A DYNAMIC EVALUATION OF LAND USE AND HABITAT QUALITY IN NINGXIA FROM 1980 TO 2020, CHINA

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Abstract. Accurate and rapid habitat quality evaluation in the Yellow River Basin is significant for the ecological protection and restoration of the Yellow River Basin. Taking Ningxia, China, as an example, this study conducted long-term and multi-angle remote sensing monitoring of the ecological environment, analyzed the spatial and temporal variation ecosystem characteristics of the arid area in the Yellow River Basin, and evaluated the effectiveness of various projects over time. Based on land use data for nine periods from 1980 to 2020, the FVC and land use change in Ningxia were studied, and the HQ was calculated using the InVEST model. The results showed that: (1) From 1980 to 2020, the FVC in Ningxia has shown a fluctuating upward trend, and the FVC on unused land and low-density grassland increased significantly. (2) From 1980 to 2020, land use in Ningxia has been greatly affected by human activities and policy factors. The six first-level categories generally show the characteristics of "three increases and three decreases:" cultivated land, forested land, and construction land increased by 11.9%, 11.9%, and 114.4%, respectively. Grassland, water area, and unused land decreased by 10.7%, 6.1%, and 10.3%, respectively. (3) The HQ in nine national nature reserves improved slightly, and the mean value increased from 0.53 to 0.54. (4) From 1980 to 2020, the HQ in Ningxia has been low and slightly degraded.
Keywords: *fractional vegetation coverage, ecosystem environment, national natural reserve, transfer matrix, Mann–Kendall's trend analysis*

Introduction

"Ecological prosperity leads to civilized prosperity, while ecological decline leads to civilized decline" (Ouyang et al., 2016) The multiple pressures of global climate change, population growth, rapid economic development, and intensified resource consumption have brought about profound impacts on the ecosystem. Environmental pollution and destruction continue to occur, and the ecological deficit is gradually expanding (Zhao et al., 2016; Zhan and Zhao, 2021) Achieving good economic development while taking into account ecological and environmental protection has become a hot issue of global concern.

Ningxia, the only Chinese province whose entire territory belongs to the Yellow River Basin, has a fragile ecological background and is surrounded by desert on three sides while experiencing drought and precipitation, making it a typical ecologically fragile area in China. Taking Ningxia as the study area, multi-temporal and multi-level monitoring

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and analysis using remote sensing technology and geographic information technology can reflect the spatial and temporal change characteristics of ecosystems in northern China as a whole. At present, China's monitoring and analysis of the ecological environment in the arid zone have expanded to include main areas with further in-depth research, including the Black River Basin (Wang et al., 2011; Li et al., 2011), Xinjiang region (Deng et al., 2017; Zhuang et al., 2021), Inner Mongolia region (John et al., 2009; Hu et al., 2012; Zhao et al., 2021), and Shanxi area (Xue et al., 2013); however, the existing research literature on Ningxia mostly focuses on short time series (Li, 2015; Cadavid Restrepo et al., 2017) and localized areas (Han et al., 2017; Yang et al., 2021). The studied research topics include primary productivity (Zhu et al., 2019), biodiversity (Sun et al., 2021), land desertification (Wang et al., 2013), fractional vegetation coverage (FVC) (Huang et al., 2019), land use change and landscape pattern analyses (Wang et al., 2015; Xing et al., 2018). There is a relative lack of region-wide, longer, and more recent time-series ecosystem assessments and driver analyses.

Remote sensing technology has the characteristics of high resolution, large scale and multi-time series (Zhang et al., 2021). We use remote sensing and geographic information technologies to analyze changes in land use, FVC, and habitat quality (HQ) in Ningxia from 1980 to 2020. These analyses reveal the temporal and spatial evolution characteristics of Ningxia's ecological environment, and discriminating the impacts of climate change and human socio-economic activities on the fragile ecological environment in arid areas. These studies provide references for subsequent rational land resource use and ecological environment management and promoting the ecological protection and high-quality development of the Yellow River Basin.

Materials and methods

General situation of the study area

The Ningxia Hui Autonomous Region is situated in the upper reaches of the middle section of the Yellow River in northwestern China, with geographical coordinates ranging from 35°14′N to 39°23′N latitude and 104°17′E to 107°39′E longitude. As shown in *Figure 1*, the geographical location of Ningxia Hui Autonomous Region is adjacent to Shanxi in the east, Inner Mongolia in the northwest, and Gansu in the south. It is located on the northwestern edge of the Loess Plateau, covering an area of 66,400 km^2 and includes nine national nature reserves. Ningxia has a relatively low terrain, mainly composed of Gobi and other desert areas, mountains, hills, and basins. Mountains surround the region on three sides, with the Yellow River located in the north. Ningxia is surrounded by sand in the west (northwest), north, and east, including the Tengger Desert, Wulanbuhe Desert, and Mu Us Sandy Land, and its ecology is fragile. However, Ningxia is a transitional desertification area in China, and its ecological position is extremely important. It is the throat that curbs the "march into the desert" and has the important mission of maintaining ecological security in northwestern China.

Ningxia's northern and southern geographies and thus climates differ, which can be divided into three major plates: the northern portion of the Yellow River irrigated area, which comprises flat terrain and fertile soil; the central arid zone, which experiences drought and minimal rain, windy, sandy, barren land, and a poor ecological environment; the southern mountainous areas which comprise hills and gullies, part of this territory is wet and cold. In terms of topography, Ningxia’s altitude is high in the southwest and low in the northeast, with a stepped decline. The elevation is between 1092 m and 2942 m.

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Climatically, the land is dry, there is minimal rain, and the annual precipitation is roughly between 170 mm and 560 mm. The climate is a continental arid climate, The average annual temperature ranges between 1 °C and 11 °C. The mountainous area in the south belongs to the semi-humid area, the irrigated area in the north belongs to the semi-arid area, and the arid area in the center is between the north and the south (Wang et al., 2021). Ningxia is located on the northwestern edge of the Loess Plateau. The evapotranspiration was the lowest in the southern mountains at 854.4 mm, and the highest in the central dry zone at 1121.6 mm. The evapotranspiration in the northern Yellow River diversion irrigation area was between the central and southern (Wang et al., 2021). Annual evapotranspiration is greater than annual precipitation, which has become the main factor in the ecological environment and social and economic development in Ningxia. Due to a restriction on Yellow River water transfer, the water supply in the northern irrigated area is limited, and this water supply depends on Yellow River water and groundwater.

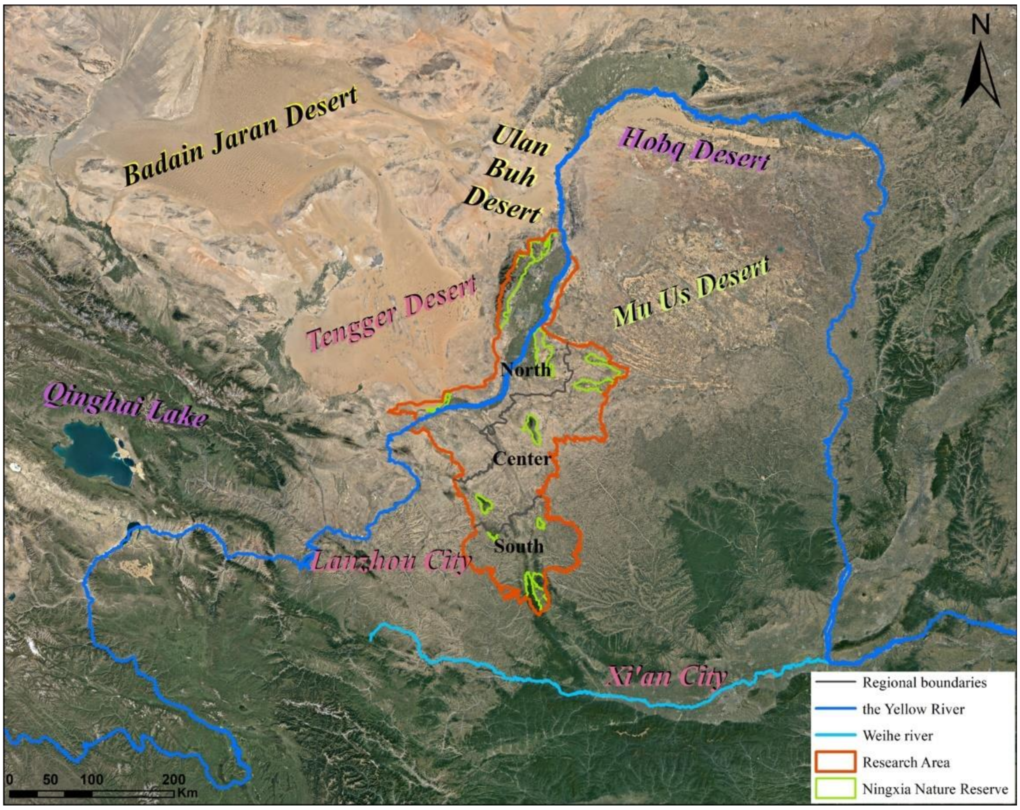

Figure 1. *Ningxia geographical location map*

Data source

The land use data are derived from the China Multi-Period Land Use Remote Sensing Monitoring Dataset (CNLUCC). This dataset is a Chinese national-scale multi-period land use/land cover thematic database constructed through manual visual interpretation using Landsat remote sensing images as the main information source(https://www.resdc.cn/DOI/DOI.aspx?DOIID=54). They include nine issues from 1980, 1990, 1995, 2000, 2005, 2010, 2015, 2018, and 2020, and the spatial resolution is 30 m. The land use types include cultivated land, woodland, grassland, water area, residential land, unused land, and 25 secondary categories (Liu et al., 2009, 2018).

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Other data include ①Meteorological data from the National Centers for Environmental Information (NCEI) under the National Oceanic and Atmospheric Administration (NOAA) is available at https://www.ncei.noaa.gov/data/global-summary-of-the-day/archive/; ② Nature reserve boundary data from the biological specimen resource sharing platform of the China Nature Reserve (http://www.papc.cn/html/folder/1-1.htm); ③ Landsat data for FVC calculation over time came from the US Geological Survey, and Landsat Collection2 data were collected from the Google Earth Engine (GEE) platform (https://code.earthengine.google.com/), which is a surface reflectivity product produced from high-precision geometric correction and radiation correction.

Fractional vegetation coverage

FVC refers to the ratio of the total plant vertical projection area in a certain area to the total area, ranging from 0 to 1. FVC can effectively reflect vegetation growth status and biomass. Because of the high costs associated with ground-based FVC measurements, remote sensing estimates are used (Li et al., 2021). In this study, a pixel dichotomy model is used to calculate the study area's FVC over time. In this study, FVC is calculated using *Formula (1)*:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{Eq.1}$$

NDVI (Normalized Difference Vegetation Index) is one of the important parameters reflecting crop growth and nutritional information, where NDVI (Normalized Difference Vegetation Index) represents the maximum synthetic NDVI value after water body masking and NDVIsoil and NDVIveg represent the NDVI values completely covered by soil and vegetation, respectively. Both NDVIsoil and NDVIveg values vary with time and space because the satellite imaging process is influenced by factors such as atmosphere, temperature, roughness, soil type, vegetation type, and humidity. Since the GEE platform does not store Landsat data regarding Ningxia before 1986, this study only calculates vegetation cover data for Ningxia from the 1986 to 2020 calendar years.

To further characterize the FVC spatial pattern, in this study, we refer to Zhao et al. (2023) to calculate the evolutionary trend in FVC. Linear tendency estimation is a common method for studying trends in geographic elements. In this study, we used the year as the independent variable and FVC as the dependent variable and fitted a one-dimensional linear regression on an image-by-image element basis based on the least squares principle to obtain the linear slope of FVC in the study area and to characterize the evolutionary trend in FVC using the slope. The Mann–Kendall (MK) trend analysis of FVC in Ningxia from 1986 to 2020 was made with reference to Xia et al. (2023) and other research studies (Li et al., 2021; Dashpurev et al., 2023), and the general FVC trend in Ningxia over the past 35 years was obtained.

Meteorological trend

Meteorological elements exert significant influences on the health and extent of FVC (Bai et al., 2022). Temperature, in particular, stands out as a pivotal determinant of plant growth. Optimal temperatures facilitate photosynthesis, thereby enhancing the photosynthetic capacity and overall productivity of vegetation. Conversely, extreme temperature conditions, whether excessively high or low, can impede growth or even

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result in plant mortality (Yuan et al., 2024). Additionally, precipitation plays a crucial role in the sustenance of plant life. Sufficient precipitation supplies the necessary moisture for plant growth, with a particularly pronounced effect in arid and semi-arid regions. An uptick in precipitation levels can markedly enhance vegetation coverage and the quality of habitats. On the flip side, reduced precipitation can correlate with diminished vegetation cover and degraded habitat quality. A study within the Yellow River Basin revealed a yearly increase in precipitation of 4.2 millimeters on average, a trend that has been beneficial for the proliferation of vegetation and has led to a notable amelioration in ecological health within the basin (He et al., 2024). In light of these findings, we have scrutinized precipitation and temperature data spanning from 1973 to 2021 to elucidate the interplay between climatic fluctuations and shifts in vegetation patterns.

Habitat quality

The InVEST model is used to assess the habitat quality index of 1980 to 2020 in Ningxia (Yang et al., 2021; Li et al., 2022). Habitat refers to a space that provides the resources and conditions for species to survive and breed. Habitat quality (HQ) refers to the degree to which a region or environment is suitable for a species' survival and reproduction. It can be used to evaluate ecosystem health and biodiversity maintenance. As an important function in ecosystem service, it is key to improving human well-being (Bao et al., 2015; Chen et al., 2016). Different land use types have different effects on the supply of ecosystem services, and reasonable land use planning and management is important for protecting and restoring the ecological environment and sustainable development. Long-term HQ assessment can identify changes in the ecological environment in this region and provide a scientific basis for formulating environmental improvement policies (Zhou et al., 2021). When species data are missing or difficult to obtain, the habitat quality module calculates the habitat quality index (HQI) based on land-use data by evaluating elements such as stress factors and each habitat type’s sensitivity to stress factors as an indirect reflection of the biodiversity in a study area. Its specific calculation method can be referred to in the literature (Zhou et al., 2021).

Based on the actual situation in Ningxia, combined with research in related fields (Huang et al., 2020; Sun et al., 2021), this study selects land types that have been greatly influenced by humans, including paddy fields, drylands, urban land, rural settlements, and other construction land, as well as unutilized land that occupies a relatively large area in the study area and possesses poor natural conditions as threat factors and refers to the related literature, expert theories, and recommendations to determine the maximum influence distance, weight, and attenuation type of threat factors on habitat suitability in each category (*Table 1*).

Table 1. *Threat factors and their maximum influence distance, weight, and attenuation type*

Threat factor	Maximum influence distance	Weight	Attenuation type
Paddy field	4	0.7	Linear
Dry land	4	0.7	Linear
Urban land use	10	1	Index
Rural residential area	6	0.8	Index
Other construction land	8	0.8	Index
Bare land	3	0.5	Linear

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Hot spot and cold spot analysis

In order to further reveal the spatial agglomeration and distribution HQ characteristics in Ningxia, this study first resampled data to reduce their resolution and converted them into point data, and then calculated the Global Moran's I index using the Moran index tool in ArcGIS spatial analysis tool. Based on the premise that these data possess spatial autocorrelation, the Getis-Ord Gi* index is calculated using the hot spot analysis tool, and the specific formula is referred to in the literature (Li et al., 2014).

The software used in this study includes InVEST 3.12.1, Excel 2021, ArcGIS 10.8, Origin 2022, IBM SPSS Statistics 26, and Matlab 2020.

Results and analysis

Characteristics of land use change

As a traditional farming and pastoral area, Ningxia's land use area in nine years from 1980 to 2020 was always as follows: grassland > cultivated land > unused land > woodland > construction land > water area. The sum of the areas of grassland and cultivated land in each period exceeded 79.0%, and the average proportion of unused land was 9.6%, while the areas of the remaining three land types did not exceed 6% (*Table 2*). From 1980 to 2020, the six first-class categories in Ningxia have generally shown the characteristics of "three increases and three decreases.” From 1980 to 2020, cultivated land, forested land, and construction land increased by 11.9%, 11.9%, and 114.4%, respectively. Grassland, water area, and unused land decreased by 10.7%, 6.1%, and 10.3%, respectively. In addition, cultivated land shows the characteristic of "first an increase and then a decrease, with an overall increase." In contrast, the water area shows the characteristic of "first a decrease and then an increase." If the beach area is not counted, the water area excluding beaches has not decreased from 1980 to 2020 but has increased by 3.8%.

Table 2. *The proportion of land type area from 1980 to 2020 (%)*

Year	Cultivated land	Woodland	Grass	Waters	Building land	Unutilized land
1980	30.2	4.8	50.7	2.1	2.1	10.0
1990	30.5	4.8	50.9	1.8	2.2	9.8
1995	33.8	5.0	47.1	1.7	2.4	9.9
2000	35.3	5.0	45.7	1.8	2.5	9.6
2005	33.5	5.5	46.3	1.9	2.8	10.1
2010	33.7	5.5	46.3	1.8	3.1	9.5
2015	34.1	5.5	45.5	1.9	3.9	9.2
2018	33.7	5.4	45.2	1.9	4.7	9.0
2020	33.8	5.4	45.3	2.0	4.5	9.0

In terms of regional differences, the northern, central, and southern parts of Ningxia accounted for 43.6%, 36.1%, and 20.3% of the study area, respectively. Cultivated land, forested land, and grassland are relatively evenly distributed in the three regions of Ningxia, but the distribution of water, building land, and unutilized land is seriously imbalanced (*Figure 2*). In 2020, for example, 79.5% of Ningxia's water, 66.8% of its

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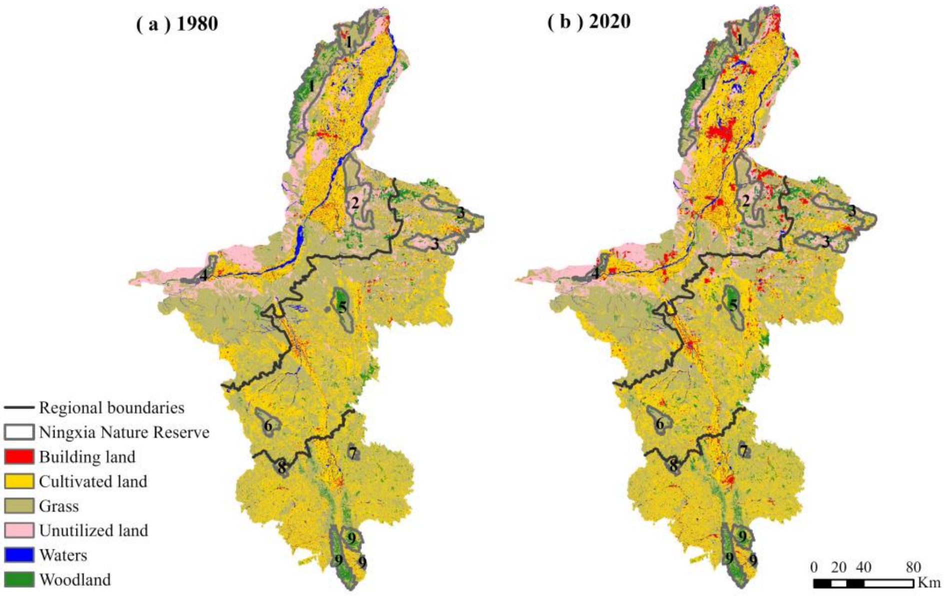
building land, 76.1% of its unutilized land, and 95.9% of its paddy fields were concentrated in the northern region, where most surface water and population resources were concentrated, and where Yinchuan, the capital of Ningxia Province, was also located. The central arid zone and the southern mountainous area are dominated by cultivated land and grassland (densities as high as 84.9% and 89.5%), with a relative shortage of surface water resources (densities of only 0.7% and 0.8%); the southern mountainous area has the highest density of forested land among the three zones (a density of 7.4%), with virtually no unutilized land (a density of only 0.1%).



1. Helan mountain national forest park(forest ecology) ; 2. Baijitan national nature reserve(desert ecology)
3. Haba lake nature reserve(desert ecology) ; 4. Shapotou national nature Reserve(desert ecology)
5. Luoshan nature reserve(forest ecology) ; 6. Nanhua mountain nature reserve(forest savannah ecology)
7. Yunwu mountain nature reserve(savannah ecology) ; 8. Huoshizhai national geopark(geological remains)
9. Liupan mountain natural reserves(forest ecology)

Figure 2. *Land use map of Ningxia in 1980 and 2020*

In order to further reflect the structural characteristics of land use and reveal information on various types of land transfers in and out of the region, this study constructed a transfer matrix of land use types in the Ningxia Autonomous Region from 1980 to 2020, to produce a proportional chord diagram of the transfer matrix of land use types as shown in *Figure 3*.

According to the proportional chord diagram, the main characteristics of land use type transfer in Ningxia from 1980 to 2020 were as follows: (1) the most transferred out land use types are grassland, cropland, and unutilized land, and the most transferred in are cropland, building land, and grassland. Moreover, cropland and grassland had a greater intensity of in and out transfer, while the unutilized land mainly transferred out included cropland, grassland, and building land; (2) the cropland area transferred in was larger than the area transferred out. The main transfer sources were grassland, unused land, and beach land, and the main transfer objects were grassland and construction land; (3) the grassland area transferred out was larger than the area transferred in, and the main transfer objects were arable land, followed by unused land and construction land, and the main transfer

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sources were arable land and unused land; and (4) there is almost no out transfer of construction land, and the main sources of transfer were grassland, arable land, and unused land.

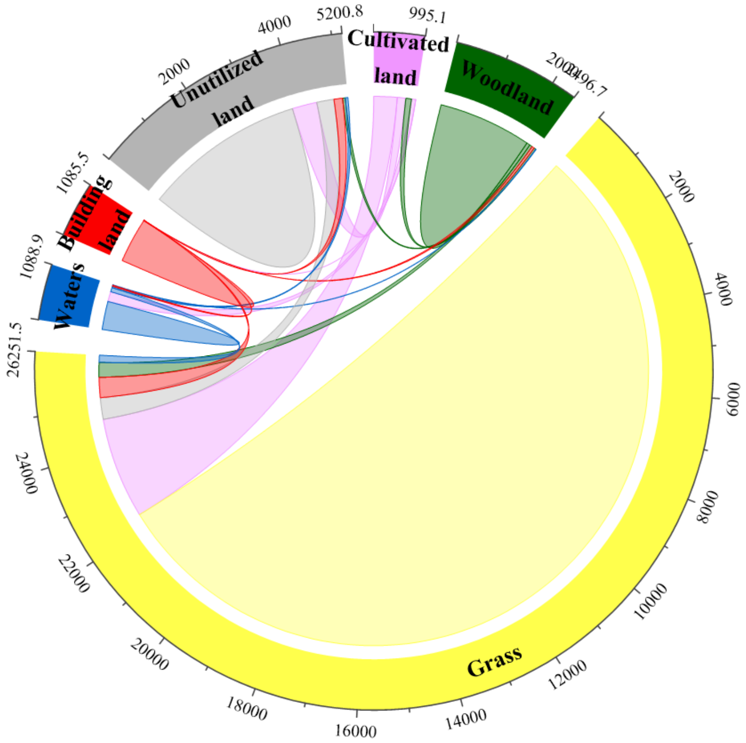

***Figure 3.** Chordal map of land use transfer ratio in Ningxia from 1980 to 2020*

Combined with *Table 2 and Table 3*, it can be seen that land use in Ningxia has changed greatly from 1980 to 2020 due to human activities. During the period from 1980 to 2000, population growth, food shortage, farmers' continuous land reclamation, and animal husbandry development led to a continuous increase in farmland area. At the same time, a large number of grasslands and unused land were eroded and occupied. The grain yield per hectare also increased exponentially with favorable factors such as land contract systems, production tools, water conservancy, crop varieties, and fertilizers (Wang, 2005). Since 2000, urbanization has been fast-tracked, and the proportion of construction land has increased sharply. The "Three North" shelterbelt project has also been extended to Ningxia, which plays an important role in improving the local ecological environment, preventing desertification, protecting water sources, and regulating the climate. Due to the policy of returning farmland to forested land, the cultivated land area has decreased, the declines in grassland and water area have been suppressed or even reversed, and the FVC has increased, which is basically consistent with the calculation results of this study.

In addition, this study counted the land use data for nine nature reserves in Ningxia from 1980 to 2020 and found that the construction land area in both desert ecological reserves and non-desert ecological reserves continued to expand, with both expanding by 93.1% and 108.9% from 1980 to 2020 (based on the area of the land category in 1980, the same hereafter). In contrast, the change trends in other land categories differed: desert ecological protected areas had grassland and unutilized land as the primary land use

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categories, water area, forested land, and grassland continued to increase (by 79.0%, 26.9%, and 8.2%, respectively), and cultivated land fluctuated but increased by 4.4%, and the increase mainly resulted from unutilized land (by 18.8%); non-desert ecological reserves had grassland and forested land as the primary land categories, and they decreased by 2.8% and 0.8%, respectively, and cultivated land, water area, and unutilized land increased by 11.3%, 4.8%, and 1.6%, respectively.

Table 3. *The overall mean value and change trend in fractional vegetation coverage in Ningxia from 1986 to 2020*

	Rate of change	**Ningxia**	**North**	**Center**	**South**	**Conservation area**	**Desert ecological reserve**	**Non-desert ecological reserves**
Multi-year average		0.32	0.29	0.25	0.46	0.29	0.17	0.36
FVC slope（%/Y)		0.17	0.14	0.12	0.35	−0.02	0.15	−0.11
Very significant decrease（%）	s<0, p<0.01	8.3	11.6	8.0	1.7	14.6	4.5	20.3
Significant decrease（%）	s<0, 0.01≤p<0.05	5.1	5.7	6.4	1.2	5.8	4.1	6.7
No significant trend（%）	p≥0.05	63.7	59.6	67.4	66.0	63.3	58.1	66.3
Significant increase（%）	s>0, 0.01≤p<0.05	6.5	4.6	5.8	11.8	4.4	6.7	3.1
Very significant increase（%）	s>0, p<0.01	16.5	18.5	12.5	19.3	12.0	26.6	3.7

Variation characteristics of fractional vegetation coverage

Fractional vegetation coverage inter-annual change characteristics

As a province more seriously threatened by desertification, the desert zone area occupies 36.7% of the total area in Ningxia (the sum of unutilized land and low-density grassland in the 1980 land use dataset). Desert zones are arid, precipitation-scarce areas with sparse or no vegetation growth. In order to reveal the multi-year dynamic characteristics of FVC in Ningxia and its desert zone and to evaluate vegetation succession characteristics, this study statistically analyzed the changes in FVC in Ningxia, the desert zone, and the non-desert zone from 1986 to 2020 calendar years (*Figure 4*).

Based on *Figure 4*, the overall FVC in the study area shows a fluctuating upward trend, reflecting the overall vegetation restoration level in Ningxia, which is gradually improving. There is much sandy land remaining in the Gobi Desert area, leading to the lowest FVC in desert areas and highest FVC in non-desert areas, but the growth trend of FVC in desert areas is more significant than in Ningxia and non-desert areas.

Additionally, we employed linear regression analysis to examine the temporal trends and the statistical significance of these trends in Forest Vegetation Cover (FVC) across three distinct geographical regions: the desert, non-desert, and Ningxia areas. The analysis revealed a significant positive trend in FVC across all three regions over time. Specifically, the linear regression model for the desert region demonstrated a highly

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significant positive correlation (p = 0.000009), significantly below the conventional 0.05 threshold. Additionally, the Ningxia region's FVC exhibited a significant positive correlation (p = 0.003), corroborating the pronounced influence of temporal factors on FVC growth. However, while the non-desert region's FVC also displayed a positive correlation trend, its p-value of 0.042 suggests a comparatively lower degree of statistical significance compared to the other regions.

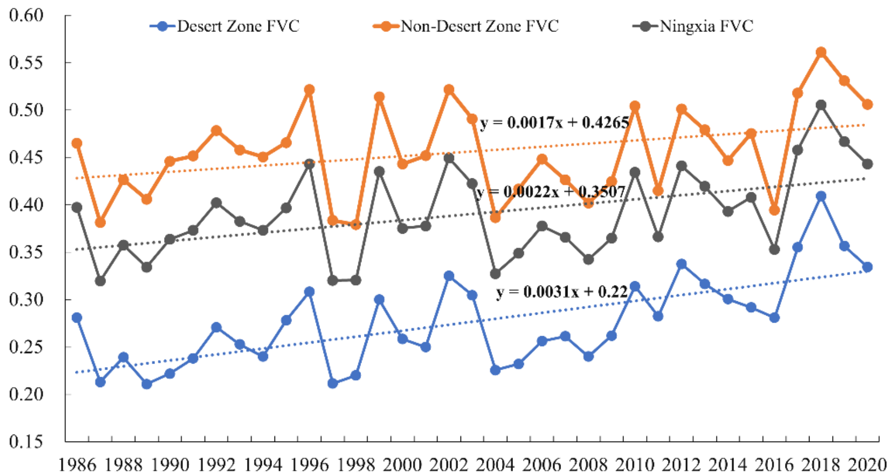

Figure 4. *Interannual variation curve of fractional vegetation coverage in Ningxia from 1986 to 2020*

Spatial characteristics of fractional vegetation coverage and its trend

Based on the statistics of mean inter-annual FVC values in different regions, this study also used a one-dimensional linear regression method to count FVC trend types and their area proportions in different regions, and the results are shown in *Table 3*.

From 1986 to 2020, the percentage of significantly degraded vegetation area in Ningxia was 13.4%, of which 8.3% was very significantly degraded area; the percentage of significantly improved vegetation area was 23%, of which 16.5% was very significantly improved area; and the percentage of basically stable area was 63.7%. The spatial characteristics of FVC changes in Ningxia are reflected in *Figure 5*. A comparative analysis shows that the FVC characteristic changes in the north, middle, and south of Ningxia are similar to those of overall FVC in Ningxia, with the basically stable area accounting for about 60%. The significantly improved area is larger than the significantly degraded area. The proportion of significantly degraded area in the southern region is the lowest, at only 2.9%, indicating that vegetation in the southern mountainous areas has maintained good development over the past 35 years, and the environment has improved continuously; the proportions of significantly degraded area and significantly improved area in the northern irrigated region is the highest among the three regions, reflecting a higher intensity of human activities in this area than in the central and southern regions. The FVC in the nine national nature reserves, as a whole, has shown a slight decreasing trend. Among them, the area of significantly improved vegetation in desert ecological reserves is higher than the significantly degraded area, and the FVC is increasing. In comparison, the area of significantly improved vegetation in non-desert ecological reserves is lower than that of the significantly degraded area, and the FVC is decreasing.

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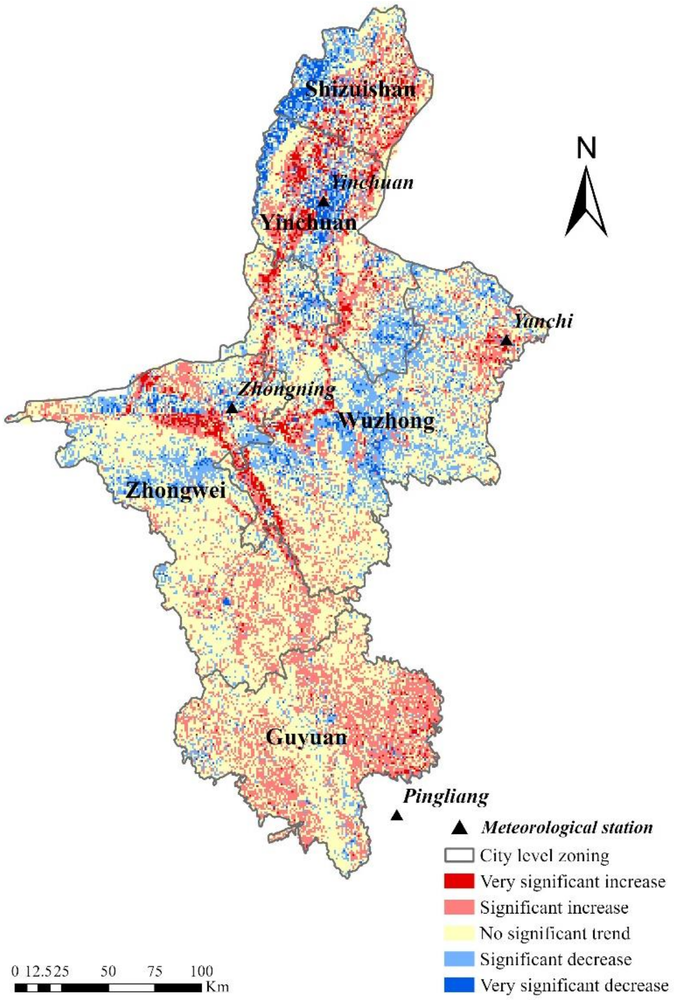

Figure 5. *Fractional vegetation coverage trend chart of Ningxia Region from 1986 to 2020*

Although human activities are gradually replacing natural elements as the main factors influencing ecosystem evolution, the impact of climate change on ecosystems should not be ignored. In recent years, the warming and humidification trend in the northern part of China has been conducive to implementing ecological protection projects and shortening ecological recovery times (Li et al., 2015; Long et al., 2018). In this study, data from two meteorological stations in Ningxia were collected, including Yinchuan station, located in the northern irrigated area, and Yanchi station, located in the central arid area. At the same time, because there are few meteorological stations in Ningxia, this study uses the meteorological station in Pingliang City, Gansu Province, adjacent to Guyuan City in Ningxia, to reflect climate change in southern Ningxia (*Figure 6 and Figure 7*).

As depicted in *Figures 6 and 7,* there is a discernible upward trajectory in the average annual temperature across Ningxia, signifying an observable trend of climatic warming. Within the northern portion of the Yellow River irrigated area of Ningxia, which benefit from abundant water resources, the temperature uptick and the expansion of the frost-free period have been instrumental in fostering vegetation growth, culminating in heightened vegetation cover. In contrast, the central arid zones, exemplified by Wuzhong City, exhibit vegetation growth constrained predominantly by water availability. Here, the surge in temperatures poses the risk of diminishing soil moisture, potentially exacerbating

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arid conditions and, by consequence, attenuating the vitality of plant life. Precipitation data fluctuate greatly, but there is no significant trend. In a comprehensive analysis of meteorological observation data from 1961 to 2019, which was collected across 20 stations in Ningxia, Wang et al. (2021) analyzed observational data from 20 meteorological stations in Ningxia from 1961 to 2019. The results showed that the change trend in annual precipitation in Ningxia was basically the same, consistent with the results of precipitation analysis in Ningxia in this study.

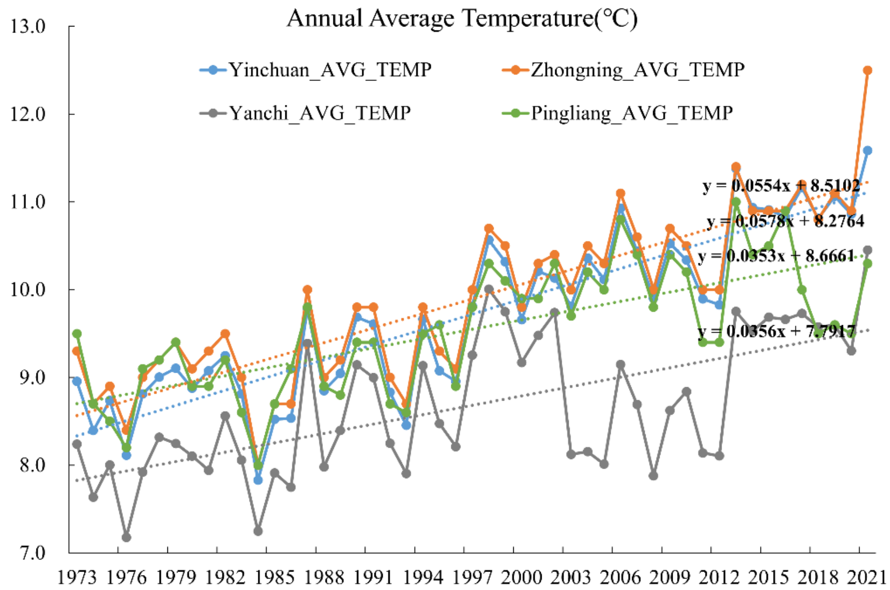

Figure 6. *The changes in annual average temperature (°C) at the Yinchuan, Zhongning, Yanchi, and Pingliang meteorological stations from 1973 to 2021*

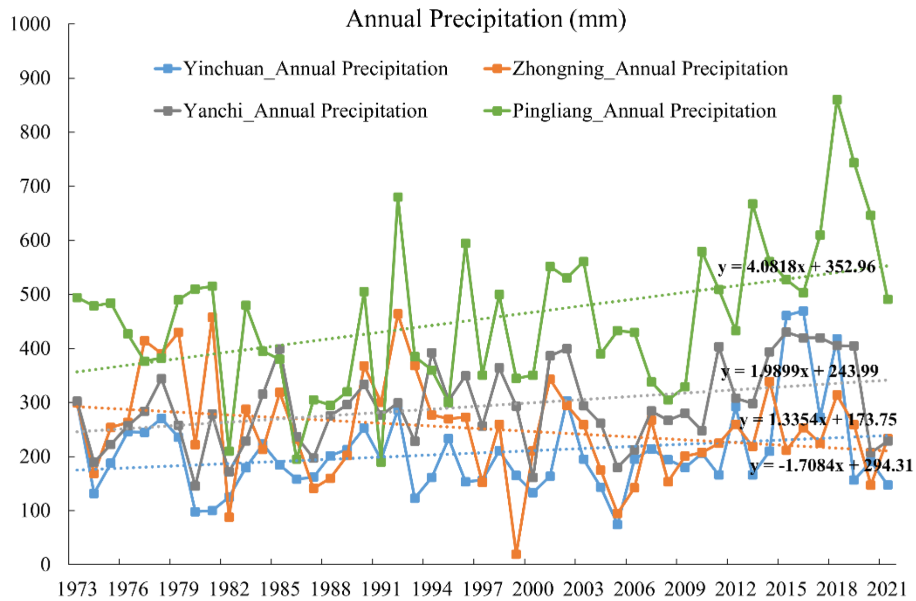

Figure 7. *The changes in annual total precipitation (mm) at the Yinchuan, Zhongning, Yanchi, and Pingliang meteorological stations from 1973 to 2021*

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Habitat quality

Temporal and spatial characteristics of habitat quality

The HQI is a quantitative index used to evaluate the health status of ecosystems in a specific region. It usually includes indicators of vegetation, soil, water, and air, which comprehensively reflects the HQ in this area. The setting of relevant parameters in the InVEST model is inevitably subjective, so this study calculates the HQ in Ningxia in different periods, focusing on its change trend, as shown in *Table 4*.

Table 4. *The area percentage and annual average value of different grades of habitat quality in Ningxia*

Year	Low (0~0.3)	Relatively low (0.3~0.6)	Medium (0.6~0.8)	Relatively high (0.8~0.9)	High (0.9~1)	Average
1980 (%)	39.37	52.78	4.66	2.52	0.67	0.427
1990 (%)	39.48	52.92	4.42	2.52	0.67	0.427
1995 (%)	42.83	49.12	4.86	2.50	0.68	0.419
2000 (%)	44.30	47.56	4.95	2.51	0.68	0.416
2005 (%)	43.67	47.31	5.77	2.58	0.67	0.419
2010 (%)	43.81	47.08	5.82	2.59	0.70	0.420
2015 (%)	45.46	45.47	5.84	2.53	0.70	0.417
2018 (%)	45.98	44.99	5.79	2.58	0.66	0.414
2020 (%)	45.72	45.14	5.93	2.50	0.70	0.415

In addition, the research results are divided into five grades (low, relatively low, medium, relatively high, and high) by combining the "natural breakpoint method" in ArcGIS. Because this study contains multi-stage results, the breakpoint thresholds are fixed at 0.3, 0.6, 0.8, and 0.9 as a whole, and the HQ statistics table for Ningxia (*Table 4*) and the HQ distribution map from 1980 to 2020 (*Figure 8*) are obtained.

HQ grade is closely related to land use type, habitat suitability, and threat factors sensitivity. Upon comparing HQ data with land use data, it is found that (1) areas with low HQ correspond to unused land, building land, and cultivated land; (2) A lower grade corresponds to grasslands with medium and low coverage, beaches in the water area, and a small amount of cultivated land; (3) The medium grade corresponds to sparsely forested land, other forested lands, high coverage grassland, water outside beaches, and a small amount of medium coverage grassland; (4) The higher grade corresponds to shrub forests, a small amount of sparse woodland, and high coverage grassland; (5) The high grade corresponds to forested land; (6) Some land use types correspond to multiple HQ grades, such as cultivated land, medium coverage grassland, and high coverage grassland, which mainly correspond to the low, low, and medium HQ levels, respectively, but in some areas, they can correspond to a small amount of higher level HQ.

Based on *Table 4* and *Figure 8*, the HQ in Ningxia has slightly deteriorated from 1980 to 2020, with the average value dropping from 0.43 to 0.42. The overall HQ is low, and the area comprising low and lower grades has accounted for more than 90%, which is mainly determined by its geographical location and climatic factors of "surrounded by sand on three sides, with minimal rain." Specifically, the area of the low-grade HQ is the widest, with an area reduction of 3,954.8 km^2 from 1980 to 2020, the middle and low-coverage grassland decreased by 3197.1 km^2, and the beach area decreased by 88.3 km^2.

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The low-grade area increased by 3,288.8 km^2, the total construction land and cultivated land increased by 3,109.3 km^2, and the unused land decreased by 536.0 km^2. The middle grade increased by 657.6 km^2. Sparsely forested land, other forested land, high-coverage grassland, and water other than beach land increased by 671.7 km^2. At the same time, the higher-grade area decreased by 6.08 km^2. Shrubbery increased by 26 km^2, the reduced part of high-coverage grassland was unknown or difficult to obtain, and the high-grade area increased by 14.4 km^2, where forested land increased by 14.4 km^2. The increase or decrease in different HQ levels basically coincides with changes in land use; however, some land types correspond to multiple HQ levels, so they are not completely consistent in area.

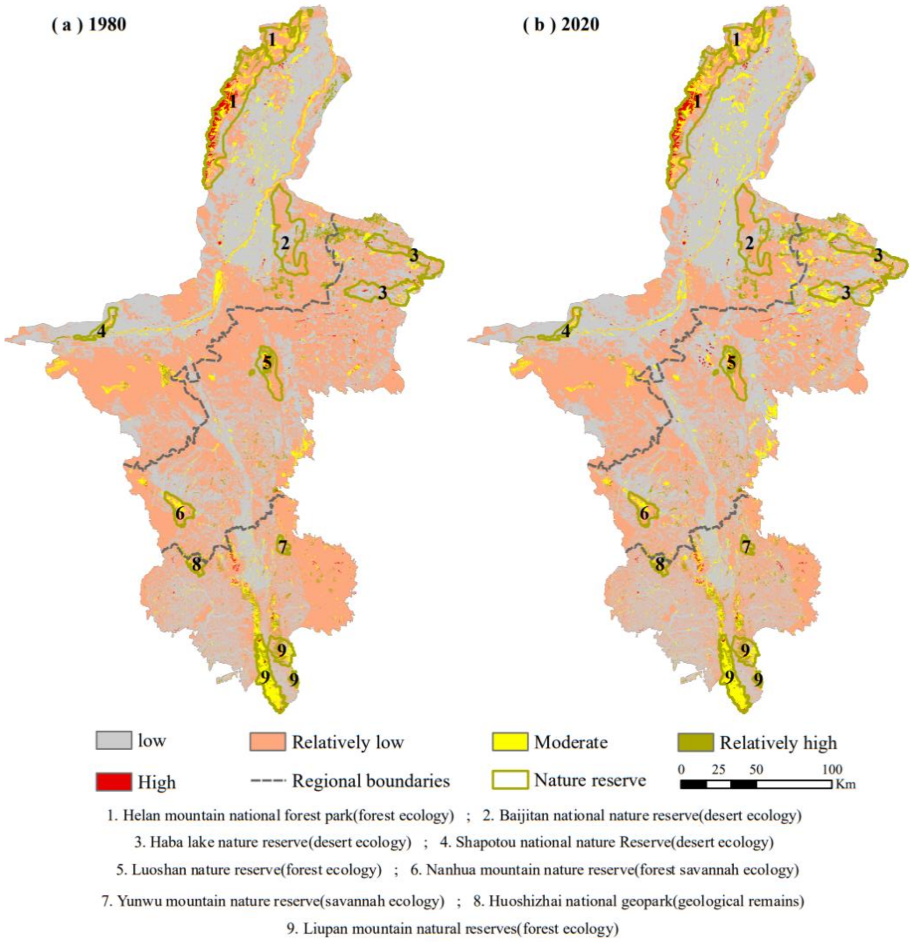

***Figure 8.** Spatial distribution and change in habitat quality in Ningxia from 1980 to 2020*

Spatially, the highest proportion of low HQ land was found in the northern irrigated area, leading to the lowest mean HQ. In contrast, the highest proportion of woodland was found in the southern mountainous area, resulting in the highest mean HQ. From 1980 to 2020, the mean HQ of the three regions decreased, with the largest decline in the northern irrigated area and the smallest in the southern mountainous area. The overall HQ of the nine national nature reserves improved slightly, with the mean value increasing from 0.53 to 0.54. However, it should be noted that the HQ in the Huoshiluzhai Danxia Landform Nature Reserve, Luoshan Nature Reserve, and Helanshan National Forest Park decreased

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by 0.02, 0.01, and 0.01, respectively. The main reasons for these decreases were increases in construction land and cultivated land (up by 115.1% and 24.5%, respectively, compared with 1980) and decreases in grassland and woodland (down by 3.7% and 1.7%, respectively, compared with 1980).

Spatial exploration of habitat change

In order to further reveal the spatial distribution law of HQ, this study first converted HQ and the graph of HQ change from 1980 to 2020 into point data, calculated the global Moran index, and performed a hot spot analysis (*Figure 9*). Statistics showed that the Moran index decreased from 0.39 in 1980 to 0.37 in 2020, indicating that the agglomeration of HQ had a dispersion trend; the Moran index of the HQ graph change was 0.21, and the z-score was 144.49, which also had a significant agglomeration distribution feature.

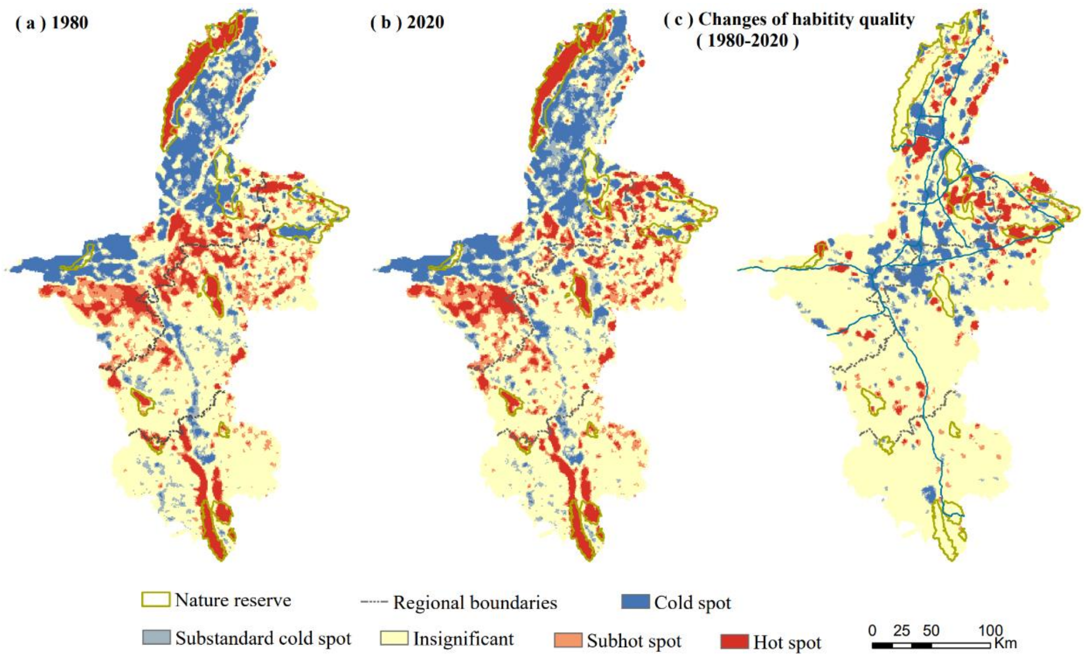

***Figure 9.** Hot spot analysis of habitat quality in Ningxia from 1980 to 2020*

Hot spot analysis helps to identify the spatial clustering locations of high-value and low-value elements. As shown in *Figure 9 (a) and (b)*, the high HQ hot spot areas are mainly distributed in Helan Mountain, near the junction of the northern irrigated area, the central arid area, and Liupan Mountain in the south of Ningxia. There are also many hot spot areas in the six non-desert ecological nature reserves. The cold spot HQ areas are mainly distributed in the northern irrigated area, the area with the highest urbanization in Ningxia, with the highest concentration of cultivated land, construction land, unused land, and a relatively poor HQ. With the expansion of urbanization, the HQ declined further. *Figure 9 (c)* shows that the areas with insignificant changes in HQ in Ningxia from 1980 to 2020 comprise the majority of the total area, and the total area showing significant improvement in HQ is lower than that showing significant degradation. The hot spots and cold spots of HQ changes are mainly concentrated in the irrigated areas north of Ningxia and the northern areas in the central arid region. The population in the south-central region

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is relatively small, the intensity of land use and development is lower than in the northern region, and the change in HQ is relatively stable. In addition, the HQ of the three desert ecological reserves have improved (by an average of 0.05) from 1980 to 2020.

Discussion

Habitat quality is mainly influenced by land use type and shows different grades in different land use types (Foley et al., 2005). Our results show that areas with high grade of habitat quality are distributed in areas with high vegetation cover such as forest land; while areas with low grade of habitat quality are distributed in areas such as unutilized land and construction land for human activities, which is more consistent with previous studies (Wu et al., 2020; Fang and Ma, 2024). From 1980 to 2020, the land use pattern in Ningxia underwent significant changes. Driven by the Western Development Policy, Ningxia experienced rapid urbanization and large-scale infrastructure construction (Wang et al., 2012), and a large amount of grassland, unused land, and natural forest land were transformed into construction land and agricultural land (*Figure 3*). A large amount of agricultural land is clustered around the construction land, and the habitat quality class of these areas is generally low (*Figure 2*). The transformation of land use types often leads to the loss of natural habitats and habitat fragmentation, which in turn affects biodiversity and ecosystem services. Tang et al. (2021) showed that the impacts of cropland expansion on the loss and degradation of natural habitats are much greater than the impacts of urban expansion. The areas with high habitat quality in Ningxia are mainly concentrated in four national nature reserves of forest ecology category, and the improvement of their ecological environment is of great significance to enhance the overall habitat quality in Ningxia. On this basis, a sound ecosystem compensation mechanism should be established to strengthen the management of the ecological environment in time and space and rationalize the planning of urban construction and the transfer of agricultural land to weaken environmental degradation.

In addition, we found that vegetation cover had a significant effect on habitat quality class (Tang et al., 2022; Wang et al., 2023), but areas with significant increase in vegetation cover did not lead to an increase in habitat quality. In southern Ningxia, for example, the significant increase in vegetation cover was accompanied by a slight decrease in habitat quality. Combined with the land use types in Ningxia, it can be found that the areas with declining habitat quality are all affected by human activities. Urban expansion, as a major trend in the development of human society (Zhang et al., 2018), has had a significant impact on the ecological environment and habitat quality. However, higher vegetation cover can mitigate a series of negative impacts of urban expansion on habitat quality to a certain extent. In addition to vegetation cover, there are other factors influencing habitat quality, among which climatic conditions are one of the key factors. Ningxia belongs to arid and semi-arid areas, and there is no significant trend in rainfall in the time series (Wang et al., 2021), but there is a significant increase in temperature. Meanwhile, Ningxia has a fragile ecological background with weak resistance and resilience to external disturbances, especially during the dry season, when the lack of moisture may limit the growth of vegetation and the recovery of ecosystems. Decision makers can plant compatible vegetation to consolidate the ecological environment according to different geographic environments. In addition, the Ningxia Hui Autonomous Region has implemented a series of economic and environmental policies in recent years aimed at promoting high-quality development and ecological and environmental protection, as well as supporting the private economy and optimizing the business environment. In the future, Ningxia should continue to promote green transformation, build a low-carbon and recycling economic system, and strengthen the ecological protection of the Yellow River Basin in order to achieve coordinated development of the economy and the environment.

This study evaluates the habitat quality of Ningxia based on long time series of remote sensing images, land use data, and meteorological data studies. In fact, the factors affecting the level of habitat quality are not only that, but also environmental pollution, soil type, ecological chain, and other aspects will affect the habitat quality (Hack et al., 2020; Ahmadi Mirghaed and Souri, 2022). Due to the high difficulty in obtaining long time-series related data. Therefore, it is difficult to quantify the effects of these factors on habitat quality. Moreover, in recent years, various kinds of extreme weather have occurred throughout China. In this study, the data of vegetation cover, land use type and climate were based on annual scale analysis, and the extreme weather could not be expressed in the annual scale data, which somewhat weakened the ecological impacts of extreme changes in climate elements. In the future, we will analyze the effects of these factors on habitat quality by studying more environmental factors and analyzing them at different scales.

Conclusions

This study analyzes the ecological environment changes and their causes in Ningxia from 1980 to 2020 from the perspectives of land use, FVC, HQ, and climate change and draws the following conclusions:

(1) From 1980 to 2020, the six first-class categories in Ningxia have generally shown the characteristics of "three increases and three decreases," with cultivated land, forested land, and construction land increasing by 11.9%, 11.9%, and 114.4%, respectively. Grassland, water area, and unused land decreased by 10.7%, 6.1%, and 10.3%, respectively, and human activities and policy factors greatly influenced land use changes.

(2) From 1986 to 2020, the FVC in Ningxia fluctuated, and the FVC of unused land and low-density grassland increased significantly, indicating that the local land greening and sand control work had achieved results. The spatial difference in FVC in Ningxia is obvious. The FVC in the southern mountainous area is stable at a high level, and the growth rate is the fastest. The FVC growth rates in the northern irrigated area and the central arid area are relatively low. Significant improvement of FVC coexists with significant degradation, and the improved area is slightly larger than the degraded area. The overall FVC of the nine national nature reserves is mainly stable and has improved. It should be noted that the FVC of the Helanshan National Forest Park has dropped significantly, with the proportion of significantly degraded area as high as 43.9% and the proportion of significantly improved area at only 5.5%.

(3) The weighting of each land type in the InVEST model varies. Although FVC has increased in Ningxia from 1980 to 2020, the expanding urban scale and encroachment of grassland, cropland, and other land types have led to a slight degradation of habitat quality in Ningxia, with the mean value of habitat quality decreasing from 0.43 to 0.42, and the overall habitat quality is still low, with the proportion of low- and lower-graded areas consistently above 90%.In terms of spatial distribution, the habitat quality in the northern irrigation area is the lowest, and the HQ in the southern mountainous area is the highest. In terms of changes, the HQ of the three areas has declined, with the largest decline in the

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northern irrigated area and the lowest in the southern mountainous area. The hot and cold spots of HQ changes are mainly concentrated in the northern irrigated area of Ningxia and the northern area of the central arid area.

(4) The HQ of the nine national nature reserves increased from 0.53 to 0.54. Among them, the Huoshizhai national geopark, Luoshan Nature Reserve, and Helanshan National Forest Park have been developed as tourist attractions, which have been greatly affected by human activities, and the quality of their habitats has been reduced.

Areas where deterioration in HQ and future change trends are not obvious need further attention and governance by local authorities, and to adhere to a prudent attitude and follow the idea of sustainable development to build a beautiful Ningxia bordering the southern side of the Yangtze River.

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