



Research article

The influence of landscape's dynamics on the Oriental Migratory Locust habitat change based on the time-series satellite data

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ARTICLE INFO

Article history:

Received 13 December 2017

Received in revised form

3 April 2018

Accepted 6 April 2018

Keywords:

Data fusion

Random forest

Time-series analysis

Locust habitat mapping

Change detection

ABSTRACT

Landscape structure and vegetation coverage are important habitat conditions for Oriental Migratory Locust infestation in East Asia. Characterizing the landscape's dynamics of locust habitat is meaningful for reducing the occupation of locusts and limiting potential risks. To better understand causes and consequences of landscape pattern and locust habitat, it is not enough to simply detect locust habitat of each year. Rather, landcover transitions causing the change of locust habitat area must also be explored. This paper proposes an integrated implement to quantify the influence of landscape's dynamics on locust habitat changes based on three tenets: 1) temporal context can provide insight into the land cover transitions, 2) the detection of locust habitat area is operated on patches rather than pixels with full consideration of landscape's ecology, 3) the modeling must be flexible and unsupervised. These ideas have not been previously explored in demonstrating the possible role of changes in landscape characteristics to drive locust habitat transitions. The case study focuses on the Dagang district, a hot spot of locust infestation of China, from 2000 to 2015. Firstly, the seasonal characteristics of typical landcovers in NDVI, TVI, and LST were extracted from fused Landsat-MODIS surface reflectance imagery. Subsequently, a landscape membership-based random forest (LMRF) algorithm was proposed to quantify the landscape structure and hydrological regimen of locust habitat at the patch level. Finally, we investigated the correlations between the specific landcover transitions and habitat changes. Within the 16 years observations, our findings suggest that the sparse reeds and weeds in the vicinity of beach land, riverbanks, and wetlands are the dominant landscape structure associated with locust habitat change ($R^2 > 0.68$), and the fluctuation in the water level is a key ecological factor to facilitate the locust habitat change ($R^2 > 0.61$). These results are instrumental for developing precision pesticide use to reduce environmental degradation, and providing positive perspectives for ecological management and transformation of locust habitats.

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1. Introduction

The Oriental migratory locust (*Locusta migratoria manilensis*) is one of the most critical pests plaguing in East Asia, severely threatening the ecology and agriculture (Ji et al., 2006). Unlike the traditional insects with host specificity, locust development

requires suitable landscape pattern and vegetation conditions within favorable breeding area, which lead to a "hot spot" effect on locust habitats, thus, an increase in local population density promote inter-individual contacts, gregarization, and migration, and further results in a severe impact on a larger area (Despland et al., 2004). China is one country suffering from serious locust calamities (Zhang and Li, 1999), especially in the region of North Dagang Reservoir of Tianjin, a hot spot of locust infestation on North of China, where the conditions are ideal for locust breeding due to reduced river and reservoir levels and an increase in abandoned farmland since the mid-1990's (Tong et al., 2006). Owing to the

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strong capacity of migration, the outbreaks of locusts in Dagang district frequently result in serious crop yield losses and ecological degradation in the entire North China Plain (Bian and Zhang, 2001; Zhang and Li, 1999). According to the statistics from the Plant Protective Station of Tianjin (TPPS), annual plague area of summer and autumn locust in Dagang was greater than 20,000 ha from 2000 to 2015, and locust density in severe plague years were recorded as high as 4000–5000 per square meter in localities that suffered from the attacks (<http://www.tjpps.cn/>), suggesting that the trend of heightened locust plague has been mostly attributed to the increasingly dry climate and landscape dynamics (Scanlan et al., 2001). Oviposition and development of locust are generally preceded by specific landscape structure and habitat conditions, such as favorable host components, suitable vegetation coverage, and hot soil temperature. Locust control services in China seek to prevent the development of dense swarms that area capable of emigration flights from the Dagang district near the Bohai bay toward the North China Plain (Ma et al., 2004), which requiring comprehensive understanding of the influence of landscape ecological dynamics on locust habitat change.

The Dagang district has an area of more than 900 km², the traditional locust infestation area exceeds 500 km² (Ma et al., 2004). As a result of ecological transition, the novel emerged locust habitat in the past decade approximately 120 km² (Liu et al., 2006). Due to the large extent of the potentially infested area, conventional approaches for locust habitats monitoring based on regular manual investigations of potential breeding areas are usually inadequate to capture the landscape pattern of locust habitat over the large areas (Ji et al., 2004). On the other hand, the inter-annual habitat change is affected by landcover transition, climate variation, and anthropogenic activities (Crooks and Cheke, 2014; Despland et al., 2004; Müller, 1976), making it more difficult to quantitatively uncover the influence of landscape's dynamic on habitat change based on the manual investigations.

To monitoring the annual locust habitat in Dagang district and assess the influence of landscape dynamics on locust habitat change, data on landcover habitat conditions area needed over large and inaccessible areas. Satellite-based remote sensing technology, that has been proven to be instrumental in addressing the challenge of scale (Ji et al., 2004), is capable of monitoring and tracking changes on landscape pattern, and detecting the cause and consequence of these changes which affected the habitat conditions for locust breeding. The spatio-temporal information provided by the single use of Landsat or MODIS imagery, however, was rarely implemented in remote monitoring of locust hot spots because of the limitations on spatial resolution and revisit frequency (Zhan et al., 2002; Hansen and Loveland, 2012). Before more advanced sensors with higher spatial resolution and revisit cycles become available, image fusion techniques must be used to provide a timely and spatially continuous overview of the habitat factors over large area for bridging merits of MODIS and Landsat data (Sun et al., 2013; Moosavi et al., 2015; Park and Na, 2007; Swathika and Sharmila, 2017). In some cases, the applications of fused satellite data for monitoring changes of land cover and temperature at the regional scale had been reported (Butt et al., 2015; Sobrino et al., 2004; Sun and Schulz, 2015; Zewdie and Csaplovics, 2015).

For the satellite-derived detection and analysis of locust habitat change, full characterization of change requires not just detection of a change, but also an understanding of the proximal cause of change. Therefore, linking the landscape dynamics caused by landcover transitions, climate changes, or human activities to locust habitat change at the patch scale is also a challenge for quantifying the influence of landscape dynamics on locust habitat change over large area (Liu et al., 2008; Tian et al., 2008). By extracting locust habitat area and detecting those landscape

changes in a consistent manner, remote sensing may provide insight into the proximal landscape's ecological characteristics associated with locust habitat change over large and partly inaccessible areas (Li et al., 2008).

In this study, attribution at the pixel scale may not work, because many landscape structure changes exert influence over a geographic patch within which a suite of pixel-scale factors transitions might jointly affect the formation of locust habitat. Therefore, method should be patch based, flexible enough to define diverse ecological factors, and able to incorporate temporal information to capture the distribution and annual dynamics of locust habitat. In this paper, we extend the application of data fusion down to sub-field scales for locust habitat extraction over Dagang district. The contributions of this research are to detect the spatial distribution of locust habitats, and to understand the cause and consequence of locust habitat change affected by the landscape dynamics, such as landcovers transition, vegetation composition variation, and land temperature change, at an annual time step from 2000 to 2015. Specifically, this paper aims: 1) to generate and evaluate seasonal characteristics of the indices derived from the fusion of Landsat-MODIS reflectance data, including triangular vegetation index (TVI), normalized difference vegetative index (NDVI), and land surface temperature (LST); 2) to propose a LMRF algorithm to extract annual locust habitat area at the patch scale; 3) to quantify the influence of landscape dynamics on locust habitat change, and provide suggestions for ecological management of locust habitats.

2. Materials and methods

2.1. Study area

Bordering Bohai Bay to the east, the study area is located in Dagang district (38°32'–38°57'N, 117°13'–117°37' E), in Tianjin Municipality, China (Fig. 1), where is a typical hot spot of Oriental Migratory Locust in North China Plain. For the scope of this study, an area of 909.2 km² was selected. This district lies in a warm temperate continental monsoon climate zone. Fluvo-aquic soils are the most widely distributed soil type. Numerous water resources, including Dagang reservoir, Duliujian river, and Lier bay, provide ideal conditions for the local wetland vegetations: reeds (*Phragmites communis trin*), Suaeda salse (L.) Pall, *Carex* sp., and *Miscanthus sacchariflorus* (Maxim.) Benth. These locations frequently suffered from droughts in spring and water-logging in summer, Common reed growth in late April, reaching its maximum vegetation coverage in the period of June to August, and senescence starts in early September. By the mid October, the common reed withers, but the dry stems remain standing through the winter. These ecological conditions provide an adequate habitat conditions for locust growth and propagation, leading to severe plagues taking place in Dagang district. Moreover, an increase in local population density facilitates inter-individual contacts and gregarization (Latchinsky, 2013), and the strong capacity of the swarm migration further impacts the ecological environment and agricultural production in North China.

2.2. Data acquisition

2.2.1. Statistics on plagues of oriental migration locusts

Tianjin Plant Protection Station (TPPS) investigated the cumulative progress of major locust outbreak areas at their key growth stages from 2000 to 2015. Considering that these data are proprietary, the specific investigation sites and the ID numbers are not provided by TPPS. For this reason, the study mainly relies on the published district-level statistic data. According to these

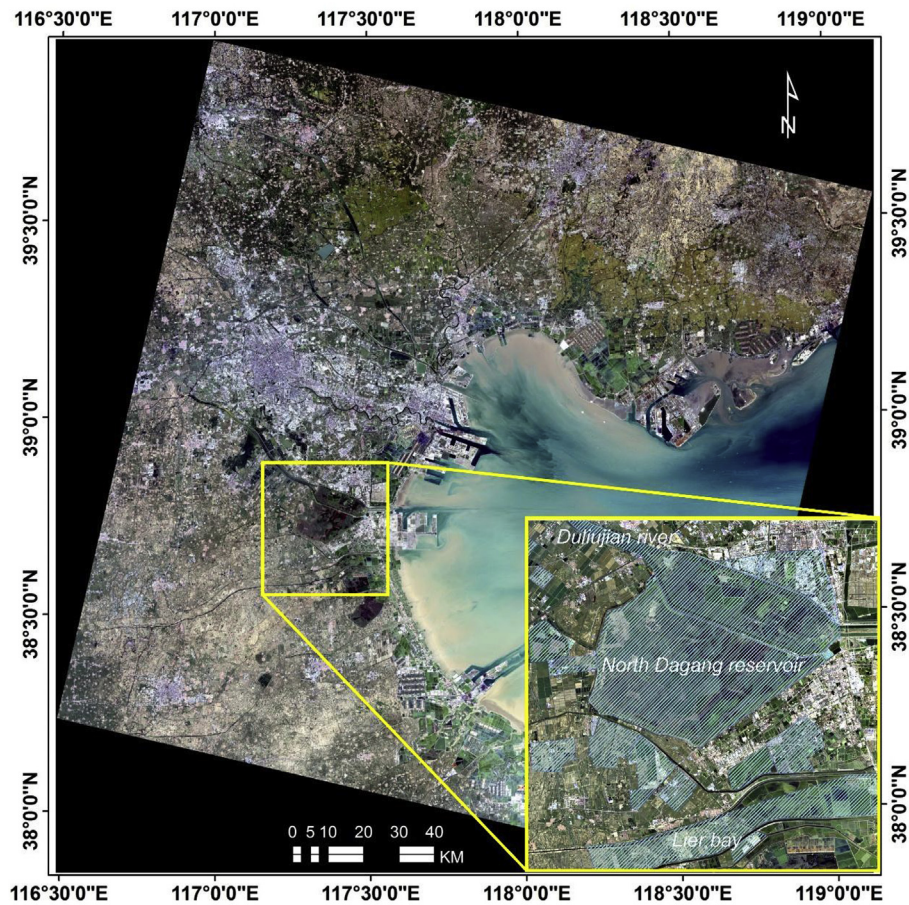


Fig. 1. Landsat scene (path 122 and row 33) containing the research area (yellow polygon in lower left corner) and potential locust areas (indigotic polygons).

investigations, the main regions of locust outbreaks area were manually extracted in ArcGIS 10.3 (indigotic polygons filled in Fig. 1).

2.2.2. Landsat and MODIS data

The cloud-free or partially cloud-free Landsat (path: 122, row: 33), including Landsat 5 for 2000 to 2011 and Landsat 8 for 2013 to 2015, and MODIS (h27v05) data from 2000 to 2015 were downloaded. Considering near nadir view and radiometric consistency are required for data fusion, the 16-day composite Nadir BRDF-adjusted Reflectance (NBAR) product (MCD43A4) at 500-m resolution was selected as the ordered MODIS data. And land surface temperature (LST) from 8-day composite MODIS product (MOD11A2) were acceptable and directly resized to 30 m directly in this study. The detailed downloaded schedule and conditions are revealed in Fig. S1 (see Supplement Material). All of the imagery of Landsat and MODIS were projected to the same UTM coordinates. MODIS data were resampled to a 30-m spatial resolution using the MODIS Reprojection Tool (MRT) for pixel to pixel comparison. No additional pre-processing was implemented since the consistency of view angles between MODIS and Landsat reflectance has been examined by Gao et al. (2017).

2.2.3. Land cover classes and reference data selection

In Dagang district, natural reeds (*P.communis*) are the dominant species, interspersed with several types of weed, such as *Suaeda salsa* (L.) Pall, *Setaria viridis* (L.) Beauv, and *S. glauca* Bunge. Meanwhile, local farms are mainly planting maize, barley, cotton,

sorghum, and peanut. Considering the particular ecological conditions of Dagang district, the landscape structure was restricted to wetland vegetation, cropland, and water. Specifically, wetland vegetation has varying susceptibility to locust infestation (Ji et al., 2006), therefore, we further split them into two subclasses of pure reeds and mixed reeds & weeds in recognition of “host importance” for locusts in wetlands. These typical land-cover types account for 90% of the wetland vegetation (Yang et al., 2007). Bare soil, settlement areas, and artificial embankments were omitted and integrated in to one class due to their lack of potential to host locusts in the study area. The definition of these typical land cover classes and their susceptibility to locust infestation are described in detail in Table 1.

The quantitative assessment of locust host categories required a reference land cover dataset. For collection of such reference data, the outline of the Landsat pixels (i.e. 30-m resolution) was overlaid on the high-resolution imagery downloaded from Google Earth. Pure pixels with only one defined land cover category were visually identified. In order to further identify the class labels, the historical national land use investigations at 30-m resolution (<http://www.resdc.cn/>) were used to label the preliminary selection of the reference pixels (e.g. wetland, cropland, water, settlement area.). However, these historical investigations were not available for every year. For this work, only the 2000, 2005 and 2010 data were collected, hence the land cover classifications of these three years are assessed. The numbers of labeled reference pixels in these three available years are listed in Table 2.

Table 1
Definition of land cover classes susceptible to locust habitat development.

Land cover class	Description
Reed	Reed monoculture, non-inundated reeds on dry or wet soil, 40%–100% vegetation coverage. Providing abundant food for locust development. The low-density regions (vegetation coverage 40%–50%) have the most potential for locust oviposition and nymph growth, the high-density regions (vegetation coverage 50%–80%) are an ideal host for locust migration. It is noteworthy that when vegetation coverage higher than 80%, the canopy closure is not suitable for locust breeding.
Reed & weed	Weed and other grass families on wet or semi-dry soil, mostly reeds, 20%–70% vegetation coverage. The soil and vegetation conditions provide an ideal habitat for locust breeding and development. The low-density regions (vegetation coverage 20%–50%) are optimal for locust oviposition and nymph growth, the high-density regions (vegetation coverage 50%–70%) are an ideal host for locust migration.
Cropland	Crops with 10%–60% vegetation coverage, mostly maize, barley, cotton, sorghum, and peanut, partly weeds and reeds. Owing to regular manual management, such as plowing and irrigation, the field conditions are not suitable for locust breeding or oviposition, but the crops with exuberant growth provide a choice for locust immigration.
Water	Including lakes, rivers, and wetland regions with low vegetation coverage. The water resources are always associated with soil moisture and temperature, which further influences the surrounding vegetation growth.
Other	Including bare soil with surface salt accumulation, settlement area comprising city and countryside, and artificial embankments, which are not a host for locust breeding.

Table 2
The number of labeled samples per land cover class in different years.

Years	Number of Reference Pixels			
	Reed	Reed & Weed	Cropland	Water
2000	1880	2462	1904	2015
2005	1875	2844	1887	1989
2010	2181	2977	1651	1247

2.3. Analytical methods

The analytical process in this paper comprises four key steps: 1) satellite data fusion, 2) land cover classifications, 3) locust habitat extraction, and 4) inter-annual change analysis of locust habitats. A workflow of the entire process is shown in detail in Fig. 2. Key techniques and methods implemented in this study are described below.

2.3.1. STARFM algorithm for data fusion

The STARFM data fusion approach, as presented in Gao et al. (2008), is used for this work. This approach has great performance in generating continuous time-series Landsat-MODIS fused data semi-automatically (Gao et al., 2017; Semmens et al., 2015). The Landsat data and the MODIS Nadir BRDF-adjusted Reflectance product (MCD43A4) were used as the input data of STARFM procedure. The fusion progress generally selects the image pairs closer to the output timeframe as the input data because they have the highest correlation with the MODIS data on the prediction date (Gao et al., 2015). In this study, the fused Landsat-MODIS reflectance was compared and assessed by the corresponding Landsat

observations that were not used in data fusion. Only clear pixels from these Landsat images were used for quality assessment at 30-m resolution.

2.3.2. Land cover classification at the pixel scale

The intra-annual landcover mapping at the pixel scale is significant for quantifying the landscape structure of locust habitat. For this purpose, a seasonality characteristics-based random forest (SCRf) classifiers were established (Gislason et al., 2006; Rodriguez-Galiano et al., 2012). The philosophy behind it is based on a set of multiple independent decision tree combinations (Breiman, 2001). This implementation produces a large scale of individual decision trees, choosing randomly from input data and training data by using a bagging or bootstrap strategy (Prinzie and Van den Poel, 2008). NDVI time-series from the fused Landsat-MODIS images were used as the seasonal features of various landcover classes. As the time-series exhibited noise, a smoothing process based on the Savitzky-Golay filter was applied to suppress the influence of low-quality data and to filter noise, which is capable of preserving higher moments within the data and reducing the bias introduced by the filter, and is mathematically defined as follow (Chen et al., 2004):

$$Y_j^* = \sum_{i=-m}^m C_i Y_{j+i} \tag{1}$$

where Y is the original value of vegetation index, Y^* is the smoothed value of vegetation index, the weights are $C_i = 1/(2m + 1)$, the m is the half-width of the smoothing window.

The accuracy of the landcover classifications were assessed by standard measures based on the confusion matrix, including the

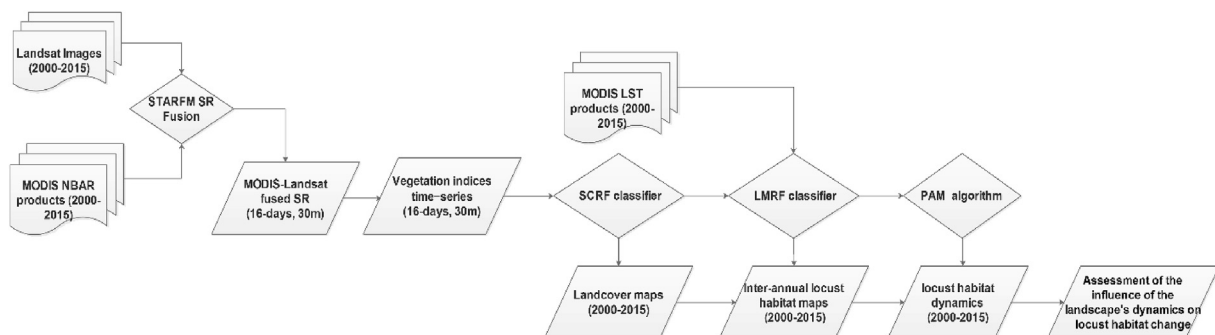


Fig. 2. Flowchart for exploring the influence of landscape's dynamics on the Oriental Migratory Locust habitat change based on the time-series satellite data.

user’s accuracy, producer’s accuracy, and overall accuracy. Classification accuracy from the confusion matrix is based on the reference pixels of the independent data set mentioned in Section 2.4. In this study, the RF algorithm was processed with python 2.7 with the standard parameter settings (Nitze et al., 2015).

2.3.3. Extraction of locust habitat at the patch scale

According to the *Technical Specification for the Investigation and Forecast of locusta migratoria manilensis (GB/T 15803-2007)*, two habitat categories of locust are defined as: 1) Permanent locust areas (PLA), which was assigned to gramineous plants, mostly reed and weed, with medium vegetation coverage, high soil moisture, and limited surface salt accumulation, provide the most favorable host plants and habitat conditions for locust feeding and oviposition. 2) Occasional locust areas (OLA), which contain weeds, reeds, and certain gramineous crops, with high vegetation coverage and temporal flooding, provide sufficient food for locust growth and are the optimal choice for locust migration. All other land cover classes represent non-locust area with a relatively low risk of locust infestation, because locusts will not lay their eggs in places such as settlement area, saline and alkaline land. Based on these specific landscape characteristics, in this part, the NDVI and TVI time-series extracted from the 8-day Landsat observations and Landsat-MODIS fused images, and LST curve extracted from 8-day MODIS composite products were employed as remote proxies of land cover categories, vegetation coverage, and land temperature (Scanlan et al., 2001).

A landscape’s membership-based random forest (LMRF) model was developed to identify the landscape pattern of permanent/occasional locust habitats at the patch level. This model linked the satellite-derived landscape structures to a 2-dimensional membership vector for locust habitat classes, and achieved classification by using a set of multiple independent decision tree. By using a moving-window approach, the membership vector M containing the estimated class memberships associated with the centroid pixel of a patch x , and $M(x)$ was defined as:

$$M_t(x, y) = \{M_{p,t}(x, y), M_{o,t}(x, y)\} \tag{2}$$

where M_t is the estimated membership degree of a central pixel (x_i, y_i) of a patch to class i ($i = \{p, o\}$) in date t , p is the permanent locust habitat, and o is the occasional locust habitat.

In order to characterize the landscape pattern of the given patch restricted by a moving window, additional information from neighboring pixels was introduced. Therefore, we computed the memberships of classes for the central pixel with a weighting function:

$$M_{i,t_0}(x_{w/2}, y_{w/2}) = \sum_{j=1}^w \sum_{k=1}^w W_{j,k} \times \frac{TVI_{t_0}(x_j, y_k) - NDVI_{t_0}(x_j, y_k)}{TVI_{t_0}(x_j, y_k) + NDVI_{t_0}(x_j, y_k)} \times \ln(LST_{t_0}(x_j, y_k)) \tag{3}$$

where, M_{i,t_0} is the membership degree of the class i in date t_0 , w is the moving window size and $(x_{w/2}, y_{w/2})$ is the central pixel of this moving window. In this function, considering the logarithmical relationship between the LST and locust habitat suitability in entomology (Chapman, 1955) and the impacts of magnitude inconsistency between vegetation indices and LST on the calculation, a logarithm transformation implemented with the raw LST values is helpful for quantifying the comprehensive influence of landscape factors on locust habitats memberships. The weight W_{ij} determines how much each neighboring pixel contributes to the estimated host performance of the central pixel. It is very important

to quantify the landscape effects, as determined by the two following measures.

2.3.3.1. *Landcover weighted coefficients.* Based on the field investigations and literature reviews, we regarded the reeds & weeds mixed area as the ideal place for oviposition and growth. Similarly, the water resources provide the ideal environment for egg hatching and nymph growth (Sobrino et al., 2004). On the other hand, pure reeds with high vegetation coverage provide sufficient conditions for locust migration, which contribute more to membership of an occasional locust habitat (Sun and Schulz, 2015). Based on these acknowledgment, we empirically assigned the land cover types with different coefficients for calculation of $M_{p,t}$ and $M_{o,t}$, respectively. The coefficients matrix ($C_{j,k}$) for each land cover type are listed in Table 3.

2.3.3.2. *Spatial distance.* Location distance between the central pixel $(x_{w/2}, y_{w/2})$ and neighboring pixel (x_j, y_k) within the moving window is defined as follows:

$$d_{j,k} = \sqrt{(x_{w/2} - x_j)^2 + (y_{w/2} - y_k)^2} \tag{4}$$

This measures the spatial distance between the central pixel and the surrounding pixels. The spatial similarity is normally better for a closer pixel; thus, the closer pixels should be assigned a higher weight.

The final step is to combine these independent factors to create a rational weight function that blends both the landscape effect and distance information at the patch scale. The combined weight function can be computed in a logarithm formula to make it less dependent on the specific differences of land cover coefficient settings:

$$W_{j,k} = \frac{1}{d_{j,k}} \times \ln(C_{j,k} \times b + 1) \tag{5}$$

where, the $W_{j,k}$ is the host performance weight of neighboring pixel (x_j, y_k) within the moving window, $d_{j,k}$ is the defined distance between the central pixel and the neighboring pixel (x_j, y_k) , $C_{j,k}$ is the defined landcover weights, which is hypothesized as a logarithm relation with the locust habitat suitability. The constant 1 is to ensure that when $C_{j,k} = 0$, the results of logarithm transformation is 0. The scale factor b is used to ensure the logarithm transformation of $C_{j,k}$ has a rational contribution of the landcover factors on fitting the $W_{j,k}$, in this study the optimal parameter b is 200.

The membership vectors $M_t(x, y)$ were used as the input features of various locust habitat categories to train the LMRF of each year. The following procedure of locust habitat extraction is the same as the general process of RF classification. As a result, twelve annual locust habitat maps were created.

For assessing the extraction results for locust habitats, Shannon entropy was employed to measure the uncertainty of classification results:

Table 3
The definition of landcover weights for permanent/occasional locust habitat.

	Reed	Reed & weed	Cropland	Water	Other
Permanent locust habitat	0.3	0.8	0.5	0.6	0
Occasional locust habitat	0.7	0.2	0.5	0.4	0

$$h(x_j, y_k) = - \sum_{i=1}^n M_t(x_j, y_k) \log_2 M_t(x_j, y_k) \quad (6)$$

where $M_t(x_j, y_k)$ is the estimated membership degree of a pixel (x_j, y_k) to class t .

In order to have a comparable measurement to classification accuracy, a proxy of confidence U was introduced to normalize $h(x)$ to have the same scale (Löw et al., 2015b). The average value U of all pixels that measured the confidence of classification was used to substitute map quality for all years (Löw et al., 2015b). It is noteworthy that this assessment of map quality is independent from reference data. The mathematical function of U was defined as:

$$U = 1 - h(x_j, y_k) \quad (7)$$

2.3.4. Inter-annual locust habitat change in response to landscape dynamics

In order to detect the landscape changes at the pixel level, a profile angle (PA) based approach is proposed. The profile angle (PA) is defined as the angle (θ) between the temporal sequencing vector $\vec{p}_i = \{p_{i,1}, p_{i,2}, \dots, p_{i,L}\}$ defined by the inter-annual time series of NDVI, TVI, and LST from satellite observations at the pixel level, and the reference temporal vector $\vec{s}_j = \{s_{j,1}, s_{j,2}, \dots, s_{j,L}\}$ defined by the averaged time-series of NDVI, TVI, and LST from the labeled auxiliary pixels of each landcover class. Here, an inverse transformation of cosine function (arccos) is used to calculate the profile angle (Dennison et al., 2004).

$$PA(\vec{p}_i, \vec{s}_j) = \theta(\vec{p}_i, \vec{s}_j) = \arccos \left(\frac{\sum_{l=1}^L p_{i,l} \cdot s_{j,l}}{\left[\sum_{l=1}^L p_{i,l}^2 \right]^{\frac{1}{2}} \left[\sum_{l=1}^L s_{j,l}^2 \right]^{\frac{1}{2}}} \right) \quad (8)$$

where L is the number of the observations of a year ($L = 23$ in this study).

In this study, we hypothesized that the time-series of unchanged pixels between two years have similar pattern, thus, the PA between unchanged pixels and the reference pixels from the labeled landcover types are consistent. Based on this hypothesis, the inter-annual landscape change was assessed by a profile angle matching (PAM) algorithm. This algorithm examines the mean PA of the temporal sequencing vectors of a given pixels and the reference temporal vectors of each landcover type, respectively, between two years, and reassigns this pixel to the class with the minimum PA. These reassignments between different years reveal the landscape dynamics of locust habitats.

To explore the relations between the landscape dynamics and corresponding locust habitat changes, a pair-wise univariate regression analysis was conducted. By comparing with the actual survey of summer and autumn locust outbreak area, the importance of each landcover change event on locust habitat variations can be evaluated. The coefficient of determination (R^2) and p -value were employed as the accuracy indicators.

3. Results

3.1. Satellite-derived locust habitat extraction

Based on the STARFM data fusion algorithm mentioned in section 2.3.1, twelve years of the Landsat-MODIS fused reflectance at 30-m were generated for Dagang District. The accuracies of the

fused reflectance were assessed by comparing them with the independent dataset of Landsat observations that were not used in the STARFM algorithm (Supplement Material, Table S1). The years 2004, 2007, and 2008 show higher biases in green, red and NIR bands, which are due in part to the large variation in biases caused by the limited input of Landsat-MODIS pairs. Therefore, considering the effects of these biases on the predicted reflectance, the analysis of 2004, 2007 and 2008 were not involved in the further works.

Eight-day TVI, NDVI and LST time-series at 30-m resolution were calculated by using the Landsat observations and Landsat-MODIS fused images (Supplement material, Fig. S2). Because the calculation of such habitat factors is depended on the quality of data fusion (Table S1 in Supplement Material), the further evaluation is not shown in this study. Based on the seasonal NDVI pattern, a series of twelve annual land cover classifications were generated by SCRF classifier (Fig. 3). The Confusion Matrix for land cover classifications is shown in Table 4, which demonstrates that the overall accuracies for the three assessment years were 84%, 91%, and 86%.

Subsequently, by combining the NDVI, TVI, and LST time-series as the input database of the LMRF model, locust habitat maps were generated over the observation period (Fig. 4), which provided evidences to back-trace the tendency of locust habitat changes over sixteen years. The confidences of the permanent and occasional locust habitat extraction were listed in Table 5, which illustrated that the significance of both habitat types were greater than 0.8 and 0.76, respectively.

3.2. Causes and consequences analysis between landscape's dynamics and locust habitat change

Area statistics of locust habitat indicate that, during 2000–2016, the permanent locust habitat area covered 211.75 km² on average (approximately 21.35% of the total), the maximum permanent locust area covered 241.55 km² in 2002, and the minimum covered 177.58 km² in 2006; the occasional locust habitat area covered 207.47 km² on average (approximately 20.91% of the total), with the maximum occasional locust area covered 254.78 km² in 2010, and the minimum covered 168.71 km² in 2000 (Fig. 5).

The spatial distributions of annual change of locust habitats from 2000 to 2015 are shown in Fig. 6. In the temporal scale, the most obvious overall change event for permanent habitats occurred from 2002 to 2003 (Fig. 6A). On the other hand, the change area of occasional locust habitats had no high-magnitude changes in each year (Fig. 6B). In the spatial scale, the detected changes comprise a notable proportion of the subtle changes in landscape structure. Combined with the pair-wise univariate correlation between the locust habitat transitions and their component land cover changes (Supplement Material, Fig. S3), it is easy to illustrate that, for the permanent habitat, the pure reed nearby the Duliujian river and Lier bay and water level of North Dagang reservoir are markedly the most significant changed places ($R^2 > 0.54$); for the occasional locust habitat, the changed in the border of water and the surrounding vegetations, such as reed or cropland, was most affected the outbreaks of locust ($R^2 > 0.61$).

4. Discussion

The integrated system proposed in this study provides insight into the spatio-temporal pattern of landscape dynamic controlling locust habitat change. Understanding the causes and consequences of habitat changes in the hot spot of locust infestation is instrumental for facilitating biological control and locust habitat management. For this prospective, an integrated method proposed in this study has many advantages. Firstly, it is fully automated and is

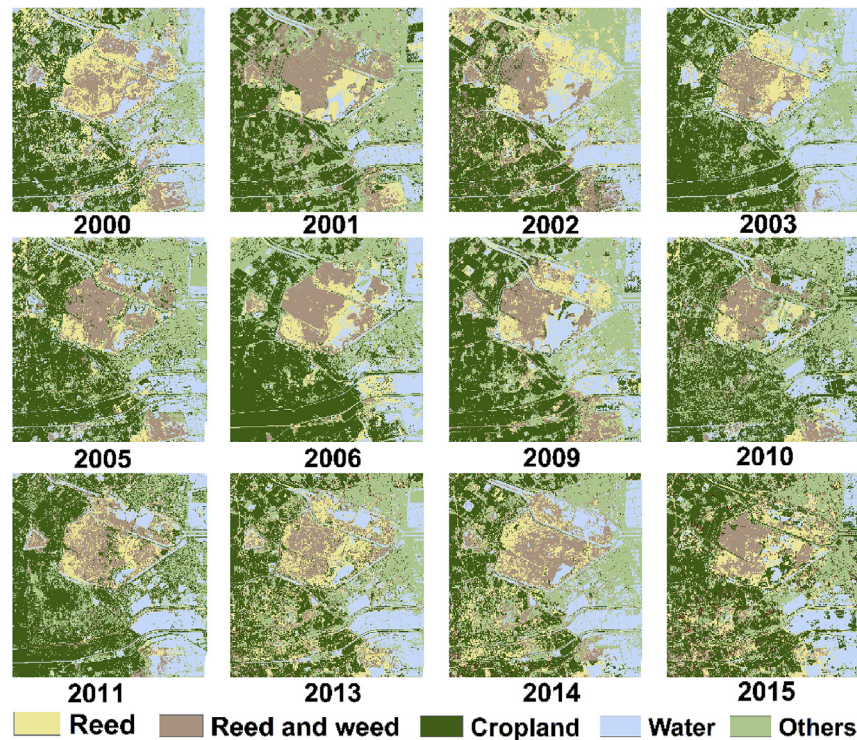


Fig. 3. Maps of annual land cover in the study area from 2000 to 2015.

Table 4
Confusion matrix and accuracy assessment of land cover classifications in 2000, 2005, and 2010.

Years	Referenced pixels						
	Reed	Reed&weed	Cropland	Water	U (%)	OA (%)	
2000	Reed	1730	345	58	20	80	84
	Reed&weed	94	1871	152	0	88	
	Cropland	56	197	1656	0	87	
	Water	0	49	38	1995	96	
	P (%)	92	76	87	99		
2005	Reed	1837	228	0	0	89	91
	Reed&weed	38	2503	57	0	96	
	Cropland	0	85	1812	0	96	
	Water	0	28	19	1989	98	
	P (%)	98	88	96	100		
2010	Reed	2007	268	66	0	86	86
	Reed&weed	87	2530	83	0	94	
	Cropland	65	119	1502	0	89	
	Water	22	60	0	1247	94	
	P (%)	92	85	91	100		

Note: U = User's accuracy, P=Producer's accuracy, OA = Overall accuracy.

capable of monitoring locust habitat changes at the patch level. In addition, there are no empirical thresholds used in the analysis. Moreover, the continuous nature of the monitoring makes the algorithm capable of using longitudinal features of remotely retrieved indicators. Geographically, the methodology can be utilized in any area of *Locust migratoria manilensis* distribution from China to other countries of East Asia because the habitat conditions and the landscape's ecological mechanisms are similar. This study may lead to reduction of the pesticide load on fragile wetlands and water resources giving rise to more sustainable locust area transition and management.

4.1. Assessment of locust habitat extraction

For summer locust, eggs laid in autumn usually over-winter and hatch in the late-spring, and for autumn locust, egg hatching will commence between two and three weeks after oviposition in the late-summer (McCulloch and Hunter, 1983). The average seasonal NDVI time series of all four landcover types showed a consistent seasonal behavior with such growth circle of locust, with the minima during the spring and maxima during the summer. Mining such seasonal features from the NDVI time-series has a tremendous impact on its operationalization potential (overall accuracy of landcover extraction greater than 84%), as it is possible to generalize the automatic land cover classification for years without training data.

The locust habitat is considered to be a spatially and temporally variable mosaic of vegetation patches with different species, which is composed by specific landscape and hydrographical structure. In order to balance the landscape characteristics of locust habitats and remote retrieved habitat factors, a combined use of multi-years NDVI, TVI, and LST curves were employed. The philosophy behind this is that, compared to the NDVI which contained distinct seasonal features of different landcovers, the TVI time-series exhibit the LAI information of the given pixels and indicates a more detailed correlation with vegetation coverage; meanwhile, the LST curves reflect the field temperature conditions which is an essential habitat factor for locust breeding and eclosion. Hence, a rational integration of such indicators by the membership function can be regarded as a reasonable proxy to identify the pre-defined locust habitat classes. Locust habitat extraction from satellite imagery requires overcoming two challenges: 1) scale mismatch, thus the habitat detection in satellite images is operated at the pixel level, but in the real world, it is identified at the patch level, and 2) separability, thus two different types of locust habitat generally comprise the same landcover constituents that have no direct

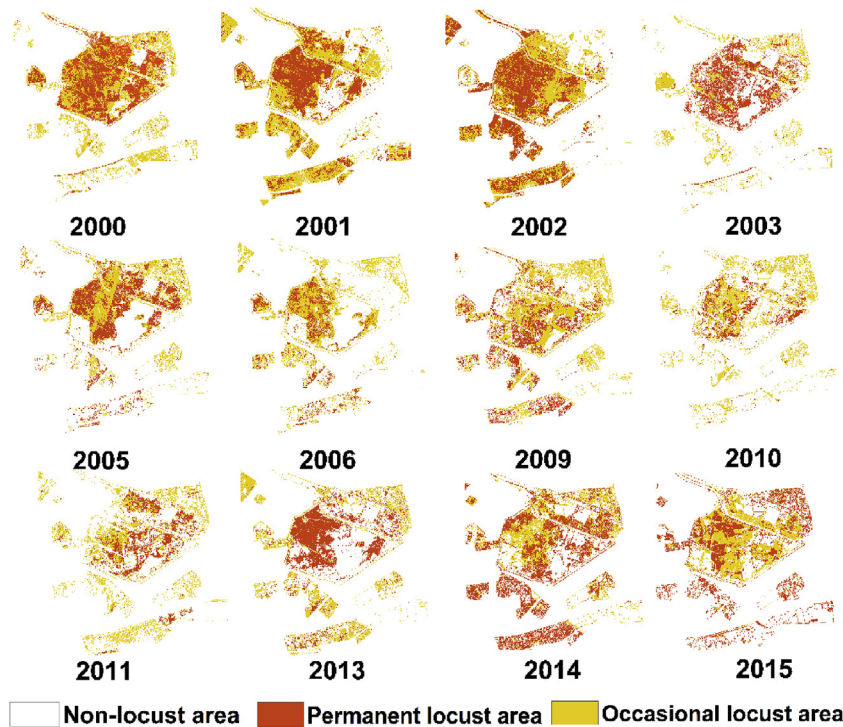


Fig. 4. Maps of inter-annual locust habitat area distribution from 2000 to 2015.

Table 5

Overall confidence (U) of the locust habitat maps based on the LMRF classifier.

	2000	2001	2002	2003	2005	2006	2009	2010	2011	2013	2014	2015
Permanent locust habitat	0.83	0.89	0.9	0.86	0.87	0.88	0.89	0.82	0.88	0.89	0.84	0.8
Occasional locust habitat	0.78	0.82	0.84	0.79	0.82	0.84	0.81	0.77	0.79	0.8	0.82	0.76

indicators for the habitat classification at the pixel scale. The merit of the proposed LMRF algorithm is to describe the landscape characters of each habitat type at the patch level, and subsequently be distinguished by factors completely calculated from the remote sensing data. Several studies have shown that high class membership is associated with high classification accuracies (Blanco et al., 2013; Löw et al., 2015a; Waldner et al., 2015), also, it is noteworthy that the moving window strategy fully considers the contributions of the neighboring land cover effects and maximally quantifies their entomological and ecological attributes. In this paper, the inter-annual locust habitat extractions with acceptable confidences ($U > 0.76$) were produced by the LMRF algorithm to support the cause and consequence analysis of landscape dynamics and habitat changes.

Although the proposed methodology is meaningful for locust habitat extraction, some limitations still need to be considered. Firstly, the composite interval from Landsat observations and MODIS-Landsat fused images is eight days, and this time lag might ignore certain temporary and unexpected environmental effects associated with locust infestation, such as floods, streams, and artificial interference, which would affect the precision of locust habitat assessment. In addition, the habitat classification could be improved if more georeferenced locust distribution data were available.

4.2. The influence of landscape's dynamics on the locust habitat changes

The landcover types within the locust habitat areas represent significant hydrological rules and vegetation requirements of typical locust habitat classes. Specifically, the mixed reed and weed area, with sparse plant density on beach land, riverbanks, and wetlands, cover 56.88% of the total permanent locust area on average (approximately 120.44 km² in the study site), which provide a plenty of food for locust migration in severe infestation years. In contrast, the pure reed areas, with a relatively dry environment and high plant density, occupy 55.36% of the total occasional locust area on average (approximately 114.86 km²), which provide ideal temperature and moisture conditions for locust breeding and enough space and food for nymph growth.

The findings presented here have strong parallels with the historical locust infestation survey from 2000 to 2016. The correlation analysis quantified the contributions of the landcover compositions of a given habitat type to the locust plague. For the permanent locust habitats, sparse reeds and weeds were concentrated in the vicinity of North Dagang reservoir, the water inflow of the reservoir was directly associated with the wetland area, and further influenced the growth of reeds and weeds in term of proportion and density. The water inflow reached its peak in 2002,

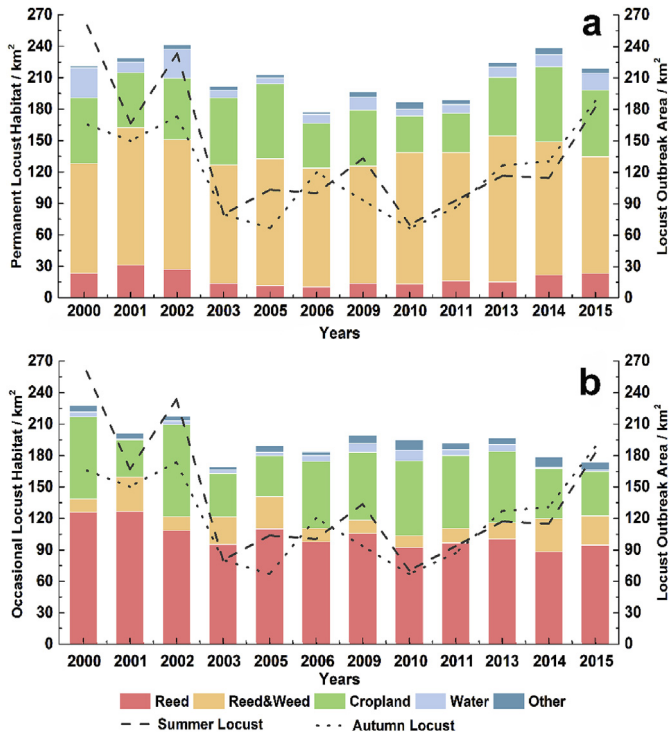


Fig. 5. The stacked plot of the inter-annual permanent locust area and the occasional locust area in the study site, the locust-infested area surveyed annually by TPPS (2000–2015) is presented as a dashed line.

because the preceding two years were also highly flooded, the acreage of water leading to wetland vegetation such as weeds and reeds was substantially increased. Sparse reed beds which harbored locust breeding sites generally followed the water level. On the other hand, for 2000–2002 and 2013–2015, summer crops

were generally harvested in June, and rotated autumn crops in August and September had better growth than other vegetation, which ensured the food was available for autumn locust migration in the severe plague years. Therefore, the permanent locust habitat areas with high locust outbreak risk were sustained expansion during these two periods.

In order to derive a more ecological meaningful analysis for the influence of land cover dynamics on the locust habitats changes, the change matrix at a four-year interval is exhibited in Table S2 (see Supplement Material). Based on these analysis, we can infer that, although there was minor increase in the length of the summers' dry periods and fluctuating water level (Poulter et al., 2013), the variations in the vegetation components likely impacted the actual locust habitat transition. The largest variation occurred in dense pure reed area, with 30.2% on average convert to sparse mixed reed and weed and 16% to water resources, which may promote the emergence of novel permanent locust habitat. The mixed reed and weed followed at 27.2% on average transformed to dense reed and 6.7% to the cropland, which lead to the decline in locust habitat area. Considering this kind of transition mainly occurred in the slight plague years, such as 2003 and 2010, the decline of habitat suitability of locust might have been caused by human intervention, which transform the natural wetland to farmland. Wetlands often experience natural water level fluctuations that result in cyclic changes to vegetation. Based on our observations, competitive displacement might have occurred in the vicinity of beach land, riverbanks, and wetlands, with 13.4% of the water resource transformed to cropland and 12.2% to pure reed. The composition of a wetland's plant communities is dynamic for various reasons, including climate change and human intervention (Anda et al., 2015). Based on our material investigations, in North Dagang reservoir, dry periods were triggered during the years of 2004–2010, and the wetland's vegetation composition of locust breeding area was partially invaded by cropland and grass species, likely this is a significantly ecological reason for locust habitat decline and slight infestation. Overall, analyzing the vegetation

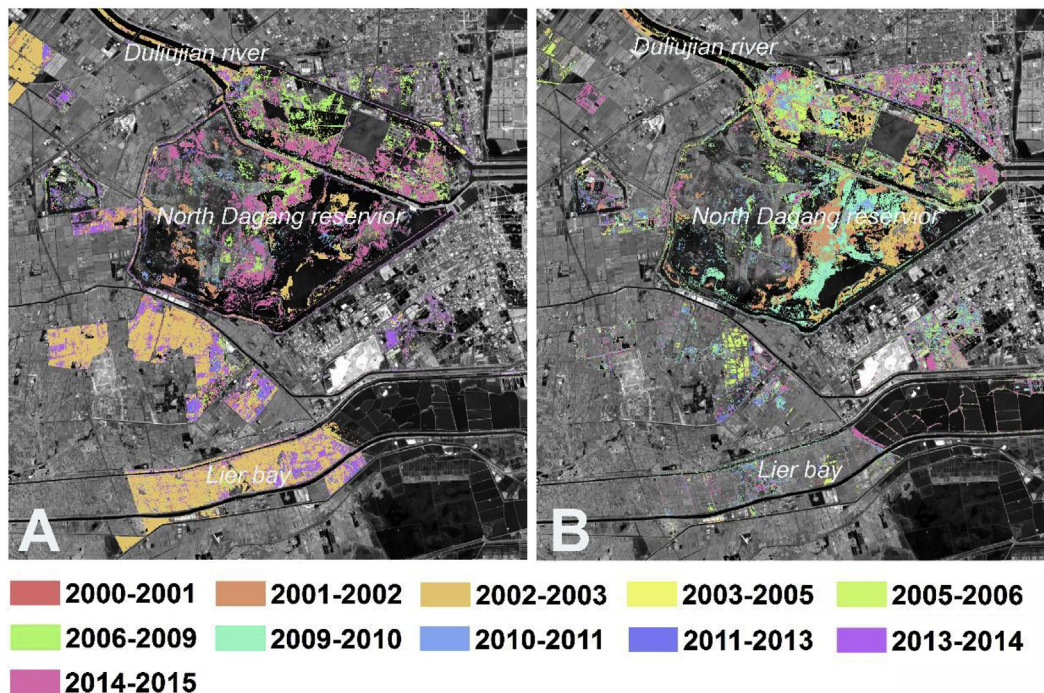


Fig. 6. Spatial distribution of change events for permanent locust habitat (A) and occasional locust habitat (B) from 2000 to 2015.

succession and landscape dynamic of a 16 year-long in Dagang District, the locust habitat changes was proven to be tightly connected to their landscape structure and hydrological regimen. The wetland vegetations (e.g. reed and weed) reveal strong and predictable seasonality, and the growth circle of locust is synchronized with them.

4.3. Suggestions to improve locust habitat management

The satellite-derived locust habitat extractions and inter-annual dynamics analysis produced by this study could provide important evidence to assist agronomic and plant protection specialists in many aspects. For one, the thematic maps of annual locust habitats comprising explicit land cover classification and vegetation growth information with high accuracy are useful for guiding land survey activities to identify the key investigation stages of locust development (i.e., locust hatching and the appearance of the early nymphal stage, respectively) and priority locations. Subsequently, the application of chemical pesticides could be guided and optimized, by concentrating on areas with high risk potential, which could result in minimizing chemical contamination in the neighboring vicinity of the numerous wetlands and water resources.

Another aspect is that, the inter-annual locust habitat dynamics reflect the process of habitat transition following changes in the physical geography and human activities. This is meaningful for locust habitat limitation in order to reduce the risk of locust infestation from a landscape ecology perspective without environmental degradation. For example, we have concluded that the extent of reed beds with sparse density in North Dagang Reservoir generally follow the water inflows, which determines the range of locust infestation potential. Hence increasing the vegetation coverage over 90% through artificial planting of non-gramineae vegetation is beneficial to restraining locust hatching and breeding. On the other hand, transforming the crop rotation strategy surrounding the North Dagang reservoir and Lier bay can limit the range of locust migration. In some studies, transforming the cropland to forest and wet field is also an option to limit locust plagues without influencing farmers' benefits.

5. Conclusion

Landscape's dynamics in ecosystem have been considered primarily factor for locust habitat change. This paper presents an integrated methodology to investigate and evaluate the influence of landscape's dynamics of locust habitat areas. The analyses are based on Landsat observations and MODIS-Landsat fused data with an 8-day interval in Dagang District, Tianjin, China. The proposed interdisciplinary approach, LMRF algorithm, to locust habitat extraction is not only a simply botanical and phenological-based one at the pixel scale. Rather, locust habitat classification in this study was based on the landscape's pattern at the patch scale. Besides, this work provide insight for the first time in the causes and consequences between the landscape's dynamic and locust habitat changes from the remote sensing perspective, by using continuous temporal changes in remote sensing descriptors dynamics and spatial assessment of the influence of landscape's structure transition. Our findings suggest that, the mixed reeds and weeds area, as the crucial water consumers, show great contribution to the constitute of permanent locust habitat, and the densely dry reed is the most important landscape component of occasional locust habitat. In addition, inter-annual fluctuation in the water level is a key ecological factor to facilitate the locust habitat change, for example, the dry periods in North Dagang reservoir during 2003 and 2009, which caused dry reed growth well, and wetland degeneration and cropland rise in consequence, resulted in a

significant decline of permanent locust habitat. These findings provide evidence for understanding the influence of landscape's dynamic on locust habitat changes, and developing a practical strategy for locust management and transition. Conducting this study in Dagang district could provide a paradigm of locust habitat management from traditional field survey to remote sensing investigation. More importantly, these findings are able to contribute toward shifting the pure chemical control of locust outbreaks to a comprehensive management of locust habitats from the perspective of landscape ecology.

Acknowledgment

This work was supported by National Key R&D Program of China (2016YFD0300702), the external cooperation program of BIC, Chinese Academy of Sciences (131211KYSB20150034), the National Natural Science Foundation of China (61661136004), the funding from Hainan (2016CXTD015), the Youth Innovation Promotion Association of the Chinese Academy of Sciences (Y4YR1300QM).

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jenvman.2018.04.028>.

References

- Anda, A., Soos, G., Silva, J.A.T.D., Kozma-Bognar, V., 2015. Regional evapotranspiration from a wetland in Central Europe, in a 16-year period without human intervention. *Agric. For. Meteorol.* 205, 60–72.
- Bian, Z., Zhang, G., 2001. Classification of Ecological Degradation and Ecological Rehabilitation in China. Thomas Telford.
- Blanco, P.D., Colditz, R.R., Saldaña, G.L., Hardtke, L.A., Llamas, R.M., Mari, N.A., Fischer, A., Caride, C., Aceñolaza, P.G., del Valle, H.F., 2013. A land cover map of Latin America and the Caribbean in the framework of the SERENA project. *Remote Sens. Environ.* 132, 13–31.
- Breiman, L., 2001. Random forest. *Mach. Learn.* 45, 5–32.
- Butt, A., Shabbir, R., Ahmad, S.S., Aziz, N., Nawaz, M., Shah, M.T.A., 2015. Land cover classification and change detection analysis of rawal watershed using remote sensing data, vol. 6, 2222–3045.
- Chen, J., Jönsson, P., Tamura, M., Gu, Z., Matsushita, B., Eklundh, L., 2004. A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter. *Remote Sens. Environ.* 91, 332–344.
- Crooks, W.T., Cheke, R.A., 2014. Soil moisture assessments for brown locust *Locustana pardalina* breeding potential using synthetic aperture radar. *J. Appl. Remote Sens.* 8, 2378–2391.
- Chapman, R.F., 1955. Some temperature responses of nymphs of *Locusta migratoria migratorioides* (R. & F.), with special reference to ggregation. *J. Exp. Biol.* 32, 126–139.
- Despland, E., Rosenberg, J., Simpson, S.J., 2004. Landscape structure and locust swarming: a Satellite's mye view. *Ecography* 27, 381–391.
- Dennison, P.E., Halligan, K.Q., Roberts, D.A., 2004. A comparison of error metrics and constraints for multiple endmember spectral mixture analysis and spectral angle mapper. *Remote Sens. Environ.* 93, 359–367.
- Gao, F., Anderson, M.C., Zhang, X., Yang, Z., Alfieri, J.G., Kustas, W.P., Mueller, R., Johnson, D.M., Prueger, J.H., 2017. Toward mapping crop progress at field scales through fusion of Landsat and MODIS imagery. *Remote Sens. Environ.* 188, 9–25.
- Gao, F., Hilker, T., Zhu, X., Anderson, M., Masek, J., Wang, P., Yang, Y., 2015. Fusing Landsat and MODIS data for vegetation monitoring. *IEEE Geosci. Remote Sens. Mag.* 3, 47–60.
- Gao, F., Morisette, J.T., Wolfe, R.E., Ederer, G., Pedelty, J., Masuoka, E., Myneni, R., Tan, B., Nightingale, J., 2008. An algorithm to produce temporally and spatially continuous MODIS-LAI time series. *IEEE Geosci. Remote Sens. Lett.* 5, 60–64.
- Gislason, P.O., Benediktsson, J.A., Sveinsson, J.R., 2006. Random forests for land cover classification. *Pattern Recognit. Lett.* 27, 294–300.
- Hansen, M.C., Loveland, T.R., 2012. A review of large area monitoring of land cover change using landsat data. *Remote Sens. Environ.* 122, 66–74.
- Ji, R., Li, D.M., Xie, B.Y., Li, Z., Meng, D.L., 2006. Spatial distribution of oriental migratory locust (*Orthoptera: Acrididae*) egg Pod populations: Implications for site-specific pest management. *Environ. Entomol.* 35, 1244–1248.
- Ji, R., Xie, B.Y., Li, D.M., Li, Z., Zhang, X., 2004. Use of MODIS data to monitor the oriental migratory locust plague. *Agric. Ecosyst. Environ.* 104, 615–620.
- Löw, F., Conrad, C., Michel, U., 2015a. Decision fusion and non-parametric classifiers for land use mapping using multi-temporal rapid eye data. *ISPRS J. Photogrammetry Remote Sens.* 108, 191–204.

- Löw, F., Knöfel, P., Conrad, C., 2015b. Analysis of uncertainty in multi-temporal object-based classification. *ISPRS J. Photogramm. Remote Sens.* 105, 91–106.
- Latchininsky, A.A.V., 2013. Locusts and remote sensing: a review. *J. Appl. Remote Sens.* 7, 5099.
- Li, Z., Wang, Y., Zhou, Q., Wu, J., Peng, J., Chang, H., 2008. Spatiotemporal variability of land surface moisture based on vegetation and temperature characteristics in Northern Shaanxi Loess Plateau, China. *J. Arid Environ.* 72, 974–985.
- Liu, Z., Ni, S., Zha, Y., Shi, X., 2006. Monitoring the plague of oriental migratory locust using multi-temporal landsat TM imagery. In: *Proceedings of SPIE - the International Society for Optical Engineering*, vol. 6200, 62000W-62000W-62008.
- Liu, Z., Shi, X., Warner, E., Ge, Y., Yu, D., Ni, S., Wang, H., 2008. Relationship between oriental migratory locust plague and soil moisture extracted from MODIS data. *Int. J. Appl. Earth Obs. Geoinf.* 10, 84–91.
- Müller, W., 1976. Seasonal locust development potential in the Niger area analyzed through ecoclimatological interpretation of satellite images. *Int. J. Biometeorol.* 20, 249–255.
- Ma, J., Han, X.Z., Shibagan, H., 2004. Remote sensing new model for monitor the East Asian migratory locust infections based on its breeding circle. *J. Remote Sens.* 4467 (7), 4468–4469.
- Mcculloch, L., Hunter, D.M., 1983. Identification and monitoring of Australian plague locust habitats from Landsat. *Remote Sens. Environ.* 13, 95–102.
- Moosavi, V., Talebi, A., Mokhtari, M.H., Shamsi, S.R.F., Niazi, Y., 2015. A wavelet-artificial intelligence fusion approach (WAIFA) for blending Landsat and MODIS surface temperature. *Remote Sens. Environ.* 169, 243–254.
- Nitze, I., Barrett, B., Cawkwell, F., 2015. Temporal optimisation of image acquisition for land cover classification with Random Forest and MODIS time-series. *Int. J. Appl. Earth Obs. Geoinf.* 34, 136–146.
- Park, J.H., Na, S., 2007. MODIS and Landsat TM data image fusion based on improved resolution method: assessing the quality of resulting NDVI images. In: *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 6742.
- Prinzie, A., Van den Poel, D., 2008. Random forests for multiclass classification: random multinomial logit. *Expert Syst. Appl.* 34, 1721–1732.
- Poulter, B., Pederson, N., Liu, H., Zhu, Z., D'Arrigo, R., Ciais, P., Davi, N., Frank, D., Leland, C., Myneni, R., 2013. Recent trends in Inner Asian forest dynamics to temperature and precipitation indicate high sensitivity to climate change. *Agric. For. Meteorol.* 178–179, 31–45.
- Rodríguez-Galiano, V.F., Ghimire, B., Rogan, J., Chica-Olmo, M., Rigol-Sanchez, J.P., 2012. An assessment of the effectiveness of a random forest classifier for land-cover classification. *ISPRS J. Photogramm. Remote Sens.* 67, 93–104.
- Scanlan, J.C., Grant, W.E., Hunter, D.M., Milner, R.J., 2001. Habitat and environmental factors influencing the control of migratory locusts (*Locusta migratoria*) with an entomopathogenic fungus (*Metarhizium anisopliae*). *Ecol. Model.* 136, 223–236.
- Semmens, K.A., Anderson, M.C., Kustas, W.P., Gao, F., Alfieri, J.G., Mckee, L., Prueger, J.H., Hain, C.R., Cammalleri, C., Yang, Y., 2015. Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sens. Environ.* 185, 155–170.
- Sobrino, J.A., Jiménez-Muñoz, J.C., Paolini, L., 2004. Land surface temperature retrieval from LANDSAT TM 5. *Remote Sens. Environ.* 90, 434–440.
- Sun, J., Zhu, H., Xu, Z., Han, C., 2013. Poisson image fusion based on Markov random field fusion model. *Inf. Fusion* 14, 241–254.
- Sun, L., Schulz, K., 2015. The improvement of land cover classification by thermal remote sensing. *Remote Sens.* 7, 8368–8390.
- Swathika, R., Sharmila, T.S., 2017. Multi-resolution spatial incorporation for MODIS and LANDSAT image fusion using CSSTARFM. In: *Region 10 Conference*, pp. 691–696.
- Tian, H.D., Ji, R., Xie, B.Y., Li, X.H., Li, D.M., 2008. Using multi-temporal Landsat ETM+ data to monitor the plague of oriental migratory locust. *Int. J. Remote Sens.* 29, 1685–1692.
- Tong, W.U., Shao-Xiang, N.I., Yun-Mei, L.I., Jiang, J.J., Chen, J., 2006. Research on the monitoring oriental migratory locust based on remote sensing retrieval of vegetation information. *Geogr. Geo-Inf. Sci.* 22, 25–29.
- Waldner, F., Canto, G.S., Defourny, P., 2015. Automated annual cropland mapping using knowledge-based temporal features. *ISPRS J. Photogramm. Remote Sens.* 110, 1–13.
- Yang, P., Shibasaki, R., Wu, W., Zhou, Q., Chen, Z., Zha, Y., Shi, Y., Tang, H., 2007. Evaluation of MODIS land cover and LAI products in cropland of North China Plain using in situ measurements and Landsat TM images. *IEEE Trans. Geosci. Remote Sens.* 45, 3087–3097.
- Zewdie, W., Csaplovics, E., 2015. Remote Sensing based multi-temporal land cover classification and change detection in northwestern Ethiopia. *Eur. J. Remote Sens.* 48, 121–139.
- Zhan, X., Sohlberg, R.A., Townshend, J.R.G., Dimiceli, C., Carroll, M.L., Eastman, J.C., Hansen, M.C., Defries, R.S., 2002. Detection of land cover changes using MODIS 250 m data. *Remote Sens. Environ.* 83, 336–350.
- Zhang, Z., Li, D., 1999. A possible relationship between outbreaks of the oriental migratory locust (*Locusta migratoria manilensis meyen*) in China and the El Niño episodes. *Ecol. Res.* 14, 267–270.