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Evolution stage identification and spatial pattern analysis of *Nitraria tangutorum* nebkhas based on Gaofen-2 satellite data

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The quantitative extraction and evolution stage identification of the *Nitraria tangutorum* nebkhas are the basis for the restoration of regional plants and the reconstruction of degraded ecosystems. In this paper, the *Nitraria tangutorum* nebkha in Dengkou County of China was taken as the research object. Through the spectral and texture information of Gaofen-2 satellite image, the quantitative extraction of *Nitraria tangutorum* nebkha area and coverage information was completed using methods of gray threshold method, mathematical morphology, FCLSU mixed pixel decomposition, kernel density spatial analysis; the current evolution stage of the *Nitraria tangutorum* nebkha was identified, and their spatial distribution characteristics were analyzed. The results showed that: (1) The user accuracy and mapping accuracy of *Nitraria tangutorum* nebkha extracted from Random Forest combined with object-oriented classification method were up to 90.32%. (2) The method proposed can achieve an accuracy of 93.76% in extracting the spatial position of *Nitraria tangutorum* nebkhas. (3) The evolution of *Nitraria tangutorum* nebkhas can be divided into three stages: embryonic or developmental stage, stable stage, and declining stage, with a proportion of 60.70%, 20.97%, and 18.33%, respectively; The *Nitraria tangutorum* nebkhas in the study area is mainly in their embryonic or developmental stage, and the proportion of *Nitraria tangutorum* nebkhas in the declining stage is also large. It can provide technical and theoretical support for the precise extraction of nebkhas in arid and semi-arid desert areas, the identification of their current evolutionary stages, and the study of their spatial distribution patterns.

Dunes are sandy landforms formed by the deposition of sand particles on the surface due to weak sand carrying capacity of air currents. According to the comprehensive classification of aeolian dunes, they can be divided into stabilized dunes, anchored dunes, and mobile dunes[1]. When the sediment of mobile dunes encounters vegetation interception and forms dunes that do not migrate with the wind and sands, stabilised dunes such as Nabkhas, Beach dune ridges, Blowout, etc. gradually form as the dunes evolve. They can also be called phytogenetic dunes[2].

Nitraria tangutorum is a shrub belonging to the *Nitraria* genus of *Zygophyllaceae* family. It often appears in the form nebkhas, and the vegetation can easily generate adventitious roots after being buried by sand. The branches can grow upright or prostrate, forming fixed and semi-fixed shrub sandbags (also called *Nitraria tangutorum* nebkha)[3–5]. In the desert transition zone of arid and semi-arid regions, *Nitraria tangutorum* communities are a widely distributed group of vegetation. They are mainly distributed in Inner Mongolia, Gansu, Xinjiang, Qinghai, Ningxia, northern Shaanxi, and the northeastern edge of Tibet, China. Because of their characteristics such as resistances of drought, saline-alkali, sand burial, wind and sand, and strong adaptability, they are excellent shrubs for vegetation restoration and reconstruction in sandy areas[6]. They are also top-level communities that effectively prevent the further expansion of desertification by windbreak and sand fixation, and maintain in the oasis-desert transition zone of arid and semi-arid areas[7,8]. Accurate extraction of *Nitraria tangutorum* nebkhas is the basis for studying their ecological functions, spatial distribution, evolutionary patterns, appearance, and structural characteristics. Therefore, the investigation of *Nitraria tangutorum* nebkhas has become one of the main tasks in desert vegetation surveying[9]. However, most studies are still based on field surveys, and there have been relatively few studies using remote sensing methods to study *Nitraria tangutorum* nebkhas. Wang[10] has used

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mathematical morphology and threshold segmentation methods to extract *Nitraria tangutorum* nebkhas in Ulan Buh Desert, based on color aerial remote sensing images. Three-dimensional extraction of *Nitraria tangutorum* nebkhas was realized by Zhang et al.[11] using aerial photographs and ground surveys. Hua et al.[12] used domestic high-resolution satellite images (resolution = 1m), multi-scale segmentation, and object-oriented classification methods to quantitatively extract *Nitraria tangutorum* nebkhas in Minqin, Gansu province of China. Zhao et al.[13] used UAVs (with a resolution of less than 0.1m) and visual interpretation methods to vectorize the *Nitraria tangutorum* and *Reaumuria songarica* in Gansu Caohu National Wetland Park. Ji et al.[14] used hyperspectral data to study the vegetation coverage of *Nitraria tangutorum* shrubs. However, these studies are all based on the extraction of *Nitaria tangutorum* nebkhas from *Nitraria tangutorum* vegetation, without fully considering the situation where some parts of *Nitraria tangutorum* nebkhas are exposed without vegetation cover, which may result in some deviation between the extracted area and the actual area.

There have been many studies on monitoring vegetation succession based on remote sensing data. For example, Song et al.[15] evaluated uncertainty factors in using multitemporal Landsat images for forest succession change, including atmosphere, topography, phenology, and sun and view angles.. Many scholars also use optical remote sensing data to classify forest succession stages or predict the age of forest stands[16–18]. Falkowski et al.[19] used indicators derived from LiDAR to calculate the average height of vegetation and canopy coverage, and then used modeling to achieve the division of six forest succession stages (Open, Stand initiation, Understory reinitiation, Young multistory, Material multistory, Old multistory). Radecka et al.[20] proposed using parameters such as vegetation coverage area, coverage, and vegetation type retrieved from airborne hyperspectral and LiDAR data to achieve the division of vegetation succession stages.

However, currently, the identification of the current evolution stage of the *Nitraria tangutorum* nebkhas is based on sample site surveys. Li et al.[7] conducted research on the morphological characteristics and growth process of three different habitats of *Nitraria tangutorum* nebkhas, and ultimately divided the growth and development of *Tamarix chinensis* nebkhas into three stages: growth, stability, and decline[7]. Han et al.[21] divided *Nitraria tangutorum* nebkhas into four succession stages: embryonic stage, development stage, stability stage, and decline stage according to the length and angle of windward slope and leeward slope as well as vegetation coverage, vegetation growth state (dead rate, seed setting rate, etc.), and nebkha soil condition (windward slope and leeward slope crust type, soil type of hilly land, etc.). Sun et al.[22] divided the evolution stage of *Nitraria tangutorum* into embryonic stage, developmental stage, stable stage, and activation stage based on the *Nitraria tangutorum* nebkha three-dimensional structural parameters (high, long axis, short axis), soil, crust type, vegetation coverage, and vegetation mortality rate of the *Nitraria tangutorum* nebkhas. There are certain differences in the development process of nebkhas in different regions, and the division stages are also slightly different. There are some differences in the development process of nebkhas in different regions, and the stages are also slightly different. At present, the standards for the evolution stage of *Nitraria tangutorum* nebkha are mostly established based on the text data of sample plot survey, which is difficult to display the form of *Nitraria tangutorum* nebkha and the growth state of *Nitraria tangutorum* vegetation in space, and the identification of the evolution stage of *Nitraria tangutorum* nebkha in non-sample areas is not further completed according to the standards for the evolution stage of survey, which is difficult to be extended to the practical application of identifying the evolution stage of *Nitraria tangutorum* nebkha and studying the spatial distribution pattern of a single *Nitraria tangutorum* nebkha with large regional mapping.

The evolution and spatial distribution of *Nitraria tangutorum* shrub nebkhas are largely affected by environmental heterogeneity (topography, geomorphology, climate, etc.), interference (grazing, land reclamation, etc.)[23]. There is competition for nutrition and water between crusts and *Nitraria tangutorum* vegetation, and the surface crusts have a certain barrier effect on precipitation, affecting the soil moisture content of sand mounds, which may also be one of the reasons for the reduction of species diversity in the evolution stage[24]. Water is a limiting factor for the survival and development of plants in arid areas. Environmental factors such as groundwater depth, the distance between shrub and farmland, and the degree of plant withered branches jointly affect the water use strategy of *Nitraria tangutorum* shrub at different evolutionary stages[25]. Roskin et al.[26] showed as well that if the nebkhas are removed (owing to droughts, strong winds, etc.), then the linear dunes disintegrate, thereby leading to desert sand remobilization. It is also possible that the development process of some nebkhas are more complex, and new nebkhas may develop again in older nebkhas under suitable environmental conditions, undergoing multiple evolutionary processes of "decline, activation, movement, and refixation"[27]. In different habitats, environmental factors have a greater impact on spatial heterogeneity, and the evolution of *Nitraria tangutorum* nebkha is also different[28].

In view of the above reasons, this paper will take *Nitraria tangutorum* nebkhas in the typical area of Dengkou County, Inner Mongolia of China as the research object, use the high spatial resolution remote sensing images of Gaofen-2 satellite (GF-2), and combine the spectral reflection characteristics of *Nitraria tangutorum* nebkhas vegetation and bare parts on the images, propose a new method of combining remote sensing and geographic information system to achieve the real-time, large-scale, high-precision quantitative extraction of *Nitraria tangutorum* nebkhas. At the same time, their spatial distribution characteristics were analyzed. It can provide a new theoretical and technical support for the research on remote sensing vegetation extraction and evolution in arid and semi-arid regions. Therefore, real-time and large-scale extraction of *Nitraria tangutorum* nebkhas has become the primary task to grasp the evolution laws of *Nitraria tangutorum*.

Data and methods
Study area
The study area is located in Dengkou County (106°8′13″ ~ 107°12′30″ N, 40°9′12″ ~ 40°58′20″ E), Inner Mongolia of China. The area is surrounded by three deserts (Ulan Buh Desert, Kubuqi Desert, and Badain Jaran Desert),

and the northeast is the Houtao agricultural area irrigated by the Yellow River. The study area is located in the desert transition zone from Ulan Buhe Desert to Dengkou County Oasis, mainly consisting of flowing linear dunes. There are a large number of barchan dunes in Ulan Buhe Desert near the south of the study area. As Yang et al.[29] pointed out, there are also a large number of barchan dunes in the southern edge of Badain Jaran Desert in the northwest of the study area (but due to the obstruction of Wolf Mountain, the desert did not invade the study area). It belongs to temperate desert continental climate, cold in winter and hot in summer, with large temperature difference between day and night. It is windy and sandy all year round, with southwest wind prevailing. The annual average wind speed is 3.4 m/s, and the instantaneous maximum wind speed is 28 m/s, with strong wind erosion. The wind speed over 45–52 days throughout the year is more than 6 m/s, and the number of strong wind and dust days in spring is the most, accounting for 47.5% and 43.8% of the whole year[30,31]. The mean annual precipitation is 145 mm, mainly concentrated from June to August, with a mean potential evaporation of 2400 mm; The mean annual temperature is 8.2 ℃, the annual sunshine duration reaches 3210 h, the frost-free period is 135 ~ 210 days[32]. The Soil type are mainly gray desert soil, brown calcium soil, and aeolian sandy soil. The geomorphic types are mainly fixed and semi-fixed sand nebkhas, with Tanggut *Nitraria tangutorum* nebkhas of varying sizes distributed in the area. *Nitraria tangutorum* is the dominant vegetation in the study area[33]. In recent decades, due to the influence of climate and human factors, a large number of *Nitraria tangutorum* communities have gradually declined and degraded, resulting in the activation of *Nitraria tangutorum* nebkhas. Fortunately, the region is now just in time for the "zigzag" battle of the Yellow River in the Three-north Project for ecological restoration and governance[34]. At the same time, habitats suitable for *Nitraria tangutorum* growth and potentially evolving have emerged in the desert edge areas[35].

Method

The purpose of this paper is to accurately extract nebkhas in arid and semi-arid desert areas, identify their current evolution stages and study their spatial distribution patterns. Using GF-2 data, the *Nitraria tangutorum* nebkha was extracted by object-oriented image segmentation and random forest classification; On this basis, threshold method, mathematical morphology, and other methods were used to realize the combination of high and low reflection areas of *Nitraria tangutorum*; Then FCLSU mixed pixel decomposition and remote sensing standards of the current evolution stage of *Nitraria tangutorum* were used to complete the division of the current evolution stage of *Nitraria tangutorum*. The methodology can be seen in Fig. 1.

Field investigation

The experimental area is located in the southwest of Dengkou County, Inner Mongolia (see Fig. 2), covering various evolutionary stages of the *Nitraria tangutorum* nebkhas. The field investigations were conduct from August 13th to 25th, 2020. The principle of the investigation is to cover the entire experimental area (imaging area), various evolutionary stages of the *Nitraria tangutorum* nebkhas, and the size of the *Nitraria tangutorum* nebkhas area.

(1) Plot setting and information acquisition of the *Nitraria tangutorum* nebkhas and their coverings.
Firstly, we selected a distribution area of *Nitraria tangutorum* nebkhas that was easy to identify, and then set up 26 plots in 30m × 30m. We used differential GPS to locate the *Nitraria tangutorum* nebkhas in each
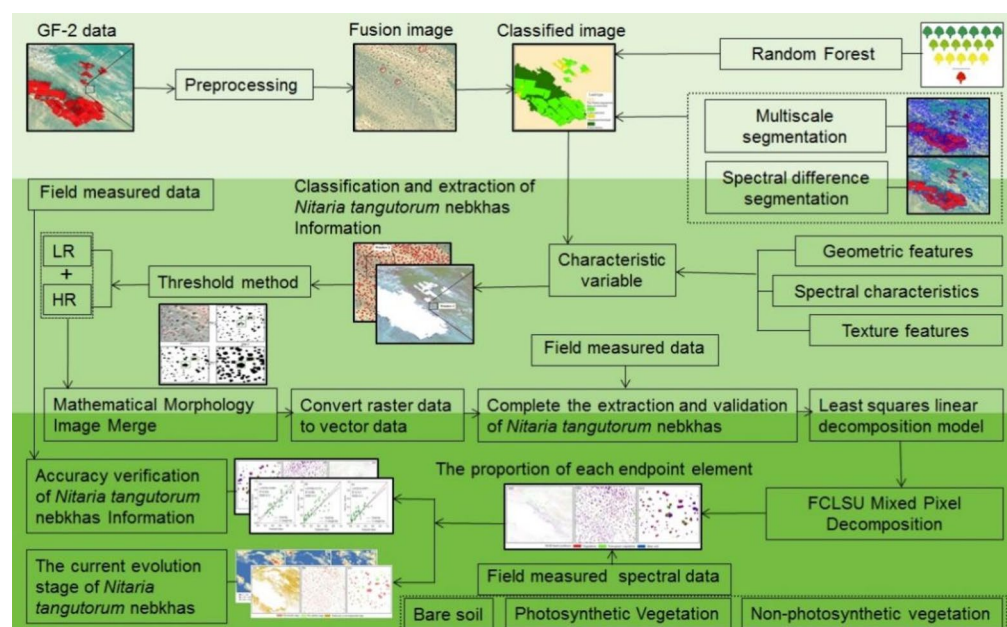

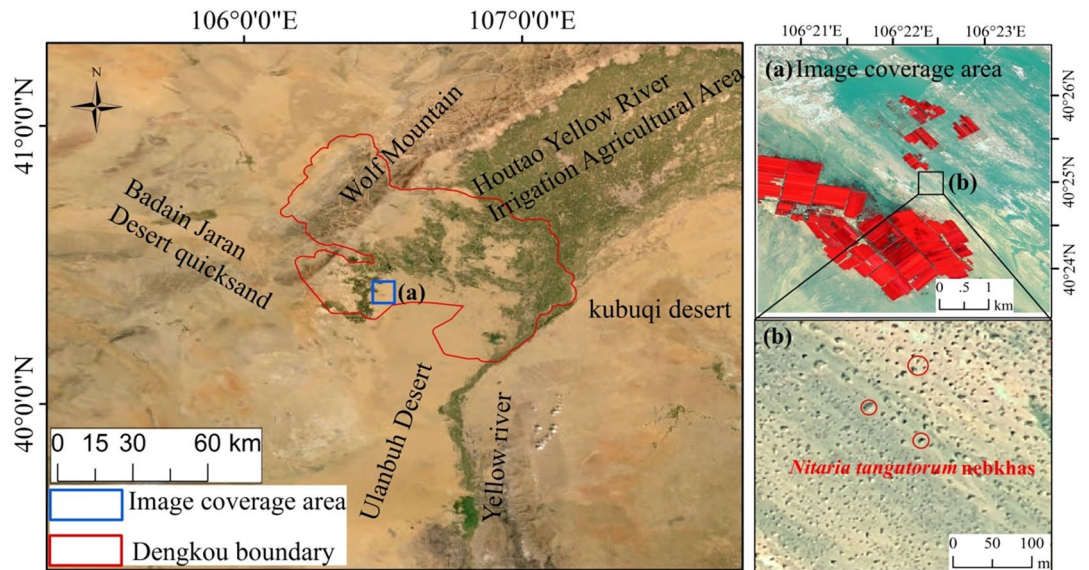**Figure 1.** Methodology of *Nitaria tangutorum* nebkhas.

Figure 2. Study area and *Nitraria tangutorum* nebkhas in local region (The left image is from online ArcGis/ArcMap/Esri/World Imagery, and the right images are from GF-2 data).

plot (with some error), and draw a rough spatial distribution map of the *Nitraria tangutorum* nebkhas in the plot. We compared on-site and image data to confirm the specific location of the *Nitraria tangutorum* nebkhas. The representative *Nitraria tangutorum* nebkhas were selected (48 in total, 20 in embryonic or developmental stages, 15 in stability stage, and 13 in decline stage) in each plot, and the coverages of their photosynthetic, non-photosynthetic vegetation, and bare soil (including crust) were obtained using photography. The photos were loaded into ArcGIS software after go back indoors, the boundaries of *Nitraria tangutorum* nebkhas were vectorized, and the photos were cropped. The training samples of photosynthetic, non-photosynthetic vegetation, and bare soil (soil crust) types of *Nitraria tangutorum* nebkhas were collected based on the RGB values of the photos; Then, the maximum likelihood classification (MLC) was used to classify RGB photos, and visual interpretation methods were used to determine the accuracy of the classification results; Finally, the area of each type of pixel was calculated based on the number of pixels, and the coverage ratio of each type of land feature was calculated. Other investigated data included length of the semimajor and semiminor axes of the *Nitraria tangutorum* nebkhas, and the basal area of the *Nitraria tangutorum* nebkhas was calculated based on these two parameters (the shape of the *Nitraria tangutorum* nebkhas was close to an ellipse).

(2)   Spectral determination of photosynthetic/non-photosynthetic vegetation and bare soil in *Nitraria tangutorum* nebkhas.

The spectral measurement of typical terrain features in *Nitraria tangutorum* nebkha was carried out using the ASD Field Spec Pro spectrometer, with a spectral range of 350-2500nm and a resampling resolution of 1nm. Measure each sample three times and take the average as the reflectance of the sample. The measurement should be carried out in cloudy, breezy, and well visible weather conditions in the sky. The main measurement content includes: the photosynthetic and non-photosynthetic parts of *Nitraria tangutorum* vegetation and other vegetation (collecting and stacking non-photosynthetic vegetation parts such as withered leaves and branches for measurement), the spectra of bare soil, crust, and quicksand; At the same time, a camera was used to record photos of spectral features and vegetation corresponding to the measurements. Establish a comprehensive and accurate spectral database of vegetation photosynthesis/non-photosynthesis and typical features in the *Nitraria tangutorum* nebkhas. Indoor, the spectral library builder of ENVI was used to create an ENVI format (. sil) spectral database using the measured average spectral values of each terminal; Then, the spectral library resampling tool was used to sample the measured spectra into four spectral bands corresponding to the central wavelength of GF-2. Finally, the FCLSU mixed pixel decomposition model was used to achieve the decomposition of each terminal.

(3)   Soil and meteorological data obtain.

Soil samples were collected from 48 typical *Nitraria tangutorum* nebkhas on the windward slope, leeward slope, and top at a depth of 0–10, 10–20, and 20–40 cm using a small soil drill from 9 to 11 am every day. The soil samples were brought back to the experiment for measurement. The soil moisture content was determined using the drying method, the soil bulk density was determined using the ring knife method, the soil pH was determined using the electrode method, the soil organic matter was determined using potassium dichromate oxidation-outer heating method[36], the available nitrogen content was determined using the alkaline dissolution diffusion method, the available phosphorus content was determined using the ammonium bicarbonate method, the available potassium content was determined using the ammonium acetate flame photometer method[37], and the soil sand content was determined using the sedimentation method[38]. The soil physicochemical factor data in this study is the average value of data from each soil layer.

Meteorological data such as precipitation, temperature, and evapotranspiration are sourced from the local meteorological bureau, the Shalin Center Meteorological Station of the Chinese Academy of Forestry in Dengkou County, and the National Qinghai Tibet Plateau Scientific Data Center (https://data.tpdc.ac.cn/). Through integration, interpolation, and mask extraction, an average annual data of 48 *Nitraria tangutorum* nebkha points from 2000 to 2020 was generated.

Image data and its preprocessing

The study selected GF-2 data from July 13, 2020. Firstly, using the PIE Basic remote sensing software module, the radiometric calibration was performed on panchromatic and multispectral images with spatial resolutions of 1m and 4m, followed by atmospheric correction using the "6S" model for multispectral images. Using DEM data (with a spatial resolution of 30m, ASTER GDEM v3(http://reverb.echo.nasa.gov/reverb/)) and orthorectified GF-1 images (with a spatial resolution of 2m), the PIE-Ortho process module (http://www.piesat.cn/website/cn/pages/product/software/pie-ortho.html) was used to complete orthorectified GF-2 panchromatic and multispectral images (using a connection point intervention model) and Pansharp method (super-resolution Bayesian) image fusion, ultimately forming a fused image with a spatial resolution of 1m. Capture the local area with *Nitraria tangutorum* nebkhas on the image as shown in Fig. 2. This area is just at the junction of agricultural area and desert area.

Feature variable screening

Three types of feature variables were selected based on image segmentation and classification, namely spectral, texture, and geometric features. The spectral features mainly included the reflectance in four bands (Red, Green, Blue, and Near infrared) and Normalized Difference Vegetation Index (NDVI) of GF-2 images. The texture features used homogeneity and contrast from the grayscale co-occurrence matrix. After comparison, texture parameters were extracted in the 45° and 135° directions and 5×5 windows.

Geometric features

In order to accurately understand the geometric characteristics of *Nitraria tangutorum* nebkhas, their information of the Semimajor axis, Semiminor axis, length–width ratio, and area were statistically analyzed using the data from 26 plots, as shown in Table 1.

From Table 1, the shape of the *Nitraria tangutorum* nebkha is approximately elliptical, with a semimajor axis of 1.55 ~ 8.62 m, a semiminor axis of 1.24 ~ 6.75 m, γ of 1.02 ~ 2.37, and an area of 2.87 ~ 58.20 m². Finally, We have repeatedly verified based on the measured data and the extraction results of *Nitraria tangutorum* nebkha images, the γ ($1 \leq \gamma \leq 2.5$) and area (area ≤ 60 m²) were selected as the geometric feature parameters for *Nitraria tangutorum* nebkha extraction.

Image segmentation

The grayscale value range of the GF-2 fusion image band ranges from 0 to 1000, and there is a certain overlap in the spectral reflectance of *Nitraria tangutorum* and other vegetation. At the same time, the spectral reflectance of the exposed area of *Nitraria tangutorum* is also very similar to the spectral characteristics of surface soil. It is difficult to directly extract *Nitraria tangutorum* nebkha by solely utilizing pixel based spectral feature information. How to distinguish the *Nitraria tangutorum* nebkha from other land types has become a prerequisite for extracting *Nitraria tangutorum* nebkha. Practice has shown that object-oriented image segmentation and classification based on spectral, texture, shape, and other information can effectively extract *Nitraria tangutorum* nebkha[12].

There are many methods for remote sensing image segmentation[39]. We used a combination of multi-scale segmentation and spectral difference segmentation to segment images, which is not only superior to single multi-scale segmentation, but also can significantly improve the phenomenon of over segmentation and under segmentation[40]. Multi-scale segmentation is a bottom-up segmentation algorithm that combines adjacent pixels or small segments on the premise of ensuring minimum average heterogeneity among objects and maximum homogeneity among internal pixels[41]. In the multi-scale image segmentation, it is affected by many parameters, such as band weight factor, segmentation scale, shape, and compactness, etc.[42]. Spectral difference segmentation is a segmentation optimization method that combines objects with closer grayscale values based on multi-scale segmentation results[43] (Liu Jiafu). The effectiveness of object fusion mainly depends on the reasonable setting of the Maximum spectral difference parameter[43].

At present, there are two methods for selecting image segmentation parameters: qualitative evaluation and quantitative evaluation. Quantitative evaluation is to evaluate the segmentation results through some index

Nitraria tangutorum nebkha parameters	Minimum value	Maximum value	Mean value
Semimajor axis (a) /m	1.55	8.62	4.51
Semiminor axis (b) /m	1.24	6.75	4.10
Length–width ratio (γ)	1.02	2.37	1.35
Area (m²)	2.87	58.2	15.82

Table 1. Statistics of geometric characteristic parameters of *Nitraria tangutorum* nebkhas. γ = a/b. The a and b represent the length and width of the outer rectangle of the *Nitraria tangutorum* nebkhas, respectively.

indexes. The optimal parameters found by this method are more accurate, but the process is complex and the applicability is not high[44]. In the band weight setting, the weight of the fourth band will generally be increased in the part highlighting the vegetation by counting the gray range, mean value and standard deviation of the four fusion bands. However, the vegetation distribution of *Nitraria tangutorum* land we focus on is less, and the gray range and standard deviation of the fourth band are small. The first three bands are the basic bands that make up RGB true color. Therefore, all four bands participate in image segmentation, and the weight is set in the way of 1:1:1:1. In the selection of other parameters, because the image area is small and the land type is relatively simple, the qualitative evaluation method is selected to determine the pros and cons of segmentation parameters, mainly depending on whether the land covered by *Nitraria tangutorum* can contain all *Nitraria tangutorum* (which is difficult to determine by quantitative evaluation), the size of spectral differences within the same land type, whether the segmentation boundary is clear and consistent with the characteristics of the actual land type boundary. Based on the above principles, we continuously experimented and analyzed the image segmentation effect, and ultimately determined the optimal parameter values for multi-scale image segmentation (scale, shape, compactness) and spectral difference segmentation (maximum spectral difference value) (Table 2). From Fig. 3, it can be seen that multi-scale + spectral difference segmentation has fewer objects to segment compared to using multi-scale image segmentation alone. It can more effectively merge objects of the same land type, reducing the difficulty and computational complexity of image classification for different land types.

Object-oriented random forest classification
The traditional random forest classification is based on pixels, and the classification results are relatively fragmented. We adopted an object-oriented random forest classification method, which can reduce the "salt and pepper effect" of classification[45]. The feature variables used in classification include seven indices: spectral (four band reflectance of GF-2 fusion image, NDVI), and texture features (homogeneity, contrast).

Random forests (RF) are an integrated classifier constructed from multiple classification trees. It should be noted that since decision trees in random forests are generated through self- sampling and random feature selection, each decision tree may give different classification results for the same input sample. This difference is one of the key characteristics of the random forest algorithm, which helps to improve the generalization ability and robustness of the ensemble model. By using a large subset of training samples to increase the diversity of classification models, the generalization and prediction ability of the model can be improved[46]. Compared with other algorithms, this model has advantages such as high accuracy, fewer parameters, and stable performance, making it widely used in remote sensing image classification[47]. Its classification mainly includes two main processes: model training and decision classification. 1) Model training: Firstly, determine the number of decision trees to be constructed (k = 100). Then, a self-service resampling method is used to perform k random samples with replacement from the training sample set, generating k different training subsets. Each training subset is used to construct a decision tree. When constructing each decision tree, randomly select n (n = 3) feature variables at each node, and finally select the optimal feature for splitting until the stopping condition is reached; 2) Decision classification: For each sample to be classified, each decision tree is classified independently, and then

Land type	Shape index	Compactness	Segmentation scale	Maximum spectral difference value
Cultivated land	0.3	0.7	200	27
Abandoned farmland	0.3	0.7	200	34
Forest district	0.1	0.9	100	30
Nitraria tangutorum nebkha covered land	0.1	0.9	100	45

Table 2. Scale segmentation parameters of land use type.
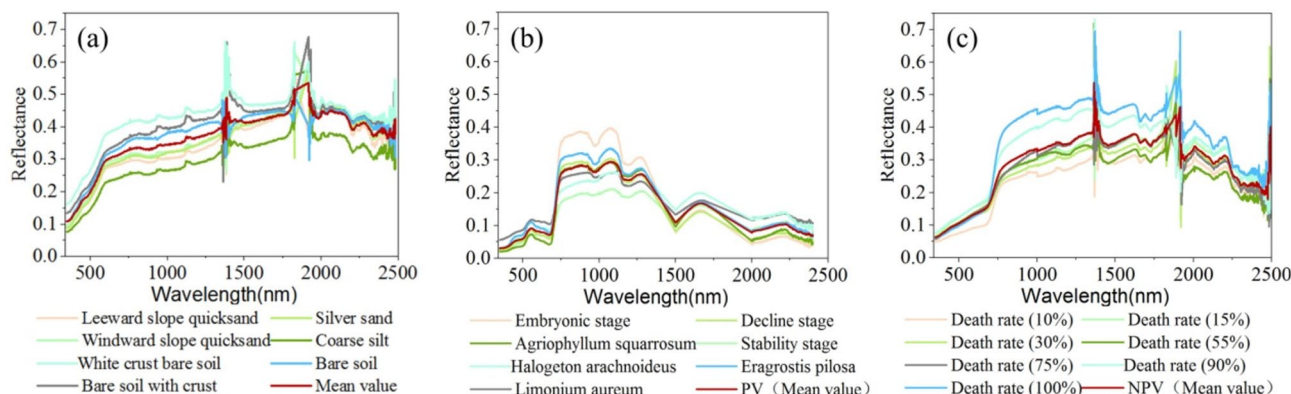

Figure 3. Spectral library of terminal values from mixed pixel decomposition. (**a**) bare soil, (**b**) photosynthetic vegetation, and (**c**) non-photosynthetic vegetation.

the classification results of the decision tree are summarized. The final classification result is obtained through the majority voting method[48].

Mathematical morphology image merge
Mathematical morphology focuses on the morphological features of images, describing their basic features and structures, and reflecting the relationships between elements and their parts in images. Due to its solid theoretical foundation and simple and efficient practical operation, this method is widely used in the analysis and processing of image shape and structure, including image segmentation, feature extraction, edge detection, image filtering and enhancement[49,50]. Mathematical morphology is composed of four basic algebraic operators: dilate, erode, opening, and closing. Erode and dilate are the most basic operations, and other operations are defined on the basis of these two operations. Actual image information extraction can construct structural elements with different shapes such as circles, crosses, rectangles, and diamonds based on image features. In order to avoid the deformation of the high reflection area and low reflection area of the extracted *Nitraria tangutorum* nebkhas in the mathematical morphology operation (large window operation will merge the adjacent *Nitraria tangutorum* nebkhas, and the small window operation may cause the high reflection area and low reflection area of *Nitraria tangutorum* nebkhas to not be completely merged). Therefore, based on the size and morphological characteristics of *Nitraria tangutorum* nebkhas in the image, we adopted window templates of 3×3, 5×5 to perform basic results of *Nitraria tangutorum* nebkhas. The three types of operations are defined as follows:

Dilate operation:

$$A \oplus B = \left\{ x \left| \left(\hat{B} \right)_x \cap A \neq \varnothing \right. \right\} \tag{1}$$

where, the dilate operation symbol is $\oplus$, and the image set A is dilated by the structural element B; $\hat{B}$ represents the image, that is, the set formed by the inversion of all elements in B; $\left(\hat{B} \right)_x$ indicates that all elements in the B image translate x.

Erode operation:

$$A \ominus B = \{ x | (B)_x \subseteq A \} \tag{2}$$

where, the erode operation symbol is $\ominus$, and image set A is eroded with structural element B.

Closing operation:

$$A \cdot B = (A \oplus B) \ominus B \tag{3}$$

where, the closing operation symbol is $\cdot$, which means that the dilate operation is performed first, and then the erode operation is performed. At the same time, the dilate and erode operations use the same structural element.

Nitraria tangutorum nebkha extraction step by step
According to field investigations and remote sensing images, the vegetation distribution on most *Nitraria tangutorum* nebkhas is uneven, with varying degrees of damage to the vegetation on the windward slope of the nebkha and the crust areas on both sides of the nebkha. This is manifested in the low reflectivity of the *Nitraria tangutorum* nebkhas covered by vegetation on the image, while strong reflections appear on the exposed windward slope or areas where vegetation has withered. We utilized this characteristic to extract the low reflection area (LR) and high reflection area (HR) separately, and then merge them with mathematical morphology to complete the extraction of *Nitraria tangutorum* nebkhas. The specific process is:

(1) Utilize object-oriented image classification methods to extract *Nitraria tangutorum* nebkha land;
(2) Use the threshold method to extract the LR region of the *Nitraria tangutorum* nebkha, and eliminate the low reflection areas without *Nitraria tangutorum* nebkha based on the geometric features ($1 \leq \gamma \leq 2.5$) and area index (area ≤ 150 m^2) of the *Nitraria tangutorum* nebkha;
(3) Extract the center point of the LR region of the *Nitraria tangutorum* nebkha and calculate the maximum side length (MAXLR) of the outer rectangle of the LR;
(4) Make a circle centered around the LR center point and with a radius of $0.65 \times$ MAXLR;
(5) Use threshold method to extract the HR region of the *Nitraria tangutorum* nebkha;
(6) Using the closing operation of mathematical morphology to merge LR and HR regions, convert raster data into vector files, and ultimately complete the extraction of *Nitraria tangutorum* nebkhas.

FCLSU mixed pixel decomposition
Ji et al.[14] used linear spectral mixing model, kernel function nonlinear spectral mixing model and bilinear spectral mixing model to extract *Nitraria tangutorum*, and found that the nonlinear spectral mixing model had no obvious advantage over the linear spectral mixing model in extracting *Nitraria tangutorum* information[24]. Therefore, we selected the fully constrained least-squares based linear unmixing (FCLSU) model which was relatively mature and easy to operate to extract the mixed pixel information of *Nitraria tangutorum* nebkha[51]. The main algorithms are as follows[39]:

$$X_i = \sum_{j=1}^{n} f_j X_{ij} + \varepsilon_i \dots i = 1, 2, \dots L; j = 1, 2, \dots, p \text{ or } D_N = M\alpha + E \tag{4}$$

$$\sum_{j=1}^{n} f_j = 1 \text{ and } 0 \le f_j \le 1 \tag{5}$$

$$J = \frac{1}{2}(M\alpha - D_N)^T (M\alpha - D_N) + \lambda(\alpha - c) \tag{6}$$

where X_i is the spectral reflectance of the i-band pixels, n is the terminal number, f_j is the proportion of terminal j in the pixel, and X_{ij} is the pixel reflectance of the terminal j in the band i, ε_i is the error term of band i. DN is the column vector of L×1 pixel gray value, M is the matrix of L×p pixel terminal gray value, α is the column vector of the proportion of terminals in the pixel of $p \times 1$, E is the error vector. J is a Lagrange function; c is an unknown p-dimensional nonnegative constraint constant vector.

In this study, the FCLSU method was used to determine the vegetation, non-photosynthetic vegetation and bare soil according to the composition characteristics of *Nitraria tangutorum* nebkha mixed pixels. Because *Nitraria tangutorum* and non-photosynthetic vegetation exist in the form of mixed pixels in GF-2 images, it is impossible to directly extract the corresponding pure terminals from the images. Therefore, the terminal values of *Nitraria tangutorum* and non-photosynthetic vegetation are the average values of all measured spectra of *Nitraria tangutorum* and non-photosynthetic vegetation. The terminal value of bare soil is determined by the average value of bare sand covered by *Nitraria tangutorum* nebkha and soil crust. The specific process is as follows: firstly, the measured spectral average data of each terminal is used to form a spectral database in ENVI format (.sil) using ENVI spectral library builder; Then the measured spectrum was resampled into four bands corresponding to the central wavelength of GF-2 by spectral library resampling tool; Finally, FCLSU mixed pixel decomposition model is used to decompose the terminals.

Multi-distance spatial clustering analysis (Ripley's K function)
This study applies Ripley's K function to analyze the spatial pattern of the degraded *Nitraria tangutorum* nebkhas. The essence of the Ripley's K function calculation process is to select radius of different scales, use these radius to determine the search range and obtain a certain number of point data, and then perform point pattern analysis on the obtained point data. The Ripley's K function can be represented by the following formula:

$$L(d) = \sqrt{\frac{A \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} k(i,j)}{\pi N(N-1)}} \tag{7}$$

where, A represents the region, N represents the number of points, d represents the distance, and k (i, j) represents the weight.

Combining Diggle's edge correction and a square root transformation, L(d) is defined as formula (8). L(d) linearize k(d) to stabilize its variance and apply confidence interval tests to verify the authenticity of the results. When L(d) is higher than the upper packet trace, the data points are clustered, randomly distributed between the upper and lower packet traces, and uniformly distributed below the lower packet trace.

$$L(d) = \sqrt{\frac{k(d)}{\pi} - d} \tag{8}$$

Extract vector data of the degraded *Nitraria tangutorum* nebkha and calculate its spatial distribution pattern in ArcGIS software.

Model accuracy verification
This study used a determination coefficient (R^2) and root mean square error (RMSE) to evaluate the accuracy of *Nitraria tangutorum* nebkha extraction area and FCLSU mixed pixel decomposition estimation of *Nitraria tangutorum* nebkha photosynthetic/non photosynthetic and bare soil coverage. The lower the RMSE and the higher the R^2, the better the extraction effect.

$$RMSE = \sqrt{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2 / n} \tag{9}$$

$$R^2 = \sum_{i=1}^{n} (\hat{y} - \bar{y})^2 \Big/ \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{10}$$

where, $\hat{y}_i$ is the measured value of the plot; y_i is the model calculate values; n is the corresponding number of plots.

Evolution stage division

In order to divide of the current evolution stage of *Nitraria tangutorum* nebkhas based on remote sensing information, we determined the evolution standard of *Nitraria tangutorum* nebkhas based on field survey data and remote sensing extraction results as follows: (1) when the area of *Nitraria tangutorum* nebkha ≤ 4 m² and the proportion of photosynthetic vegetation ≥ 0.7 (or the proportion of non-photosynthetic vegetation and bare soil < 0.3), *Nitraria tangutorum* nebkha is in the embryonic or developmental stage; (2) When the area of *Nitraria tangutorum* nebkha > 4 m² and the proportion of photosynthetic vegetation ≥ 0.7 (or the proportion of non-photosynthetic vegetation and bare soil < 0.3), *Nitraria tangutorum* nebkha is in a stable stage; (3) When the proportion of photosynthetic vegetation in *Nitraria tangutorum* nebkha < 0.7 (or the proportion of non-photosynthetic vegetation and bare soil ≥ 0.3), *Nitraria tangutorum* nebkha is in the decline stage.

Results

Classification results and accuracy verification of land types

The object-oriented random forest classification method was used to classify the land types in the study area. The data involved in the classification included reflectance of 4 bands, NDVI, homogeneity and contrast texture information of GF-2, a total of 7 bands. The classification results were shown in Fig. 4. We selected 177 validation sample data to evaluate the accuracy of classification results, and the evaluation results were shown in Table 3. It can be seen that the overall classification accuracy can reach 84.18%, of which the user accuracy and mapping accuracy of cultivated land classification are 80.43%, and the main misclassification and omission are forest areas and abandoned cultivated land; The user accuracy and mapping accuracy of abandoned farmland were 77.42% and 82.76%, and the main misclassification and omission were farmland and *Nitraria tangutorum* nebkha covered land; The user accuracy and mapping accuracy of forest classification were 84.21% and 80.00%, and the main misclassification and omission were farmland and *Nitraria tangutorum* nebkha covered land; The classification accuracy of *Nitraria tangutorum* nebkha covered land is the highest, and the user accuracy and mapping accuracy reach 90.32%. Although there are errors and omissions, the proportion is relatively small.
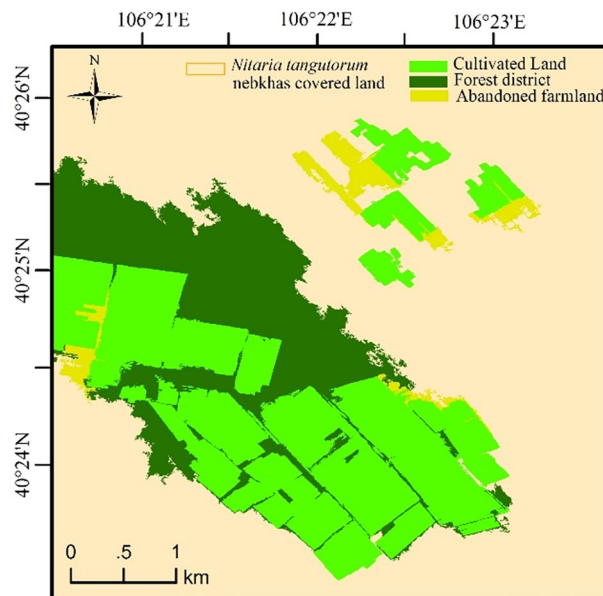

Figure 4. Image classification results.

Land type	Cultivated land	Abandoned farmland	Forest district	*Nitraria tangutorum* nebkha covered land	User accuracy /%
Cultivated land	37	3	5	1	80.43
Abandoned farmland	4	24	0	3	77.42
Forest district	3	1	32	2	84.21
Nitraria tangutorum nebkha covered land	2	1	3	56	90.32
Mapping accuracy /%	80.43	82.76	80.00	90.32	
Overall accuracy = 84.18%	Kappa = 0.71				

Table 3. Accuracy evaluation of land type classification results.

The classification results can better distinguish *Nitraria tangutorum* nebkha covered land and other land types, and laid a good foundation for the next step of *Nitraria tangutorum* nebkha extraction.

Extraction and accuracy verification of *Nitraria tangutorum* nebkhas

Nitraria tangutorum nebkhas were extracted by 2.8 step-by-step extraction method. The extraction results were shown in Fig. 5. The extraction process was shown in Fig. 6.

The field survey data were selected to verify the accuracy of the extracted *Nitraria tangutorum* nebkhas from spatial location and extraction area. A total of 48 *Nitraria tangutorum* nebkhas were measured in the field, and 93.75% of *Nitraria tangutorum* nebkhas were extracted successfully. Figure 7 is the accuracy verification diagram of *Nitraria tangutorum* nebkha extraction area. From Fig. 7a, it can be seen that the linear determination coefficient R^2 of the real area and extracted area from *Nitraria tangutorum* vegetation is 0.79, and the root mean square error (RMSE) is 9.03; while the R^2 of the real area and extracted area from the method proposed in this paper is 0.88, the RMSE is 5.39 (Fig. 7b). The accuracy of the method proposed in this paper in extracting the area of *Nitraria tangutorum* nebkhas is higher than that of using *Nitraria tangutorum* vegetation alone. At the same time, we found that the bare soil in the high reflection area of *Nitraria tangutorum* dunes cannot be extracted well when the area is less than 4 m^2, which is mainly caused by the low resolution of the image.

Coverage information extraction and accuracy verification of *Nitraria tangutorum* nebkhas

The spectral information measured in the field was used to decompose the mixed pixels of *Nitraria tangutorum* nebkhas in GF-2 image using FCLSU method (Fig. 8). And then the proportions of photosynthetic vegetation, non-photosynthetic vegetation, and bare soil in *Nitraria tangutorum* nebkhas were calculated, which can provide a basis for determining the evolution stage of *Nitraria tangutorum* nebkhas. In order to verify the accuracy of mixed pixel decomposition of FCLSU method, the linear regression analysis was performed on the extraction results using 48 field measured proportion data of photosynthetic vegetation, non-photosynthetic vegetation and bare soil of *Nitraria tangutorum* nebkhas (Fig. 9). The results showed that the R^2 of photosynthetic vegetation, non-photosynthetic vegetation and bare soil information were 0.76, 0.69 and 0.73, and the RMSE were 0.12, 0.14 and 0.11. It shows that the FCLSU method can be used to extract the coverage information of *Nitraria tangutorum* nebkhas.

Evolution stage division and distribution of Nitraria tangutorum nebkhas

The current evolution stages of *Nitraria tangutorum* nebkhas according to the above standards were shown in Fig. 10. The proportion of *Nitraria tangutorum* nebkhas in the embryonic or developmental stage, stable stage, and declining stage was 60.70%, 20.97%, and 18.33%, respectively. It can be seen that the main body of *Nitraria tangutorum* nebkhas in the study area was in the embryonic or developmental stage, but the proportion of declining *Nitraria tangutorum* nebkhas was not small, so the ecological restoration and reconstruction of *Nitraria tangutorum* nebkhas should be strengthened. Figure 11 is the kernel density distribution map of *Nitraria tangutorum* nebkhas at various evolution stages. The *Nitraria tangutorum* nebkhas at embryonic or developmental stages was distributed around the study area, and the most densely distributed area was located in the northeast of the study area; the *Nitraria tangutorum* nebkhas at the stable stage was mainly distributed in the northeast and northwest of the study area; the *Nitraria tangutorum* nebkhas at the decline stage was located in the northeast of the study area.
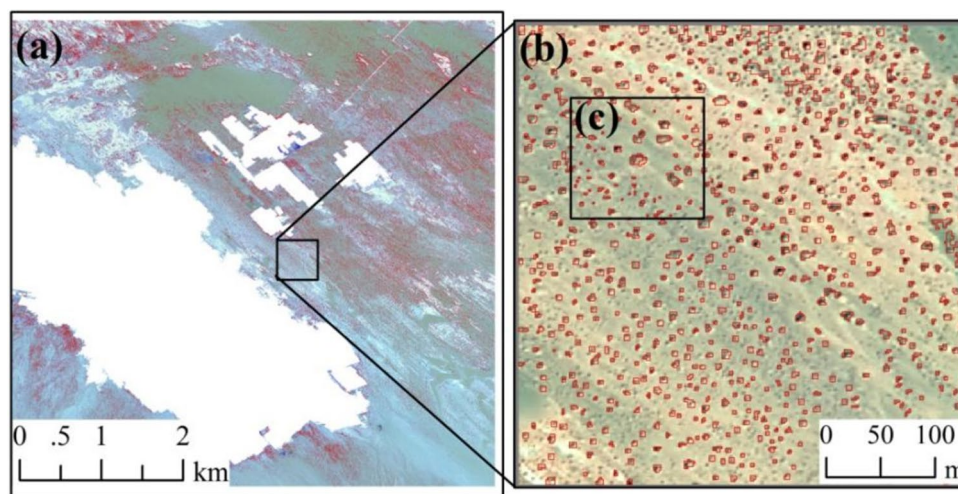

Figure 5. Extraction results of *Nitraria tangutorum* nebkhas (the red part in the figure is the extracted *Nitraria tangutorum* nebkhas).
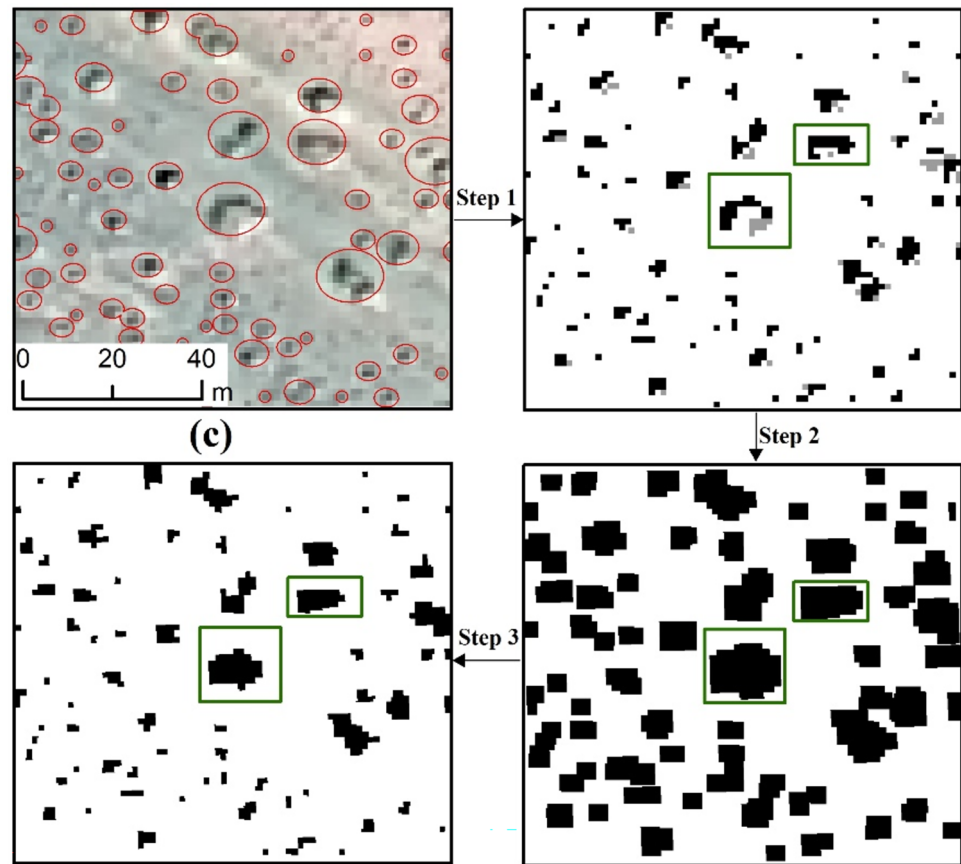
Figure 6. Flow chart of *Nitraria tangutorum* nebkhas extraction (**Step 1** refers to the extraction of low reflection area (LR) and high reflection area (HR); **Step 2** refers to the dilate operation of LR and HR areas; **Step 3** is the result of erode calculation).
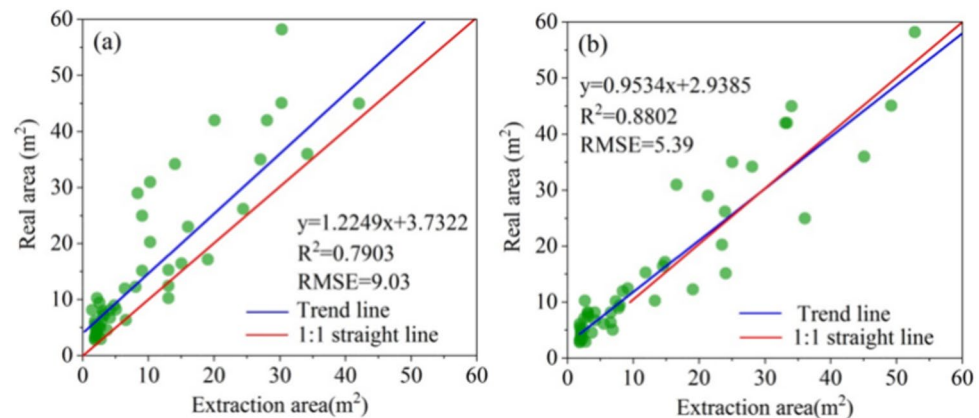

Figure 7. Scatter plots between extraction area and real area for *Nitraria tangutorum* nebkhas: (**a**) *Nitraria tangutorum* nebkhas extracted using only *Nitraria tangutorum* vegetation;(**b**) *Nitraria tangutorum* nebkhas extracted using the method proposed in this study.

Multi-distance spatial clustering analysis of different evolution stages of *Nitraria tangutorum* nebkhas

Figure 12 is a multi-distance spatial clustering analysis based on (Ripley's K function) *Nitraria tangutorum* nebkhas at each succession stage. It can be seen that the observed value of K was greater than the expected value of K in the embryonic or development stage, stable stage, and decline stage of *Nitraria tangutorum* nebkhas, indicating that the clustering degree of this distribution was higher than the random distribution of this distance (analysis
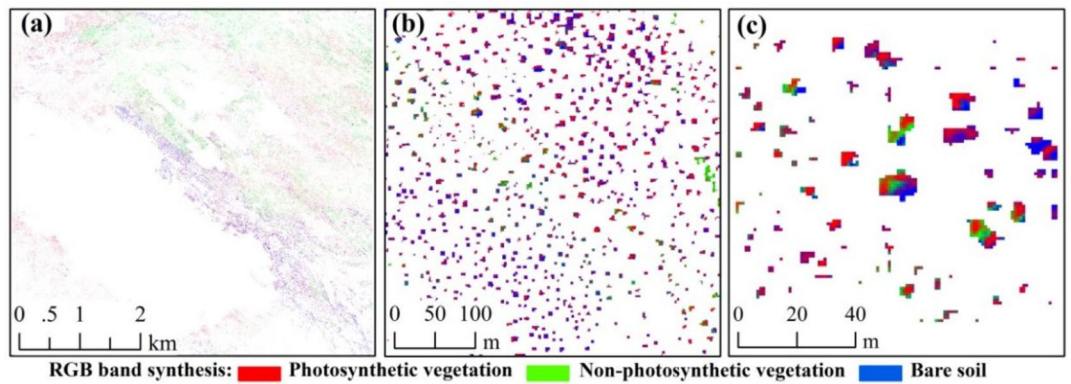
Figure 8. RGB Composite image of *Nitraria tangutorum* nebkhas using FCLSU mixed pixel decomposition method.
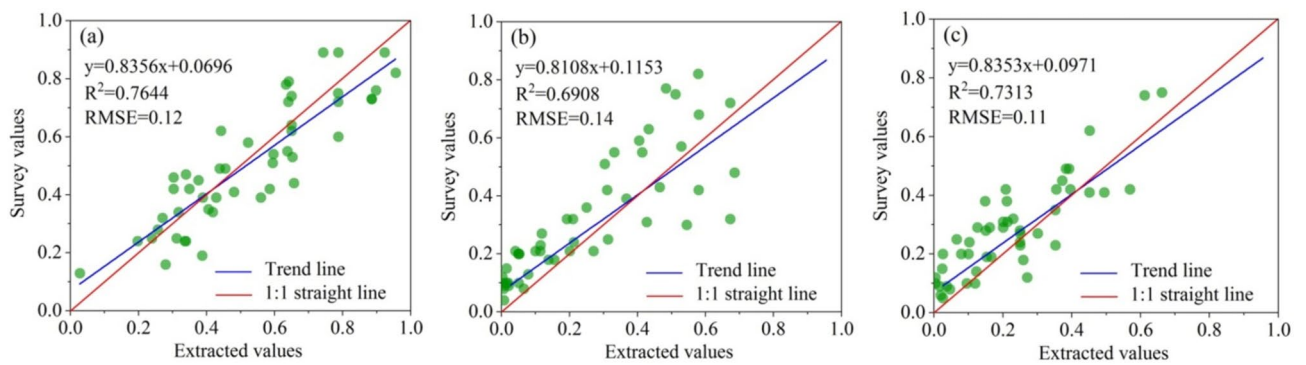

Figure 9. Accuracy verification of mixed pixel decomposition for each component of *Nitraria tangutorum* nebkhas: (**a**) Photosynthetic vegetation component ; (**b**) Non-photosynthetic vegetation component ; (**c**) Bare soil component.
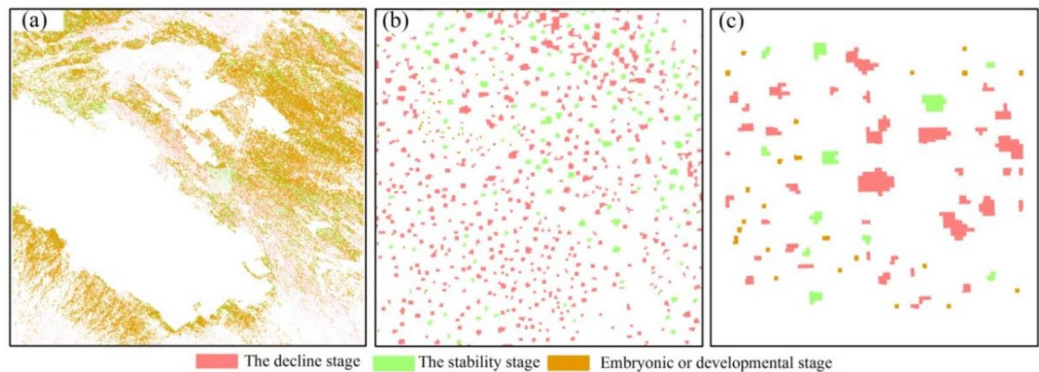

Figure 10. Distribution map of the current evolution stages of the *Nitraria tangutorum* nebkhas: (**a**) Whole study area; (**b**) Window 1; (**c**) Window 2.

scale). And the observation value of K was greater than that of HiConfEnv value, and the spatial clustering was statistically significant. It can be seen from Fig. 12a that when the observed value of K was at 825 m, the difference between the observed value of K and the expected value of K at the embryonic or developmental stage of *Nitraria tangutorum* nebkhas was the largest, and the clustering degree was the highest at this distance. It can be seen from Fig. 12b that when the observed value of K was at 794 m, the difference between the observed value of K and the expected value of K in the stable stage was the largest, and the clustering degree was the highest at this distance; It can be seen from Fig. 12c that when the observed value of K was at 827 m, the difference between the observed value of K and the expected value of K in the decline stage was the largest, and the clustering degree was the highest at this distance. Therefore, the spatial distribution of *Nitraria tangutorum* nebkhas at each succession
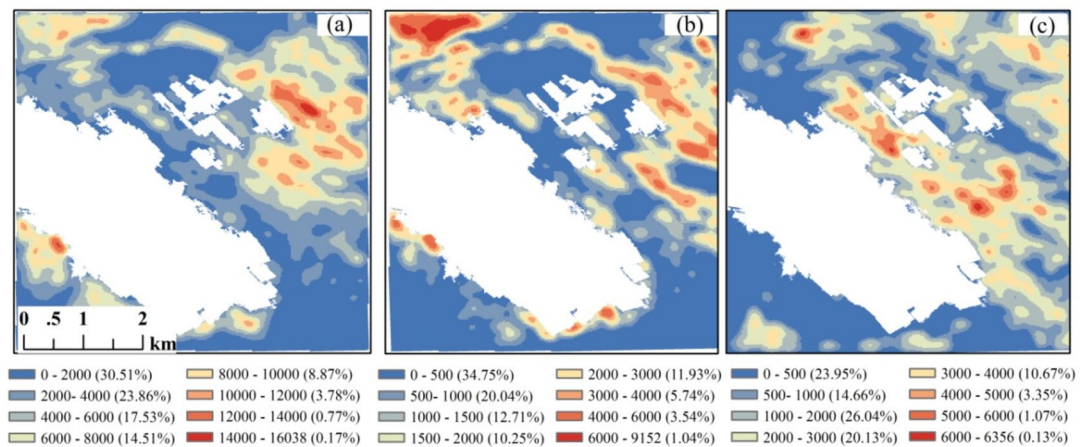
Figure 11. Kernel density distribution map of *Nitraria tangutorum* nebkhas in current evolution stages: (**a**) Embryonic or developmental stages; (**b**) Stability stage; (**c**) Decline stage.

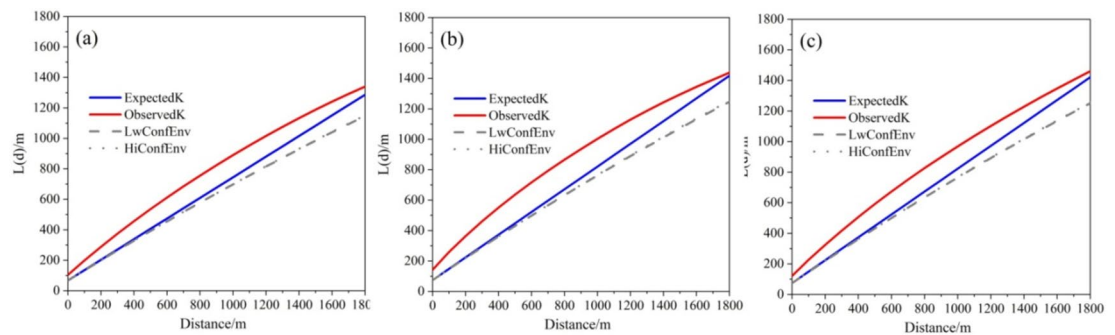**Figure 12.** Multi-distance spatial clustering analysis based on Ripley's K function of *Nitraria tangutorum* nebkhas in each succession stage: (**a**) Embryonic or developmental stages; (**b**) Stability stage (**c**) Decline stage.

stage presented an aggregation effect, and the clustering degree of *Nitraria tangutorum* nebkhas at each succession stage was the highest when the distance was about 800 m.

Discussions

Nitraria tangutorum nebkha extraction and its evolutionary stage identification

Some scholars have also conducted research on the extraction of *Nitraria tangutorum* nebkhas. Wang et al.[52]. used aerial images with a ground resolution of 0.05–0.2 m and used supervised and unsupervised image classification methods to extract white thorns, achieving an accuracy of over 90%[52]. Wang et al. used image segmentation and mathematical morphology methods to extract white spines from aerial photographs, achieving an accuracy of 91.2%[10]. We used winter GF-2 images in 2017 to extract *Nitraria tangutorum* nebkhas using texture information of maximum and minimum value differences, geometric characteristics of *Nitraria tangutorum* nebkhas, and methods such as multi-scale segmentation, object-oriented classification, and threshold extraction. The result shows that the accuracy of extracting the position of *Nitraria tangutorum* nebkhas is 94%, the regression coefficient (R^2) is 0.77, and RMSE is 5.77[12]. But these extracts are all based on the extraction of *Nitraria tangutorum* vegetation, without considering the situation where many areas of *Nitraria tangutorum* nebkhas are exposed without vegetation coverage, and the calculated area is smaller than the actual area of *Nitraria tangutorum* nebkha. The *Nitraria tangutorum* nebkha extraction method proposed in this study not only calculated the area covered by *Nitraria tangutorum* vegetation, but also calculated the exposed area without vegetation coverage, and the calculated area of *Nitraria tangutorum* nebkha is more consistent with the actual area. Through comparison with other studies, it has been found that the accuracy of *Nitraria tangutorum* nebkhas extracted from GF-2 images is slightly lower than that of aerial photographs, mainly due to the lower spatial resolution of GF-2. However, extracting *Nitraria tangutorum* nebkhas from high-resolution image data based on this resolution has more advantages in cost and extraction range, which can achieve efficient extraction of *Nitraria tangutorum* nebkhas in large areas. The identification of the current evolution stage of vegetation is a prerequisite and foundation for its scientific ecological conservation and targeted vegetation restoration and reconstruction. However, the current identification standards for the evolution stage of *Nitraria tangutorum* nebkhas are based on ground investigations, which are time-consuming, labor-intensive, and inefficient, and only stay at the level of theoretical research, making it difficult to promote and apply. For this purpose, this study extracts a recognition technology that utilizes remote sensing methods to achieve large-scale and real-time recognition of the current evolution

stage of *Nitraria tangutorum* nebkhas, and the feasibility of this method is verified through the research results of this study.

The spatial distribution pattern of *Nitraria tangutorum* nebkhas in different evolutionary stages

The spatial structure of plant populations refers to the distribution of different numbers of individuals within their internal vegetation. It can reflect not only the resource allocation patterns of individual populations, but also the spatial distribution patterns, development trends, and their interrelationships with the environment[53]. The spatial distribution of *Nitraria tangutorum* nebkhas in each succession stage of this study area shows a clustering effect, and the clustering degree of white spines in each succession stage is highest at a distance of about 800m. The *Nitraria tangutorum* nebkhas in two different climate types on the transition zone between the desert area on the northern edge of the Ordos Plateau and the riverbank, which are not far from the research area, are mainly distributed in clusters within a 100 m plot. This may be a reflection of the desert ecosystem's protective effect on plants[54]. Xia's[55] research showed that the distribution pattern of *Nitraria tangutorum* nebkhas in the transition zone from the Ordos Plateau to the Loess Plateau varies at different evolutionary stages and scales within a 100m plot. The primary stage, developmental stage, and mature stage of *Nitraria tangutorum* nebkhas exhibit a clustered distribution, while the declining stage exhibits a random distribution. The *Nitraria tangutorum* nebkha was initially randomly generated, and then new vegetation gradually gathered around these nebkhas, forming new ones. This may be related to population reproduction and environmental heterogeneity, which is the result of long-term adaptation and selection of *Nitraria tangutorum* nebkhas to the environment. Yu's[23] study showed that the distribution of *Nitraria tangutorum* nebkhas in three different climate types on the northern edge of the Ordos Plateau showed a uniform distribution pattern on a small scale within a 100m plot, and a random distribution pattern on a medium to large scale, mainly due to environmental heterogeneity caused by water conditions. In the study of the transition zone between desert and oasis in Minqin, Gansu, the number of small nebkhas at different developmental stages within a 60m plot is largely determined by the patch gaps created by individual large nebkhas. On a small scale, they tend to be evenly distributed, while on a large scale, they tend to be randomly distributed due to their small number of individuals. The morphological characteristics of *Nitraria tangutorum* nebkhas are key factors affecting the formation and development of nebkhas, as well as influencing the distribution of patterns[56]. A study on the near flowing sand area at the southern edge of the Badain Jaran Desert found that the distribution density of *Nitraria tangutorum* nebkhas is relatively high and clustered in the transition zone, while the distribution density of *Nitraria tangutorum* nebkhas in the desertification zone is relatively low and randomly distributed. This can be attributed to the boundary effect, which is determined by the complexity of environmental factors or interference factors in the boundary zone[57].

The spatial structure of plant population is the distribution of the number of different individuals in its internal vegetation. It can not only reflect the resource allocation mode of individual population, but also reflect the spatial distribution pattern, development trend of population and the relationship between them and the environment[53]. In the early succession stage of *Nitraria tangutorum* nebkhas, the vegetation seeds always take the mother as the center in the process of diffusion, reproduction, and settlement, which is limited by space. This limitation is the main reason for the population aggregation and distribution. With the continuous population succession, the dominant species of *Nitraria tangutorum* nebkhas gradually occupy the space resources, forming a stable aggregation and distribution pattern[58–60]. The sporadicity of provenance distribution, spatial distance, and other factors cause the aggregation distribution of *Nitraria tangutorum* nebkha population. Affected by provenance, the establishment process of *Nitraria tangutorum* nebkha population is often uneven, asynchronous, and presents a dot or patch shape, which makes the distribution of *Nitraria tangutorum* nebkhas at different succession stages have strong spatial heterogeneity, and then causes it to form a spatial aggregation distribution pattern.

The spatial pattern distribution of vegetation populations is influenced by the diffusion, reproduction, and settlement of the parent centered source, as well as various factors such as biological effects (such as competition) and abiotic effects (such as climate, soil, etc.) in the habitat of plant populations, resulting in different forms of individual diffusion and distribution in different regions[22,58–60]. The spatial pattern changes with the change of spatial scale, and the inferred results depend heavily on the choice of spatial scale[61]. The area of *Nitraria tangutorum* nebkhas extracted from remote sensing data in this study has a larger scale compared to other ground survey plots, and the study area is also different, resulting in different distribution patterns of *Nitraria tangutorum* nebkhas. But overall, there may be random or mean distribution in small scale ranges, but in large scale, it appears to be clustered distribution. The distribution of *Nitraria tangutorum* nebkhas in China has obvious regional clustering characteristics (such as Minqin in Gansu, the northern edge of the Ordos Plateau in Inner Mongolia, the Alxa region, and the eastern part of Ningxia, which are arid and surrounded by deserts). Next, we will use remote sensing techniques to extract larger scale areas of *Nitraria tangutorum* nebkhas and verify the inference we mentioned earlier.

Driving factors of *Nitraria tangutorum* nebkha succession and spatial pattern

From the previous discussion, it can be seen that the *Nitraria tangutorum* nebkhas in the study area exhibit significant clustering effects in space at various evolutionary stages, and many factors will affect the distribution of their evolutionary patterns. To explore the dominant factors in the evolution and distribution pattern of *Nitraria tangutorum* nebkhas, we investigated and collected a large amount of meteorological, soil, and other data, and conducted Person correlation analysis and t-significance test with the current evolution stage. For desert vegetation, drought caused by low precipitation, strong solar radiation, and high evaporation directly affects the distribution and growth of surface vegetation, thereby affecting the evolution and diversity of vegetation communities[62].

Figure 13 showed the correlation analysis between evolution stages of *Nitraria tangutorum* nebkhas, meteorological factors (precipitation, air temperature, solar radiation, evapotranspiration), and soil physical and chemical factors (soil moisture, soil bulk density, soil organic matter, available K, alkali-hydrolysable N, available P, sand content, pH value, and soil crust). The correlation between meteorological factors and the evolution stages of *Nitraria tangutorum* nebkhas was relatively low, which may be due to the small scope of the study area and small numerical difference, which was not enough to explain the heterogeneity of the distribution of *Nitraria tangutorum* nebkha evolution stages. Soil moisture is one of the main driving factors for many ecological processes in arid desert areas. Under conditions of low precipitation and high evaporation, the amount of gravitational water infiltration determines the growth of vegetation in arid areas[63]. The correlation between the evolution stages of *Nitraria tangutorum* nebkhas and soil moisture was high (R = −0.80), showing a highly negative correlation, indicating that the higher the succession stage of *Nitraria tangutorum* nebkhas, the less its moisture content, which is consistent with the view of Yang et al.[64]. The correlation coefficient R^2 of *Nitraria tangutorum* nebkhas and soil crusts was 0.92, showing a highly positive correlation, indicating that the higher the succession stage of *Nitraria tangutorum* nebkhas, the more complete the development of soil crusts and the larger the area of crusts. Soil crust plays an important role in evolution of *Nitraria tangutorum* nebkhas by altering the soil moisture content. *Nitraria tangutorum* nebkhas has a few or no crusts on leeward slope during its embryonic and developmental stages. Both windward and leeward slopes of *Nitraria tangutorum* nebkhas have crusts during its stable and declining stages, and the crusts are relatively complete with the largest area[22]. In the embryonic and development stages of *Nitraria tangutorum* nebkhas, due to less soil crusts, precipitation is easy to infiltrate, and the soil moisture content is the largest. The soil crust area and thickness of *Nitraria tangutorum* nebkhas in the stable and decline stage reach the maximum, precipitation is difficult to infiltrate, and the soil moisture content is low. Only when a large precipitation event occurs, the water can infiltrate[25]. The evolution stages of *Nitraria tangutorum* nebkhas had no significant correlation with soil bulk density, soil organic matter, available K, available P, soil sand content, pH, and total N[65,66]. These conclusions were consistent with the results of our study. In addition to the above factors, the succession of *Nitraria tangutorum* nebkhas is also affected by factors such as groundwater depth and sand source conditions. These data will be collected and discussed in depth next.

Disadvantages of this study

The evolution standard of white prickly tissue in this article is slightly different from other studies. When dividing the evolution stages of *Nitraria tangutorum* nebkhas, it is difficult to accurately separate the embryonic stage and the development stage due to the overlap of vegetation (photosynthesis/non-photosynthesis), *Nitraria tangutorum* nebkha area, and other remote sensing parameters, and there are many similarities between the two stages. Therefore, the two stages are combined into embryonic/development stages in this study. In the field survey, it was found that *Nitraria tangutorum* in some sample plots existed in the form of single plant without nebkha formation. Although some *Nitraria tangutorum* vegetation had formed accumulated nebkhas, the height of
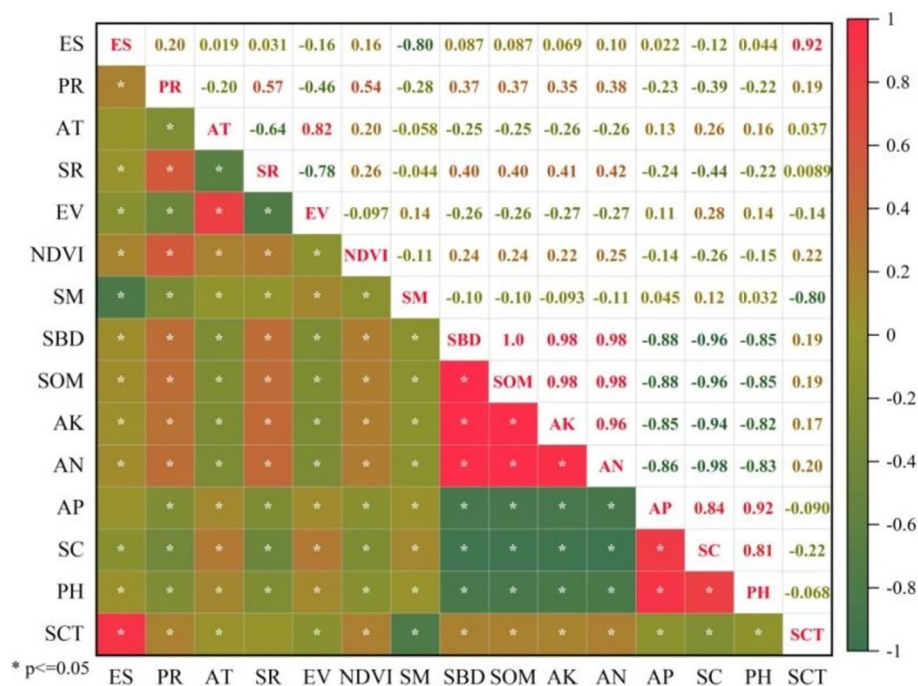

Figure 13. The correlations between the succession stages of *Nitraria tangutorum* nebkhas and driving. (Precipitation (PR), Air temperature (AT), Solar radiation (SR), Evapotranspiration (EV), Soil moisture (SM), Soil bulk density (SBD), Soil organic matter (SOM), Available K (AK), Alkali-hydrolysable N (AN), Available P (AP), Sand content (SC), Soil crust (SCT).)

nebkhas was very low (less than 10 cm), which is easily confused with other non-nebkha vegetation in the remote sensing image, and the problem of missing extraction will occur in the process of *Nitraria tangutorum* vegetation extraction. The morphology of *Nitraria tangutorum* nebkhas is close to the cone in the development stage, and close to the semi-ellipsoid in the stable shape[22]. In this study, due to the characteristics of image resolution and grid data, the extracted *Nitraria tangutorum* nebkha edges are irregular zigzag shape, which is slightly different from the actual *Nitraria tangutorum* nebkha edges. The improvement method is to switch to higher resolution remote sensing images. The decomposition of mixed pixels of remote sensing images requires that the number of terminals less than or equal to the number of bands minus 1. This study only three terminals of bare soil, photosynthetic vegetation, and non- photosynthetic vegetation, and only these terminals were used to divide the evolution stages of *Nitraria tangutorum* nebkhas limited to the less GF-2 bands (four multispectral bands). However, in fact, some other characteristics of *Nitraria tangutorum* nebkhas are also closely related to its evolution process. For example, the most obvious feature in the development and evolution of *Nitraria tangutorum* shrub is the formation and evolution of surface crusts[25]. There is a high correlation between the succession stages of *Nitraria tangutorum* nebkhas and their height and volume ($R^2 > 0.9$), which is more accurate than using the area parameter of *Nitraria tangutorum* nebkhas ($R^2 = 0.83$) to divide the succession stages of *Nitraria tangutorum* nebkhas[22,25]. The addition of these information may improve the division accuracy of the evolution stages. At the same time, *Nitraria tangutorum* nebkhas are mostly located in arid and semi-arid areas, with open vegetation canopy and large proportion of non-photosynthetic vegetation, and the red edge effect of vegetation on remote sensing images is not obvious. Moreover, the twigs and leaves of *Nitraria tangutorum* shrub are crisscrossed and fine, and the photosynthetic/non-photosynthetic vegetation and soil crusts are generally at the centimeter scale, so it is difficult to achieve high-precision monitoring and evaluation with conventional satellite remote sensing methods. At present, there are two main schemes to realize the research of the centimeter resolution level of the single *Nitraria tangutorum* nebkha and the large area of the *Nitraria tangutorum* nebkhas, one is the UAV tilt photography technology, and the other is the UAV laser radar combined with hyperspectral technology. However, for desert areas without obvious landmarks, the accuracy of 3D real scene modeling of *Nitraria tangutorum* nebkhas and *Nitraria tangutorum* vegetation is worse than that of Lidar combined with hyperspectral technology. At the same time, it carries fewer camera bands. Therefore, the next step will be to explore the information extraction technology of *Nitraria tangutorum* nebkhas based on Lidar and hyperspectral technology, extract more shape and coverage information parameters of *Nitraria tangutorum* nebkhas, and realize high-precision division of succession stages. Remote sensing and field observations as techniques for monitoring nebkhas and dune dynamics, however, numerical simulations and mathematical modelling have been pushing forward our understanding of nebkhas substantially in the last decades. Roskin et al.[26] have developed conceptual models and simulations to predict the formation and elongation of linear sand dunes in deserts owing to the growth of nebkhas. Nield and Baas[67] proposed a developmental process model for dunes using cellular automata principles, simulating the response of dune morphology to sand source changes, vegetation distribution, vegetation growth density and characteristics. Gabarrou et al.[68] used a time-series virtual wind generated by a stochastic model combined with a morphodynamic dune model to simulate the response of coastal transverse dune mobility to changing winds. Therefore, our next step will draw on previous models of nebkha development and evolution, combined with remote sensing recognition technology for the current evolution stage of nebkhas and future climate data to simulate the future evolution trend of nebkhas, and help promote the development of theoretical and technological research on nebkhas.

Conclusions

Taking the *Nitraria tangutorum* nebkhas in Dengkou County of Inner Mongolia, China as the main research object, this paper quantitatively extracted the *Nitraria tangutorum* nebkhas by using object-oriented classification and mathematical morphology based on the spectrum, texture, and geometric characteristics of GF-2 images. The object-oriented random forest classification method was used to classify the land types in the study area. The classification accuracy of *Nitraria tangutorum* land was the highest, and the user accuracy and mapping accuracy reached 90.32%. The low reflection area (vegetation part) and high reflection area (bare part) of *Nitraria tangutorum* nebkhas were extracted and combined by gray threshold method, geometric characteristics, and mathematical morphology. The spatial position extraction accuracy of *Nitraria tangutorum* nebkhas can reach 93.06%. In terms of area accuracy, the linear regression coefficient R^2 is 0.88, and the RMSE is 5.39. This method creatively constructs a variable window circumscribed circle according to the center point and area size of vegetation area in *Nitraria tangutorum* nebkha. The mathematical morphology method is used to realize the accurate combination extraction of vegetation area and bare area in *Nitraria tangutorum* nebkha, which breaks through the limitation of extracting only the vegetation part of *Nitraria tangutorum* nebkha to replace the whole *Nitraria tangutorum* nebkha. Based on the actual field survey and remote sensing extraction index characteristics of *Nitraria tangutorum* nebkha at different evolution stages, this paper determines the evolution standard of *Nitraria tangutorum* nebkha, and creatively promotes the theoretical research of *Nitraria tangutorum* nebkha evolution to the level of practical application.

We proposed a division criterion of *Nitraria tangutorum* nebkha evolution stages based on remote sensing. The *Nitraria tangutorum* nebkhas in the study area were divided into embryonic or development stage, stable stage, and decline stage, accounting for 60.70%, 20.97%, and 18.33%, respectively; *Nitraria tangutorum* nebkhas in embryonic or developmental stage was mainly distributed around the study area, and the most densely distributed area was located in the northeast of the study area; The *Nitraria tangutorum* nebkhas in the stable stage was distributed in the northeast and northwest of the study area; *Nitraria tangutorum* nebkhas in decline stage was located in the northeast of the study area. The main body of *Nitraria tangutorum* nebkhas in the study area was in the embryonic or development stage, and the proportion of *Nitraria tangutorum* nebkhas in the decline

stage was also large. Therefore, the ecological protection and restoration of *Nitraria tangutorum* nebkhas in the study area should be strengthened. The purpose of this paper is to provide technical and theoretical support for the accurate extraction of *Nitraria tangutorum* nebkhas in arid and semi-arid desert areas, the identification of their current evolution stage and the study of their spatial distribution pattern.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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