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Land use/cover changes in the Oriental migratory locust area of China: Implications for ecological control and monitoring of locust area

Longlong Zhao[a,b], Wenjiang Huang[c,*], Jinsong Chen[a,b], Yingying Dong[c], Binyuan Ren[d], Yun Geng[c,e]

[a] Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, 518055, China
[b] Shenzhen Engineering Laboratory of Ocean Environmental Big Data Analysis and Application, Shenzhen, 518055, China
[c] Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, 100094, China
[d] National Agro-Technical Extension and Service Centre, Ministry of Agriculture, Beijing, 100026, China
[e] University of Chinese Academy of Sciences, Beijing, 100049, China

A R T I C L E I N F O

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A B S T R A C T

The Oriental migratory locust (*Locusta migratoria manilensis*) is a threat to agriculture in China. The locust area is defined as an area possessing a suitable breeding habitat for this locust and has a locust outbreak at least once per decade. Ecological control of the locust area is an effective approach to manage locust with minimal environmental degradation. The formation and dynamic changes of locust areas are greatly affected by land use/cover changes (LUCC). Clarifying the LUCC in the locust area is significant for implementing rational ecological control strategies and detecting timely potential locust areas. This paper proposed a patch-based habitat suitability assessment (PHSA) method for nationwide locust area extraction. Then, a multi-temporal binary coding method was used to detect the locust area dynamic changes from 1995 to 2017. Subsequently, the relationship between LUCC and the extinction and formation of locust areas in different ecotypes was quantitatively investigated. Results show that the area of the locust area has greatly reduced over the past 20 years, and the distribution range has a large degree of temporal and spatial variation. The extinction of the locust area is closely related to the LUCC from cropland and wetland to woodland and artificial surface. It is also related to changes from grassland to cropland and woodland. The newly formed locust area shows opposite LUCC trends. These results provide practical strategies and guidance for ecological control and early monitoring of locust areas. They are instrumental in reducing pesticide use and achieving more sustainable agriculture.

1. Introduction

The Oriental migratory locust (*Locusta migratoria manilensis* (Meyen)) is one of the most destructive insect pests in China. More than 1.5 million hectares of land are infested annually, threatening crop production, and economic stability (Li et al., 2010; Yang and Ren, 2018). The area infested by the locust varies yearly due to climate change, water system change, and human activities (Calvão and Pessoa, 2015), and this increases the challenge of green prevention and control (GPC, such as ecological regulation and physical control) of locusts (Yao et al., 2017a). China has not conducted a recent systematic survey of the locust area, which makes the prediction and prevention of locust outbreaks difficult (Zhu, 1999). Traditional empirical approaches, based on artificial spot investigations, have been used for locust monitoring. These are inefficient, inaccurate, and likely to overlook useful prevention measures. Due to the extensive locust distribution, these spot investigations are unlikely to provide efficient and targeted management of the locust (Ji et al., 2004). Satellite-based remote sensing technology can be useful for monitoring the large areas of locust habitat (Sivanpillai et al., 2006; Cressman, 2013; Mohammed et al., 2015; Renier et al., 2015). However, there are few studies on locust area delineation. A large-scale and high-precision method for locust area identification is needed for more accurate and efficient locust control.

China has developed an integrated management technology for locusts based on ecological control (in areas where the breeding environment can be modified), combined with biological control (fungal pathogen applied when locusts are low to medium density) and chemical control (pesticides applied when locusts reach a high-population density) (Zhu and Chen, 2010; Ren et al., 2017). However, because locust habitats are mostly in coastal areas, along the rivers, lakes, and

* Corresponding author.
E-mail address: huangwj@aircas.ac.cn (W. Huang).

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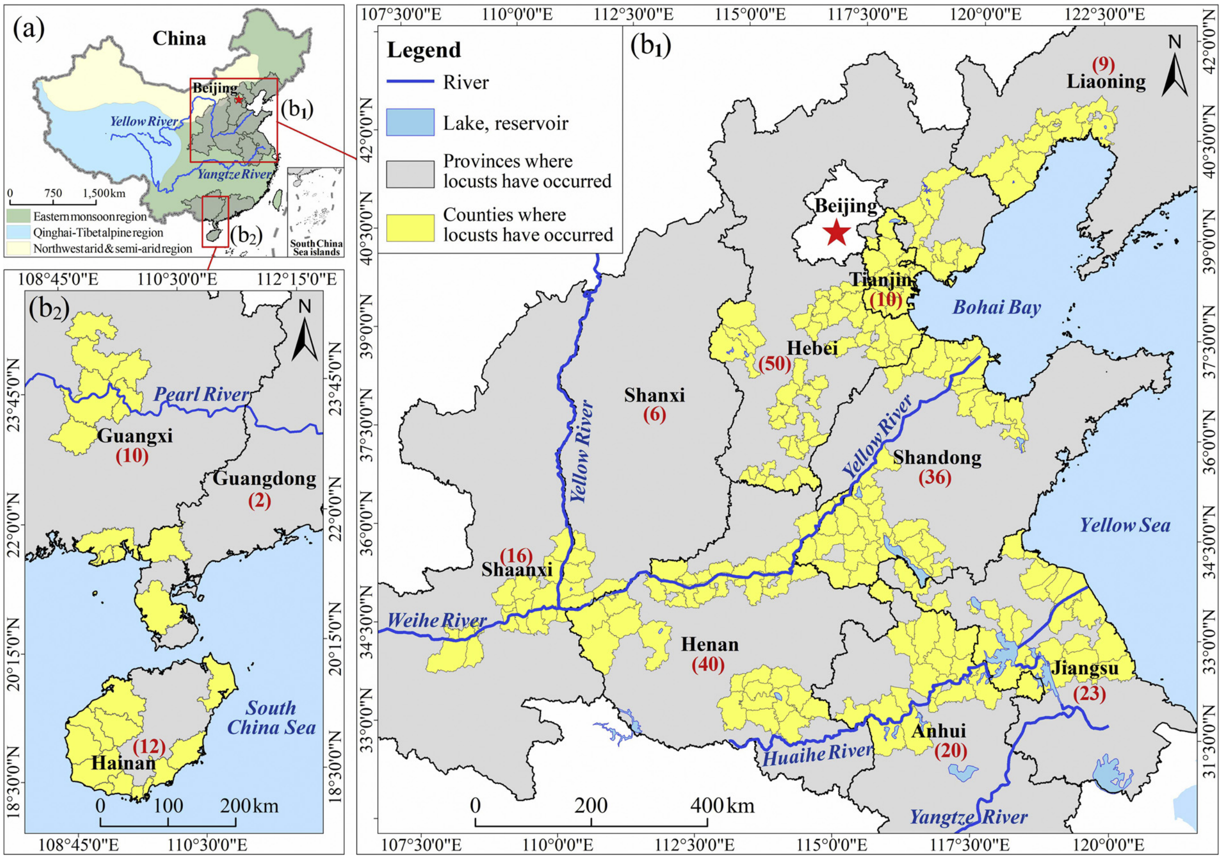

Fig. 1. (a) The geographical location and climatic region of the study area in China; (b_1) & (b_2) The specific locations of 234 counties (yellow polygons, namely the study area) in 12 provinces (gray polygons) where locusts had been reported during at least one year from 1990 to 2018. The red numbers represent the number of counties in each province (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

other water sources, the use of chemical pesticides in these areas can cause serious environmental problems. These problems include water pollution, soil pollution, biodiversity reduction and environment damage (Everts and Ba, 1997; Maute et al., 2015; Adriaansen et al., 2016; Maute et al., 2017; Chiaia-Hernandez et al., 2017; Singh et al., 2018). Pesticide use can therefore compromise the goals of least-toxic pest management and sustainable agriculture (Gomiero et al., 2011; Buckwell et al., 2014; Bais-Moleman et al., 2019). According to Puyun Yang, a pest control expert from the National Agro-Tech Extension and Service Center, the control efficiency of the above three measures is 70 %, 20 %, and 10 % respectively (personal communication). Compared with chemical control, ecological control can achieve long-term control of locusts by transforming and reducing the breeding environment of locust with minimal environmental degradation. Therefore, ecological control of locust areas by habitat modification has an important role in achieving locust population management and supporting sustainable agriculture.

Successful oviposition and development of locusts generally depend on specific landscape structure and habitat conditions. These include favorable host components, suitable vegetation coverage, optimal soil temperature, moisture and salinity, and required water sources (Shi et al., 2018). Locust habitat is affected by natural factors, such as changes in climate, water level, and river systems (Stige et al., 2007; Yu et al., 2009; Propastin, 2013; Li et al., 2017), and human activities such as afforestation, dams construction, and urban expansion (Zhu, 1999; Li et al., 2003, 2008; Tian et al., 2009; Yang and Ren, 2018). Land use/cover change (LUCC), is a direct consequence of nature and human interactions (Liu et al., 2010; Anett et al., 2011; Matinfar et al., 2013; Li and Gao, 2017; Yao et al., 2017b). It can provide essential information for locust area extraction. The key to locust area dynamic changes are habitat changes caused by LUCC. Quantitative influence analysis of LUCC on locust area evolution can help to evaluate the success of ecological control efforts in China and provide an insight into the timely detection of potential locust areas over large and often inaccessible areas. Previous investigations have studied locust occurrence mechanism (Ni, 2002; Ma et al., 2005; Deveson, 2013; Renier et al., 2015), classified and evaluated locust habitat (Bazelet and Samways, 2011; Chen and Wang, 2012; Shen, 2015; Löw et al., 2016), and explored the major factors contributing to locust outbreaks (Tian et al., 2011; Chen et al., 2014; Li et al., 2015). However, additional data are needed for a full understanding of locust outbreaks and management. For example, there is little information on the drivers of locust area evolution related to LUCC and their applications for ecological control of locust areas.

Landscape structure changes can impact geographical patches within which a series of pixel-scale factor transformations might collectively affect locust habitats (Shi et al., 2018). In this study, we used a method based on habitat suitability assessment on patches. It combines spatiotemporal information to extract locust areas over a large scale by balancing the satellite-derived long-term parameter and landscape structure. A locust area is defined as one in which locust outbreaks occur at least once every 10 years (Zhu, 1999). We extracted the spatial distribution of locust areas at about a 10-year interval, from 2005 to 2017 and explored the relationship between locust area evolution and LUCC. The goal of this study was to help pest managers implement effective ecological control measures to manage known locust areas and to monitor potential locust areas, on a timely basis, to promote green pest management and sustainable agriculture. The specific objectives were (1) to propose a method with strong universality for large-scale identification of locust areas based on habitat suitability assessment on a patch scale; (2) to quantify the influence of LUCC on locust area evolution in different ecotypes by monitoring dynamic changes of 1995, 2005 and 2017; and (3) to provide suggestions for ecological control of known locust areas and the monitoring of potential locust areas.

2. Materials and methods

2.1. Study area

The habitats of the Oriental migratory locust in China are mainly depressions, plains, and hills south of 42 °N at elevations ranging from 2 to 50 m (Zhu, 1999). A total of 234 counties (city, district) in 12 provinces (municipality, autonomous region) reported locusts during at least one year from 1990 to 2018. These 234 counties, with a total area of 311,423 km^2, were selected as the study area (Fig. 1). The study area is located in the Eastern monsoon region of China (Fig. 1a) and is mainly distributed along the Bohai Bay, the middle and lower reaches of the Yellow River, the Weihe River, the Huaihe River, some depressions in North China, and the coastal areas of Hainan, as well as the riverbanks in southwestern Liaoning, southern Guangdong, and central Guangxi. The area includes numerous rivers, channels, ponds, lakes, and reservoirs along which there is a suitable habitat for the locust (Fig. 1b_1, b_2). Based on the formation structure and causes, the locust area in China can be divided into four ecotypes: coastal locust area (CoLA), riverine locust area (RiLA), lakeside locust area (LaLA), and waterlogged locust area (WaLA) (Ma et al., 1965; Zhu, 1999). The study area covers all the locust distribution areas in China documented in the past 30 years, including all ecotypes of the locust area.

2.2. Data acquisition and processing

2.2.1. Satellite data

Habitat conditions in the locust areas reflect long periods rather than brief, transient periods. They should be derived from multi-year and multi-scene remote sensing images. Therefore, the satellite data obtained in this study included Landsat TM from 1993 to 1997, 2003–2007, and Landsat OLI from 2015 to 2018, which covered the entire study area. Images of areas during periods of the key growth stages of locusts (May to August) were used. These data were used to obtain average vegetation coverage for locust area extractions of 1995, 2005 and 2017, respectively. Considering the cloudy and rainy weather in the southern area, images from May to August were used for the area covered the locust area of Guangdong, Guangxi and Hainan Provinces (the Southern locust area for short), and images from June to July were used for the locust area of the other provinces (the Northern locust area for short). Vegetation coverage (F_c) was calculated by the Google Earth Engine (GEE) using formulation 1.

$$F_c = (\mathrm{NDVI} - \mathrm{NDVI}_{soil})/(\mathrm{NDVI}_{veg} - \mathrm{NDVI}_{soil}) \quad (1)$$

where F_c is the vegetation coverage with values ranging from 0 to1, NDVI is the normalized differential vegetation index, NDVI_{soil} is the NDVI value of pure bare soil pixel, and NDVI_{veg} is the NDVI value of pure vegetation pixel.

The *Landsat.simpleComposite* algorithm provided by GEE was used to composite the multi-year Landsat images. The cloud coverage of images used was less than 10 %. The detailed acquisition time and count of the selected images of each year for vegetation coverage calculation are shown in Table A1 (Supplementary material). All the data used were projected to WGS_1984_Albers coordinates and resampled to a 30-m spatial resolution in ArcGIS 10.3.

2.2.2. Land use/cover products

National land use/cover (NLUC) products at a 30-m resolution of 1995 and 2005 provided by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences were used for the locust area extraction of 1995 and 2005. These data consisted of six classes (woodland, grassland, wetland, cropland, artificial surface, and “others”) with a classification accuracy of 94 % and 38 subclasses with an overall accuracy of 86 % (Editorial Committee on Land cover map of the People’s Republic of China (ECLCC, 2017). Global land cover (GLC) products at 30 m resolution of 2017 (http://www.chinageoss.org/) were used for the locust area extraction of 2017. These data included ten classes (cropland, forest, grassland, shrubland, wetland, water, tundra, impervious surface, bareland, and snow/ice) with an overall accuracy > 71 % (Gong et al., 2013). The classification accuracy of these two products met the study requirement of locust area extraction accuracy. To unify the classification standards, the two kinds of products were reclassified into seven classes (woodland, grassland, wetland, water, cropland, artificial surface, and “others”). The detailed reclassification rule and the description of each class are shown in Table A2 (see Supplementary material).

2.2.3. Occurrence records of the Oriental migratory locust

National Agro-Tech Extension and Service Center (NATESC) and Plant Protection Stations of the provinces, cities, and counties provided detailed historical occurrence statistics, pictures and documents of Oriental migratory locusts from 1990 to 2018, including habitat conditions, occurrence areas, occurrence locations, severity grade, and control measures. Some records are available in detail down to the town and village levels. After a comprehensive analysis of these materials, the national locust area regionalization data of 1995, 2005, and 2017 were manually extracted in ArcGIS 10.3 based on the locust occurrence locality data of 1990–1999, 2000–2009, and 2010–2018, respectively. The occurrence records were important indicators of locust areas different from suitable area and validation data for locust area extraction accuracy.

2.2.4. Soil data and auxiliary data

Current soil characteristics reflect the history of soil evolution (Guan, 2016). The geography and environments of a region generally do not change greatly over short periods. The existing national soil classification system of China is mostly based on the second national soil survey conducted in the 1980s. Therefore, the soil types in the study area were considered unchanged during the multi-period locust area extraction. The relatively new 1:1,000,000 National soil database released by the Institute of Soil Science, Chinese Academy of Sciences in 2008 was used. Besides, the National 1:100,000 basic geographic information data updated in 2015 (http://www.webmap.cn/) were used to determine the extent of the study area and show the distribution of the locust area from 1995 to 2017.

2.3. Analytical methods

The flowchart in Fig. 2 describes our methodology. It shows the analytical processing steps and the data used. First, the locust area extraction method was based on habitat suitability assessment at the patch level. Then, spatiotemporal dynamic change monitoring of the locust area, from 1995 to 2017, was conducted based on a multi-temporal binary coding method. Finally, the impact of LUCC on locust area evolution based on a land-use transfer matrix method was analyzed. The key techniques and methods used in this study are described below.

2.3.1. Locust area extraction at the patch scale

Based on a comprehensive effects analysis of the terrain, climate, soil, vegetation, hydrology, and human activities on locust breeding, combined with the research objectives of this study, under the principles of being indispensable, relatively stable, different, and accessible, four factors of vegetation coverage, soil type, land use/cover type, and locust area regionalization data were employed as locust habitat suitability assessment factors.

A patch-based habitat suitability assessment (PHSA) model was

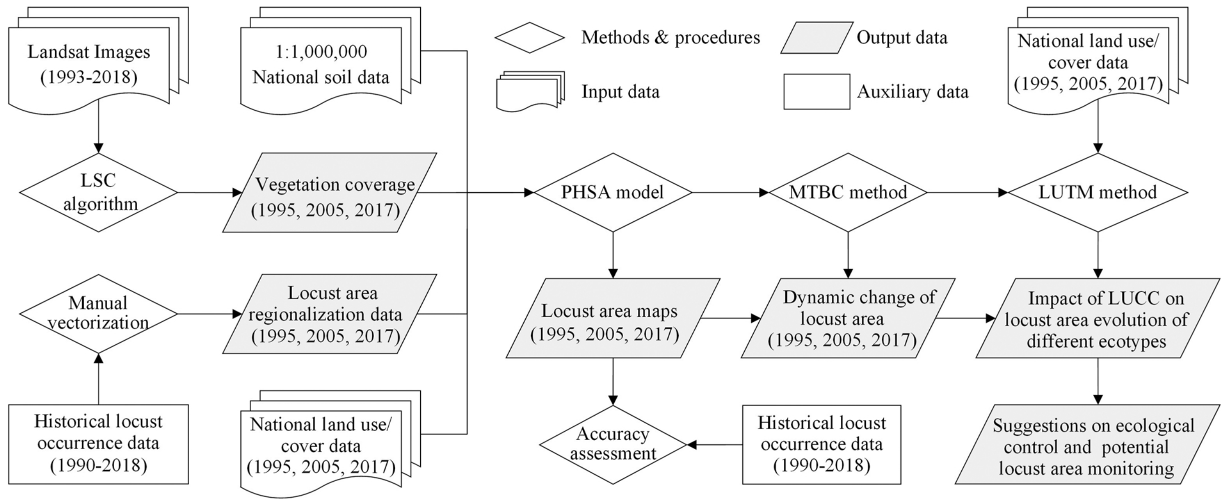

Fig. 2. Flowchart for exploring the impact of LUCC on the locust area dynamic changes and its implications for locust area control and monitoring. Note: LSC, Landsat Simple Composite algorithm provided by GEE; PHSA, Patch-based Habitat Suitability Assessment model used to extract locust area; MTBC, Multi-temporal Binary Coding method used to detect the dynamic changes of locust area; LUTM, Land-Use Transfer Matrix method used for relationship analysis between LUCC and locust area evolution.

proposed to extract the locust area. By using a moving-window approach, the membership degree of three habitat suitability assessment factors (vegetation coverage, soil type, and land use/cover type) was obtained at the patch scale, which introduced additional information from neighboring pixels of a given patch was restricted by a moving window. The locust area regionalization data was not graded for suitability since it was binary data used as an indicator of locust sources. The patch-based membership degree $M_{t,p}$ was calculated with the following formula:

$$M_{t,p}(x_{(w+1)/2}, y_{(w+1)/2}) = \sum_{j=1}^{w}\sum_{k=1}^{w} W_{j,k} M_t(x_j, y_k) \Bigg/ \sum_{j=1}^{w}\sum_{k=1}^{w} W_{j,k} \tag{2}$$

where $M_{t,p}$ $(x_{(w+1)/2}, y_{(w+1)/2})$ is the membership degree of assessment factor t ($t=$ {1, 2, 3}) at the patch scale. w, an odd number, is the moving window size and $(x_{(w+1)/2}, y_{(w+1)/2})$ is the central pixel of this moving window. $W_{j,k}$ is the weight which determines how much each neighboring pixel contributes to the central pixel and M_t (x_j, y_k) is the membership degree of the factor t at the pixel scale. These two parameters were determined by the following two methods:

1) Determination of $W_{j,k}$

The spatial similarity is normally better for a closer pixel, so the closer pixels should be assigned a higher weight. Thus, the reciprocal of the spatial distance between the central pixel and neighboring pixels within the moving window was adopted as the weight, which is defined as follows:

$$W_{j,k} = \frac{1}{d_{j,k}} = \frac{1}{\sqrt{(x_{(w+1)/2} - x_j)^2 + (y_{(w+1)/2} - y_k)^2}} \tag{3}$$

where $d_{j,k}$ is the spatial distance between the central pixel $(x_{(w+1)/2}, y_{(w+1)/2})$ and the surrounding pixels (x_j, y_k).

2) Membership degree of the assessment factors at the pixel scale M_t (x_j, y_k)

With the large distance from north to south, the soil types of the locust area in China varied with different ecotypes within the locust area (Zhu, 1999). Different soil types have different effects on the occurrence of locusts even within a single ecotype (Qiu, 2006). Thus, the soil type suitability membership degree determination was carried out on a regional basis (Table 1). The locust usually prefers vegetation communities dominated by gramineous plants and crops of wheat, maize, sorghum, and rice. The optimum vegetation coverage for locust reproduction is from 15 % to 50 %, and when it is > 80 % or < 10 % there are few locusts (He and Huang, 2016). Based on field investigations and literature reviews, grasslands and wetlands are ideal places for locust reproduction since they provide the most favorable host plants. Cropland also provided optimal food for locusts in several years. Although locusts cannot survive long submersion in water, water sources often provide an ideal environment for egg hatching and nymph growth. Locusts will not lay eggs in settlement areas, saline, and alkaline lands (Sobrino et al., 2004; Shi et al., 2018). Based on this information, we empirically assigned each assessment factor with four suitability degrees: most suitable, sub-suitable, general suitable, and unsuitable, and the suitability was assigned as 4, 3, 2, 1, respectively. The assessment criteria are shown in Table 1. The relatively high suitability degree of water was balanced by that of low vegetation coverage in the assessment model.

Then an assessment index (*HSI*) of the patch-based habitat suitability assessment (PHSA) model for locust area extraction was established and calculated as follows:

$$HSI(x, y) = \left[\sum_{t=1}^{n} W_t \cdot M_{t,p}(x, y)\right] \times L(x, y) \tag{4}$$

where HSI (x, y) is the habitat suitability assessment index with values ranging from 1 to 4, $M_{t,p}$ (x, y) is the membership degree of factor t at the patch scale, $n = 3$. W_t is the weight of factor t, which was empirically determined as 0.20, 0.35, and 0.45, corresponding with soil type, vegetation coverage, and land use/cover type, respectively. $L(x, y)$ is the locust area regionalization data with a value of 0 or 1. By applying the PHSA model to three typical locust areas where locusts occur almost every year (Dagang District in Tianjin, Dongying District and Kenli District in Shandong, and Dongfang City in Hainan), a threshold of 2.75 for locust area extraction was determined. This means that areas with $HSI > 2.75$ are locust areas.

For assessing the accuracy of the locust area extraction results, a correlation analysis method between the extraction locust area and locust occurrence was employed, and an R^2 value was calculated to measure the accuracy.

$$R^2 = [correl(x, y)]^2 = \left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}\right)^2 \tag{5}$$

where *correl* (x, y) is the correlation coefficient of x and y with values ranging from –1 to 1. x_i is the area of locust area extracted in province i, y_i is the area of locust occurrence area in province i, n is the number of provinces where had reported locusts. $\bar{x}$ and $\bar{y}$ are the mean value of x_i

Table 1
Assessment criteria for the factors on Oriental migratory locust habitat suitability.

Assessment factors		Most suitable	Sub-suitable	General suitable	Unsuitable
Soil type	CoLA around Bohai Bay and the Yellow Sea	Coastal tidal soil	Coastal salinized tidal soil, Salinized swamp tidal soil	Coastal salinized soil	Coastal swamp soil, Swamp tidal saline soil
	RiLA along the Yellow River and the Huaihe River	Eutric fluvisol, Calcaric fluvisol	Lime concretion black soil, Viscous fluvisol	Calcareous cambisol, Gleyic cambisol	Accumulated anthrosol, Gleyic luvisol, Gleyic solonetz
	LaLA in North China, along the Huaihe River and Weishan Lake	Silic alluvial soil, Calcaric fluvisol	Mollic gleysol, Salinized tidal soil	Calcareous cambisol, Calcareous gleysol,	Accumulated anthrosol, Calcic luvisol
	WaLA in Huang-huai watershed	Eutric fluvisol, Calcaric fluvisol	Tide brown soil, Alkaline sand black soil	Saturated vertisols, Saturated planosol	Gleyic luvisol
	WaLA in North China and the Haihe River watershed	Coastal tidal soil	Salinized swamp tidal soil	Calcareous gleysol	Gleyic luvisol, Mollic solonchak
	Tropical savannah locust area in Hainan and RiLA in Guangdong and Guangxi	Chromic cambisol, Ferric luvisol	Monocrystalline ferralsol, Dystric regosol	Yellow ferralsol, Ferralic cambisol	Haplic luvisol, Orthic acrisol, Accumulated anthrosol
Vegetation Coverage		15 %–50 %	50 %–75 %	10 %–15 % or 75 %–85 %	< 10 % or > 85 %
Land use/cover type		Grassland, Wet land	Cropland, Water	–	Woodland, artificial surface, "others"
Suitability assignment		4	3	2	1

Note: CoLA, coastal locust area; RiLA, riverine locust area; LaLA, lakeside locust area; WaLA, waterlogged locust area.

Table 2
Multi-temporal binary coding method for dynamic monitoring of locust area.

Bit	Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
Period	Null	Null	Null	Null	Null	2017	2005	1995

and y_i. And y_i here is the annual average area of locust occurrence areas in province i in corresponding years, namely, 1990–1999, 2000–2009, and 2010–2018.

2.3.2. Spatiotemporal dynamic change monitoring of locust area

Multi-temporal spatial change analysis of remote sensing image interpretation or classification results usually uses the GIS overlay analysis method. This method not only has a large workload but also is not conducive to the analysis of finely divided units. The extraction results of the locust area in the three periods in this paper had a large amount of data volume with a mass of fragmentation, so this work used the multi-temporal binary coding (MTBC) method (Wang et al., 2016) to describe the locust area dynamics. This method can obtain a byte-type dynamic change image of the locust area, which can express the dynamic changes of the locust area of the three periods at the pixel scale with minimum storage space. One byte has 8 bits from Bit0 to Bit7. Bit0, Bit1, and Bit2 respectively represented the distribution of the locust area in 1995, 2005, and 2017, and Bit3, Bit4, Bit5, Bit6, and Bit7 were null (Table 2). For the three period locust area maps with consistent 30-m spatial resolution, the gray value ($V_{year,\ i}$, $i = 0, 1, 2$) of pixels belonging to the locust area is 1, and the value of pixels which are not locust area is 0. By taking the equation below, a byte-type dynamic change image of locust area in the past 20 years was obtained (Fig. 6a):

$$V_{dyna} = \sum_{i=0}^{n} 2^i \cdot V_{year,i} \tag{6}$$

where V_{dyna} is the gray value of the dynamic change image, $V_{year,\ i}$ is the gray value of locust area maps in the ith period, $n = 2$, and $i = 0, 1, 2$ represent 1995, 2005 and 2017, respectively. If the gray value of a pixel is 5, the corresponding binary is "101", indicating that the pixel is locust area in 2017 and 1995, but is not a locust area in 2005. Therefore, the statistical distribution of gray value in dynamic change image can quickly and accurately obtain the spatial change information of the locust area in different periods.

After the dynamic change monitoring of locust area, four evolution types were defined: 1) the extinct locust area, areas with gray values of 1 or 3, namely the pixels with binary code of "001" or "011", 2) the newly formed locust area, areas with gray values of 4 or 6, namely the pixels with binary code of "100" or "110", 3) the repetitive locust area, areas with gray values of 2 or 5, namely the pixels with binary code of "010" or "101", and 4) the stable locust area, areas with gray values of 7, namely, the pixels with binary code of "111" (Table 4). These evolution types were used for the impact analysis of LUCC on locust area evolution.

2.3.3. Impact analysis of LUCC on locust area evolution

To explore the relationship between LUCC and locust area evolution, the land-use transfer matrix (LUTM), which reflects the total area of each land use/cover type in a specific period and also reflects the transfer process of each land use/cover type from the initial period to the terminal period, of locust area evolution type was calculated. Then two indices, the transition probability index (*TPI*) and the proportional differentials index (*PDI*), are proposed to describe the influence of land use change on locust area evolution quantitatively. The *TPI* index indicates the probability of land use transition from land use/cover type i to type j, and its formula is the following:

$$TPI_{ij} = \frac{S_{ij}}{\sum_{j=1}^{n} S_{ij}} \tag{7}$$

where TPI_{ij} is the transition probability from land use/cover type i to type j. S_{ij} is the area of the land converted from land use/cover type i to type j. n is the number of land use/cover types and $n = 7$, $i = 1, 2, 3……, n$.

The *PDI* is defined as the differentials between the proportion of one land use/cover type in the terminal period and the proportion in the initial period. It shows the change tendency of one land use/cover type of different locust area evolution types visually. The *PDI* was calculated by the following equation:

$$PDI = \frac{S_{i,t_2}}{\sum_{i=1}^{n} S_{i,t_2}} - \frac{S_{i,t_1}}{\sum_{i=1}^{n} S_{i,t_1}} \tag{8}$$

where *PDI* is the proportion differentials, S_i is the area of the land use/cover type i, t_1 is the initial period, and t_2 is the terminal period, n is the number of land use/cover types, and $n = 7$.

The impact of LUCC on locust area extinction and formation was analyzed from two aspects, the land use/cover type conversion analysis of the two evolution types and the land use/cover type proportion changes analysis in the different ecotypes. The former was based on a land-use transfer matrix and proportion transfer matrix (*TPIs*), which provide information on the conversion relationship of all land use/cover types. The latter was based on the *PDIs* of each land use/cover type in different ecotypes, which provides information on land use/cover composition change. The essence of the repetitive locust area is the extinction and formation of the locust area in two periods. Therefore, according to the correspondence between the evolution type and the land use/cover data in the three periods (Supplementary material, Table A3), the land-use transfer matrices of 1995–2005 and 2005–2017 and land use/cover type proportion change line charts of different evolution types were calculated.

3. Results

3.1. National locust area extraction of 1995, 2005 and 2017

By combining the patch-based suitability membership data of the soil type, vegetation coverage, land use/cover type, and locust area regionalization data as the input database of the PHSA model, locust area maps of China in 1995, 2005 and 2017 were generated. Four correlation analysis charts (Fig. 3), three for each period and one for all three periods, were generated based on the statistics of areas of locust area and locust occurrence area of each province in the three periods (Supplementary material, Table A4). The results indicated that the area of the extracted locust area was highly correlated with the area of actual locust occurrence area ($R^2 = 0.78$) (Fig. 3d). The correlation in 1995 was relatively lower than the other two periods and this may have been due to the lack of historical data in the early 1990s ($R^2 = 0.63$, 0.89 and 0.94 in 1995, 2005 and 2017, respectively) (Fig. 3a–c). These results indicated that the PHSA model proposed in this study has sufficiently high accuracy to satisfy research needs.

The locust areas were manually divided into four ecotypes (CoLA, RiLA, LaLA and WaLA) based on their formation environment (Fig. 4). The distribution maps showed that the general distribution of the locust area in China was relatively stable in the past 20 years but had several changes in local areas. The spatial distribution of the CoLA and the RiLA was more stable than that of the LaLA and the WaLA. The total locust area in 2017 was 866,800 ha, and the total area in 1995 was 1,247,500 ha. This indicates a decreasing trend (a reduction of 30.52 %), while the number of counties with locusts fluctuated (Table 3). This reduction may indicate a locust area reduction due to locust area management efforts. However, there were many new locust areas formed, possibly due to climate change, human activities, or other causes. Fig. A1 (see Supplementary material) compared the area and proportion of each ecotype of the locust area in the three periods. Among the four ecotypes, the RiLA had the largest area and the WaLA had the smallest area (Fig. A1a). All ecotypes had a decreasing trend in the three periods except for the RiLA from 1995 to 2005 (Fig. A1b). This might be due to the dry period in 2002 and 2003, which provided many suitable habitats for locust reproduction along the rivers (Tian et al., 2011). The proportion of the RiLA showed an increasing trend and the WaLA showed a decreasing trend (Fig. A1c), indicating that the ecological control of the latter in China had achieved success. The RiLA was more difficult to control since new riverbanks were continuously formed as a result of river channel migration.

Among the four ecotypes of the locust area in the three periods, the cropland area was the largest, followed by wetland, water, and grassland. The areas of the woodland, artificial surface, and "others" land use/cover types, which were not suitable for locust breeding, were relatively low and were a little higher in 2017 than in 1995 and 2005. This may be due to the lower classification accuracy of land use/cover data in 2017 (Fig. 5a). The percentages of the crop in the RiLA and the WaLA were higher than that in the LaLA and the CoLA, while the wetland showed opposite characteristics. The percentage of water in the LaLA and the percentage of grassland in the RiLA were higher than the other three ecotypes (Fig. 5b). All of these characteristics illustrated that the change of crop had a greater impact on the RiLA and the WaLA; the change of wetland had a greater impact on the CoLA and the LaLA; the change of water had a greater impact on the LaLA; the change of grassland had a greater impact on the RiLA.

3.2. Dynamic changes of locust area and its evolution

Using the multi-temporal binary coding method, a dynamic change image of locust area from 1995 to 2017 was generated (Fig. 6a), and then a locust area evolution map was obtained according to the definition of locust area evolution types (the extinct locust area, the newly formed locust area, the repetitive locust area, and the stable locust area) proposed in this paper (Fig. 6b). Table 4 illustrates how evolution types were determined. The histogram of the dynamic change image shows that there are fluctuations in the number of pixels of each gray value and the number of pixels with values ranging from 1 to 4 is larger than that ranging from 5–7. This indicates that the temporal and spatial variability of locust areas is high. China appears to have made progress in the ecological control of locust areas from 1995 to 2017 despite the emergence of new locust areas.

Area statistics of four evolution types of the locust area indicate that the extinct locust area covered 914,100 ha (approximately 40.54 % of the total), the newly formed locust area covered 533,300 ha (approximately 23.66 % of the total), the repetitive locust area covered 622,700 ha (approximately 27.62 % of the total), and the stable locust area covered 184,400 ha (approximately 8.18 % of the total). The large area extinction of the locust area was accompanied by an area of newly formed locust area. The total area was reduced, but a considerable area within the regions continued to have locust occurrences. This indicated that conditions for locust reproduction in these regions were unstable. The proportion of stable locust area was the least but locusts occur every year in these areas making them focus areas for locust control. Stable locust areas are mainly on lands closest to rivers, lakes, and beaches (Fig. 6b), reflecting the "water attachment" preferences of locusts (Li et al., 2017). The water level of these areas fluctuates making them unsuitable for ecological control. The stable locust areas were the most stable and suitable ecological environment for locust reproduction, making them key areas for locust management.

3.3. LUCC in locust area of different evolution types

Land-use transfer matrix and probability matrix based on *TPIs* (Supplementary material, Table A5) and land use/cover type proportion change line charts based on *PDIs* (Fig. 7) for 1995–2005 and 2005–2017 were generated. The relationships between LUCC and locust areas evolution were analyzed separately in the extinct locust areas and

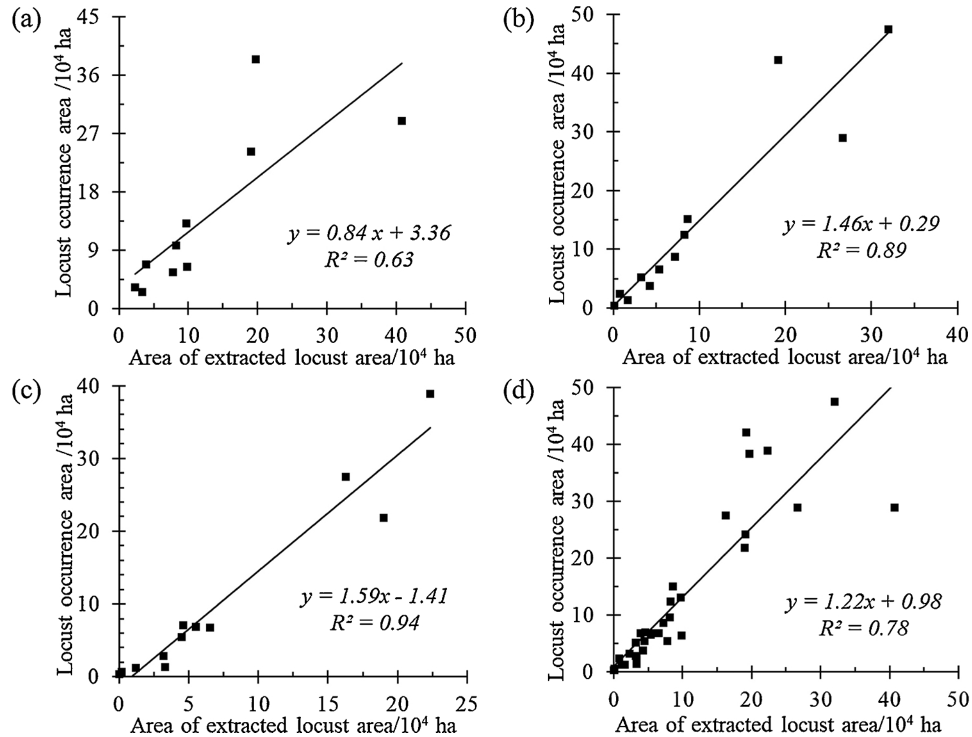

Fig. 3. The correlation charts between the areas of extracted locust area and locust occurrence area for 1995 (a), 2005 (b), 2017 (c), and all three periods (d).

the newly formed locust areas.

3.3.1. Relationship between LUCC and locust area extinction

For the extinct locust area, the transition probabilities of all land use/cover types in 2005–2017 are much higher than those in 1995–2005, indicating that the LUCC in 2005–2017 was more intense (Table A5 in supplementary material). The extinction of the locust area is accompanied by a large proportional increase of woodland and artificial surface and a large proportional reduction of wetland and cropland. The grassland shows a slightly decreased trend. The water changes are irregular, and the proportion change of the "others" is not obvious (Fig. 7a). Combined with the conversion relationship of all the land use/cover types (Table A5), we believe that the extinction of the locust area is closely related to the conversions of cropland and wetland to woodland, artificial surface, water and the conversion of grassland to cropland and woodland.

The line charts of the land use/cover type proportion change of 1995–2005 (Fig. 7c) and 2005–2017 (Fig. 7e) show that in the extinct locust area, the CoLA and the LaLA are more susceptible to changes in wetland and water. The reduction of cropland had a stronger impact on the RiLA than on other ecotypes and the impact of artificial surface change on CoLA in the last 10 years was stronger than that in the first 10 years. The impact of water changes on the four ecotypes was complicated with no obvious pattern. The LUCC in the WaLA was the least obvious among the four ecotypes, which indicates that the land use/cover types in WaLA are relatively stable.

3.3.2. Relationship between LUCC and locust area formation

The same characteristics of LUCC were seen in the newly formed locust area, and the LUCC in 2005–2017 was more intense than in 1995–2005 (Table A5 in Supplementary material). This can also be seen from the higher absolute values of *PDI* of the other six land use/cover types, except for wetland in 2005–2017(Fig. 7b). The formation of the locust area is accompanied by a reduction of woodland, artificial surface and water, and an increase of grassland and cropland, while the proportion changes of wetland and "others" are less obvious (Fig. 7b). Combined with the conversion relationship of all the land use/cover types (Table A5), we believe that the formation of the locust area is closely related to the transformations from woodland, artificial surface, water, and "others" to cropland and grassland and the transformation from cropland to grassland.

In proportional change line charts of 1995–2005 (Fig. 7d) and 2005–2017 (Fig. 7f), except for the water and cropland in the LaLA of 1995–2005, other land use/cover types of the four ecotypes in the two periods show the same trend as Fig. 7a. This may have been caused by the land around lakes which was cropland in 1995 being classified as water in 2005. The trend of LUCC in 1995–2005 was not as obvious as in 2005–2017. This study only analyzed the LUCC of four ecotypes from 2005–2017. In the newly formed locust areas, the RiLA and LaLA are more susceptible to reductions of water and artificial surface. The increase of cropland, the increase of grassland, and the reduction of wetland had a stronger impact on the CoLA, and the reduction of woodland had a stronger impact on the WaLA.

4. Discussion

4.1. Assessment of locust area extraction

Locust development is affected by habitat factors, such as terrain, climate, vegetation, soils, and hydrology (Zhu, 1999; Latchininsky and Sivanpillai, 2010; Propastin, 2013; Löw et al., 2016; Shi et al., 2018). Human activities also affect the environment of locust habitats (Qiu, 2006; Badr et al., 2015; Ren et al., 2017). The concept of locust area is based on the theory of ecology and disaster. It refers to an area that has a suitable ecological environment for locust reproduction, and where locusts occur every year and have outbreaks at least once per decade (Zhu, 1999). The extraction of locust areas should consider long-term habitat conditions. Temperature and precipitation are the two main climatic factors for locust reproduction, but short-term temperature changes or precipitation changes only affect the seasonality and locust population within a given year and does not change the essence of an area being a locust area. On the other side, precipitation affects locust eggs by affecting soil moisture, so the rainfall factor can be replaced by soil factors in the extraction of locust areas. The terrain and the climate

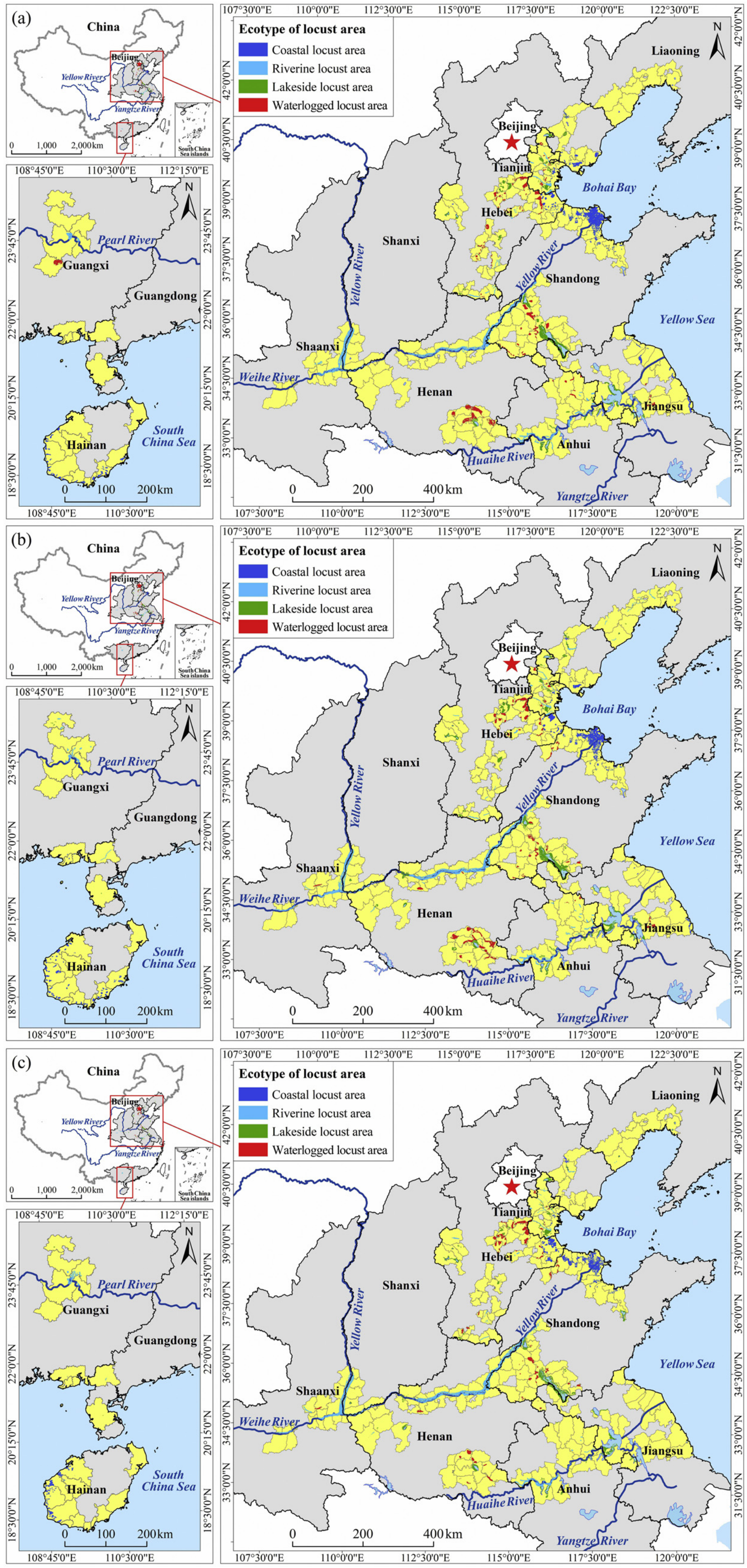

Fig. 4. Distribution maps of four ecotypes of locust area in China in 1995 (a), 2005 (b) and 2017 (c). Note: The tropical savannah locust areas in Hainan (Ding, 1995) are assigned as costal locust area in this study since the macro factor affecting the locust outbreak in Hainan is maritime climate.

Table 3
Statistics of the areas and proportions for four ecotypes of locust area in 1995, 2005 and 2017.

Period		CoLA	RiLA	LaLA	WaLA	Total area	Distribution range
1995	Area/10^4 ha	32.32	40.57	28.22	23.64	124.75	172 counties in 10 provinces
	Proportion/%	25.91	32.52	22.62	18.95	–	
2005	Area/10^4 ha	24.62	44.52	28.36	20.00	117.50	204 counties in 12 provinces
	Proportion/%	20.95	37.89	24.14	17.02	–	
2017	Area/10^4 ha	19.28	35.65	17.41	14.34	86.68	186 counties in 12 provinces
	Proportion/%	22.24	41.13	20.09	16.54	–	

Note: CoLA, coastal locust area; RiLA, riverine locust area; LaLA, lakeside locust area; WaLA, waterlogged locust area.

Table 4
Statistics on dynamic change and evolution type of locust area in 1995, 2005 and 2017.

V_{dyna}	Binary code			Evolution type	Area (10^4 ha)	Histogram
	2017	2005	1995			
1	0	0	1	Extinct	57.54	
2	0	1	0	Repetitive	47.38	
3	0	1	1	Extinct	33.88	
4	1	0	0	Newly formed	35.53	
5	1	0	1	Repetitive	14.90	
6	1	1	0	Newly formed	17.80	
7	1	1	1	Stable	18.44	

are relatively stable over long periods. We believe that these two factors in the study area were suitable for locust reproduction because locust outbreaks had occurred here. Therefore, the climate and the terrain can be disregarded when extracting locust areas. National-scale soil moisture and salinity data are difficult to obtain. The soil type, a reflection of soil moisture and salinity, can be used as a proxy indicator for soil factors in locust habitat suitability assessment. And the LUCC, a direct consequence of nature and human interactions, can reflect the vegetation type, hydrological condition, and human activities (Liu et al., 2014). Therefore, soil type and LUCC together with vegetation coverage can be used to assess the habitat suitability of a given region. A region that is otherwise suitable for locust reproduction does not always become a locust area if there is no insect source there. Hence, this study introduced historical locust occurrence information as a constraint indicator for locust area extraction. These four factors consider the ecological and disaster concepts of locust areas, making the extraction method more comprehensive and reasonable. While obtaining extraction factors, we also considered the long-term nature of the locust area. Composited Landsat images with fine spatial resolution and long-time span used for vegetation coverage extraction provided historical vegetation conditions for assessing habitat suitability. Soil data, land use/cover data, and historical locust area regionalization data of three periods used here reflect the habitat conditions in the study area over a long period.

Locust habitat is spatially and temporally variable and composed of multispecies vegetation patches with specific hydrographical and landscape structure (Shi et al., 2018). As a geographical continuous patch, the locust area is strongly affected by landscape changes. The patch-based habitat suitability assessment (PHSA) model proposed here used a moving window method to consider the influence of the neighboring pixels on the central pixel. It effectively characterized the landscape ecological structure of the locust habitat and also eliminated the noise carried by the remote sensing image itself. The model also considered the differences between the south and the north part of the locust habitat in China when determining the membership degree of assessment factors and the threshold of the *HSI* for locust extraction. This makes the model more applicable over a larger, national scale. The locust area extraction results of 1995, 2005, and 2017 have a high correlation with the actual occurrence area (overall R^2 = 0.78), which means that the PHSA model is reliable and the results can be used to evaluate the impacts of LUCC on locust area evolution.

4.2. Influence of LUCC on locust area evolution

Locust habitat is formed during water level changes of seas, rivers, lakes, reservoirs, or water conditions changes of depressions, producing environments suitable for locust reproduction and development. These habitats include beaches, wetlands, wastelands, and grasslands. As locusts develop, they can move to surrounding farmland to obtain more food. The evolution of the locust area is essentially a change in the environment suitable for the locust, which is influenced by both natural and human factors. As an intuitive descriptor of the interaction between human activities and the natural environment, LUCC has an important impact on the evolution of locust areas (Liu et al., 2014; Shi et al., 2018). It can change the suitable environment of locusts (promote or inhibit locust reproduction) and cause the formation and extinction of locust areas. By analyzing the ecological control measures in locust areas of different ecotypes over the past 20 years provided by NATESC, we summarized the natural and human factors that caused locust area evolution in different ecotypes and their positive and negative impacts

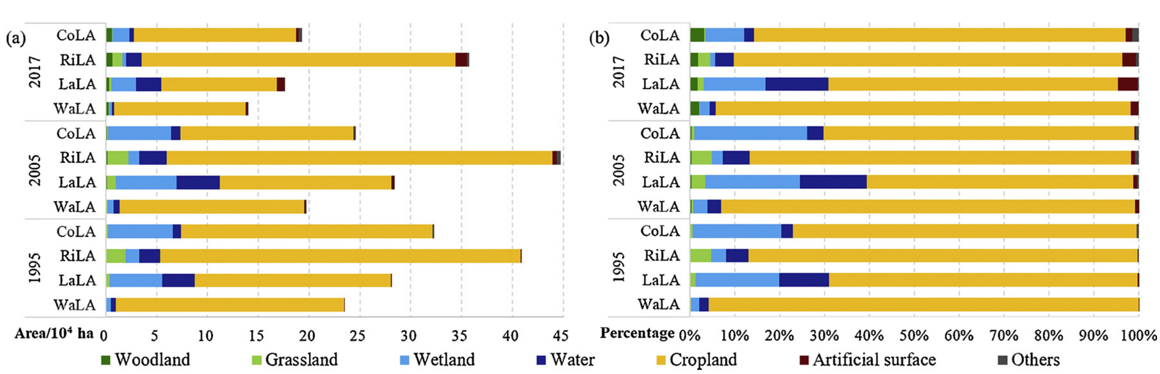

Fig. 5. The area stacked bar chart (a) and percentage stacked bar chart (b) for all land use/cover types in different ecotypes of locust area in the three periods. Note: CoLA, coastal locust area; RiLA, riverine locust area; LaLA, lakeside locust area; WaLA, waterlogged locust area.

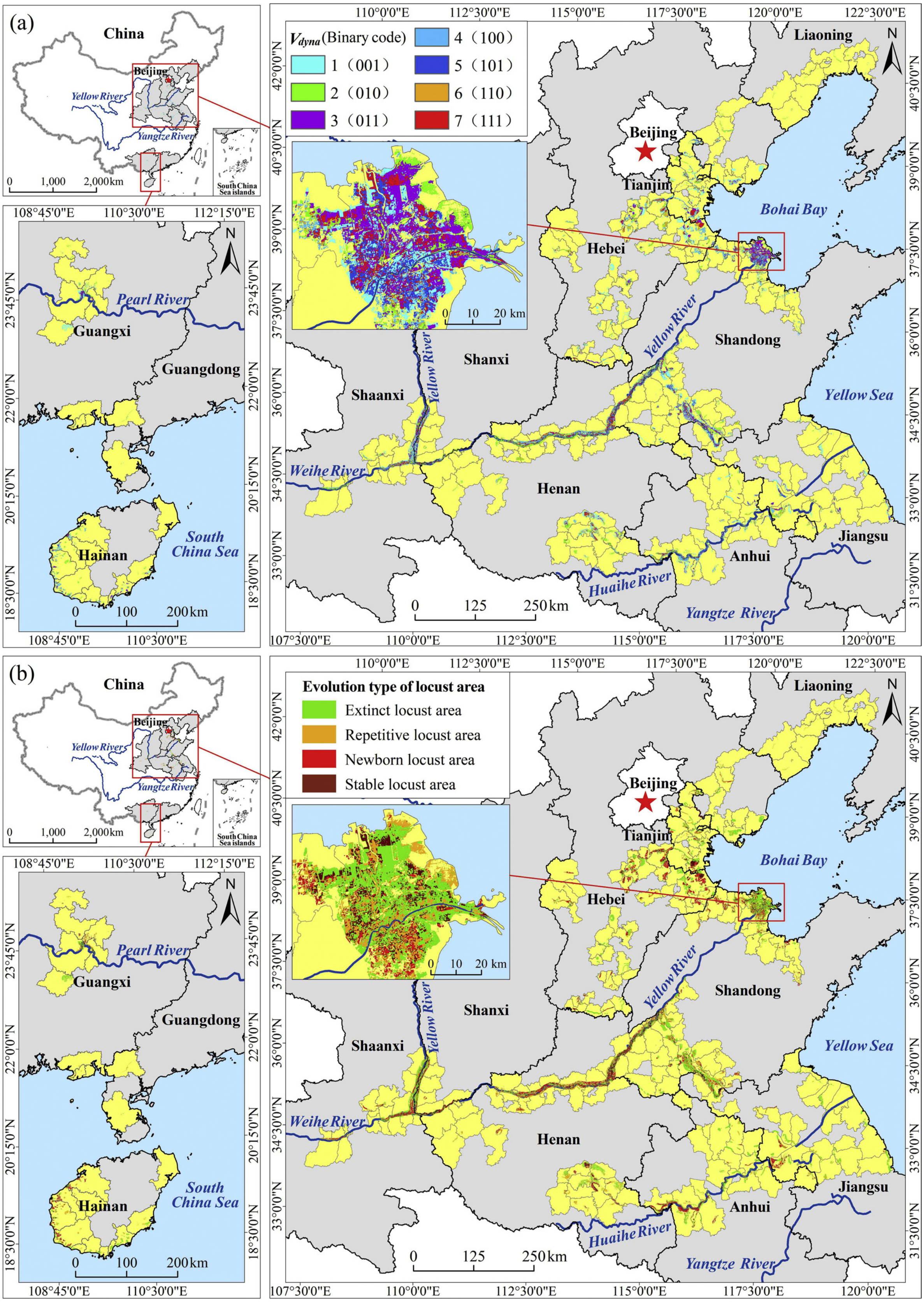

Fig. 6. Dynamic change map (a) and evolution map (b) of locust areas in China from 1995 to 2017. The meanings of V_{dyna} and binary code are shown in Table 4.

on locust reproduction, as well as the land use/land cover changes corresponding to different measures (Table 5). These analyses, on one hand, can explain the LUCC results obtained in this study, on the other hand, can provide scientific guidance for locust area ecological control in different ecotypes.

The extinction of locust areas is mainly due to the ecological

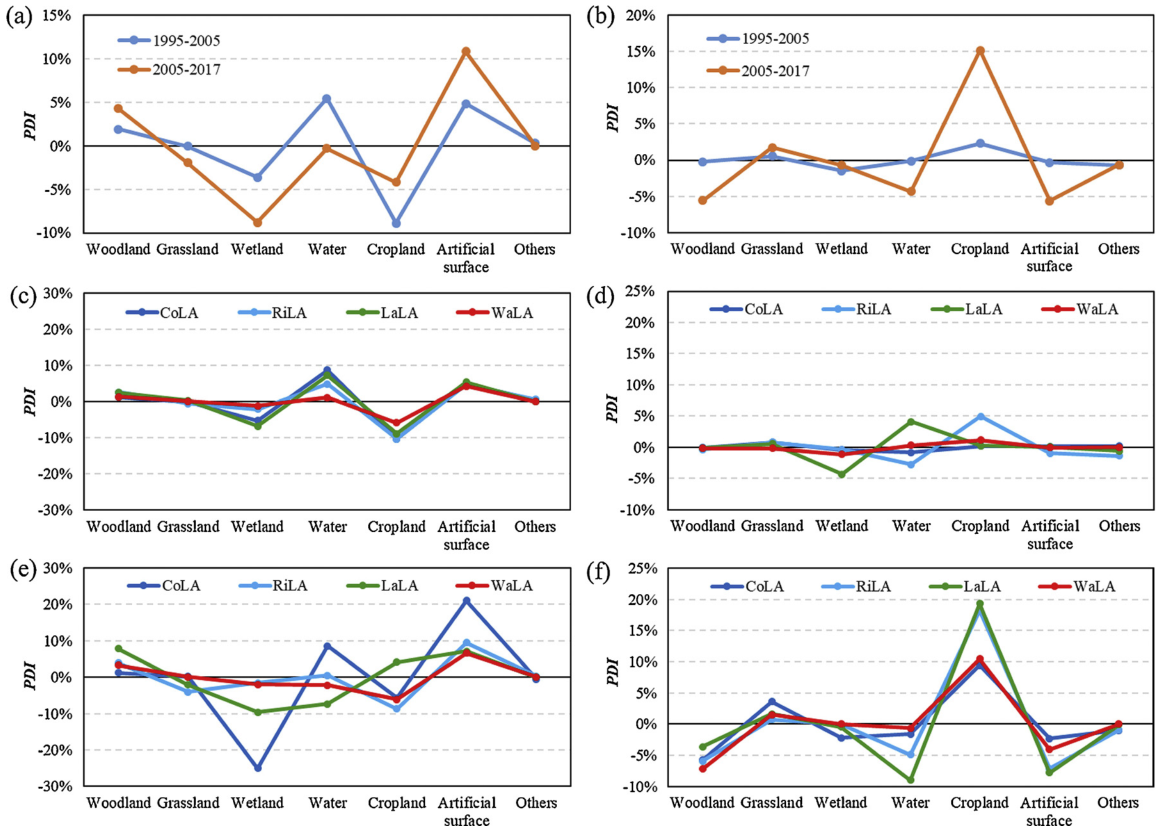

Fig. 7. Line charts for the land use/cover type proportion change of overall (up images) and four ecotypes in 1995–2005 (middle images) and 2005–2017 (bottom images) in the extinct locust area (left column) and the newly formed locust area (right column). Note: CoLA, coastal locust area; RiLA, riverine locust area; LaLA, lakeside locust area; WaLA, waterlogged locust area.

manipulation of human beings, with little impact from natural factors (Table 5). China has carried out extensive ecological control measures in all four ecotypes of the locust areas. These measures included afforestation (returning farmland or grassland to forest), wasteland reclamation, intensive cultivation, aquaculture development, and vegetation transformation. In the CoLA and LaLA, ecological management measures such as grassland enclosures, cultivation of reeds, and salt production were also adopted. Urban and rural construction policies such as real estate and tourist industry development in these two ecotypes of the locust area also completely changed the environments suitable for locusts. In the RiLA, LaLA and WaLA, dams, reservoirs, and other water conservancy facilities were built to stabilize water levels, beaches, and low-lying lands. Plant protection staff also excavated ditches to clear river channels to solve the problem of water accumulation and drainage, and then achieved their goal of reducing the suitable locust area. All these measures achieved the purpose of reducing the locust area by reducing locust food plants and oviposition areas, destroying eggs, and changing the suitability of the breeding habitat. The impacts of natural factors on the extinction of locust areas were mainly reflected in two aspects: (1) the rise of water level of rivers, lakes, and reservoirs caused by precipitation or other factors increased the water area and reduced the locust habitat. Suitable locust habitat was inundated, and (2) the migration of river channels made the water environment suitable for locust breeding disappeared. The LUCC corresponding to these influence factors were mainly the conversions from cropland and wetland to woodland and artificial surface, and conversions from grassland to cropland and woodland. The transformation of water was complicated, which is consistent with the analysis above. It is worth mentioning that cropland has both positive and negative effects on locust presence. We can analyze this phenomenon from two aspects. One is that when cropland is abandoned or cultivated extensively, reduced plowing behavior will reduce damage to locust eggs, increasing the number of locusts. The other is that when farmers conduct intensive cultivating, or grassland or wasteland is reclaimed to arable land, frequent agricultural activities will destroy the eggs and greatly reduce the occurrence of locusts. Therefore, we believe that whether cropland is suitable for the breeding of locusts mainly depends on the tillage method.

Table 5 shows that the influences on newly formed locust areas were mainly natural factors, and human activities were secondary. In all four ecotypes of locust areas, along with the river flow reduction due to climate change and river evolution, the water-level changes of the rivers, lakes, reservoirs and meandering river channels, new beaches, wetlands, and wastelands were continuously formed, as well as wastelands not cultivated due to droughts and floods in river-floodplains or low-lying areas. These areas provided large expanses of suitable habitat for locust reproduction. Besides, the soils in the CoLA were severely salinized and grasslands with low-level utilization also provided suitable habitats for locusts. Among the human activities affecting the newly formed locust areas, extensive farming was the most common factor leading to the emergence of locust areas in the four ecotypes. A low multiple cropping index increases the locust density in abandoned farmland. Abandoned fishery facilities and excess logging in the CoLA, reservoir construction in the RiLA, and increased water storage of lakes and reservoirs in the LaLA could cause the originally unsuitable environment to again be suitable for locust reproduction. China is now directing more attention to the protection of water sources and it prohibits the spraying of pesticides in surrounding areas. This restriction could increase locust populations around water sources and result in a suitable locust breeding environment. These factors were expressed, by LUCC, as woodland, artificial surface, and water transformed into cropland and grassland, or cropland was converted into grassland. This

Table 5
Influencing factors analysis of different ecotypes in extinct and newly formed locust areas and LUCC corresponding to these factors.

Evolution type	Ecotype	Natural factors and human activities affecting the evolution of locust area and their impact on locust breeding environment	Corresponding LUCC
Extinct locust area	CoLA	*Tree planting.* Reduce locust food supply since they prefer gramineous plants, and eliminate the oviposition environment of locusts.	2 or 3 → 1
		Wasteland reclamation and crop planting. Reduce locust food supply, and destroy locust eggs by plowing over the soil during cultivation.	2 or 3 → 5
		Intensive cultivation. Destroy locust eggs by plowing over the soil during frequent farming.	2 → 5
		Urbanization expansion, such as real estate and tourist industry development. Transform locust habitat to an unsuitable environment completely.	2 or 3 → 6
		Salt factories construction. Transform locust habitat to an unsuitable environment completely.	2 or 3 → 6
		Aquaculture development. Create a stable water environment to reduce locust habitat.	2 or 3 → 4
		Grassland enclosure and reeds growth through water storage. Increase vegetation coverage to over 90% to restrain the growth of locusts.	–
		Vegetation transformation. Change the gramineous plants that locusts prefer into plants they don't like, such as cotton, alfalfa, and so on.	2 or 3 → 1 or 5
	RiLA	* ***Migration of river channel makes the old beach get higher***. Make a suitable water environment for locust reproduction disappeared.	2 or 3 → 5
		Wasteland reclamation. Transform wasteland to woodland, cropland, or pasture which are unsuitable for locust reproduction.	2 or 3 → 1 or 5
		Dams, reservoirs, and ditches construction. Stabilize water level to prevent the formation of new suitable locust habitat.	2 or 3 → 4
		Intensive cultivation. Destroy locust eggs by plowing over the soil during frequent farming.	2 → 5
		Vegetation transformation. Change the gramineous plants that locusts prefer into plants they don't like, such as cotton, alfalfa, and so on.	2 or 3 → 1 or 5; 5 → 1
		Plant trees and increase vegetation coverage. Decrease food supply and deteriorate the oviposition environment of locusts.	2 or 3 → 1
		Fish ponds excavation and aquaculture development. Transform locust habitat into fish ponds to reduce the suitable habitat of locusts.	2 or 3 → 4 or 6
	LaLA	*Development zone construction, such as real estate development in Tianjin.* Transform locust habitat into an unsuitable environment completely.	2 or 5 → 6
		Aquaculture development. Change saline-alkali wastelands, depressions, and reservoir beaches full of reeds into fish ponds or shrimp ponds to reduce suitable locust habitat.	2 or 3 → 4 or 6
		Water conservancy construction and drainage ditch digging. Stabilize water level and beaches, making habitats unsuitable for locust reproduction any more.	2 or 3 → 5
		Large-area intensive reeds planting. Increase vegetation coverage and reduce oviposition environment to restrain locust reproduction.	–
		Wasteland and depression reclamation. Change wasteland and depression into a paddy field or cotton field to reduce locust habitat.	2 or 3 → 5
		Vegetation transformation. Change vegetation into a non-gramineous plant to reduce the food supply of locusts.	2 or 3 to → 1 or 5
		Intensive cultivation. Destroy locust eggs by plowing over the soil during frequent farming.	3 → 5
		****Larger water areas caused by high precipitation***. Change beaches into the water, making it unsuitable for locust reproduction.	2 or 3 → 4
		Plant trees and bring in birds to consume locusts. Reduce the food supply of locust and expose locusts to predators.	2, 3 or 5→ 1
	WaLA	*Water conservancy construction and river channels dredging.* Solve problems of water storage and drainage issues to create unsuitable habitat for locust reproduction.	2, 3 or 4→ 5
		Large-scale forest network transformation. Reduce food supply and eliminate the oviposition environment of locusts.	2, 3 or 5→ 1
		Improve multiple cropping index, transform vegetation structure, and develop intensive cultivation. Reduce food supply by growing crops locusts don't favor such as sesame, peanuts, and cauliflower, and destroy locust eggs, creating unsuitable habitat for locusts.	2 or 3 → 1 or 5
		Wasteland and depression trimming and reclamation. Change wasteland and depressions into paddy field or cotton field; destroy locust eggs by plowing over the soil.	3 → 5
		Create stable water environment and develop aquaculture. Destroy locust eggs and deteriorate habitat environment to reduce habitat area.	2 or 3→ 4 or 6

(*continued on next page*)

Table 5 (*continued*)

Evolution type	Ecotype	Natural factors and human activities affecting the evolution of locust area and their impact on locust breeding environment	Corresponding LUCC
Newly formed locust area	CoLA	***The greenhouse effect and global climate warming move the high-temperature zone northward.** The increased effective accumulated temperature can greatly reduce the overwintering mortality of locust eggs, enlarging the area of suitable habitats.	–
		Extensive cultivation. Due to high salt and alkali content in the soil, the low-yield farmland in the CoLA is usually extensively cultivated, making wastelands among it provide favorable conditions for locust reproduction.	5 → 2 or 3
		***New beaches are constantly formed at the mouth of the Yellow River.** The low utilization rate of these new beaches, coupled with humidity climate conditions, provides ideal vegetation and soil conditions for locust reproduction.	4 → 2 or 3
		***Intertidal and tidal zones in coastal areas continue to form wasteland and grassland**. Plants among these uncultivated lands such as thatch, reed, and weed provide suitable habitat for locusts.	4 → 2 or 3
		Abandonment of fisheries along coastal beaches. Lacking management in the fishery area leads to an increasing population of locusts, making new suitable locust habitat formed.	4 or 6 → 2 or 3
		Excess logging, such as the deforestation in Hainan. As forest decreases, savanna, and grassland increase, forming a tropical savanna ecological landscape is suitable for locust reproduction.	1→ 2 or 5
	RiLA	***New floodplain and river beaches are formed continuously as river channel swings**. These new beaches are largely uncultivated or extensively cultivated, providing an ideal environment for locust reproduction.	1 or 5→ 2
		***Drought climate reduces river runoff, beaches, and wastelands get exposed**. The exposure of wasteland enlarges the suitable habitat of locusts.	4 → 2 or 3
		***Droughts and floods alternate frequently along the Huaihe River.** Wasteland which is not easy to cultivate forms, providing suitable habitats for locusts.	1 or 5→ 2
		Reservoir construction makes residents moved out. Farmland gets abandoned and new wastelands form; a new suitable locust habitat is formed.	5 → 2
	LaLA	***The dehydration area of lake, reservoir, and low-lying reed field increased year by year due to the abnormal climate, ecological environment, and water level changes.** Large-area depressions full of reeds are exposed all year round being lack of management, forming a suitable habitat for locusts.	4 or 5→ 2
		*** The area of the water surface continued to expand due to the increased water storage capacity of some reservoirs.** New wasteland is formed continuously on the low-lying side of the reservoir, providing a new suitable habitat for locusts.	4 → 2 or 3
		Implementation of ecological environmental protection measures of water source protection areas. Pesticide spraying is forbidden around these areas, leading to increased locust populations and eventually the formation of a new locust area.	4 → 2 or 3
	WaLA	***Low-lying areas are prone to alternate droughts and floods due to large interannual variability of precipitation, forming wasteland.** Wasteland which is not cultivated provides an ideal environment for locust reproduction.	4 → 2 or 3
		Low multiple cropping index and extensive cultivation in depression farmland. Provide suitable habitat for locusts.	5 → 2

Note: 1. CoLA, coastal locust area; RiLA, riverine locust area; LaLA, lakeside locust area; WaLA, waterlogged locust area. 2. Italics are the influencing factors of locust area evolution. Bold words with asterisks (*) are natural factors, and the rest are human factors. What follows are their impacts on the locust breeding environment. 3. The numbers in the last column represent the type of land use/cover. 1, woodland; 2, grassland; 3, wetland; 4, water; 5, cropland; 6, artificial surface. "2 or 3→1" means the land use/cover types changed from grassland or wetland to woodland. "-" means the influencing factors didn't change the land use/cover type.

conclusion is consistent with the analysis results.

We conclude that the evolution of the locust area is closely related to LUCC, and the long-term management of locust areas can be achieved through prudent planning of land use/cover types. Dynamic monitoring of LUCC can also enable early monitoring of potential locust areas.

4.3. Suggestions for locust area management and monitoring

The extracted national locust area and the relationship between locust area evolution and LUCC could provide practical strategies and guidance for local government agencies, agronomic, and plant protection specialists. First, compared with the traditional empirical locust area zoning method conducted by local plant protection staff based on artificial point field surveys, the patch-based habitat suitability assessment (PHSA) model used for locust area extraction here, supported by planar continuous habitat data derived from satellite data, has higher confidence, accuracy, and efficiency, which could help avoid locust habitat omissions. The model can also be used for locust infestation risk assessment to guide field survey investigators to identify locations of locust reproduction. Chemical pesticide treatments could then be guided and optimized by concentrating on areas with a high risk of locust infestation. This could minimize pesticide applications in neighboring areas, especially areas around water sources, and reduce the negative impacts caused by pesticide spraying (Gomiero et al., 2011; Löw et al., 2016).

Second, the long-term locust area dynamics and its evolution process are the results of locust habitat transitions under the combined influences of natural environment changes and human activities. The influence analysis of LUCC on locust area extinction provides an insight into the ecological management of known locust areas to transform the suitable habitat with minimal environmental degradation. For instance, we found that the extinction of locust areas is often accompanied by the conversion of cropland and wetland to woodland, artificial surface and water bodies, or the conversion from grassland to cropland. Different ecotypes of locust areas respond differently to LUCC. Hence, in addition to carrying out extensive afforestation, wasteland reclamation, and intensive cultivation, the following measures can be implemented in different ecotypes of locust area to transform the ecological environment of the suitable habitat: (1) in the CoLA, where is sparsely populated and with large saline wasteland, develop aquaculture and salt factories in tidal flats, enclose grassland, or store water to grow reeds; (2) in the RiLA, where new beaches often form, construct dams, reservoirs, and ditches to stabilize the water level, transform the crop rotation strategy and adjust the planting structure; (3) in the LaLA, which mostly scattered around the water source, encourage tourism development, real estate development, or ecological aquaculture; (4) in the WaLA, where flood occurs frequently, dig ditches and dredge river channels to solve water storage and drainage issues, conduct wastelands and depression trimming and reclamation. All the above measures are beneficial to reduce the locust breeding environment and eventually achieve sustainable agriculture by a thorough transformation of the suitable habitat without chemical pesticide application.

The third aspect is to combine the frequent updates on land use/

cover dynamics with our findings to monitor potential locust areas. The natural changes of the river channels and the decline of water level in rivers, lakes, and reservoirs in dry years will form new beaches, which are generally not cultivated. These areas can represent new habitats for locusts. Also, unreasonable deforestation, disorderly reclamation of existing farmland or extensive farming system, and abandonment in aquaculture areas along the beaches can easily lead to large-scale land waste and create conditions suitable for locust reproduction. Environmental protection policies, such as those prohibiting the spraying of pesticides around water reserves, could easily lead to an increase in locust populations and the formation of new locust areas. Therefore, attention should be given to changes in land use/cover types along rivers, changes in water levels of rivers, lakes, reservoirs, and other water bodies, and conversion of farming systems. Ecological environmental changes around protected water sources and other inaccessible areas have important implications for early monitoring of potential locust areas.

5. Conclusions

Based on the habitat suitability assessment of Oriental migratory locust, this paper proposed a PHSA model to extract the locust area of China. The extraction results of 1995, 2005, and 2017 showed that the area of the locust area has greatly reduced over the past 20 years. The distribution range of locust area showed obvious dynamic changes with a large degree of temporal and spatial variation. The evolution of the locust area is closely related to land use/cover change (LUCC). The extinction of the locust area is mostly accompanied with land use/cover type conversions from cropland and wetland to woodland and artificial surface, and conversions from grassland to cropland and woodland, and the newly formed locust areas show opposite LUCC transformation trends. Long-term management of locust areas can be achieved through prudent planning of land use/cover types. Dynamic monitoring of LUCC can enable early monitoring of potential locust areas. These findings provide guidance and practical strategies for ecological control of known locust areas and early monitoring of potential locust areas. More importantly, these findings can contribute to changing the chemical control of locusts to environment-friendly management of locust areas. This could lead to a reduction of pesticide application to the agroecological environment to achieve more sustainable agriculture.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.107110.

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