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# Spatio-Temporal Pattern of Land Degradation from 1990 to 2015 in Mongolia

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## Highlights

- A map of land degradation and restoration with 30 m resolution in Mongolia was obtained for the first time.
- For the past 25 years, the trend of land change in Mongolia was dominated by land degradation.
- Land degradation is accompanied by ongoing restoration of some land areas, and the capacity for land restoration is gradually improving.
- The central regions of Mongolia are the area with the most significant land degradation, and the combined effects from natural and socioeconomic factors are the main driving forces.
- The northwestern and northeastern parts of Mongolia is the most significant land restoration area, and owns relatively sufficient water resources for improving land restoration.

**Declarations of interest: none.**

**Abstract:**
Land degradation is an important environmental problem facing the world. "Land Degradation Neutrality" is one of the core indicators in the 15th goal of the "United Nations Sustainable Development Goals" for 2030. Mongolia is an important country for global land degradation. The increasingly serious land degradation has caused a direct impact on the ecosystem of the entire Mongolian plateau. We analyzed the patterns of land degradation and restoration during 1990–2010 and 2010–2015 and determined the driving forces behind the variations, by using fine resolution land cover data for the first time in Mongolia. The results showed that the spatial distribution of newly increased land degradation and restoration have a strong transitional nature. For the past 25 years, the trend of land change in Mongolia was dominated by land degradation. However, land degradation was accompanied by ongoing restoration of some land areas, and the capacity for land restoration has been gradually improved. This study discovers a series of typical land degradation and restoration regions and provides an interpretation of the driving forces in these areas. The joint effects of natural and socioeconomic factors have been found to result in land degradation and restoration in different regions.

**Key words:** Land degradation; distribution pattern; Mongolia; driving force; remote sensing; monitoring

## 1. Introduction

Land degradation is an important ecological and environmental problem facing the world. Land degradation leads to a loss of available grassland resources, a decrease in biological production, and the deterioration of the ecological environment (Li, 2018). One of the top 15th main tasks of the United Nations Sustainable Development Goals (SDGs) for 2030, which is "*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*". By 2030, the target 15.3 of SDGs is aiming to mitigate desertification as stated that, "*By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world*", and targeting to tackle this issue and achieving the goal of Land Degradation Neutrality (LDN) by 2030 (UNDP, 2015; UNCCD, 2015). However, we confront serious challenges especially in the arid and semi-arid areas, where land degradation and desertification are extensively existed.

Mongolia is one of the severe locations that suffers land degradation (Hansen, 2015). In Mongolia, grassland is the most common land cover of terrestrial ecosystem that is affected by climatic factors, such as precipitation, sunshine, wind, temperature, etc. (Xu et al., 2009). During 1961–2006, the numbers of vegetation species in Mongolia's forest steppe, natural grassland, mountain meadow, desert steppe, and desert have largely decreased by 50.0%, 44.7%, 30.3%, 23.8%, and 26.7%, respectively. The numbers of vegetation species have continued to decrease annually, and the grasslands have continued to become severely degraded (Buren, 2011).

By 2009, at least 72% of Mongolia's land were degraded, owing to continue the expansion of desertification, including the provinces of Uvs, Dundgovi and Dornogovi (Bai et al., 2015). In 2017, according to data from the Ministry of Natural Environment and Tourism of Mongolia, more than

76.8% of the land has suffered from varying degrees of desertification. The desertification affected areas including in Dornod and Hentiy, both of which ordinarily have good grassland coverage (Chen et al., 2017), which has been threatened by extending desertification. Severe land degradation has caused direct impact on the ecosystem of the entire Mongolian plateau and its adjacent areas. That poses a warning to regional ecological security over the country and extensively to other parts in northeast Asia.

Accurately understanding the status and dynamics of land degradation in Mongolia is the key to solve this Regional land degradation issue in Northeast Asia. Scholars have carried out some large-scale studies on desertification and land degradation in the Mongolian plateau. For example, Liu and coworkers (2007) determined the fractional vegetation cover (FVC), modified soil adjusted vegetation index (MSAVI), Albedo, land surface temperature (LST), and temperature vegetation dryness index (TVDI) through inversion of National Oceanic and Atmospheric Administration (NOAA) and Moderate Resolution Imaging Spectroradiometer (MODIS) data. As a result, they found that from 1995–2001 in China and Central Asia, the level of desertification at a spatial resolution of 1 km, which reflects the severity of the distribution of desertification.

Whilst, Unurbaatar et al. (2014) extracted information regarding desertification on the Mongolian Plateau from MODIS data for the years of 2001–2010, and analyzed the spatial distribution pattern of desertification and the trends in variation over the Mongolian Plateau. They found that land undergoing moderate desertification was expanding from northwestern Mongolia to southeastern Mongolia, such as Dundgovi and Dornogovi regions. That means these land areas are undergoing extremely severe desertification, where mainly distributed in southern Dundgovi, Omnogovi, and Dornogovi. Through an inversion of MODIS data, Zhuo et al. (2007) determined the normalized difference vegetation index (NDVI), MSAVI, FVC, LST, and drought index. So as to generate a status map of desertification at a spatial resolution of 1 km for the Mongolian plateau in 2006. They found that the land suffering from extremely severe desertification was mainly distributed in the Central Gobi and Badain Jaran Deserts.

In fact, most of these studies rely on data with coarse spatial resolution (e.g., 1 km spatial resolution), and can therefore only acquire macro-distributions and general trends for changes to desertification or land degradation (Lu, et al., 2004; Lv et al., 2014). Unfortunately, these studies cannot provide a detailed information of the spatial-temporal patterns of the land degradation in Mongolia. That is the constraint and barrier to control on-going degradation and ensuring the regional sustainable development. With the improvement of the spectral resolution, time resolution and spatial resolution in remote sensing data, more sensors have been used, in order to achieve more accurate monitoring results to tackle land degradation (Meusburger, et al., 2010; Wang, et al., 2015; Mansourb, et al., 2016). Dawelbait et al. (2012) acquired Landsat images of 1987 and 2008, and analyzed them to evaluate the desertification processes in the Central North Kurdufan State (Sudan). Liu et al. (2017) used the MOD13Q1 data with 250 m resolution from 2000–2014, as the data source that obtained to understand the dynamic change and transfer matrix of land desertification in the Silk Road Economic Zone via the decision tree classification method. Nevertheless, the research above shows that most of the studies on land degradation have used the coarse resolution data (e.g., 250 m, 1 km, etc.), and fewer studies have used higher-resolution images, e.g., Landsat series data with 30-m resolution.

In this manuscript, we aim to use the object-oriented remote-sensing image interpretation to understand the Spatio-Temporal Pattern of Land Degradation from 1990 to 2015 in Mongolia. We acquired land cover data for the years 1990, 2010, and 2015 at a resolution of 30 m in Mongolia. We then analyzed the changes of land cover types in 1990, 2010, and 2015, by using geographic information system (GIS) spatial analysis technology and acquired land degradation patterns occurring over the past 25 years. Finally, we identified typical regions undergoing the process of land degradation in Mongolia and identified the driving factors for land degradation.

## 2. Materials and methods

### *2.1. Study area*

The entire territory of Mongolia is selected as the research area, as shown in Figure 1. Mongolia is a typical landlocked country located in the interior of central Asia, at the north of the Mongolian plateau at a latitude of 42°–52° and a longitude of 88°–120°. Mongolia is located and bordered by China to the east, south, and west and by Russia in the north. It has an area of approximately 1.5665 million $km^2$, with 21 provinces. The overall topography of Mongolia is plateau which gradually decreases from west to east. The northwest of the country is characterized by high mountains, the south by the Gobi and desert, and the east by plains (Wang et al., 2018). The majority of the regions have a continental temperate grassland climate, with evident seasonal changes in Mongolia (Batjargal, 1997).

Insert Figure 1 here.

There is a scarce annual average precipitation only with about 120–250 mm, with 70% of that being is intensively precipitated during the July and August in summer (Buren, 2011). Strong winds and volatile weather systems are well-known features in Mongolia. The vegetation of Mongolia is mainly composed of Siberian coniferous forest in the north and central Asian steppe, and desert in the south (Wei, 2008). The total population was 3.2 million at the end of 2018, according to the National Bureau of Statistics, Mongolia (National Statistics Office of Mongolia, 2019). However, Mongolia is sparsely populated in terms of density, with less than two people per square kilometer, and its population distribution varies greatly among regions.

### *2.2. Data sources*

In this study, 270 Land Satellite Thematic Mapper (Landsat TM) remote sensing images and 135 Land Satellite Operational Land Imager (Landsat OLI) remote sensing images were acquired. Among them, there were 135 Landsat TM images from 1990 and 2010, and 135 Landsat OLI images from 2015.

The imaging data were taken between June and September in three different years. Most images have shorter imaging time intervals. Their spatial resolution is 30 m, and the cloud coverage was less than 5%. Blue, green, red, near infrared (NIR), short-wave infrared 1 (SWIR1), short-wave infrared 2 (SWIR2) and middle infrared (*MIR*) are the main bands in these images. The Landsat TM and OLI images were obtained from the United States Geological Survey website (USGS) (http://earthexplorer.usgs.gov/).

The auxiliary data used in this study includes the following: 1) digital elevation model (DEM ) and slope data, with spatial resolutions of 30 m (source: Thematic Database for Human-Earth System, Chinese Academy of Sciences, http://www.data.ac.cn); 2) statistics on average annual temperature, average annual precipitation, population, and livestock (source: Mongolia's statistical information service website, http://www.1212.mn [21]); and 3) field investigation data of land cover types in Mongolia acquired by this research team in 2013.

### *2.3. Methods*

#### 2.3.1. Data pre-processing

The remote sensing images are already georeferenced before we acquired them, and the coordinate system is the world geodetic system (WGS-1984). A number of steps were involved in the pre-processing of our data. First, the selected images were pre-processed, including radiometric and atmospheric correction. Radiometric correction is the process of eliminating all types of distortions in the image data (Zhu et al., 2010).

In this study, the radiometric calibration module in ENVI (The Environment for Visualizing Images) 5.1 was used to achieve radiometric correction. Atmospheric correction is the process of eliminating the radiometric error caused by atmospheric influences, and retrieving the true surface reflectance of ground objects (Zheng, et al., 2004). This was completed using the FLASSH module in the ENVI 5.1. Before atmospheric correction, the sensor type, ground elevation, image generation time, atmospheric model parameters, and results of radiometric correction should be successively added in this module. Finally, with the vector data from the Mongolian administrative division and buffer zones, the remote sensing images were clipped and mosaicked to synthesize an image map covering the entire study area.

#### 2.3.2. Remote-sensing interpretation of land cover data

In this study, an object-oriented remote sensing interpretation was used to obtain fine resolution data for land cover. Firstly, the eCognition software was used for multiresolution segmentation and spectral difference segmentation of each image in different years. The images were segmented into homogeneous polygons (namely, objects) of varying sizes, according to the spectral heterogeneity between pixels (Yue, 2011; Ma et al., 2015). Then, the objects are classified according to specified rules, taking full advantage of the textural, spatial, and spectral characteristics of ground objects (Cao et al., 2016; Ren et al., 2017; Wang et al., 2018).

By employing a land cover classification system with 30 m resolution developed by Wang et al (Wang et al., 2018) in Mongolia, we extracted information regarding areas of forest, meadow steppe, real steppe, desert steppe, cropland, built areas, water, barren lands, sand, and desert in Mongolia. The technical flowchart for classification is shown in Figure 2. There are some differences in land cover classification systems between China and Mongolia. This land cover classification system is established according to the landscape characteristics of Mongolia and the differences of vegetation coverage (Wang et al., 2018).

For example, according to the vegetation coverage, the grassland is divided into three categories (meadow steppe, real steppe, and desert steppe), and the areas with vegetation coverage of less than 5% is described as barren lands. However, the land cover classification system in Mongolia pays more attention to geography, topography, altitude and other factors. Grassland is divided into high mountain steppe, riparian meadow steppe, dry steppe, and desert steppe, according to the topographic and geomorphic characteristics.

Insert Figure 2 here.

The NDVI, normalized difference water index (NDWI), and normalized difference soil index (NDSI) were calculated using the following equations.

$$NDVI = (NIR - R) / (NIR + R), \quad (1)$$

$$NDWI = (G - SW) / (G + SW), \quad (2)$$

$$NDSI = (MIR - NIR) / (MIR + NIR), \quad (3)$$

Where R (TM = B3, OLI = B4) and NIR (TM = B4, OLI = B5) denote the reflectivity of the red and near infrared bands, respectively, and G (TM = B2, OLI = B3) and MIR (TM = B5, OLI = B6) denote the reflectivity of the green and mid-infrared bands, respectively.

Table 1 shows the interpretation rules and the reference threshold. The NDWI was used for distinguishing water, clouds, shadow, and other land types (Bo, 1996). The NDWI can effectively inhibit vegetation and highlight water information. Then, the water is classified by setting the NDWI threshold. We classified objects that had NDWI < = 0 as cloud and shadow, and then modified the actual land cover types under the cloud and shadow in combination with Google Earth. NDVI is an index commonly used to extract vegetation information (Tobu et al., 1997). The objects with NDVI < = 0.1 were classified as non-vegetation areas.

According to the characteristics of forest and meadow steppe (with a high NDVI value), establishing the rule that an object within a certain number of pixels near a river is meadow steppe, to distinguish the meadow steppe along a river and forest. The forest in the high mountainous area was divided by setting a DEM threshold. We classified objects that had DEM > 1800 m as forest. The vegetation of meadow steppe and real steppe was sparse compared to that of forest, and the NDVI value was relatively low. We classified objects that had 0.4 <= NDVI < 0.5 and 0.2 <= NDVI< 0.4 as meadow steppe and real steppe, respectively. As the NDVI value was relatively small and the vegetation coverage was in the range of 5% to 10% in the desert steppe, we classified objects that had 0.1 < NDVI < 0.2 as desert steppe. Vegetation coverage for barren lands and sand was below 5%. Sand is characterized by a contiguous distribution, extremely low vegetation coverage, and high reflectivity. According to this feature, we chose NDSI and Brightness to distinguish between sand and barren lands. Cropland is easy to identify through its regular shape and can be accurately identified in terms of the compactness of the parameters (Kindu et al., 2013). We classified objects that had compactness <= 1.4 as cropland. The built area and desert were mainly identified through visual interpretation, combined with human-computer interactive modification.

Insert Table 1 here.

2.3.3. Land degradation information and processing

Land degradation refers to the decline in, or loss of, biological or economic productivity and diversity in rain-fed land (dry farmland), irrigated land, grassland, pasture, forest, and woodland in arid, semiarid, dry, and semi-humid regions, owing to either utilization of the land, or the action of one or multiple agents (Ci, 2000).

Land degradation processes can be reflected through changes in the land cover. Based on the land cover data sets, we defined forest, meadow steppe, and real steppe as non-degraded lands. Desert steppe, barren lands areas, sand, and desert land were defined as degraded land if these areas were once non-degraded lands, as mentioned above. With technical support from a GIS spatial analysis module, we superposed land cover data, and generated variation maps in land cover for regions in Mongolia during the years of 1990–2010 and 2010–2015. In this study, spatial overlay analysis was used to superpose the land cover data of 1990 with the land cover data of 2010, and to superpose the land cover data of 2010 with the land cover data of 2015, to thereby analyze the changed parts, respectively.

Then, we extracted the changed areas of land cover types with land degradation, and obtained distribution maps of newly-increased land degradation in Mongolia from 1990–2010 and from 2010–2015. By analyzing the land degradation status in Mongolia, we identified the developing trend of land degradation over the 25-year period, and analyzed the driving forces behind the land degradation process.

Land cover data for 1990, 2010, and 2015 in Mongolia were produced using an object-oriented method. The results show an overall accuracy for the classification of land cover at 82.26% for 1990, 92.34% for 2010, and 92.75% for 2015. The data sources for this accuracy verification are mainly composed of three parts: the field verification points in 2013 (50 points), longitude and latitude intersection verification points downloaded from the "*Degree Confluence Project*" (http://www.confluence.org/, 119 points), and high-resolution sample points obtained from Google (140 points). Thus, we collected a total of 309 verification points. In 2013, we performed a field investigation in Mongolia. We evenly arranged 50 field verification points with the help of GPS instruments, and manually interpreted the local land cover types based on our prior knowledge and land cover interpretation criteria. As compared with the classification results obtained by Wei et al. and Tian et al. (Wei *et al.*, 2008; Tian *et al.*, 2014), this remote-sensing interpretation data set is more precise and accurate. In terms of resolution, this study obtained land cover data of Mongolia with a resolution of 30 m, which was much higher than the results with 1 km resolution of Wei et al. In terms of the overall classification accuracy, the overall classification accuracy of the results obtained by Tian et al. is 72.66%, which is lower than the accuracy of the results obtained in this study.

## 3. Results

### *3.1. Spatial distribution pattern of different land cover types*

Table 2 shows the statistics for area and proportion of the different land cover types. Table 3 shows the main land cover types in the different provinces of Mongolia. The phrase “main land cover types” refers to the land cover types whose area exceeds 30% of the total area of the province. Moreover, according to area, we arrange them from large to small. Fig. 3 shows the spatial distribution characteristics found in different land cover types.

Insert Table 2 here.

Insert Table 3 here.

Fig. 3(a) illustrates the distribution of different land cover types in Mongolia in 1990. Desert steppe accounted for approximately 14.78% of the total area of Mongolia, mainly distributed in northwest, central, and northeast Mongolia. It was specifically distributed in the northern and western parts of Bayan-Olgiy, the northern and eastern parts of Uvs, the central and northwestern parts of Hovd, the northern and southeastern parts of Dzavhan, the western part of Arhangay, the northern part of Bayanhongor, the north-central part of Ovorhangay, the central part of the Dundgovi, the northern part of the GoviSumubel, the southeastern part of the Kentiy, the southeastern border of the Dornogovi, the northwestern and central part of Dornod, and western and southern Suhbaatar. Barren lands accounted for approximately 46.06% of the total area of Mongolia that mainly distributed in the northwest and south of Mongolia. This land cover was specifically distributed in the western and southern parts of Uvs, the northern and southern parts of Hovd, the western part of Dzavhan, the western and southern parts of the Govi-Altay, the central part of Bayanhongor, the central and southern parts of Ovorhangay, the southern and eastern parts of Dundgovi, Omnogovi, and the northern and western parts of Dornogovi. Sand and desert were mainly distributed in the western part of Dzavhan, the northwest part of Govi-Altay, the central part of Omnogovi and the eastern part of Dornogovi.

Fig. 3(b) shows the distribution of different land cover types in Mongolia in 2010. Desert steppe accounted for approximately 16.56% of the total area of Mongolia, mainly distributed in the western, central and northeastern regions of Mongolia. It was specifically distributed in the western and southern parts of Bayan-Olgiy, northern Uvs, central Hovd, northeastern and southern parts of Dzavhan, northern and central parts of Govi-Altay, western and southern parts of Hovsgol, western and central parts of Arhangay, sporadic areas in the north and central parts of Bayanhongor, northern part of Ovorhangay, north central of Dundgovi, north central part of GoviSumubel, south of Kentiy, the southern part of Dornod, and the central and eastern parts of Suhbaatar. Barren lands accounted for about 47.83% of the total area of Mongolia, mainly distributed in the west and south of Mongolia.

It was specifically distributed in the northeastern part of Bayan-Olgiy, the north-central and southern parts of Uvs, the western border region of Dzavhan, the western and southern parts of the Govi-Altay, the southern border area of Hovsgol, the central and southern parts of Bayanhongor, the eastern and southern parts of Ovorhangay, the southern part of Dundgovi, Omnogovi, the western and southern parts of Dornogovi, and the southwestern part of Suhbaatar. Sand and desert were mainly distributed in the western border area of Dzavhan, the northwestern border area of Govi-Altay, the western and southern part of Omnogovi, and the central part of Dornogovi.

Fig. 3(c) shows the distribution of different land cover types in Mongolia in 2015. Desert steppe accounted for approximately 22.17% of the total area of Mongolia, and was mainly distributed in western, central, eastern, and northern border areas of Mongolia. It was specifically distributed in Bayan-Olgiy, northern and eastern parts of Uvs, the western and central parts of Hovd, the most of Dzavhan, the northwestern and central parts of Govi-Altay, the western and southern parts of Hovsgol, the western part of Arhangay, the northern and central parts of Bayanhongor, the western part of Bulgan, the western and central parts of Ovorhangay, the southern part of Tov, the northern part of Dundgovi, the northeastern part of Hentiy, the eastern part of the Govisumubel, the central part of Dornod, and most of Suhbaatar. Barren lands accounted for approximately 42.77% of the total area of Mongolia, and mainly distributed in the southern and northwestern provinces of Mongolia. It was specifically distributed over the western and southern parts of Uvs, the northeastern and southern parts of Hovd, the central and southern parts of Govi-Altay, the central and southern parts of Bayanhongor, the central and southern parts of Ovorhangay, the most of Omnogovi, central and southern parts of Dundgovi, and most of Dornogovi. Sand and desert were mainly distributed in western Dzavhan, the northern border area of Govi-Altay, the southern part of Omnogovi and central Dornogovi.

Insert Figure 3 here.

*3.2. The spatial distribution pattern of land degradation and restoration*

The newly-increased areas and proportions of land degradation and restoration in Mongolia are shown in Table 4. Table 5 shows the main types of land degradation or land restoration in each province of Mongolia. Fig. 4 shows the typical regions of land degradation and land restoration between 1995-2010 and 2010-2015in Mongolia. The barren lands can be restored to grassland under certain precipitation conditions, while the sand and desert can hardly be further restored. Therefore, desert and sand to barren lands can be considered as types of restoration.

Insert Table 4 here.

Insert Table 5 here.

3.2.1. The spatial distribution pattern of land degradation and restoration in Mongolia from 1990 to 2010

Fig. 4 (a) shows the distribution of newly-increased degradation regions in Mongolia from 1990 to 2010. The degraded land was mainly distributed in the northwest and south of Mongolia in a zonal manner, in a massive area encompassing much of the middle and northeast of Mongolia, and in a scattered small area in the north of Mongolia. From 1990 to 2010, the newly-increased area of degradation was about 215,155.35 $km^2$, accounting for about 13.75% of the total area of Mongolia. The main form of land degradation is where non-degraded lands have degraded into desert steppe, and where either non-degraded lands or desert steppe have become barren lands. The areas that have degraded from non-degraded lands to desert steppe are distributed in the northern part of Mongolia in strips and scattered areas, and in the central and northeastern part of Mongolia in blocks.

This land was specifically distributed in the western part of Hovsgol, the northeastern and southeastern parts of Dzavhan, western and central Arhangay, northeastern Bayanhongor, the northwestern part of Ovorhangay, the southwestern part of Bulgan, the southern border region of Tov, the northern part of Dundgovi, the southern part of Hentiy, the northeastern and southern parts of Dornod, and the central and northeastern parts of Suhbaatar. This land accounted for about 6.97% of the total area of Mongolia.

The areas that have degraded from desert steppe to barren lands were distributed in the northwest and south of Mongolia in a strip, and in the central part in a block. This land specifically distributed in the eastern and southeastern parts of Bayan-Olgiy, the central and southeastern parts of Uvs, the northwest and central parts of Hovd, the northwestern part of Dzavhan, in sporadic spots in the central part of Govi-Altay, the northern part of Bayanhongor, the western and northeastern parts of Ovorhangay, the northwest and central parts of Dundgovi, the central part of Omnogovi, the northern part of Govisumubel, the southern border of Hentiy, southeast and east of Dornogovi, and southwestern Suhbaatar. This land accounted for about 4.27% of the total area of Mongolia.

The areas that have degraded from non-degraded lands to barren lands were distributed in northern Mongolia in a zonal pattern, and were scattered over the northwestern, central, and northeastern areas in a spot-like manner. They were specifically distributed in the eastern part of Uvs, the central and northeastern parts of Dzavhan, southern Hovsgol, northern Dundgovi, central

Dornod, and the northeastern part of Suhbaatar. This land accounted for about 1.75% of the total area of Mongolia.

Five typical regions of land degradation in Mongolia during 1990-2010 are shown in Fig. 4 (a). Typical region 1 is distributed in a narrow strip from north to south across the Altai mountains in northwest Mongolia. Typical region 2 is distributed in the northern part of Mongolia as broken blocks. This region is in the Paulene Mountains, comprised with rich forest resources. Typical region 3 is mainly distributed in a square block in the northeastern part of Bayanhongor and the western part of Arhangay. Typical region 4 is distributed in a trapezoidal block covering the eastern part of Arhangay, the southern border of Tov, and the northwest and central parts of Dundgovi. Typical region 5 is a patchy and large degraded area concentrated in the northeastern part of Mongolia.

Fig. 4 (b) shows the distribution of newly-increased restoration regions in Mongolia from 1990 to 2010. The restored land is mainly distributed in the northwest of Mongolia in strips, and in the middle and northeast of Mongolia in broken blocks. From 1990-2010, about 137,203.64 $km^2$ of land in Mongolia was restored to varying degrees, accounting for about 8.77% of the total area. The main forms of land restoration comprise desert steppe being restored to non-degraded lands, and barren lands being restored to desert steppe. The areas that were restored from desert steppe to non-degraded lands were distributed in the north-central and north-eastern parts of Mongolia in broken blocks. This land was specifically distributed in the northeastern part of Uvs, the northern and central parts of Dzavhan, the southern part of Hovsgol, the western part and the eastern border of Bulgan, the eastern part of Arhangay, the northern part of Ovorhangay, the southwestern part of Tov, the southeastern part of Hentiy, the western and southeastern parts of Dornod, and the northwestern part of Suhbaatar. This land accounted for about 4.25% of the total area of Mongolia.

The areas that were restored from barren lands to desert steppe were distributed in the northwestern and eastern parts of Mongolia in strips. This land was specifically distributed in the western and southern parts of Bayan-Olgiy, the northwestern part of Uvs, the central part of Hovd, the southwestern and southern parts of Dzavhan, the northern and central parts of Govi-Altay, the southwestern part of Arhangay, the northwestern and central parts of Bayanhongor, the northern part of Ovorhangay, the central and northeastern parts of Dundgovi, the southwestern part of Govisumber, the northern and eastern parts of Dornogovi, and the southern border of Dornod, and the southern part of Suhbaatar. This land accounted for about 3.38% of the total area of Mongolia.

Three typical regions of land restoration in Mongolia during 1990-2010 are shown in Fig. 4 (b). Typical region 1 is distributed in the western and southern parts of Bayan-Olgiy in strips. Typical region 2 is distributed in the northern and central parts of Dzavhan in blocks. Typical region 3 is distributed in the northeastern part of Mongolia in blocks. It is specifically mainly distributed in the northwestern part of Dornod, and the western part of Suhbaatar.

### 3.2.2. The spatial distribution pattern of land degradation and restoration in Mongolia from 2010 to 2015

Fig. 4 (c) shows the distribution of newly-increased degradation regions from 2010 to 2015. The degraded areas were mainly distributed in northwest Mongolia in a zonal manner, and were clustered in the northern and central parts of Mongolia in fragmented blocks. From 2010 to 2015, the newly-increased land degradation area of Mongolia was approximately 128,144.83 $km^2$, accounting for about 8.19% of the total area. The main forms of land degradation are non-degrading land degrading to desert steppe and desert steppe degraded to barren lands. The regions that degraded from non-degraded lands to desert steppe were mainly distributed in the northern and central parts of Mongolia as fragmented blocks.

This land was specifically distributed in the eastern part of Uvs, the northern and central parts of Dzavhan, the eastern and southern parts of Hovsgol, the north corner and southern part of Arhangay, the northeastern part of Bayanhongor, the central part of Bulgan, the northwestern part of Ovorhangay, the eastern part of Selenge, the eastern and southern parts of Tov, the northern and southern parts of Hentiy, the northwestern and central parts of Dornod, and the western part of Suhbaatar. This land accounted for about 4.48% of the total area of Mongolia.

The areas that degraded from desert steppe to barren lands were mainly distributed in northwest Mongolia in a strip, and in the central part in a fragmented block. This land was specifically distributed in the western and southern parts of Bayan-Olgiy, the western part of Uvs, the central part of Hovd, the eastern and southern parts of Dzavhan, the central part of Govi-Altay, the southern border of Hovsgol, the southwestern border of Arhangay, the northern and central parts of Bayanhongor, the central part of Ovorhangay, the northern part of Dundgovi, the southern border of Hentiy, the northeastern part of Dornogovi, and the southwestern part of Suhbaatar. This land accounted for about 2.04% of the total area of Mongolia.

Two typical regions of land degradation in Mongolia during 2010-2015 are shown in Fig. 4 (c). Typical region 1 is distributed in the southern part of Selenge, the northern part of Tov and Ulaanbaatar. Typical region 2 is distributed in the northern and the southern parts of Hentiy.

Fig. 4 (d) shows the distribution of newly-increased restoration regions in Mongolia from 2010 to 2015. The restored areas were mainly distributed in west Mongolia in a zonal manner, and were clustered in the central and northeastern parts of Mongolia in fragmented blocks. From 2010 to 2015, about 202,097.95 $km^2$ of land in Mongolia was restored to varying degrees, accounting for 12.92% of the total area. The main forms of land restoration were barren lands being restored to desert steppe, and desert steppe being restored to non-degraded lands. The areas that were restored from barren lands to desert steppe were distributed in the western part of Mongolia in narrow strips, and in the central part of Mongolia in fragmented blocks. This land was specifically distributed in Bayan-Olgiy, the northern and western parts of Uvs, the central part of Hovd, the western and northeastern parts of Dzavhan, the northern and central parts of Govi-Altay, the southern part of Hovsgol, the northern and central parts of Bayanhongor, the central part of Ovorhangay, the northwestern part of Dundgovi, the eastern part of Govisumber, the northwestern and eastern parts of Dornogovi, the southwestern part of Suhbaatar, and the southeastern part of Dornod. This land accounted for about 7.14% of the total area of Mongolia.

The areas that were restored from desert steppe to non-degraded lands were distributed in the northern and northeastern parts of Mongolia in fragmented blocks. This land was specifically distributed in the eastern and southern parts of Dzavhan, the northern part of Govi-Altay, the central part of Arhangay, the southern border of Tov, the southern part of Hentiy, the northern and eastern parts of Suhbaatar, and the central and eastern parts of Dornod. This land accounted for about 4.35% of the total area of Mongolia.

Two typical regions of land restoration in Mongolia during 2010-2015 are shown in Fig. 4 (d). Typical region 1 is distributed in the northern and central parts of Govi-Altay, and the central part of Bayanhongor in strips. Typical region 2 is distributed in the central and northeastern parts of Dundgovi, the most parts of Govisumber, and the northwestern part of Dornogovi.

Insert Figure 4 here.

## 4. Discussion

### *4.1. The spatiotemporal distribution characteristics for land cover, newly-increased degraded and restored land in Mongolia*

According to the spatial distribution pattern of different types of land cover in Mongolia in 1990, 2010, and 2015, the distribution of non-degraded lands, desert steppe, and barren lands show evident transition characteristics. From north to south and northeast to southwest, the successive land cover types were originally non-degraded lands, desert steppe, and barren lands.

Areas where land degradation in Mongolia have a strong transitional nature. The degree of land degradation gradually increased from northeast to southwest Mongolia. In addition, it can be found from Fig. 4 (a) and (c) that most land degradation areas during 1990 - 2010 are in the west, south and east sides of the land degradation areas during 2010 - 2015. That is, the land degradation areas from 1990 to 2010 like a half ring, with just half wrapped around the land degradation areas from 2010 to 2015. It can be discovered that in the past 25 years, the land degradation areas in the northwest of Mongolia have gradually expanded to the northeast, the land degradation areas in the middle have gradually expanded to the north, and the land degradation areas in the northeast of Mongolia has shown a trend of development from northeast to northwest. That is to say, the land degradation areas show a trend of expanding in a semiring towards the center of the half ring.

The areas where land restoration has occurred in Mongolia also have a certain transitional nature. The degree of land restoration gradually increased from southwest to northeast Mongolia. At the same time, we found that the area of land restoration showed an increasing trend in the past 25 years. From 2010 to 2015, the area of land restoration area has been larger than that of the land degradation area, and the proportion of the net land degradation area in the total area is -4.73%. That is to say, the overall change of land in Mongolia during 2010 - 2015 was mainly based on restoration. However, from 1990 - 2010, the proportion of net land degradation area in the total area was 4.98%. Thus, the general trends of land change in Mongolia from 1990 to 2015 was land degradation.

There are some differences in land cover classification systems between the National atlas of Mongolia and this study. The land cover classification system of the land cover map in Mongolia from National atlas of Mongolia pays more attention to geography, topography, altitude and other factors. The classification system and results in this study are obtained objectively based on remote sensing images, which reveal the relative changes of land cover and the development trend of land degradation and land restoration in Mongolia in the past 25 years. In the future, we will continue to strengthen the study on land cover classification methods, and input more ground investigations and local knowledge to further improve the classification accuracy.

### *4.2. An analysis of the driving forces behind land degradation and restoration in Mongolia*

#### 4.2.1. An analysis of the driving forces behind land degradation

(1) Natural factors

Temperature and precipitation are climatic factors with evident characteristics of distribution in a horizontal zone, and are some of the most important driving factors affecting the land degradation process in Mongolia.

Over the last 40 years the average global temperature has increased by 0.74 □, but the average temperature in Mongolia has increased by 1.5 to 2.5 □, 2–3 times the global change (Buren, 2011). Meanwhile, according to a statistical analysis of meteorological data collected by the Mongolian meteorological stations (National Statistics Office of Mongolia, 2019), the temperature in Mongolia showed a slow upward trend and significant fluctuations during 2000–2015 (as shown in Fig. 5). In those 16 years, the difference between the maximum annual average temperature and the minimum annual average temperature was 2.9 °C. Because of the fluctuation and rising of temperature, the growth and succession of vegetation was interfered (Munkhtsetseg et al., 2007). This process could ultimately result in a reduction in vegetation coverage, a decline in vegetation productivity, serious degradation of the grasslands, and the acceleration of overall land degradation.

Insert Figure 5 here.

Because Mongolia is in arid and semi-arid regions, the amount of precipitation has an important impact on the growth of vegetation in the region (Shi, 2009). According to the average annual precipitation data released by the website of Mongolia Statistical Information Service, in this study area, the average annual precipitation from 2008 to 2011 was 4669.00 mm, and the average annual precipitation from 2012 to 2015 was 4520.50 mm (National Statistics Office of Mongolia, 2019).

Thus, precipitation presented an overall declining trend. In addition, changes to the regional distribution of precipitation were evident, as precipitation gradually decreased from north to south. With the decrease of precipitation in this area, vegetation growth in this area was restrained. The precipitation mainly occurs from June to September in Mongolia, and heavy rainfall occurs in some areas. Precipitation is scarce in the spring and winter; thus, drought increases during these months, inhibiting vegetation growth and accelerating land degradation (Bu, 2011). The intensive rainstorms in summer and autumn aggravate soil erosion, the accumulation of the by-products of this erosion, surface fragmentation, and the reduction in the size of soil particles. This expands the areas of bare land, accelerates the process of land degradation, and increases the risk of floods during the rainy season.

(2) Socioeconomic factors

Overgrazing can accelerate land degradation in Mongolia. Animal husbandry is one of the pillar industries of Mongolia. With the increase in both the international and domestic consumption of cashmere, the number of breeding Mongolian goats increased by about 3.3857 million over the ten years between 2006 and 2015, with a growth rate of about 75.70% (as shown in Fig. 6 (a)) (National Statistics Office of Mongolia, 2019).This resulted in serious overloading of the pasture land. Owing to the strong feeding capacity of goats, when the grassland is poor, they will directly chew the grass roots, causing serious damage and direct degradation of the grassland.

Excessive and unscientific mining activities enhanced by mining enterprises also could exacerbate land degradation. Mongolia is an important exporter of mineral resources in Asia. Southern Mongolia has abundant mineral resources such as coal, fluorite, tungsten, gold, iron, and tin (Li et al., 2016). Many mining enterprises are gathered in a relatively small area, the mining technology is relatively backward, and the scale of mining is not limited. Therefore, the local surface vegetation is destroyed, and the land surface structure is changed, resulting in the decline of the land quality and a serious land degradation problem. In addition, abandoned mineral deposits and the accumulation of abandoned mining soil has increased the amount of sand in the soil, increasing the momentum of dust flow and aggravating land degradation (Aorenqi et al., 2010).

Rapid urbanization also increases the risk of land degradation. In the 1990s, the government of Mongolia announced a "*Civil Liberties*" policy concerned with areas for habitation (Buren, 2011). This policy encouraged herdsmen to move in large numbers to resource-gathering areas, such as around important traffic arteries, near water sources such as rivers and lakes, or into provincial capitals and Ulaanbaatar, thus greatly accelerating the urbanization process of Mongolia.

As shown in Fig. 6 (b), the urban population of Mongolia increased by about 474,500 from 2006 to 2015, an increase of about 29.26% (National Statistics Office of Mongolia, 2019). Owing to a lack of adequate planning and management, in the process of moving to the city herdsmen have occupied significant amounts of land, and have built many family courtyard houses where people and their livestock (e.g. cattle, lambs, etc.) are living together. This situation has caused inefficient land utilization, wasted significant land resources, and reduced the vegetation coverage of local areas, thereby increasing the risk of land degradation. With the increase in the degraded land area, the available land is constantly reduced, which further increases the cost of urbanization and reduces the ability for the sustainable development of cities and towns.

Insert Figure 6 here.

Increasing infrastructure development also could aggravate land degradation. To promote economic development, Mongolia has made great efforts to develop railways, highways, and other infrastructure, and has built many transportation systems connecting major cities and industrial bases. Under the increasing demand for infrastructure, the demand for soil for construction has also continued to increase. To reduce construction cost, many developers often extract the soil (as construction materials) directly beside the sites. However, most projects have not been adopted any reclamation or environmental trade-off practices after the project, leading to bare surfaces and a high degree of fragmentation, and accelerating the process of land degradation.

Scholars have carried out land degradation monitoring and driving force analysis in Inner Mongolia, China (Ma et al., 2017). It is found that the carrying capacity of grassland, grassland reclamation and population are the main factors. Precipitation and average temperature in summer are also important factors that aggravate grassland degradation. Unreasonable exploitation of energy and mineral resources is another important factor leading to grassland degradation. These are similar to the main driving forces of land degradation in Mongolia.

However, there are differences between Inner Mongolia and Mongolia in nature, climate conditions and policy guidance. Some corresponding ecological projects have been established in China, such as returning farmland to forest and grass, and artificial afforestation (Zhen et al., 2019). These ecological projects have inhibited the process of land degradation to some extent. Therefore, this experiment can be referred by Mongolia for their land degradation combatting according to similar ecological and climatic conditions in the two countries.

#### 4.2.2. An analysis of the driving forces behind land restoration

We found that land change in Mongolia presents a pattern of land degradation in overall and land restoration in local regions. In view of this characteristic, we took typical regions of land restoration as the entry point to complete the driving force analysis combined natural and socioeconomic factors.

Typical region 1 in Fig. 4 (b): The restored land in this area is mainly distributed in the western and southern Bayan-Olgiy. Bayan-Olgiy is located at the top of the Altai mountains of Mongolia. Due to the high altitude, the weather is cold and snow is widespread. But driven by global warming, the temperature gradually rises and some snow begins to melt.

Furthermore, it brings relatively sufficient water to promoting vegetation growth in some areas. In addition, the number of livestock in this region declined sharply between 1990 and 1993, with a decline proportion of more than 80% (National Statistics Office of Mongolia, 2019). Although the situation has improved since 1993, the number of livestock increased slowly. By 2015, the number of livestock only recovered to about 64% of its number in 1990. Due to the small number of livestock, the destruction of vegetation is relatively small, which is conducive to land restoration.

Typical region 2 in Fig. 4 (b): The restored land in this area is mainly distributed in the northern and central Dzavhan. From 1990 to 2010, the population declined by 30% in Dzavhan (National Statistics Office of Mongolia, 2019). Although the population increased between 2010 and 2015, the increase was small. As the population decreased, human activities also weakened, and the disturbance to the environment was not serious relatively. Thereby, it created certain conditions for land restoration in this region.

Typical region 3 in Fig. 4 (b): The restored land in this area is mainly distributed in the northeastern Mongolia, including northwestern part of Dornod, and the western part of Suhbaatar. As Mongolia is located in inland, the East Asian monsoon can only reach the eastern edge of Mongolia. It brings relatively sufficient precipitation to the east of Mongolia, which is conducive to vegetation growth and creates conditions for land restoration in this region. In addition, the typical region c has flat terrain, numerous rivers and lakes, and abundant water resources. The relatively suitable natural conditions are also conducive to land restoration in the region.

Typical region 1 in Fig. 4 (d): The restored land in this area is in the central part of Bayanhongor, where has many lakes and river valleys. The northeastern part of Govi-Altay is the source of many small rivers with abundant water resources. The central part of Govi-Altay has many mountains and snow cover all year round. Since 2010, the annual average temperature in Govi-Altay and Bayanhongor has gradually risen above 0 □ (National Statistics Office of Mongolia, 2019). Some snow began to melt, which in turn provided additional water for vegetation growth. Therefore, with the temperature gradually appropriate and the increase of water resources in this typical region, the trend of land restoration is increasingly obvious.

Typical region 2 in Fig. 4 (d): The restored land in this region is distributed in the central and northeastern parts of Dundgovi, the most parts of Govisumber, and the northwestern part of Dornogovi. Because this typical region is close to the China-Mongolian Railway mainlines, owing modernised transportation networks and rich mineral resources. Many international mining enterprises set up factories and mines are located here. However, the exports of mineral products showed a declining trend in Mongolia during 2010-2015. Especially from 2010 to 2013, the volume of exports decreased by nearly 20% (National Statistics Office of Mongolia, 2019). Therefore, due to the depression of the mineral industry during this period, the expansion of production could not be continued, and the degree of damage to the land was reduced, which provided the possibility for land restoration in the region.

## 5. Conclusion

In this study, we acquired 30 m high-resolution data on land degradation and restoration in

Mongolia using remote-sensing interpretation and GIS spatial analysis approaches. Through the analysis of land degradation and restoration, it was found that the spatial distribution of regions of newly-increased land degradation and restoration have a strongly transitional nature. The degree of land degradation increases gradually from northeast to southwest, areas of newly-increased land degradation are gradually expanding to the northern border areas, and the degree of land restoration increases gradually from southwest to northeast of Mongolia.

At the same time, we identified seven regions where land degradation is getting more serious, by the evidence of five particular regions that are requiring land restoration immediately. Based on the results of the land degradation and restoration monitoring, we demonstrate that the combined effect of natural and socioeconomic factors has resulted in the land degradation in Mongolia. Significant fluctuations in temperature and reductions in precipitation are crucial factors. Overgrazing, excessive and irrational mining, rapid urbanization, and inappropriate and unplanned development of infrastructure contribute to the land degradation.

This study also infers that global warming creates conditions appropriate for land restoration in alpine snow regions, springs, river valleys, and other areas with abundant water resources. The East Asian Monsoon provides the possibility of land restoration in the eastern border areas of Mongolia. The fluctuant decline of population and livestock in the less developed areas of the northeastern border regions of Mongolia have also contributed to the land restoration in the region. However, the driving forces of degradation and restoration are not restricted to specific locations that means more detailed studies on driving force analysis for these specific typical regions will be strengthened and understood the phenomenon in future. We admitted that there is the limitation in this study with the time interval selected for the land degradation and restoration analysis was uneven.

Lastly, we conclude that to reveal the more comprehensive and detailed process of land degradation and restoration in Mongolia, we will conduct encryption analysis at intervals of 5 or 10 years and will improve to our understanding of the degradation pattern in future.

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## Tables and Figures

### 1. Figures

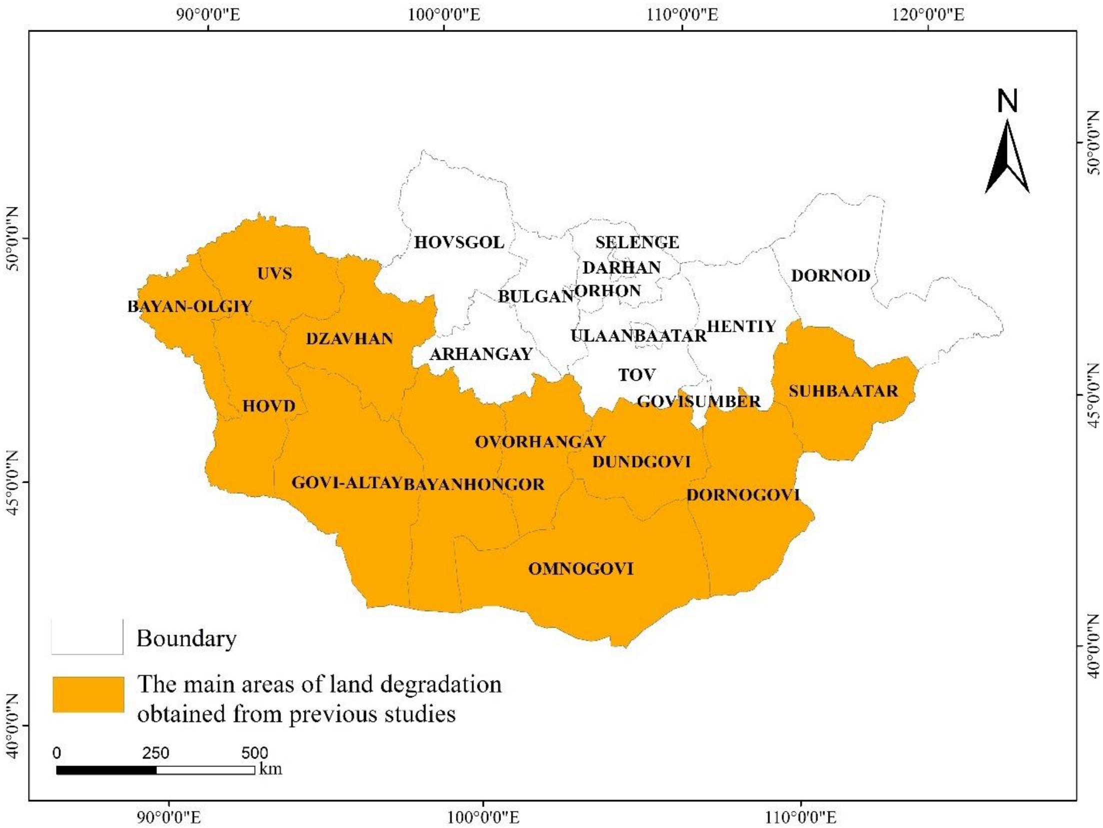



**Fig. 1.** The distribution map of provinces and the main areas of land degradation in Mongolia.

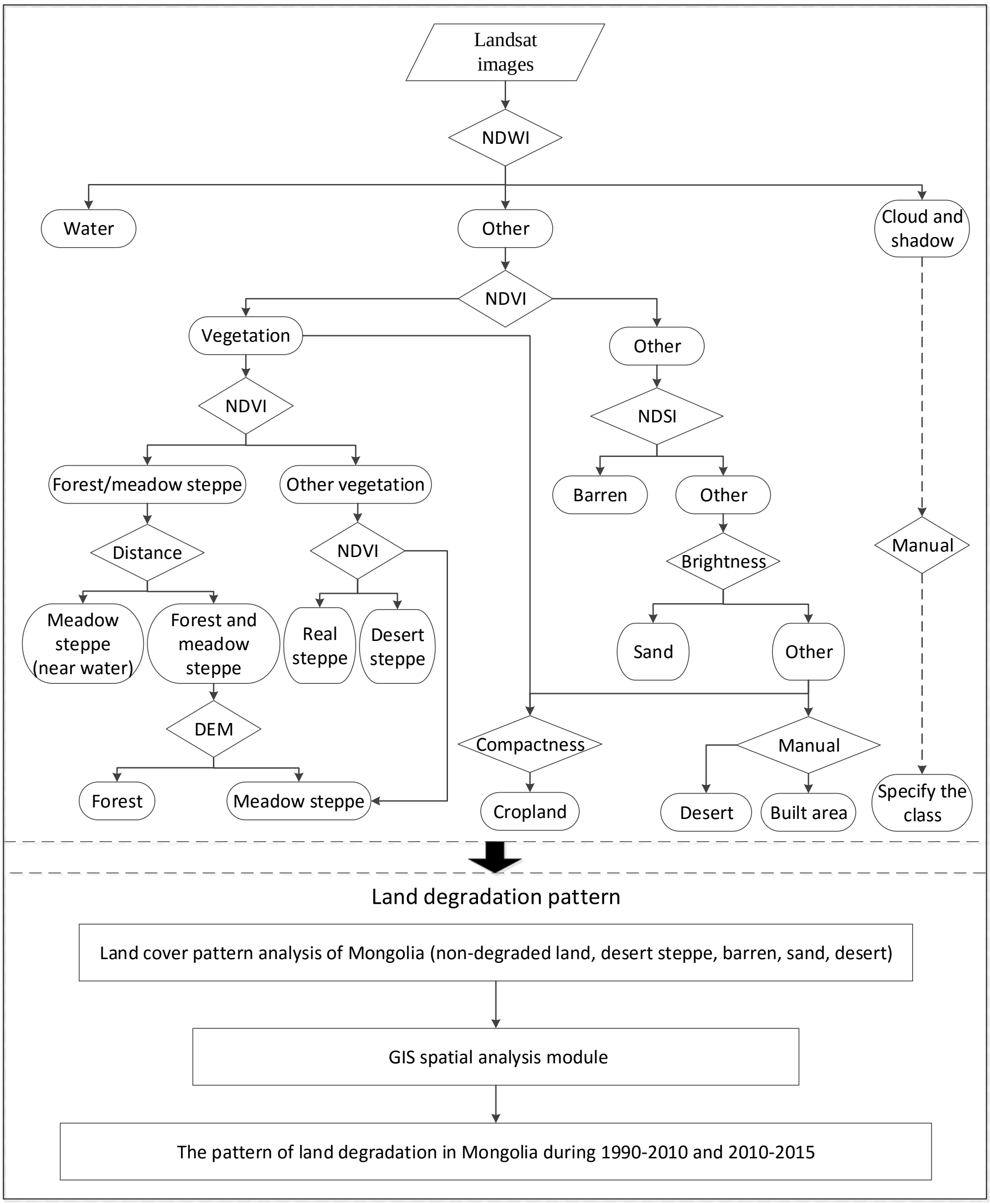
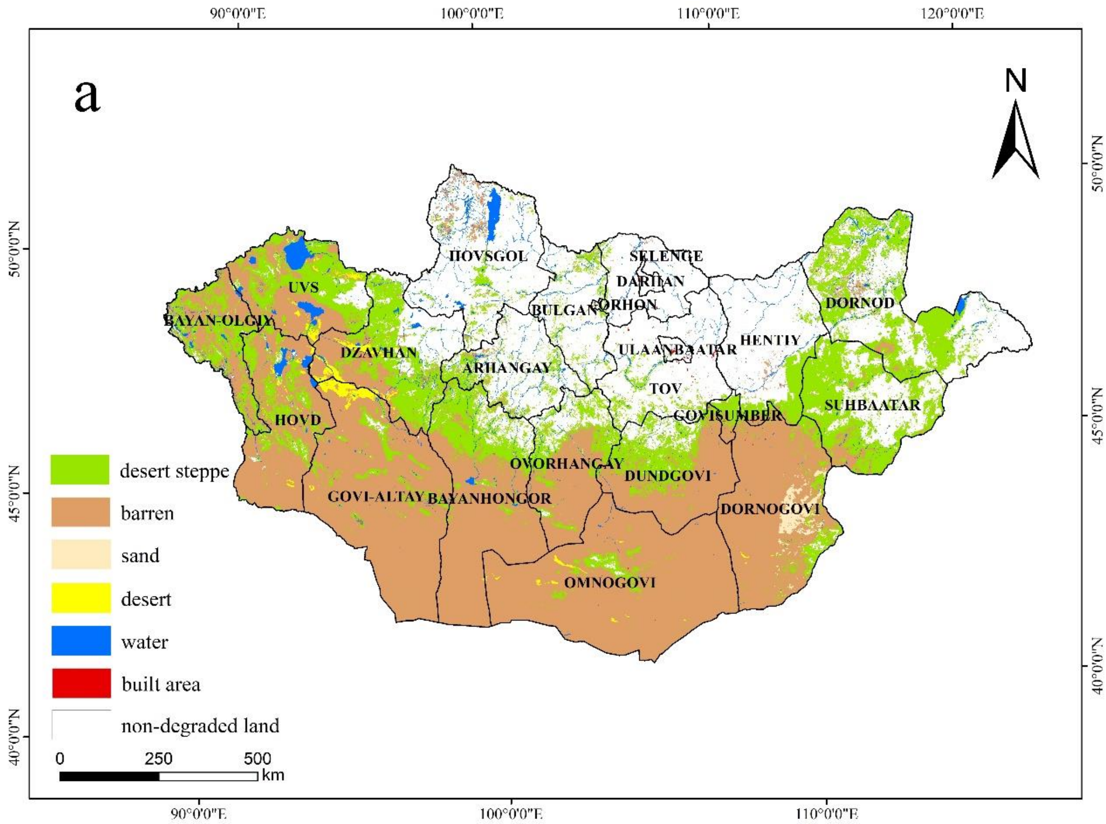



**Fig. 2.** The technical flowchart of land degradation information extraction in Mongolia (NDWI: Normalized Difference Water Index; NDVI: Normalized Difference Vegetation Index; NDSI: Normalized Difference Soil Index; DEM: Digital Elevation Model; GIS: Geographic Information System).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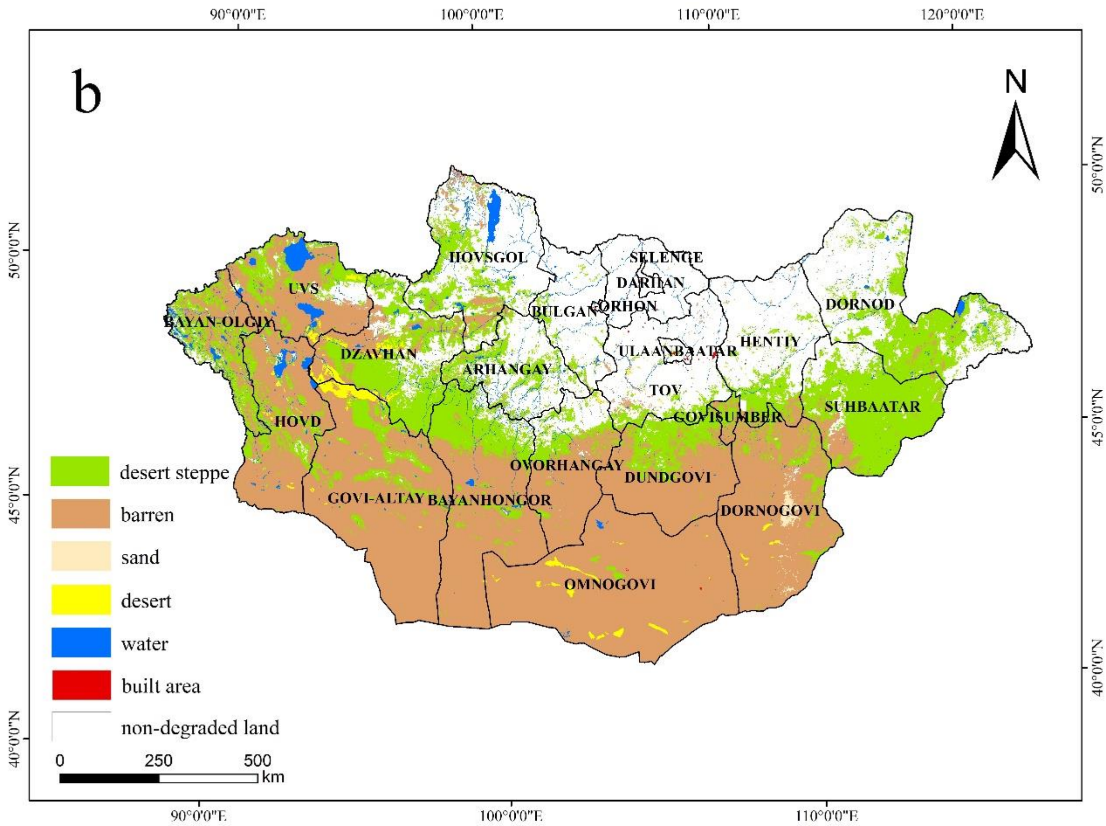
40°0'0"N
HOVSGOL
SELENGE
DARHAN
ORHON
BULGAN
UVS
BAYAN-OLGIY
DZAVHAN
ARHANGAY
ULAANBAATAR
HENTIY
DORNOD
TOV
GOVISUMBER
SUHBAATAR
HOVD
OVORHANGAY
DUNDGOVI
GOVI-ALTAY
BAYANHONGOR
DORNOGOVI
OMNOGOVI
desert steppe
barren
sand
desert
water
built area
non-degraded land
0
250
500
km


b
N
90°0'0"E
100°0'0"E
110°0'0"E
120°0'0"E
50°0'0"N
45°0'0"N
40°0'0"N
HOVSGOL
SELENGE
DARHAN
ORHON
BULGAN
UVS
BAYAN-OLGIY
DZAVHAN
ARHANGAY
ULAANBAATAR
HENTIY
DORNOD
TOV
GOVISUMBER
SUHBAATAR
HOVD
OVORHANGAY
DUNDGOVI
GOVI-ALTAY
BAYANHONGOR
DORNOGOVI
OMNOGOVI
desert steppe
barren
sand
desert
water
built area
non-degraded land
0
250
500
km

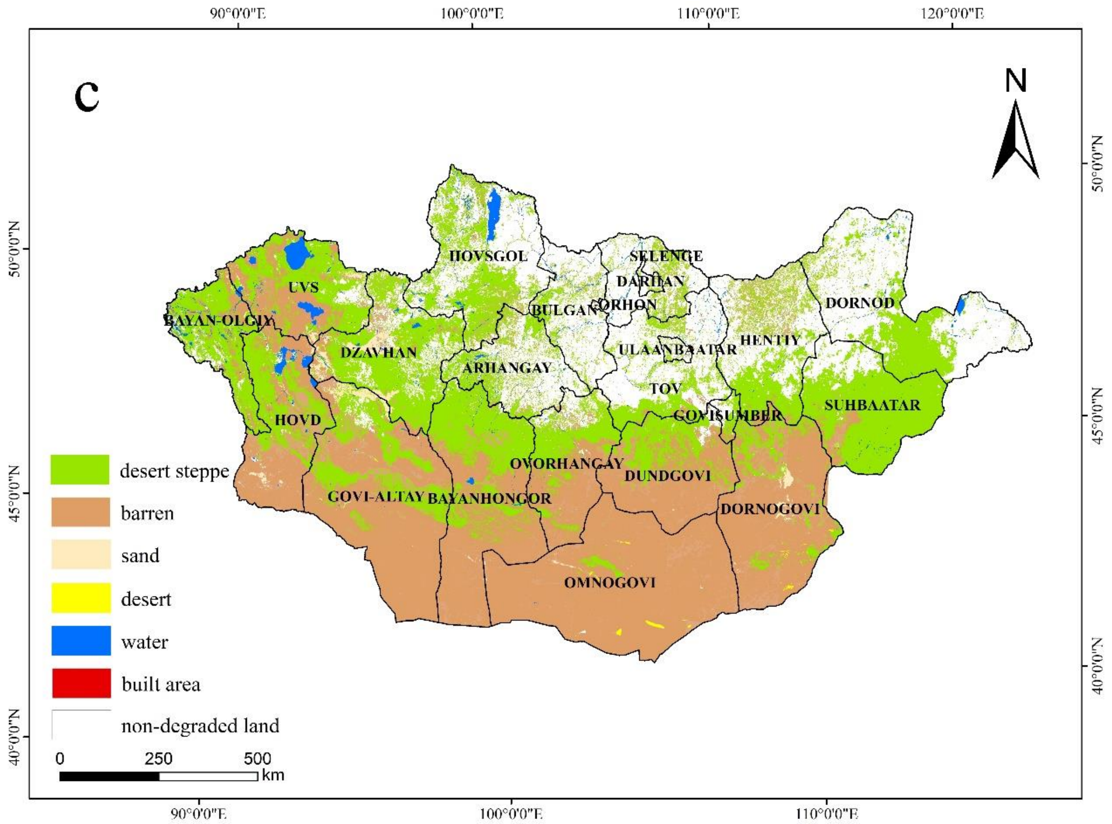
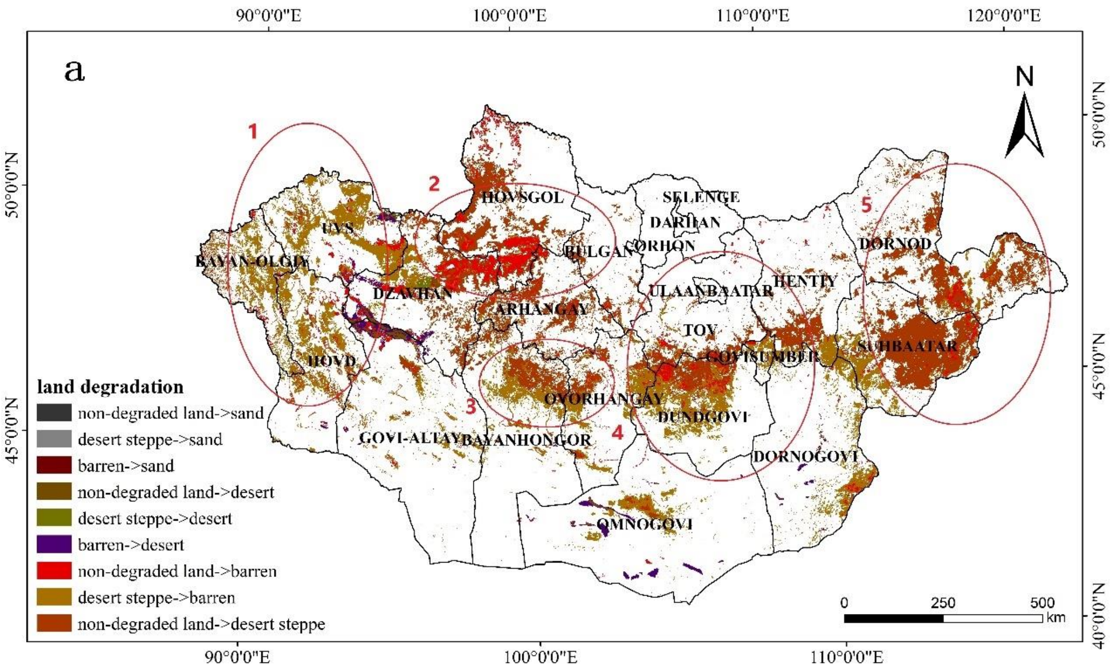
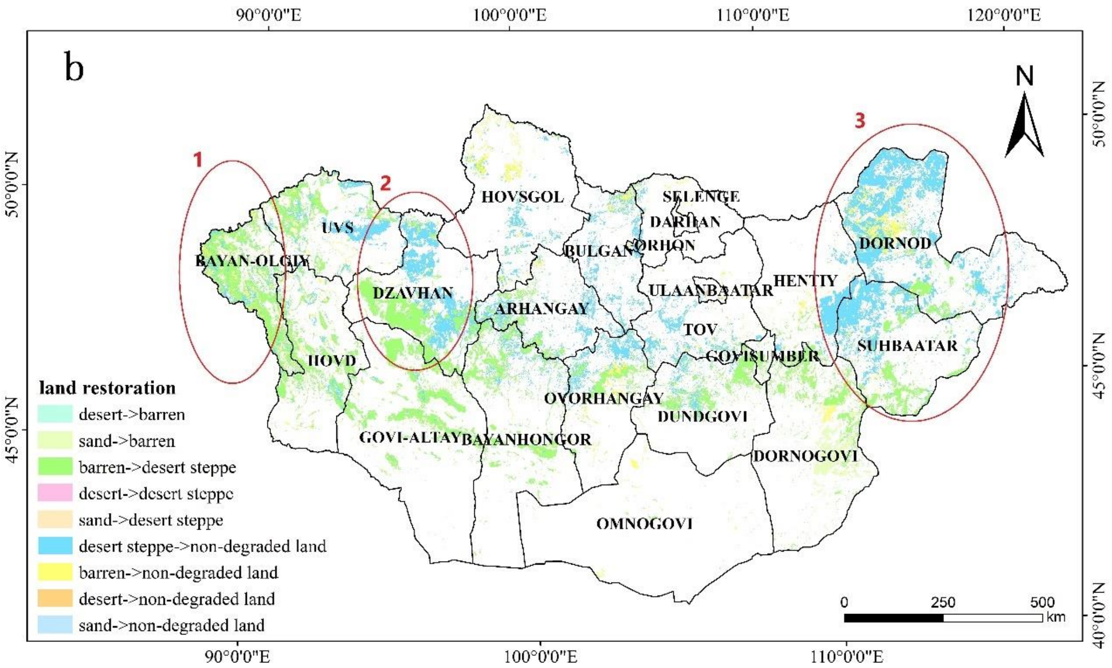
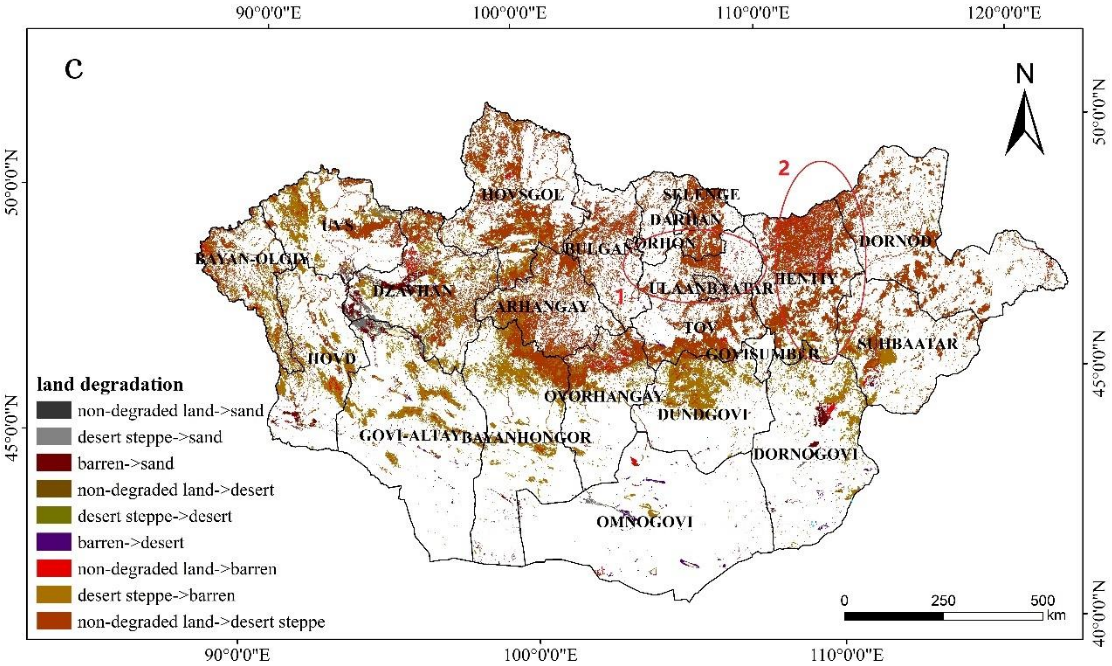



**Fig. 3.** The distribution map showing different types of land cover in Mongolia. (a) 1990, (b) 2010, and (c) 2015.




b
land restoration
desert->barren
sand->barren
barren->desert steppe
desert->desert steppe
sand->desert steppe
desert steppe->non-degraded land
barren->non-degraded land
desert->non-degraded land
sand->non-degraded land
BAYAN-OLGIY
UVS
DZAVHAN
HOVD
GOVI-ALTAY
BAYANHONGOR
HOVSGOL
ARHANGAY
BULGAN
SELENGE
DARHAN
ORHON
ULAANBAATAR
TOV
HENTIY
GOVISUMBER
OVORHANGAY
DUNDGOVI
DORNOGOVI
OMNOGOVI
DORNOD
SUHBAATAR
N
0 250 500 km


c
land degradation
non-degraded land->sand
desert steppe->sand
barren->sand
non-degraded land->desert
desert steppe->desert
barren->desert
non-degraded land->barren
desert steppe->barren
non-degraded land->desert steppe
BAYAN-OLGIY
UVS
DZAVHAN
HOVD
GOVI-ALTAY
BAYANHONGOR
HOVSGOL
ARHANGAY
BULGAN
SELENGE
DARHAN
ORHON
ULAANBAATAR
TOV
HENTIY
GOVISUMBER
OVORHANGAY
DUNDGOVI
DORNOGOVI
OMNOGOVI
DORNOD
SUHBAATAR
N
0 250 500 km

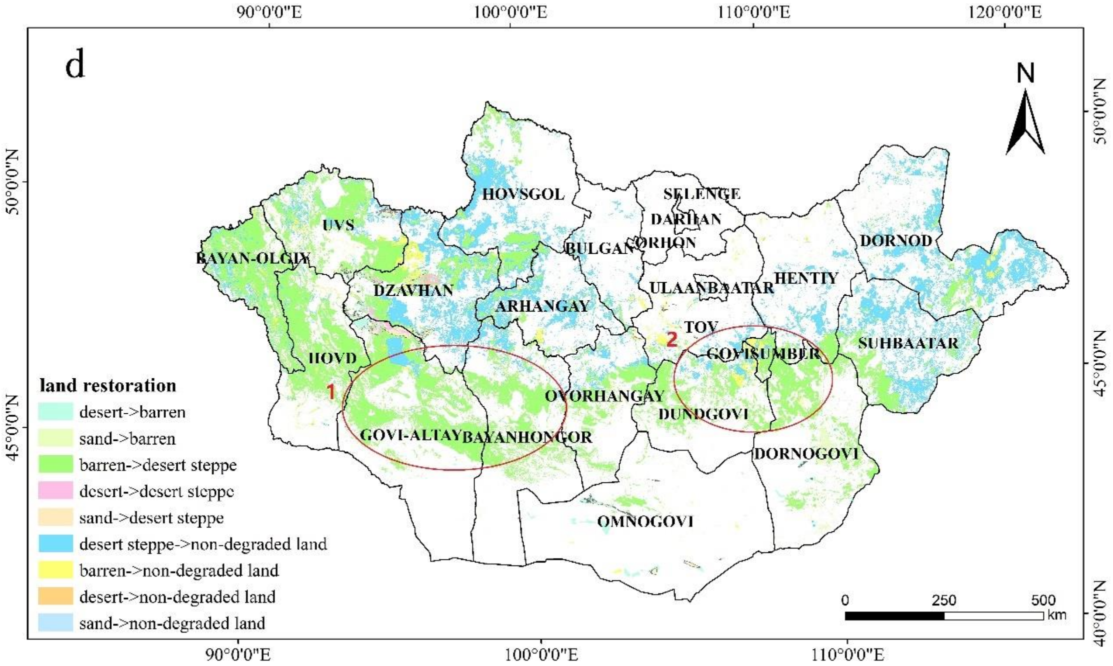



**Fig. 4.** Typical regions of land degradation and land restoration between 1995-2010 and 2010-2015 in Mongolia. (a) 1990-2010 (land degradation), (b) 1990-2010 (land restoration), (c) 2010-2015 (land degradation), and (d) 2010-2015 (land restoration).

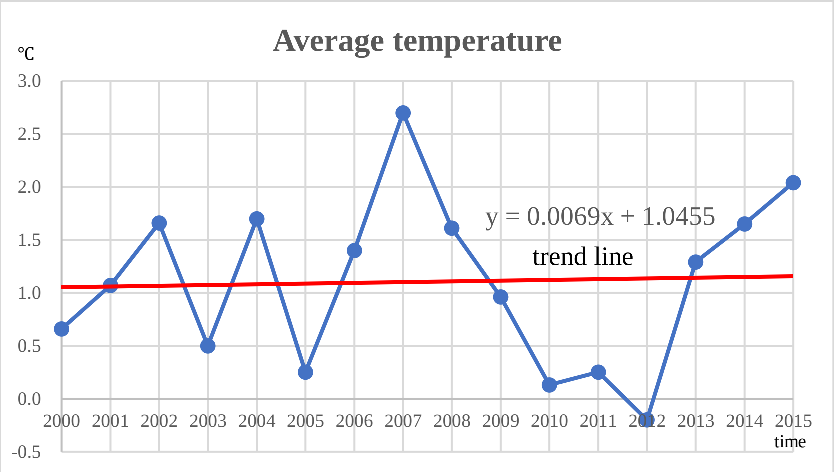
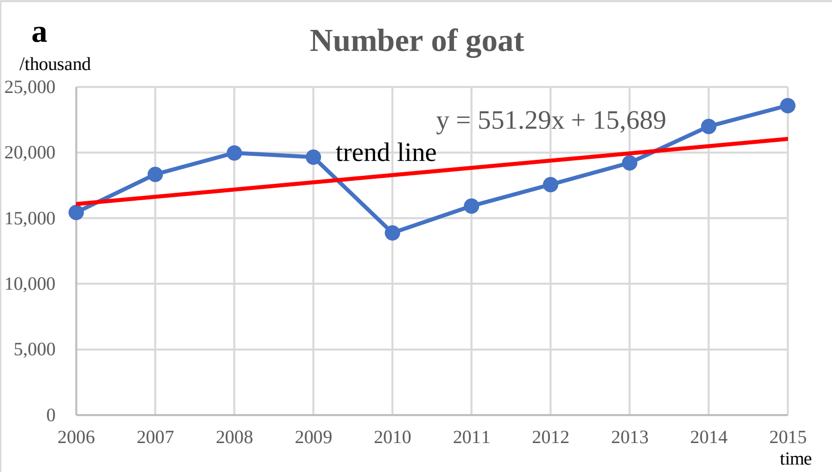



**Fig. 5.** The annual average temperature in Mongolia.



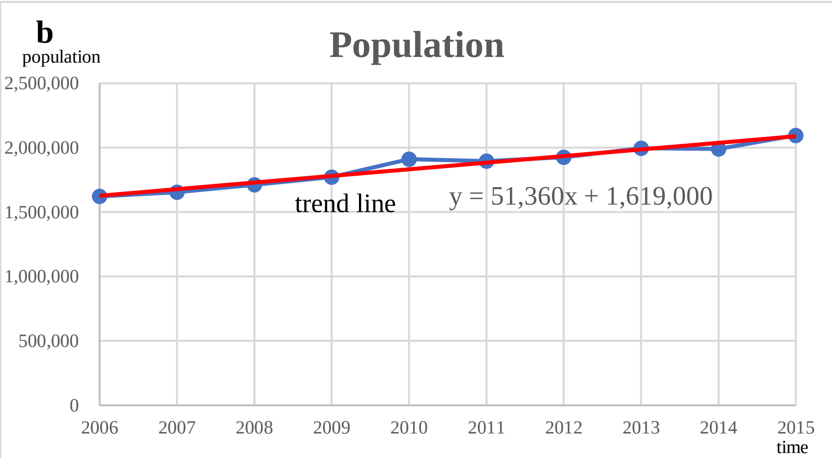




**Fig. 6.** The annual urban population and the annual number of goats in Mongolia. (a) number of goats (b) urban population.

## 2. Tables

**Table 1.** Interpretation rules and reference thresholds used in land cover classification.

| Land cover types | Rules and reference threshold |
|---|---|
| forest | NDVI > 0.5; DEM > 1800 m |
| meadow steppe | 0.4 <= NDVI < 0.5; Distance to water < 40 pixels; DEM< = 1800 m |
| real steppe | 0.2 <= NDVI< 0.4 |
| desert steppe | 0.1 < NDVI < 0.2 |
| barren lands | NDSI > 0.03 |
| desert | visual interpretation |
| sand | Brightness >= 600 |
| cropland | Compactness <= 1.4 |
| built area | visual interpretation |
| water | NDWI > 0.036 |

**Table 2.** Areas and the proportion of different land cover types in Mongolia (non-degraded lands comprise forest, meadow steppe, and real steppe).

| Time | Land cover types | Area ($km^2$) | Proportion (%) |
|---|---|---|---|
| 1990 | desert steppe | 231,266.83 | 14.78 |
| | barren lands | 720,467.43 | 46.06 |
| | sand | 5798.06 | 0.37 |
| | desert | 9403.75 | 0.60 |

| | | | |
|---|---|---|---|
| | non-degraded lands | 597,432.27 | 38.19 |
| | total | 1,564,368.34 | 100 |
| 2010 | desert steppe | 259,083.51 | 16.56 |
| | barren lands | 748,187.64 | 47.83 |
| | sand | 1929.98 | 0.12 |
| | desert | 11,514.17 | 0.74 |
| | non-degraded lands | 543,617.98 | 34.75 |
| | total | 1,564,368.34 | 100 |
| 2015 | desert steppe | 346,761.95 | 22.17 |
| | barren lands | 669,109.76 | 42.77 |
| | sand | 20,074.40 | 1.28 |
| | desert | 1724.90 | 0.11 |
| | non-degraded lands | 526,722.82 | 33.67 |
| | total | 1,564,368.34 | 100 |

**Table 3.** The main land cover types in different provinces of Mongolia ("NDL" refers to "non-degraded lands", non-degraded lands comprise forest, meadow steppe, and real steppe).

| Province | Main land cover types | | |
|---|---|---|---|
| | 1990 | 2010 | 2015 |
| Bayan-Olgiy | desert steppe, barren lands | desert steppe, barren lands | desert steppe |
| Hovd | barren lands, desert steppe | barren lands, desert steppe | barren lands, desert steppe |
| Govi-Altay | barren lands | barren lands | barren lands, desert steppe |
| Uvs | desert steppe, barren lands | barren lands, desert steppe | desert steppe, barren lands |
| Dzavhan | desert steppe, barren lands | desert steppe | desert steppe |
| Bayanhongor | barren lands, desert steppe | barren lands, desert steppe | barren lands, desert steppe |
| Hovsgol | NDL | NDL, desert steppe | desert steppe, NDL |
| Arhangay | NDL | NDL, desert steppe | desert steppe, NDL |
| Ovorhangay | barren lands | barren lands, NDL | barren lands, desert steppe |
| Omnogovi | barren lands | barren lands | barren lands |
| Bulgan | NDL | NDL | NDL, desert steppe |
| Selenge | NDL | NDL | NDL, desert steppe |
| Darhan | NDL | NDL | NDL |
| Orhon | NDL | NDL | NDL |
| Tov | NDL | NDL | NDL, desert steppe |
| Ulaanbaatar | NDL | NDL | NDL |
| Dundgovi | barren lands, desert steppe | barren lands, desert steppe | barren lands, desert steppe |
| Govisumber | desert steppe, barren lands | desert steppe, barren lands | desert steppe, NDL |
| Dornogovi | barren lands | barren lands | barren lands |
| Hentiy | NDL | NDL | NDL, desert steppe |
| Dornod | desert steppe, NDL | desert steppe, NDL | NDL, desert steppe |
| Suhbaatar | desert steppe, NDL | desert steppe | desert steppe |

**Table 4.** Areas and the proportion of land degradation and land restoration in Mongolia ("NDL" refers to "non-degraded lands", non-degraded lands comprise forest, meadow steppe, and real steppe).

| Time | Degradation | Area (km²) | % | Restoration | Area (km²) | % |
|---|---|---|---|---|---|---|
| 1990-2010 | NDL→sand | 0.21 | 0.00001 | desert→barren lands | 35.05 | 0.002 |
| | desert steppe→sand | 9.89 | 0.0006 | sand→barren lands | 4255.66 | 0.27 |
| | barren lands→sand | 502.64 | 0.03 | barren lands→desert steppe | 52,893.64 | 3.38 |
| | NDL→desert | 6244.73 | 0.40 | desert→desert steppe | 42.60 | 0.003 |
| | desert steppe→desert | 866.69 | 0.06 | sand→desert steppe | 106.12 | 0.007 |
| | barren lands→desert | 4387.99 | 0.28 | desert steppe→NDL | 66,503.51 | 4.25 |
| | NDL→barren lands | 27,357.60 | 1.75 | barren lands→NDL | 12,967.07 | 0.83 |
| | desert steppe→barren lands | 66,815.85 | 4.27 | desert→NDL | 395.70 | 0.03 |
| | NDL→desert steppe | 108,969.75 | 6.97 | sand→NDL | 4.29 | 0.0003 |
| | total | 215,155.35 | 13.75 | total | 137,203.64 | 8.77 |
| 2010-2015 | NDL→sand | 161.32 | 0.01 | desert→barren lands | 3259.61 | 0.21 |
| | desert steppe→sand | 1183.87 | 0.08 | sand→barren lands | 963.04 | 0.06 |
| | barren lands→sand | 11,470.10 | 0.73 | barren lands→desert steppe | 111,765.26 | 7.14 |

| | | | | | |
|---|---|---|---|---|---|
| NDL→desert | 16.36 | 0.0010 | desert→desert steppe | 854.68 | 0.05 |
| desert steppe→desert | 21.27 | 0.0013 | sand→desert steppe | 53.05 | 0.003 |
| barren lands→desert | 913.36 | 0.06 | desert steppe→NDL | 68,099.91 | 4.35 |
| NDL→barren lands | 12,326.79 | 0.79 | barren lands→NDL | 16,221.74 | 1.04 |
| desert steppe→barren lands | 31,916.81 | 2.04 | desert→NDL | 880.37 | 0.06 |
| NDL→desert steppe | 70,134.95 | 4.48 | sand→NDL | 0.29 | 0.00002 |
| total | 128,144.83 | 8.19 | total | 202,097.95 | 12.92 |

**Table 5.** The main types of land degradation or land restoration in each province of Mongolia ("NDL" refers to "non-degraded lands", non-degraded lands comprise forest, meadow steppe, and real steppe).

| **Province** | **Main types of land degradation or land restoration** | |
|---|---|---|
| | **1990-2010** | **2010-2015** |
| Bayan-Olgiy | barren lands→desert steppe, desert steppe→barren lands | barren lands→desert steppe, desert steppe→barren lands |
| Uvs | desert steppe→barren lands, barren lands→desert steppe | barren lands→desert steppe, desert steppe→barren lands |
| Hovd | desert steppe→barren lands | barren lands→desert steppe, desert steppe→barren lands |
| Dzavhan | desert steppe→NDL, barren lands→desert steppe | desert steppe→NDL, barren lands→desert steppe |
| Govi-Altay | barren lands→desert steppe, desert steppe→barren lands | barren lands→desert steppe, desert steppe→barren lands |
| Hovsgol | NDL→desert steppe, NDL→barren lands | desert steppe→NDL, barren lands→desert steppe |
| Arhangay | NDL→desert steppe | desert steppe→NDL, NDL→desert steppe |
| Bayanhongor | NDL→desert steppe, desert steppe→barren lands | barren lands→desert steppe, NDL→desert steppe |
| Bulgan | NDL→desert steppe, desert steppe→NDL | desert steppe→NDL |
| Ovorhangay | desert steppe→barren lands, NDL→desert steppe | barren lands→desert steppe, NDL→desert steppe |
| Omnogovi | desert steppe→barren lands, barren lands→desert | not change significantly |
| Selenge | not change significantly | NDL→desert steppe |
| Orhon | not change significantly | not change significantly |
| Darhan | not change significantly | NDL→desert steppe |
| Tov | NDL→desert steppe | NDL→desert steppe |
| Ulaanbaatar | not change significantly | NDL→desert steppe |
| Dundgovi | desert steppe→barren lands, NDL→desert steppe | barren lands→desert steppe, desert steppe→barren lands |
| Govisumber | desert steppe→barren lands, barren lands→desert steppe | barren lands→desert steppe |
| Hentiy | NDL→desert steppe, desert steppe→NDL | NDL→desert steppe, barren lands→desert steppe |
| Dornogovi | desert steppe→barren lands, barren lands→desert steppe | barren lands→desert steppe, desert steppe→barren lands |
| Dornod | desert steppe→NDL, NDL→desert steppe | desert steppe→NDL, NDL→desert steppe |
| Suhbaatar | NDL→desert steppe, desert steppe→NDL | desert steppe→NDL, barren lands→desert steppe |