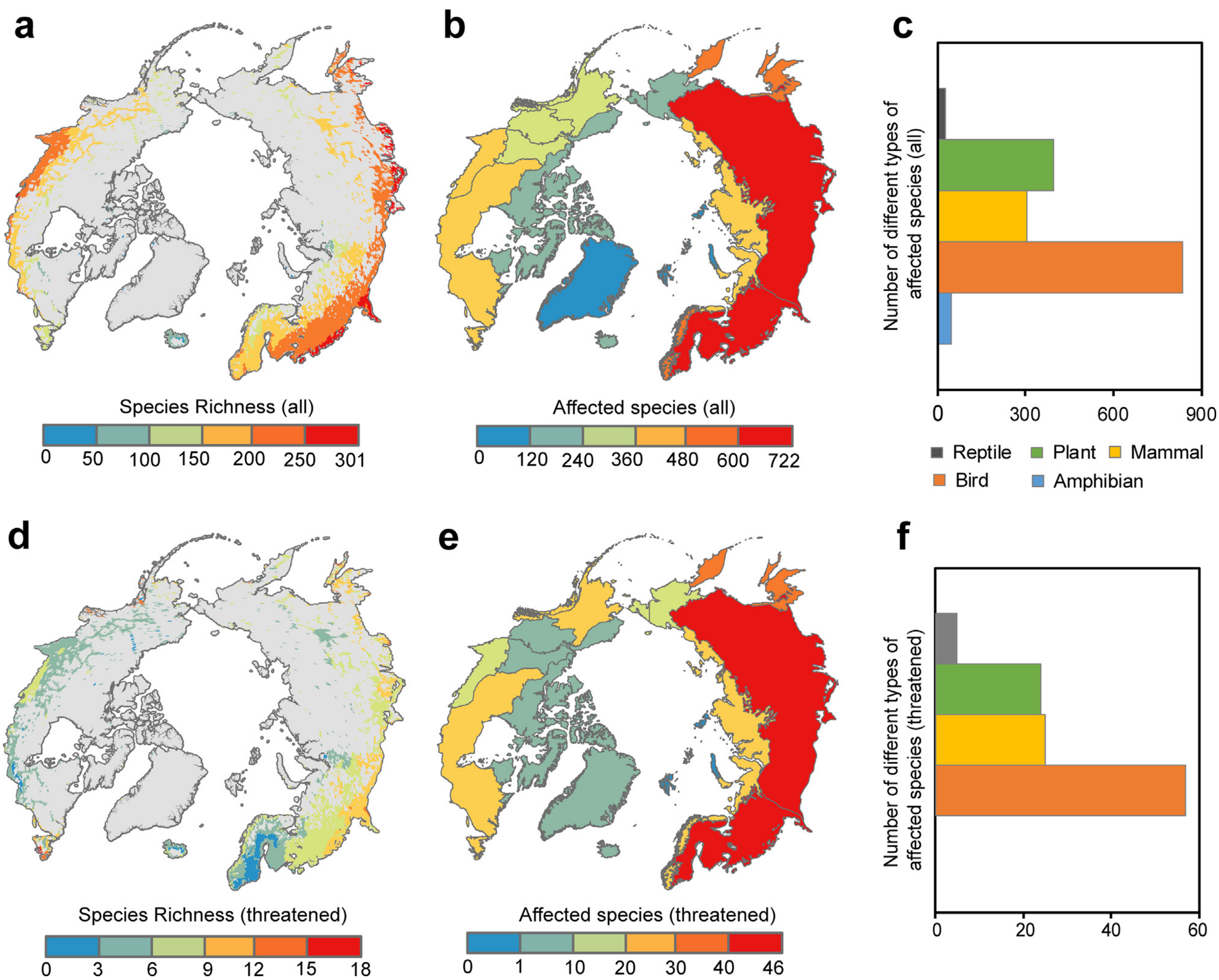

Fig. 5. Threats to biodiversity from human activity expansion across the Arctic region. (a–c) Number of species affected by human activity expansion at the 25 km × 25 km tile (a) and bioregional (b) scales, and across different types (c). (d–f) Threatened number of species affected by human activity expansion at the 25 km × 25 km tile (d), bioregional (e) scales and across different types (f). The threatened species refer to the vulnerable, endangered, and critically endangered species Red List categories of the International Union for Conservation of Nature (IUCN).

4. Discussion

This study presents a spatially explicit and coherent assessment of human activity expansion across Arctic bioregions during the first two decades of the 21st century, using a state-of-the-art, satellite-derived land-cover dataset. We further analyzed the resulting direct and visible ecological impacts, including habitat loss, reduced vegetation resilience, and biodiversity decline. To our knowledge, this is the first comprehensive evaluation covering the entire Arctic using consistent data and a unified analytical framework. The findings enhance our understanding of the Arctic's rapid transformations—its drivers, processes, and ecological implications—and provide a knowledge base for developing more effective conservation strategies to support a sustainable Arctic future.

Our analysis produced consistent and dynamic maps showing widespread human activity expansion, characterized by considerable spatial heterogeneity. The rate of artificial surface expansion across Arctic ecoregions (1.3 %/yr) is significantly higher than the global average, whereas cultivated land expanded at a slower pace (0.05 %/yr). Artificial surfaces were the primary indicator of human expansion, comprising 81 % of all changes, in contrast to Asian highlands where cultivated land is dominant (Yang et al., 2022). Between 2000 and 2020, the Arctic recorded relatively limited expansion of cultivated land (0.9 %) compared to 13.5 % in the Asian highlands, but a higher expansion of artificial surfaces (26.2 % vs. 13.5 %). These differences likely reflect disparities in socioeconomic development, including population trends, income, education, and technological progress. Most Arctic states are highly developed, with low or negative population growth. Instead of expanding agriculture, they focus on infrastructure development and ecological restoration. Interestingly, cultivated land even shrank in four Arctic bioregions—most notably in the West Eurasian Taiga Forests, Siberian Boreal Forests & Mountain Tundra, and Scandinavian Birch & Coastal Conifer Forests.

We also assessed whether human activity expansion is linked to population dynamics. However, no significant correlation was found between expansion and population density or population change, at either the bioregion level (Fig. S4 in the Supplementary materials) or the 25 km × 25 km grid scale (Fig. S5 in the Supplementary materials). This suggests that other factors, such as increased resource exploitation (Kumpula et al., 2011), tourism (Runge et al., 2020), and the emergence of Arctic shipping routes (Carson and Peterson, 2016; Ehrich et al., 2019; Müller et al., 2023), may be driving human activity expansion, especially artificial surface development. Climatic limitations—such as short growing seasons, permafrost, and low temperatures—also restrict agricultural development in the high Arctic (Ward Jones et al., 2022). While climate warming is lengthening growing seasons and improving conditions for agriculture, future cultivation will also depend on market forces, technology, policy, and price fluctuations (Dong et al., 2016; Klöffel et al., 2022).

Our findings highlight the broad ecological consequences of human activity expansion, which has led to widespread habitat loss, increased fragmentation, and reduced vegetation resilience. The encroachment has mainly affected forests, grasslands, and tundra, though the degree of impact varies across regions. Habitat fragmentation has increased in most areas, generally following the spatial pattern of human expansion rate. These changes are associated with overall declining ecological resilience, raising the risk of critical ecological transitions in Arctic bioregions, similar to findings in Amazon rainforests (Wang et al., 2024). In addition, the expansion of human activities has directly reduced the living space of 97.5 % of Arctic species, including 111 that are listed as threatened. While climate change remains the primary driver of Arctic environmental change (Carson and Peterson, 2016), our results show that human activity expansion is also contributing significantly to ongoing ecological transformations. Greater attention is therefore needed to address the cumulative and interacting impacts of local human activities alongside global climate change.

This study provides a foundation for investigating macro-scale human activity and its ecological consequences in the Arctic. Nonetheless, several limitations must be acknowledged. First, although we used advanced satellite-based data, the detection of human activity in the Arctic remains imperfect. Our classification system includes only two broad categories—artificial surfaces and cultivated land—which limits the granularity of analysis. Future studies would benefit from more detailed, standardized, and spatially explicit mapping of diverse human activities (e.g., settlements, transport infrastructure, and industry) (Liu et al., 2023). It is necessary to quantify the contribution of different human activities to natural habitat and vegetation resilience, and achieve more precise attribution of impacts. Second, we focused primarily on the direct and visible impacts of human activity on habitats and biodiversity, which is based on disturbances resulting from expanding human activity area, such as noise, air and water pollution. However, human activity expansion can, on the other hand, decrease the habitat quality by increasing disturbances across surrounding natural habitats, which may even worse than its direct impacts (Ren et al., 2022). More research is therefore needed to capture the indirect, cascading, and often invisible impacts on ecological functions, habitat quality, and species persistence, by improving ecosystem service model or strengthening integrated ecological impact assessment. In particular, assessments should consider species-specific habitat requirements and adaptive capacities (Newbold et al., 2016). Third, our biodiversity analysis was based mainly on regional species richness. While species richness generally decreases with latitude (Fig. S6 in the Supplementary materials), this does not capture the full ecological importance of certain areas. For example, hotspots of rarity-weighted richness—particularly for threatened species—exist at higher latitudes (Fig. S7 in the Supplementary materials). Thus, future conservation planning should also account for the aggregate importance of areas to the species they support.

5. Conclusions

In this study, we systematically assessed the expansion of human activity and its ecological effects across Arctic and sub-Arctic regions from 2000 to 2020, by combining satellite-based land-cover datasets, vegetation resilience indicators, and species distribution data. The results reveal that human activity has expanded widely across the Arctic over the past two decades, with a total increase of 3.7 % (13,000 km^2), primarily through the development of artificial surfaces. This expansion has significantly impacted ecosystems—reducing natural habitats, degrading vegetation resilience. A total of 1,650 terrestrial species are affected, including 7.0 % that are classified as threatened.

These findings underscore the urgent need for stronger ecological protection in the Arctic, with specific consideration of regional patterns and the externalities of different types of human activities. To this end, the Arctic Council should promote collaboration among Arctic states and local communities to manage natural habitats in ways that conserve biodiversity while respecting traditional livelihoods, such as subsistence hunting and fishing. In parallel, transformative societal changes are needed to address the ecological crises driven by both climate change and local human pressures. Specifically, future Arctic protection strategy could include expanding protected areas, strengthening ecological protection policies, by integrating human activity mapping into Arctic eco-environment monitoring framework, implementing systematic ecological impact assessments and explicitly spatial planning, and enforcing stricter regulations on infrastructure development. Meanwhile, a “tailored to local conditions” approach is needed across bioregions, focusing on species-specific habitat dependencies and their sensibility and resilience in response to various drivers. In addition, it is necessary to develop integrated Earth system models, co-produce bottom-up scenarios, and identify sustainable pathways for Arctic socio-ecological systems. Coordinated actions across scales and sectors—supported by clear targets and robust governance—will be essential to safeguarding the Arctic’s future.

Data availability

The Globeland30 land-cover products are available from the National Geomatics Center of China (https://www.webmap.cn/main.do?method=index). World’s terrestrial ecoregions are available from the Ecoregions2017 (https://ecoregions.appspot.com/). AMAP and AHDR boundaries are available from the Arctic Portal (https://arcticportal.org/). The MODIS13C2 Enhanced Vegetation Index (EVI) dataset is available from the NASA LP DAAC (http://doi.org/10.5067/MODIS/MOD13C2.006). The terrestrial vertebrate and plant species data are available from the IUCN Red List database (version 6.2, updated in January 2019; https://www.iucnredlist.org). The bird species data are available from the Birdlife International website (http://datazone.birdlife.org/home). The LandScan Global Population Database are available from the Oak Ridge National Laboratory (https://landscan.ornl.gov/).

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Bo Su: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haipeng Feng:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation. **Deliang Chen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Guoyan Yang:** Writing – review & editing, Software, Methodology, Data curation. **Xinrong Yan:** Writing – review & editing, Investigation, Data curation. **Xiaona Wang:** Writing – review & editing, Investigation, Data curation. **Hans W. Chen:** Writing – review & editing, Investigation. **Ziqian Zhong:** Writing – review & editing, Investigation. **Lan Wang-Erlandsson:** Writing – review & editing, Investigation, Funding acquisition. **Juan C. Rocha:** Writing – review & editing, Investigation. **Tinghai Ou:** Writing – review & editing, Investigation. **Amy Lauren Lovecraft:** Writing – review & editing. **Xin Li:** Writing – review & editing. **Bin He:** Writing – review & editing. **Song Xu:** Writing – review & editing, Data curation. **Hongyu Zhao:** Writing – review & editing, Data curation. **Chao Yang:** Writing – review & editing, Data curation. **Jianbang Wang:** Writing – review & editing. **Tingfeng Dou:** Writing – review & editing. **Minghu Ding:** Writing – review & editing. **Bin Chen:** Writing – review & editing, Supervision. **Cunde Xiao:** Writing

– review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2026.100481.

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