Habitat International 117 (2021) 102436

Contents lists available at ScienceDirect

Habitat International

journal homepage: www.elsevier.com/locate/habitatint

Does rural residential land expansion pattern lead to different impacts on eco-environment? A case study of loess hilly and gully region, China

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ARTICLE INFO

Keywords:
Rural residential land
Expansion patterns
Habitat quality
Spatial restructuring
Loess hilly and gully region
China

ABSTRACT

Land use change and its impacts on eco-environment attract great attentions. Earlier studies shed light on the impacts of urban build-up land and agriculture land. Yet, knowledge about the impacts of rural residential land on eco-environment, especially from different expansion patterns perspective, is relatively limited. Taking Baota District, a typical city in loess hilly and gully region during the period of 1990–2015 as a case study, this paper analyzed rural residential land and habitat quality changes based on land-use data (30-m spatial resolution), and further used direct/indirect measurement model to explore the impacts of different expansion patterns of rural residential land on eco-environment. Results showed that the growth rate of rural residential land decreased first and then increased during study period, and the pattern of edge expansion has the largest scale among the newly added residential land. Moreover, the eco-environment in northern area of Baota District had been significantly improved, especially the habitat quality of shrubs and grasslands. Unfortunately, this study found that the eco-environment around cities and townships deteriorated dramatically. Environment policy, land engineering projects and residential land changes were important driving factors on eco-environment changes. Furthermore, this study verified the difference in indirect impacts of rural residential land expansion patterns on eco-environment (infilling pattern < edge-expansion pattern < leapfrog pattern) based on direct/indirect measurement model. According to the findings of this work, we proposed several implications for rural spatial restructuring. We hope these findings and suggestions could provide valuable information for rural development, and further improving regional ecological security.

1. Introduction

Land use activities is closely linked to eco-environment and socio-economic. Unfortunately, land use activities have changed the world's landscapes and brought tremendous impacts on eco-environment by clearing forests, practicing agriculture or expanding built-up area (Kertésza, Nagyb, & Balázs, 2019; Tolessa, Senbeta, & Kidane, 2017). As such, conserving eco-environment whilst meeting socioeconomic development demands has become a focus of attention. Researchers have carried out a large amount work about eco-environment changes caused by land use process for better understanding how land use activities affect eco-environment (Chuai et al., 2016; Daniel, Smith, Belden, McMurry, & Swain, 2015).

The impacts of land use activities on eco-environment were mainly manifested in regional climates (Kalnay & Cai, 2003), global carbon cycle (Houghton & Hackler, 2001, pp. 46–69), hydrologic cycle (DeFries & Eshleman, 2004; Eduful & Shively, 2015), and biodiversity (Peng, Pan, Liu, Zhao, & Wang, 2018; Song, Robinson, & Zhou, 2017). For example, land-use change affected regional climate by changing the exchange of energy and water between surface and atmosphere (Xiao & Weng, 2007). Land-use change as well affected the process of global carbon cycle. Since 1990, 12.5% of anthropogenic carbon emissions was resulted from land use change (Houghton et al., 2012). Besides, land-use change threaten biodiversity through the loss and fragmentation of habitats, which exacerbated the decrease of species that were essential for the production and provision of various ecosystem services (Newbold et al., 2015; Huang, Tang, Liu, & He, 2020). In this sense, exploring the impacts of land use activities on habitat quality was of great significance for the conservation of regional eco-environment.

Habitat quality represented the ability of the eco-environment providing suitable living conditions for species (Polasky, Carpenter, Folke, & Keeler, 2011; Bai, Xiu, Feng, & Liu, 2019). Current literature on

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https://doi.org/10.1016/j.habitatint.2021.102436
Received 12 September 2020; Received in revised form 12 August 2021; Accepted 6 September 2021
Available online 17 September 2021
0197-3975/

habitat quality mainly focused on three aspects. One was the habitat quality assessment of specific species by measuring veracious species demographic, distribution, and individual condition data (Johnson, 2007). This type of researches, which need species occurrence data, was usually carried out in small-scale area due to expensive data acquisition. For example, Knutson, Hines, Powell, Friberg, and Niemi (2006) selected annual productivity and population growth rate for 27 species of land birds as parameters to assess forest habitat quality (upland and floodplain) in the portions of Midwestern United States based on field data. Second, the comprehensive evaluation of the regional habitat quality using ecological indicators system or ecological process models (Riedler, Pernkopf, Strasser, Lang, & Smith, 2015; Sun, Jiang, Liu, & Zhang, 2019). The InVEST-Habitat Quality model (IHQ) was commonly used to produce habitat quality maps, especially in the areas lacking direct data of biodiversity. For example, Aneseyee, Noszczyk, Soromessa, and Elias (2020) found that biodiversity varied with the changes in ecological characteristics and was damaged by land use activities. Third, the habitat quality responded to human socio-economic activities, such as urban expansion, agricultural expansion and road construction (Song, Liu, He, & Lu, 2020; Talukdar, Pal, Chakraborty, & Mahato, 2020; Tang et al., 2021; Wu, Lin, Chiang, & Huang, 2014). For example, Miserendino et al. (2011) demonstrated that urban land expansion lead to the deterioration of quality of river habitats. Haddad et al. (2015) found that the expansion of human populations, cropland and urban centers will inevitably continue to reduce and fragment natural habitats, thereby threatening biodiversity and ecosystem services. To better reflect the impact of human activities on eco-environment, we focused mostly on the ability of the eco-environment providing suitable living conditions for non-human species. Additionally, the International Union for the Conservation of Nature Threats Classification System defined man-made construction areas as a threat to biodiversity. Therefore, habitat quality was defined as the ability of the eco-environment providing suitable living conditions for non-human species in this paper. Compared with traditional definition of habitat quality, the current definition used in this paper had limitation, because our focus was mainly on non-human habitats.

Although existing studies have achieved fruitful results in the assessment of habitat quality and responses of habitat quality to human activities, few studies focused on the responds of habitat quality to rural residential land expansion (Alqurashi & Kumar, 2016; Huang et al., 2019). In 2018, there were still 3.39 billion people living in rural areas in the world which needed a huge supply of ecological products to maintain rural development. In addition, the research on the impacts of land use activities on habitat quality was mainly from a comprehensive perspective, and there were few exploratory studies from the perspectives of direct/indirect impacts. Therefore, it is necessary to explore the impacts of rural development on eco-environment, especially from the perspective of direct and indirect impacts. This study will fill a knowledge gap about the impacts of land use changes on eco-environment by adopting quantitative approach for measuring direct/indirect impacts of rural residential land expansion on eco-environment.

China's loess hilly and gully region was recognized as an ecologically fragile region on earth for its serious soil erosion issue, and the average soil erosion modulus of this region was higher than 5000 t km^{-2} a^{-1}. (Fu et al., 2016; Li, Li, Fan, & Long, 2019). The fragile ecological environment was very sensitive to human activities. Unfortunately, the land resources that could be utilized in this region were very limited. The hillside area above 15° accounted for 50–70% of the total area. Thus, land use activities in this region posed a serious threat to local ecological environment. Along with the development of socio-economy, eco-environment degradation had become seriously in this region because of the unreasonable land use activities. In order to prevent the eco-environment from deteriorating further, Chinese government had implemented policies such as "Grain for Green Project", "new-countryside construction" and "ecological civilization". Therefore, the aims of this work were (1) to investigate spatial-temporal change of rural residential land in the loss hilly and gully region during 1990–2015, (2) to analyze the spatial-temporal change of eco-environment, and (3) to clarify the different impacts of rural residential land expansion patterns on eco-environment, and attempt to provide some potential rural spatial restructuring strategies in the loess hilly and gully region.

2. Research background and theoretical framework

Residential land is a space for villagers to engage in living and production activities, and it is also a reflection of the state of rural social and economic development. The market reforms in the 1980s promoted a building craze in rural areas by increasing incomes of farmers that fueled the encroachment on farmland (Wang, Su, Wang, & Tao, 2012). For this reason, Chinese government adopted strict farmland protection measures. For example, the transactions of rural houses between village collectives and urban dwellers were prohibited. (Wang, Wang, Su, & Tao, 2012). However, the rapid urbanization process had brought challenges to the implementation of the rural housing regime. Many rural dwellers and even rural collectives engaged in illegal land transactions with urban dwellers driven by interests, which led to the development of informal land markets such as small property-rights houses and urban villages (Lin, 2009). In Baota District, the problem of small property-rights houses had gradually become prominent. Especially since 2013, the government had strictly restricted farmers' applications for cave dwelling construction, which further stimulated the development of small property-rights houses in rural areas.

Since China had not yet formed a complete exit mechanism for rural homesteads, empty and abandoned homesteads could not be effectively dealt with, which indirectly lead to the increase of rural residential land. For example, in 2018, there were 137 million migrant workers in China working in cities, and their houses in countryside were idle all the year round (National Bureau of Statistics, 2018). New residents could only build houses around the village, which lead to the increase of rural residential land. In addition, the development of urbanization and industrialization promoted the increase of household income, which in turn increased the willingness of residents to improve their living conditions (Liu, Yang, Li, & Li, 2017). For example, the per capita disposable income of rural residents in Baota District increased from 1487 yuan in 2000 to 9090 yuan in 2015 and the per capita housing consumption of rural residents also increased from 199.9 yuan to 1785.5 yuan, an increase of more than seven times. Population expansion and family structure miniaturization had increased the number of households, and stimulated the increase in housing land demand (Chen, Liu, Lu, & Li, 2021; Porta et al., 2013). For example, the average population per household in China decreased from 3.44 in 2000 to 3.10 in 2015, while the number of households increased by 61.1 million. Especially in Baota District, the rural population increased from 235,338 in 2000 to 299,284 in 2015, while the family population decreased from 3.74 to 3.09. Further, land engineering, as an important way to improve the intensive utilization of land resources, has been widely carried out in China. Project implementation content gradually shifted from focusing on agricultural land consolidation to comprehensive improvement activities such as agricultural land, rural residential land, urban construction land, and unused land development (Liu & Wang, 2019). For example, to achieve the goals of livable living space, efficient agricultural production and ecological environment protection, Baota District of Yan'an City implemented gully land consolidation project and land creation project, which greatly changed the local land use landscape pattern.

In the man-land system, human activities and the natural geographic environment were intricately related. The eco-environment system provided necessary materials and energy for residents to engage in living and production activities, especially the land resources needed by residents (Fig. 1). During 1996–2016, China's rural residential land area increased by 9295 square kilometers, equivalent to half the size of Beijing city (Liu, Ye, & Lin, 2019). Rural residential land expansion lead

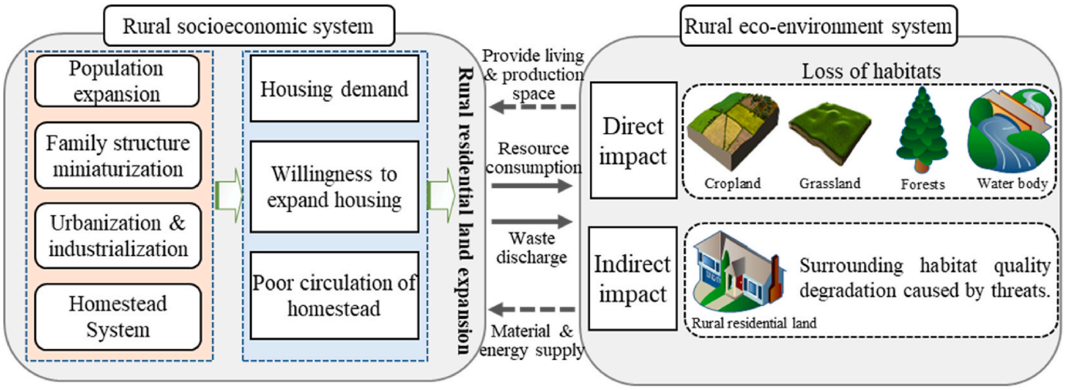

Fig. 1. Theoretical framework diagram of the relationship between residential land and eco-environment.

to direct degradation of regional habitat quality by occupying habitats. For example, cropland, grassland and forests were the main habitat types encroached by rural residential land expansion in China. (Liu et al., 2017; Long, Liu, Wu, & Dong, 2009). Besides, residential land was the main place for residents' life and production, and it had an indirect impact on the surrounding habitats as a source of threat. For example, organic-chemical pollution, garbage deposition and human trampling, caused by human activities, applied pressure on eco-environment through changing soil characteristic and quality drastically (Moreira, Fonseca, Vergílio, Calado, & Gil, 2018). Although the eco-environment system has self-repair capabilities, if the intensity of human activities exceeds this threshold, the damage to the eco-environment will be catastrophic. Therefore, the analysis of the eco-environment effect of rural residential land expansion will help the government to weigh up rural development and eco-environment protection.

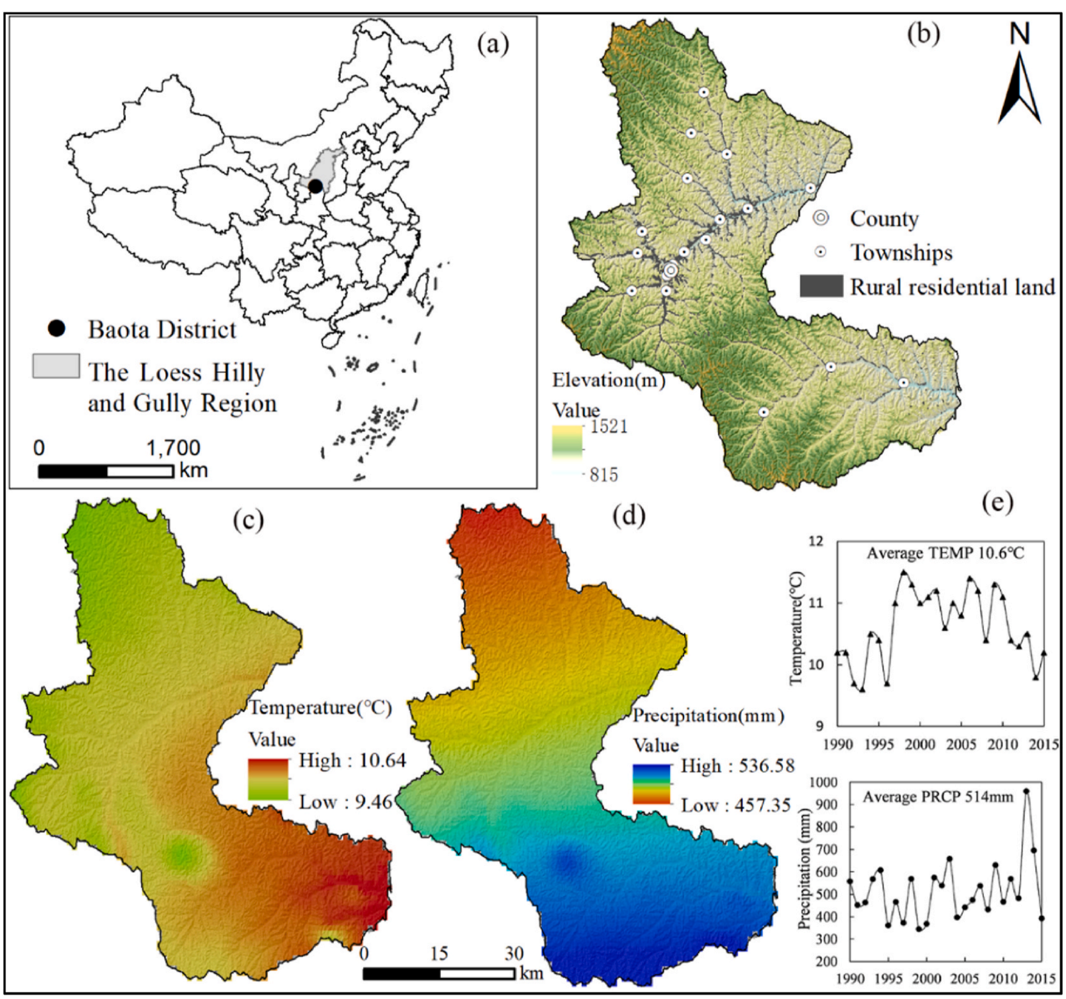

Fig. 2. Location of Baota District. Subfigure (a) is the location of Baota District in China; Subfigure (b) is the distribution of rural residential land in Baota District; Subfigure (c) is the distribution of temperature in Baota District; Subfigure (d) is the distribution of precipitation in Baota Distrit; Subfigure (e) is the change of temperature and precipitation in Baota District.

3. Materials and methods

3.1. Study area

As a typical ecologically fragile region, the loess hilly and gully region were undergoing drastic land use changes. Specifically, rural residential land in this region expanded 173.3 km^2 from 1990 to 2015. As a consequence, the ecological environment was seriously threatened. For example, there were 35 km^2 grassland transformed to rural residential land, and 12.3 km^2 forests transformed to rural residential land. In addition, since the construction of ecological civilization was proposed, the loess hilly and gully region has become a key area for ecological protection in China. Considering the above reasons, we selected the loess hilly and gully region as a case area to quantitatively analyze the impacts of rural residential land expansion on the eco-environment.

Baota District was a typical valley city located in the loess hilly and gully region (109°14′-110°50′, 36°10′-37°2′) (Fig. 2). The city occupied approximately 3545 km^2, including rural residential land with 19.6 km^2. In terms of topographical features, the hillside area above 15° accounted for 50.8% of the total area, and the gully density was 3.04–5.01 km/km^2. In terms of climate characteristics, the annual precipitation of Baota was around 500 mm, and the annual evaporation with 1579.7 mm was almost three times of the precipitation. The annual temperature in Baota District was 10.6 °C, and the accumulated temperature above 10 °C was 3245 °C that mainly meet the needs of the one-crop farming system (Liu, Liu, Liu, & Chen, 2021). With the development of industrialization and urbanization, the real GDP per capita in Baota District achieved 70 thousand yuan in 2015.

3.2. Data and preprocessing

The 30-m spatial resolution land-use data (1990, 1995, 2000, 2005, 2010, and 2015) used in this paper were provided by Chinese Academy of Sciences, as well as Resources and Environmental Science and Data Center (http://www.resdc.cn). These datasets were generated from Landsat remote sensing images by manual visual interpretation. Land-use types were classified as forest land, shrub wood land, dense grass land, sparse grass land, reservoir, swamp, river, cropland, urban land, rural residential land, industrial land, road, and bare soil. We further adjusted the classification of urban land and rural land based on urban boundary, obtained from government website (http://www.onegreen.net/). In addition, we randomly selected 100 points (600 points in total) in each year land-use map and used Google Earth high spatial resolution images to verify the remote sensing interpretation accuracy of land use types. We also adopted field survey to acquire ownership of land-use types. The overall accuracies of land-use maps in 1990, 1995, 2000, 2005, 2010 and 2015 were all higher than 90%.

The 30-m spatial resolution digital elevation model data was generated from SRTM V4.1 dataset based on WGS84 ellipsoid projection. Elevation and slope data, which were used to analyze the change characteristics of habitat quality, were both generated from DEM data by utilizing ArcGIS 10.2 software.

3.3. Statistics and analysis

Evaluating the impact of rural residential land expansion on habitat quality was the main research content of this article. We used the InVEST-HQ model to carry out the assessment of habitat quality, which mainly includes the following steps: The first step was to predetermine the measure of maximum biodiversity in a given habitat type; the second step was to assess the biodiversity degradation score of a given type of habitat; the third step was to translate degradation score into a habitat quality value using a half saturation function (Fig. 3). Further, we evaluated the impact of rural residential land expansion on habitat quality based on direct/indirect measurement model. It should be noted that we focused mostly on the ability of the eco-environment providing suitable living conditions for non-human species. Habitat suitability represented the survival suitability of non-human species. Therefore, the more natural and complex the habitat was, the more suitable the habitat was. In addition, there was two types of impact that rural residential land could have on habitat quality. First, direct impact through the occupation of habitat patches. Second, indirect impact through household sewage pollution. In this study, the threat level of rural residential land to habitat quality was determined mainly based on the sensitivity of habitat to threat source, the threat distance and other parameters, rather than the direct biodiversity loss data. The detailed analysis method is explained as follows.

3.3.1. Definition of the expansion patterns of rural residential land

The definition of land use expansion pattern has always been an issue for geographers. Previous studies generally focused on urban build-up land expansion (Bhatta, 2010), and hardly concerned the expansion of

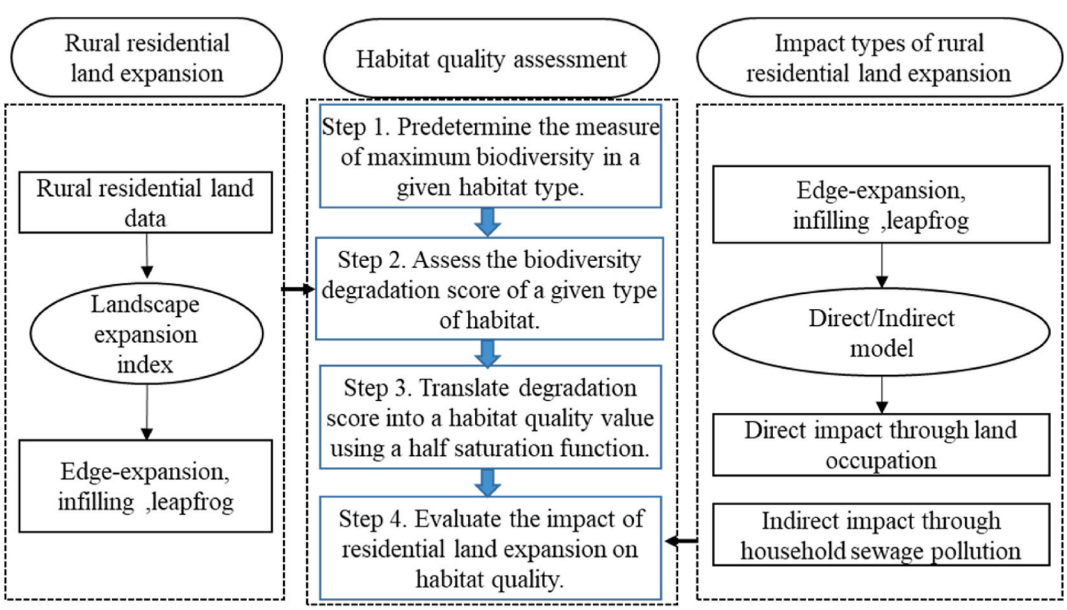

Fig. 3. Data analysis step diagram.

rural residential land. Edge-expansion, leapfrog expansion and infilling expansion were recognized as the basic types of urban expansion (Wilson, Hurd, Civco, Prisloe, & Arnold, 2003; Yu & Zhou, 2017). Studies have shown that urban expansion in developing countries was dominated by edge-expansion and leapfrog expansion, while urban expansion in developed countries was dominated by infilling expansion. Some researchers have also found that there was a difference between rural residential land expansion and urban expansion. For example, Tian, Qiao, and Gao (2014) pointed out that the expansion of a single village was significantly different with the expansion of urban, and very few infilling patterns occurred in rural residential land expansion because of the little scale. However, due to the limited developing space in the loess hilly and gully region, the newly-added rural residential land was mainly distributed along the valley, which lead to the common phenomenon of residential land connecting between villages. In this study, we defined the infilling pattern as a new rural residential land that fills in gaps among old rural residential lands or fills the hole within an old residential land. Edge-expansion pattern was defined as a new rural residential land spreading from the border of existing rural residential land. Leapfrog pattern was defined as a new rural residential land isolating from the existing rural residential land (Liu, Zhang, & Wang, 2016; Xu et al., 2007).

Landscape expansion index (LEI) was an indicator that described or analyzed the change of landscape pattern, and was widely used to define the expansion pattern of artificial construction land (Xu, He, Liu, & Dou, 2016). Compared with conventional landscape indices, LEI has the advantage of detecting the process of landscape pattern change within multiple time points. Buffer analysis, a spatial analysis functions of GIS, was used in the calculation of LEI. The buffer zone was defined as the zone with specified distance around a newly grown residential land. The analysis could be used to determine which rural residential land was within or outside the defined buffer zone (Liu et al., 2010). In this paper, we used LEI to identify the expansion patterns of rural residential land, and the formula was as follow:

$$\text{LEI} = \frac{A_1}{A_1 + A_2} \times 100 \quad (1)$$

in which A_1 represented the intersecting area of the old rural residential land and buffer zone, while A_2 represented the cross area between the formerly zone of non-rural residential land and the buffer zone. According to LEI values, the expansion of rural residential land was defined into three patterns: edge-expansion ($0 < \text{LEI} \leq 50$), leapfrog ($\text{LEI} = 0$) and infilling ($50 < \text{LEI} \leq 100$).

3.3.2. Evaluation of habitat quality

Habitat quality was closely related to biodiversity. In our case, habitat quality represented the ability of the eco-environment providing suitable living conditions for non-human species. In general, species diversity was a simple measure of biodiversity. Thus, areas with higher habitat quality would afford higher native species richness and represented higher levels of biodiversity. If the biodiversity of the area was threatened and dropped, it meant that the quality of the habitat in the area was reduced (Gong, Xie, Cao, Huang, & Li, 2019; Hou, Lyu, Chen, & Fu, 2017; Sun et al., 2019; Zhang, Zhang, et al., 2020). According to the Habitats Classification Scheme (Version 3.1), developed by the International Union for Conservation of Nature and Natural Resources (IUCN) and relevant literature, we subdivided habitats into a secondary classification based on land use types (Table 1).

The multi-service of InVEST provided an effective tool for exploring the relationship of ecological environment and economic goals (Sharp et al., 2016). Considering Habitat Quality model (IHQ) was one of the key models in InVEST to evaluate and map the habitat quality. IHQ model was utilized to quantitatively analyze the spatial-temporal distribution of habitat quality in Baota District, and the hypothesis of the model was that the higher habitat quality the richer biodiversity. Two

Table 1
Habitat types classification.

Habitat types of IUCN	Subclass	References
Forest	Forest land	IUCN. (2019); Bai et al. (2019)
	Shrub wood land	IUCN. (2019); Bai et al. (2019)
Grassland	Dense grass land	IUCN. (2019); Bai et al. (2019)
	Sparse grass land	IUCN. (2019); Bai et al. (2019)
Wetlands	River	IUCN. (2019); Bai et al. (2019)
	Reservoir	IUCN. (2019); Bai et al. (2019)
	Swamp	IUCN. (2019); Bai et al. (2019)
Artificial - Terrestrial	Cropland	IUCN. (2019); Bai et al. (2019); Zhu et al. (2020)

variables determined the value of habitat quality in IHQ model: Habitat suitability score (H_j) and threat level (D_{xj}).

Habitat suitability score was a parameter reflecting the suitability that a habitat type afforded biodiversity. In our case, the more natural and complex the habitat was, the more suitable the habitat was for non-human species. For example, forest had abundance species and provided suitable living conditions for species, thus the habitat suitability score of forest was higher. Since cropland was substantially affected by human activities, its habitat suitability score was lower. Thus, based on the principle of biodiversity conservation and the relevant published literature focused on the loess hilly and gully region, we assigned the habitat suitability score of each habitat. (Table 2) (Hou et al., 2017; Gong et al., 2019; Liu & Wang, 2018).

Besides the data of habitat quality suitability, the model also required data on habitat threat and its effects on habitat quality. Threat sources referred to the factors that threaten the biodiversity of habitats. Considering urbanization, industrialization and agricultural activities play an important role in habitat loss, fragmentation, and degradation, we selected urban land, rural residential land, industrial land, roads and cropland as the threat factors in this study (Gong et al., 2019; Polasky, Nelson, Pennington, & Johnson, 2011).The impact of threats on habitat in a grid cell is mediated by followed parameters.

- The first parameter was the relative impact of threat, w_r. It referred to the different degree of damage caused by threat sources to habitats, under the equal other conditions. For example, industrial land mainly decreased habitat quality through organic-chemical pollution that caused a very serious damage on habitat quality. By contrast, roads mainly decreased habitat quality through human trampling that caused low damage on habitat quality. The parameter of relative impact was determined based on the way that threat factors decreasing habitat quality and the existing research results whose study area were located in the loess hilly and gully region (Liu & Wang, 2018; He, Shi, Fu, & Yuan, 2020) (Table 3)
- The second parameter of threat factors was the spatial impact distance, d_{rmax}. Spatial impact distance referred to the maximum distance that the threat factors could threaten on habitats. More recent research suggested that biodiversity was threatened by the intensity of human activities (Gosselin & Callois, 2018; Verma et al., 2020). As the spatial distance from habitats to threat sources increased, the damage degree of threat factors on habitats would decline (Zhang, Zhang, et al., 2020). The parameter of d_{rmax} was determined based on the existing research results whose study area were located in the loess hilly and gully region (Liu & Wang, 2018; He et al., 2020) (Table 3). The impact of threat r that originated in grid cell y on habitat in grid cell x was given by i_{rxy}.

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}}\right) \text{ if linear} \quad (2)$$

$$i_{rxy} = exp\left(-\left(\frac{2.99}{d_{rmax}}\right)d_{xy}\right) \text{ if exponential} \quad (3)$$

in which, d_{xy} was the linear distance between grid cells x and y and d_{rmax}

Table 2
The habitat suitability score and sensitivity of habitat types to each threat factor.

Habitat types	Habitat suitability score	Threats				
		Urban	Rural residential land	Industrial land	Road	Cropland
Forest land	0.9	0.6	0.5	0.65	0.7	0.3
Shrub wood land	0.7	0.5	0.4	0.55	0.6	0.4
Dense grass	0.6	0.5	0.4	0.5	0.5	0.5
Sparse grass	0.5	0.5	0.4	0.5	0.5	0.5
River	0.8	0.8	0.7	0.9	0.65	0.2
Reservoir	0.8	0.7	0.6	0.8	0.6	0.1
Swamp	0.8	0.7	0.6	0.7	0.6	0.1
Cropland	0.3	0.3	0.2	0.4	0.2	0

Table 3
Maximum distance and relative impact of the threat factors affecting habitat quality.

Threat factors	Maximum distance of influence/km	Relative impact	Decay type	References
Urban land	5	0.8	Exponential	He et al. (2020)
Rural residential land	2.5	0.5	Exponential	Liu and Wang (2018)
Industrial land	6	0.8	Exponential	Liu and Wang (2018)
Road	2	0.4	Linear	He et al. (2020)
Cropland	1.5	0.6	Exponential	He et al. (2020)

was the maximum effective distance of threat r's reach across space.

- The final parameter was the sensitivity of habitats to threat sources, S_{jr}. We assigned the sensitivity of habitats to threat sources based on biodiversity conservation objectives (Forman, 2000; Lindenmayer et al., 2008). Generally, the natural environment is more sensitive to threat sources than artificial environment. Specifically, river, reservoir, swamp, forest land and shrub wood land were mainly natural environment, dense grass and sparse grass were mainly semi-artificial environment, and cropland was artificial environment in the loess hilly and gully region. Thus the sensitivity of cropland to threat sources was lower than other habitats. (Baral, Keenan, Sharma, Stork, & Kasel, 2014; Gong et al., 2019; Liu & Wang, 2018; Polasky, Nelson, et al., 2011).

The total threat level, representing the biodiversity degradation score, in grid cell x with habitat type j was given by D_{xj}.

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y i_{rxy} S_{jr} \tag{4}$$

in which, w_r was the relative impact of threat r, i_{rxy} was the impact of threat r that originated in grid cell y on habitat in grid cell x, S_{jr} was the sensitivity of habitat j to threat r. The biodiversity degradation score in our case was evaluated based on threat parameters instead of direct biodiversity data.

Finally, the biodiversity degradation score was translated into a habitat quality value using the followed function:

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right) \tag{5}$$

in which Q_{xj} was the habitat quality of xth grid cell in habitat type j, H_j was the habitat suitability score of habitat type j, ranging from 0 to 1 (from low to high, respectively), D_{xj}^z was the threat level in xth grid cell with habitat type j, z was the normalization constant, k was the half-saturation constant. Habitat quality was a continuous variable in the InVEST model. Values approaching 0 corresponded to the lowest biodiversity, and values close to 1 indicated the highest biodiversity (Tang et al., 2021). According to the relevant published literature, whose study areas were located in China's loess hilly and gully region (Hou et al., 2017; Gong et al., 2019; Liu & Wang, 2018), we divided the habitat quality into 5 grades (equal interval): (1) (0–0.2]- Very low habitat quality; (2) (0.2–0.4]- Low habitat quality; (3) (0.4–0.6]- Medium habitat quality; (4) (0.6–0.8] - High habitat quality; (5) (0.8–1] - Very high habitat quality (Table 4).

3.3.3. Assessment the impacts of rural residential land expansion on eco-environment

The impacts of rural residential land expansion on eco-environment were divided into direct and indirect impacts according to the influence path. Direct impact referred to the habitat quality loss caused by rural residential land occupying habitats (Tan & Li, 2013; Tian et al., 2014); and indirect impact referred to the surrounding habitat quality degradation caused by rural residential land expansion through household sewage pollution (Upadhaya & Dwivedi, 2019). The impact of rural residential land expansion on eco-environment was calculated based on the IHQ model by regulating threat sources. Two scenarios of habitat quality were calculated in this study. Scenario 1: The threat source included rural residential land expansion; Scenario 2: The threat source removed rural residential land expansion, and then evaluated the habitat quality. Specifically, the formulas of calculating direct and indirect impact were as followed:

$$\Delta E_1 S = \frac{\sum_{j=1}^{m} \sum_{x=1}^{n} Q_{jxt_1}}{N} - \frac{\sum_{j=1}^{m} \sum_{x=1}^{n} Q_{jxt_0}}{N} \tag{6}$$

$$\Delta E_2 S = \left(\frac{\sum_{j=1}^{m} \sum_{y=1}^{n} Q_{jyt_1}}{N} - \frac{\sum_{j=1}^{m} \sum_{y=1}^{n} Q_{jyt_0}}{N} \right) - \left(\frac{\sum_{j=1}^{m} \sum_{y=1}^{n} Q'_{jyt_1}}{N} - \frac{\sum_{j=1}^{m} \sum_{y=1}^{n} Q'_{jyt_0}}{N} \right) \tag{7}$$

Where $\Delta E_1 S$ was the direct loss of habitat quality caused by the expansion of rural residential land, $\Delta E_2 S$ was the indirect loss of habitat quality

Table 4
Features of each habitat quality level in Baota District.

Grades	Value	Features
Very high habitat quality	(0.8–1]	Have the richest biodiversity and provide the best ecosystem services for mankind
High habitat quality	(0.6–0.8]	Possess a relative rich biodiversity and provide a relative well ecosystem services for mankind
Medium habitat quality	(0.4–0.6]	Have a medium-level rich biodiversity, and provide basic ecosystem services for mankind
Low habitat quality	(0.2–0.4]	Biodiversity is low, and its vegetation coverage is low
Very low habitat quality	(0–0.2]	Biodiversity is extremely low, and ecosystem services are seriously damaged

caused by the expansion of rural residential land, Q was the habitat quality calculated at scenario 1, Q' was the habitat quality calculated at scenario 2, x was the grid cell occupied by rural residential land, y was the grid cell did not occupied by rural residential land, j was land use type, t_0 was the initial year, t_1 was the finial year, N was the total grid number. This model was suitable for measuring the impact process of specific threat sources on habitat quality within multiple time points.

4. Results

4.1. Rapid growth of rural residential land

The scale of rural residential land in Baota District increased dramatically during 1990–2015 due to rapid urbanization, with an average annual change rate of 3.13% (Fig. 4a). The growth rate of rural residential land decreased first and then increased. Specifically, because of the implementation of "Grain for Green" policy, which inhibited the expansion of rural residential land, the average annual change rate of rural residential land during 2000–2005 was 1.2% lower than average level. In contrast, the fastest growth period of rural residential land was 2010–2015 with 2.95% higher than the average annual change rate of 1990–2015. Besides, the expansion of rural residential land mainly distributed at the elevation between 900 m and 1050 m accounting for 78.3% of the total newly-added area, and at the hillside below 15° accounting for 84.3% of the total newly-added area (Fig. 4b and c).

Furthermore, the pattern of edge expansion had the largest scale among the newly added residential land. Specifically, edge expansion pattern was 757.34 ha, accounting for 71.76% of the total expanded area of rural residential land. Leapfrog and infilling patterns were 211.92 ha and 86.05 ha, accounting for 20.08% and 8.16% of the total expanded area of rural residential land, respectively (Fig. 4d).

4.2. Spatial-temporal change of habitat quality

The total area assessed by IHQ was 354.5 thousand ha, and the habitat quality of Baota District in 1990 and 2015 were separately 0.43 and 0.48 based on Equation (5), which indicates that the overall quality of habitat has developed in the course of study. However, we observed that the quality of habitats has a large spatial difference during the study period. As shown in Fig. 5, the area of habitat quality between 0.1 and 0.4 decreased 55.7 thousand ha, and the area of habitat quality between 0.4 and 0.8 increased 43.4 thousand ha during 1990–2015 in Baota District, which mainly distributed in northern rural areas. We also discovered that the area of very low habitat quality between 0 and 0.1 increased 2.97 thousand ha, which mainly distributed around urban and townships. Furthermore, the change rate of habitat quality was proportional to slope, and normally distributed as the altitude increased. The steep slope with the elevation of 1100 m–1300 m were the areas with obvious habitat quality improving.

The quality changes of different habitat types were also obviously different. As shown in Fig. 6, cropland, river and swamp decreased 202.7 ha high-level quality habitats, and increased 4.9 thousand ha low-level quality habitats. Besides, the average habitat quality of cropland, river and swamp decreased 0.01, 0.28 and 0.15. These all indicated that the biodiversity of crop, river and swamp were decreasing. Furthermore, the habitat quality of forest and grassland had been improved. Forest land, shrub wood land, dense grass land and sparse grass land increased 29.8 thousand ha high-level quality habitats. The average habitat quality of shrub wood land, dense grassland and sparse grass increased 0.03, 0.04 and 0.07 that indicated the biodiversity of these habitats were improved. In addition, reservoir increased 149.7 ha high-level quality habitats, and the average habitat quality increased 0.09 that indicated the biodiversity of reservoir improved.

On the whole, the area expanding of medium-high quality habitats and the habitat quality increase of shrub wood land, dense grassland and sparse grass led to the regional habitat quality improvement over the past two decades in Baota District.

4.3. Impacts of rural residential land expansion on eco-environment

There are two types of impact that RRLE could have on habitat quality. First, direct impact through land occupation. For example, forest or swamp turned into residential land. Second, the indirect impact of a new residential area on its surrounding area. For example,

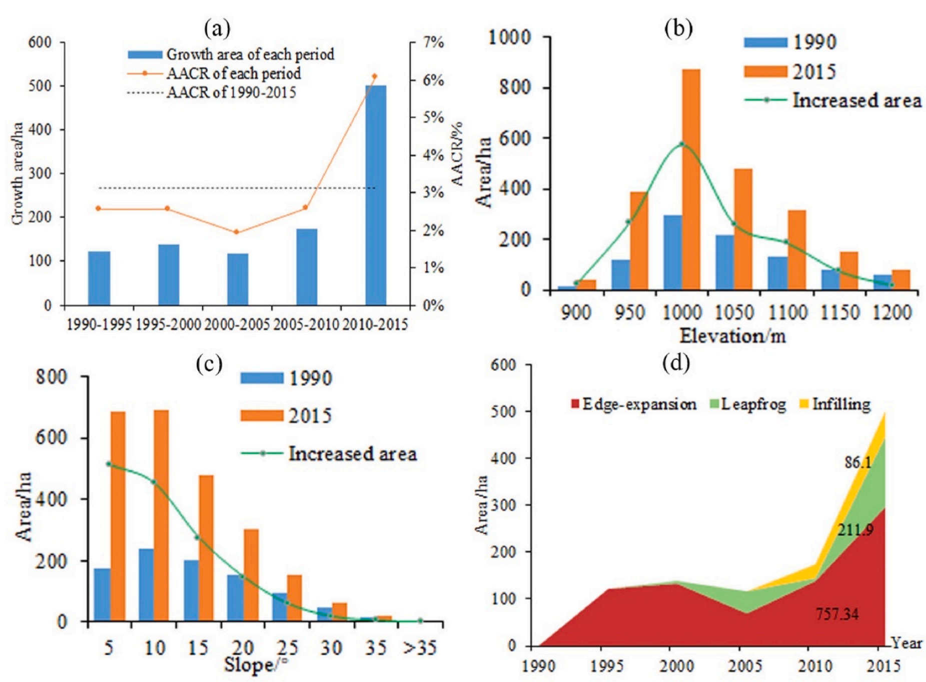

Fig. 4. The growth of rural residential land in Baota District, 1990–2015. Subfigure (a) showed the growth area and average annual growth rate of rural residential land; Subfigure (b) showed the relation between elevation and the expansion of rural residential land; Subfigure (c) showed the relation between slope and the expansion of rural residential land; Subfigure (d) showed area stacked chart of the expansion patterns of rural residential land.

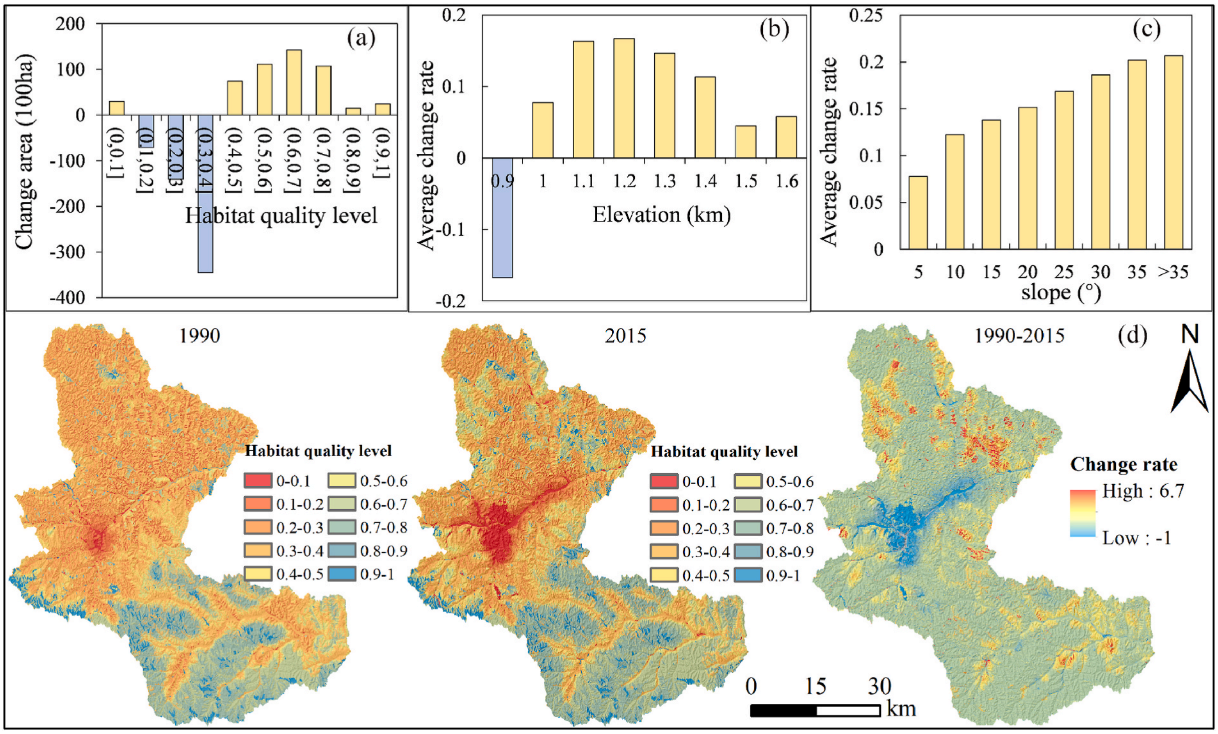

Fig. 5. Spatial-temporal distribution of habitat quality in Baota, 1990–2015. Subfigure (a) showed area change of each habitat quality level. Subfigure (b) showed the correlation between elevation and change rate of habitat quality. Subfigure (c) showed the correlation between slope and change rate of habitat quality. Subfigure (d) showed the spatial distribution of the change rate of habitat quality.

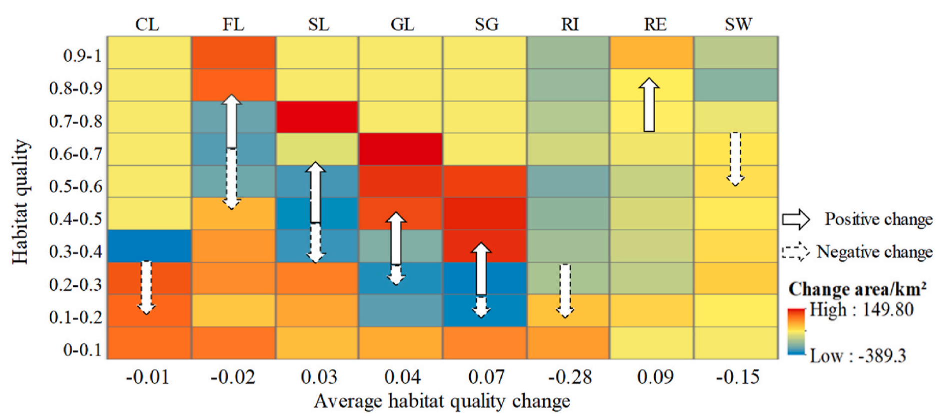

Fig. 6. Habitat quality change trends of each habitat type in Baota during 1990–2015, of which CL: Cropland; FL: Forest land; SL: Shrub wood land; GL: Dense grass land; SG: Sparse grass land; RI: River; RE: Reservoir; SW: Swamp.

Table 5
Occupied land by the expansion of rural residential land, 1990–2015.

Habitat types	Total area (ha)	Edge-expansion		Leapfrog		Infilling	
		Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Cropland	796.9	556.2	69.8	163.0	20.5	77.8	9.8
Forest land	60.1	57.5	95.6	1.8	3.0	0.8	1.3
Shrub wood land	6.6	5.7	86.8	0.3	4.5	0.6	8.8
Dense grass	38.6	29.1	75.5	9.5	24.5	0	0
Spare grass	123.1	91.1	74.0	26.0	21.1	6.0	4.9
River	22.7	12.4	54.7	9.4	41.4	0.9	3.8
Reservoir	5.1	5.1	100	0	0.0	0	0.0
Swamp	2.2	0.2	9.7	2.0	90.3	0	0.0
Direct loss of HQ	0.26%	0.11%		0.08%		0.07%	

household sewage from residential land that include nutrients and sediments.

The direct loss of habitat quality caused by the rural residential land expansion through occupying habitats in Baota District was 0.26% (Table 5). This meant that the expansion of rural residential land had reduced the biodiversity of Baota District by 0.26% through occupying habitats. Edge expansion had the greatest direct impacts on the quality of habitats, reducing the habitat quality by 0.11%, followed by leapfrog pattern and infilling pattern. From the perspective of loss area, edge expansion, leapfrog and infilling patterns in Baota District caused a massive cropland loss of 556.2 ha, 163.0 ha and 77.8 ha, accounting for 69.8%, 20.5% and 9.8% of the total loss of cropland, respectively. In addition, the area of spare grass land transformed to edge-expansion, leapfrog and infilling pattern were 91.1 ha, 26 ha and 6 ha, accounting for 74%, 21.1% and 4.9% of the total loss of spare grass land, respectively. Furthermore, areas of forest land were reduced 57.7 ha, 1.8 ha and 0.8 ha by edge-expansion, leapfrog and infilling patterns.

The indirect loss of habitat quality caused by the expansion of rural residential land in Baota District was 0.79% (Fig. 7). This meant that the expansion of rural residential land had degraded the biodiversity of Baota District by 0.79% through effecting the surrounding habitats. Edge expansion had the greatest indirect impacts on the quality of habitats, reducing the habitat quality by 0.38%, followed by leapfrog pattern (0.22%) and infilling pattern (0.19%). Moreover, the infilling pattern per square kilometer lead to a 0.049% indirect loss of habitat quality that was less than edge-expansion pattern (0.05%) and leapfrog pattern (0.057%). In addition, the indirect impacts, caused by rural residential land expansion patterns to each habitat type, were also different. Due to the discharge of household sewage, the biodiversity of swamps and river were most indirectly affected by the expansion of rural residential land. Affected indirectly by the expansion of rural residential land, the biodiversity of the swamps and river had dropped by 14.37% and 11.23%. On the contrary, shrub wood land was mainly distributed in hillside areas far away from residential land, so the shrub wood land was least affected by the indirect impact of rural residential land expansion. Affected indirectly by the expansion of rural residential land, the biodiversity of the shrub wood land had dropped by 0.18%.

5. Discussion

5.1. Possible factors impacting habitat quality change

Human-land relationship evolution largely resulted in eco-environment change in rural regional system. In the loess hilly and gully region, macro-scale environment policy, meso-scale land engineering projects and micro-scale residential land change were important

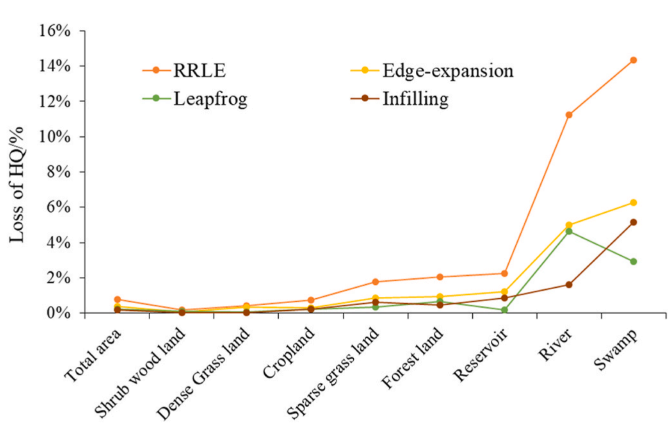

Fig. 7. Indirect impact of each expansion pattern of rural residential land on habitat quality of land use types, of which RRLE: rural residential land expansion.

driving factors on eco-environment changes.

Habitat quality in the northern rural areas of Baota District increase significantly, especially in the steep slopes and high altitudes areas over the past 25 years. The habitat quality of shrub wood land, dense grass land and sparse grass land all improved during the study period, which was consistent with the previous research in Baota District (Hou et al., 2017). These results were possibly attributed to the implementation of "Grain for Green" policy. This policy stipulated that areas with severe soil erosion, low grain output and slopes above 25° in mountainous and hilly area were the main targets for returning farmland to forests/grass (Cao, Xia, Xian, Guo, & Zheng, 2020). Baota District government released that the forest-grass coverage rate has increased to 68.2% since the implementation of reforestation (http://www.yanan.gov.cn). In this study, the area of forest increased 8.3 thousand ha during the study period, of which 82.1% transformed from cropland. The area of grassland enlarged 25.3thousand ha, of which 99.6% transformed from cropland. The scale of forest and grassland habitats has increased significantly during the study period. Meanwhile, the "Grain for Green" policy also had great impact on livelihoods of local residents. Residents gradually migrated from hillsides to valleys and towns so as to reduce the human disturbances on the forest/grass habitats and result in the quality of forest and grass obviously improved (Lu, Xu, Liang, Gao, & Ning, 2013). Therefore, the implementation of "Grain for Green" policy had effectively improved the quality of local habitats.

Moreover, land engineering projects also had great influence on habitat quality. Land creation project and gully land consolidation project were two major construction projects implemented in Baota District since the new century. The land creation project, covering 10.5 square kilometers, created flat ground by levelling hills and filling valleys, and occupied substantial forest and grass, which lead to the degradation of habitat quality around urban area (Liu & Li, 2014). Land creation project provided new development space for Baota District, alleviating the shortage of land resources, but it brought the loss of ecological service functions. On the contrary, the gully land consolidation project alleviated the issue of cropland declining, including dam system construction, gully drainage, ditch head treatment, slope protection and farmland irrigation (Liu & Li, 2017). Gully land consolidation project improved the diversity of landscapes by increasing the area of farmland, forest land and reservoirs (Li, Li, et al., 2019), and greatly facilitated vegetation improvement, ecosystem stability, biodiversity protection and enhancement of flood control capacity.

It is undeniable that under the influence of "Grain for Green" policy, the habitat quality of Baota District has been improved (Cao, Li, Liu, Chen, & Wang, 2018). However, the rural residential land expansion inevitably has a negative impact on local environment (Long et al., 2009). As illustrated in Fig. 8, the rate of rural residential land expansion was significantly negative correlating to the rate of habitat quality improvement. Rural residential land in Baota District gradually distributed from hillsides to new rural community around towns because of the implement of "Grain for Green" policy and the new-countryside construction project. The migration from rural residents to townships and the increased residential land decreased the quantity and quality of surrounding habitats. Cropland, grassland and forest land were the main habitat types occupied by rural residential land expansion (Liu et al., 2017). The expansion of rural residential land in Baota District respectively occupied 796.9 ha of cropland, 123.1 ha of sparse grassland, and 60.1 ha of forest land, causing a degradation of biodiversity.

5.2. Different impacts of each expansion pattern of rural residential land on eco-environment

To evaluate the impacts of each expansion pattern of rural residential land on eco-environment, the direct and indirect impacts of rural residential land expansion on habitat quality were generated in this study. The intensity of direct impact was largely related to the scale of each

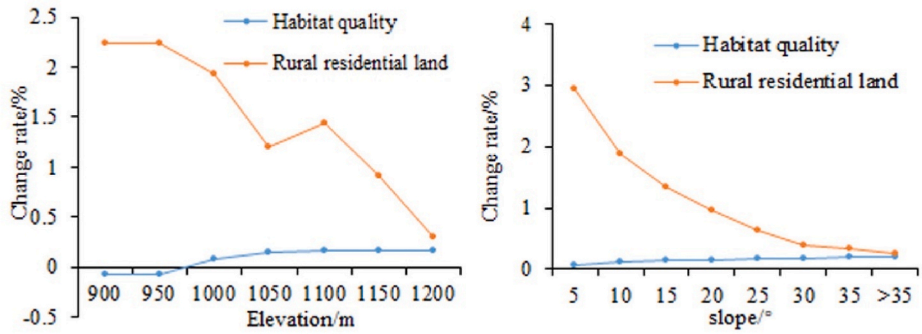

Fig. 8. Spatial coupling between rural residential land expansion rate and habitat quality change rate.

expansion pattern of rural residential land and the habitat quality score of the occupied land (Xu et al., 2016). In China's rural areas, edge expansion was the main expansion pattern of rural residential land on account of the homestead policies restrictions and living habit (Tian et al., 2014). The expansion scale of leapfrog pattern was relatively small, covering new rural communities, post-disaster reconstruction communities and self-built houses of individual farmers. The expansion scale of infilling pattern was also small, mostly distributed around county or towns with dense and fast-growing settlements. Therefore, edge-expansion pattern usually had the greatest direct influence on eco-environment, which was consistent with this study. Besides, the direct loss was as well related to the habitat quality score of occupied land. On the premise of same expansion area, the higher initial habitat quality of occupied land, the greater direct loss of eco-environment.

In addition, the indirect impact of rural residential land expansion was mainly related to the spatial morphology of different expansion patterns, the influence radius of rural residential land, the scale of rural residential land expansion and the sensitivity of the surrounding habitat to rural residential land (Fischer & Lindenmayer, 2007; Sharp et al., 2016). Fischer and Lindenmayer (2007) indicated that fragmentation of landscapes had negative impact on habitat quality. Thus, rural residential land expansion patterns had different effects on eco-environment according to the spatial morphology difference. Assuming that the ecological environment of rural system was homogeneous, then under the same expansion scale, the indirect influence area changed because of different spatial morphology. The law of change was infilling pattern < edge-expansion pattern < leapfrog pattern, and the results of this study also confirmed the hypothesis. In this study, the indirect loss of habitat quality caused by the infilling pattern (0.04%) per unit area was lower than that caused by the edge-expansion pattern (0.05%) and leapfrog pattern (0.06%). Therefore, edge-expansion pattern was the main reason for the degradation of habitat quality from the perspective of rural residential land expansion scale. However, the leapfrog expansion pattern posed the greatest potential threat to habitat quality under the same expansion scale.

5.3. Policy implications for rural spatial restructuring

According to the spatial variability of habitat quality and the different impacts of rural residential land expansion patterns on eco-environment, some possible policy recommendations for rural spatial restructuring were put forward. Firstly, the analysis results indicated that the newly-added rural residential land and habitat quality improvement areas in Baota District had different spatial trends. For example, newly-added rural residential land were mainly distributed in low-altitude, low-slope valley areas; habitat quality improvement areas were mainly distributed in steep slopes areas with an elevation between 1100 m and 1300 m. The phenomenon of functional zoning of living space and ecological space in rural areas was gradually prominent. (Figs. 4 and 5). Mitigating the conflict between living-production space and ecological space was the overarching issue for balancing rural development and ecological security (Yang, Bao, & Liu, 2020). Compared with broken habitats, the integrity and concentration of habitat patches were more conducive to the protection of biodiversity (Li, Chen, & He, 2015). Therefore, in the process of rural spatial restructuring, the zoning management of multi-functional spaces and the centralized protection of ecological space should be strengthened, especially in ecologically fragile areas.

In addition, the centralized and contiguous development model centered on small townships should be the direction of rural spatial restructuring (Fig. 9). The small and scattered rural residential land distribution pattern was not only unfavorable for supporting infrastructure, but also increased the threat level of surrounding eco-environment. Considering the different impacts of rural residential land expansion patterns on ecological environment, the concentrated and contiguous development of rural residential land was more conducive to the protection of eco-environment. Because the centralized development mode could reduce the occurrence of leapfrog expansion, an expansion pattern that was the most threatening to surrounding habitats, and it was convenient for supporting infrastructure. Small townships, as sub-centers of the county, have complete basic public service facilities, and they are also the ideal areas for villages to gather and develop nearby. For example, concentrating the new added rural residential land of villages into townships, and resetting the houses of hollow Village residents into townships.

Furthermore, the implement of relevant land regimes would effectively guarantee the spatial optimization and reconstruction of rural residential land. The unclear subject of rural land property rights and the unreasonable circulation of rural land element market had negatively affected the efficiency of rural residential land optimization in the current situation (Tu & Long, 2020). It was urgent to promote the innovation of rural land regime through the improvement of property value and income evaluation mechanism, land circulation market monitoring and control mechanism to ensure the implementation of rural spatial restructuring.

5.4. Limitations

Limited by high-resolution land-use data, we only used observational land-use data at specific time points to explore the variation of rural residential land and its impact on habitat quality. Time series data should be used to quantitatively assess the dynamic process of the impact of rural residential land expansion on habitat quality. In addition, identification of appropriate parameters for modeling had always been a challenge issue in the habitat quality assessment research. The parameters of habitat suitability and threat level for the IHQ model in this study were mainly identified based on experts' experience and published literature, ignoring the variations within the same type of habitat. We would further improve our approach by field sampling or a biogeochemical model in future study.

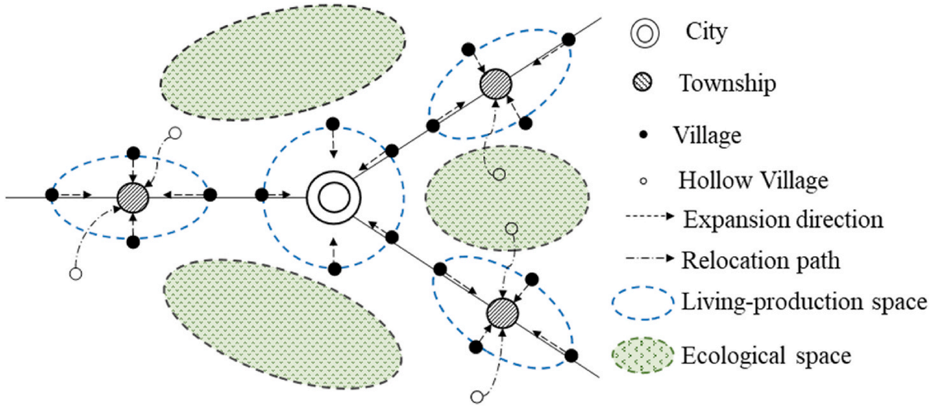

Fig. 9. A conceptualization of the models of rural spatial restructuring.

6. Conclusion

In this study, we analyzed rural residential land and habitat quality changes in Baota from 1990 to 2015 based on land use datasets (30-m spatial resolution), with the help of IHQ model. We also proposed a quantitative method to measure the direct/indirect impacts of rural residential land expansion on eco-environment. Results indicated that: (1) The newly-added rural residential land and habitat quality in Baota District had large spatial differences during the study period, meanwhile they had different spatial tendency characteristics. The emerging of functional zoning of living space and ecological space in rural areas was gradually prominent. (2) Although edge-expansion pattern was the main reason for the degradation of habitat quality, the leapfrog expansion pattern potentially raised the greatest threat to habitat quality. (3) We believed that strengthening the management of rural multifunctional zoning and the centralized and contiguous development model centered on small townships would be the direction of rural spatial restructuring in ecologically fragile region. This study proposed a quantitative method to measure direct/indirect impacts of rural residential land expansion on eco-environment, and further explored the different impacts of rural residential land expansion patterns on eco-environment. Ultimately, this provides a better understanding of the impacts of rural residential land on eco-environment, especially from different expansion patterns perspective.

CRediT authorship contribution statement

Zongfeng Chen: Conceptualization, Data curation, Methodology, Writing – original draft. **Yurui Li:** Formal analysis, Writing – review & editing. **Yansui Liu:** Supervision, Funding acquisition. **Xueqi Liu:** Formal analysis, Data curation.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 42001204, 41931293 and 41801175). We are grateful to two anonymous reviewers who made valuable and constructive comments on an earlier version of this manuscript.

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