Vegetation growth variation in relation to topography in Horqin Sandy Land

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1. Introduction

Desertification signifies land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities (UNCCD, 2004). Desertification devastates land resources, diminishes ecosystem productivity, reduces ecological functions, and is deemed as a serious environmental problem in many arid, semi-arid, and dry sub-humid regions (Duan et al., 2014; Zhao et al., 2014). China is one of the countries that are susceptible to desertification. By 2014, predominantly in north and northwest China, the area of desertification covered 27.2% or 261,160 km², involving 18 provinces and 528 counties (State Forestry Administration, 2015). Desertification has caused direct economic loss of tens of billions RMB annually (Lu and Wu, 2002; Ge et al., 2016), and is also an essential obstacle to ecological safety and local socio-economic development, especially in northern China (Yang et al., 2005; Zhang et al., 2012; Qi et al., 2012; Wang et al., 2013).

Horqin Sandy Land, one of the four largest sandy lands, and belonging to an ecologically fragile region, agro-pastoral transitional, and semi-arid zone, is located in north China. Historically, the Horqin region was covered in grassland. However, population and food pressure has increased gradually since the 1950s (the “food for the program” policy was applied to settle pressure), leading to a major loss of grassland area (Song and Zhang, 2006). Anthropogenic activities were the primary causes of sandy desertification, including excessive reclamation, overgrazing, and extensive deforestation (Sui and Yuan, 2007; Wang et al., 2008; Lautenbach et al., 2011). Ground vegetation cover and topsoil loss have occurred through cultivation, livestock grazing and trampling (Pei et al., 2008; Verón et al., 2011; Kairis et al., 2013). Consequently, vegetation cover gradually decreased and soil was increasingly exposed to wind erosion, resulting in the sandy desertification area increasing from 42,300 km² in 1959 to 61,008 km² in 1987 (Wu, 2003).

To effectively manage sandy desertification, governments launched ecological restoration strategies, including the Three-North Shelterbelt Project (1978–present), the Grain for Green Project (1999–present), and the Beijing and Tianjin Sandstorm Source Treatment Project (2001–2010) (Li et al., 2017). Grazing exclusion was also employed by local governments, to prevent livestock from heavily grazing grassland (Miao et al., 2015). Previous studies confirmed that grazing exclusion...
was effective in restoring natural vegetation, increasing soil nutrient availability, and improving biodiversity and ecosystem services (Li et al., 2012; Wu et al., 2014; Tang et al., 2016). The expansion of sandy desertification was gradually controlled in a governing context and the desertification area reduced to 32, 633 km² in 2015 from 52, 894 km² in 2000 (Duan et al., 2019). Vegetation was crucial for maintaining the ecological system security and services in ecologically fragile areas (Li et al., 2013). However, the Horqin Sandy Land is characterized by sand dunes alternating with interdune lowland (Liu et al., 2016) and environmental conditions, such as soil water content, nutrients, and particles, appear to be regulated by topography, which affects vegetation growth and distribution (Zuo et al., 2008). Thus, analyzing vegetation growth at different topographic positions is essential for rational land utilization, sustainable development, and optimized pattern.

There have been some studies on the relationship between topography and vegetation (Zhao et al., 2011; Gantsetseg et al., 2017; Svoray and Karnieli (2011) explored the temporal and spatial relationships between topography and aboveground net primary production of annuals in a semi-arid area. Wei et al. (2019) investigated the response of soil water content and aboveground biomass of grassland vegetation to precipitation and topography through field investigation. Zhou et al. (2019) analyzed vegetation growth at different topographic positions in Horqin zuoyihou Banner using derived land surface temperature (LST). Miyasaka et al. (2014) assessed the effects of different restoration measures and sand dune topography on vegetation restoration in the Horqin Sandy Land.

Vegetation index, derived from satellite images, has attracted more attention due to the advantage of time-saving and efficient. As a common vegetation index, NDVI can represent terrestrial vegetation growth (Zhang et al., 2013), because it is closely related to photosynthetically active radiation (Myneni et al., 1997). In previous studies, NDVI was widely used in crop area estimation (King et al., 2017; Song et al., 2017), crop mapping (Chen et al., 2018; Araujo Picoli et al., 2018), yield forecasting (Lai et al., 2018; Petersen, 2018), and vegetation monitoring (Li et al., 2017; Gao et al., 2017). Nevertheless, NDVI is susceptible to the soil background at low vegetation coverage and easy to saturate at high vegetation coverage (Huete et al., 1997; Nicholson and Farrar, 1994). This study, therefore, uses an improved vegetation index, GRNDVI (Zhao et al., 2011), to characterize the vegetation growth in Horqin area more accurately, and explores the changes in vegetation growth along topography and related factors.

Therefore, the main aims of this study were to: 1) analyze cropland and grassland growth at different topographic positions by calculating GRNDVI; 2) derive the soil wetness at different topographic positions; and 3) propose some methods to optimize the land use pattern based on vegetation growth and soil wetness to promote ecological balance and sustainable development.

2. Materials and methods

2.1. Study area

As one of the four largest sandy lands in China, Horqin Sandy Land is located in the east of Inner Mongolia and northeast of China. It lies between 117°49' to 123°42'E and 41°41' to 46°05'N, is composed of 15 counties and covers an area of 12.51 × 10⁶ km² (Fig. 1). The study area is characterized by a typical semi-arid continental monsoon climate. The winter is cold and windy, summer is warm and rainy. The annual average temperature ranges from 3 to 7°C. The annual average precipitation ranges from 300 to 500 mm, and is mainly concentrated in summer, while the annual average evaporation varies between 1500 and 2500 mm. The altitude ranges from 24 to 2043 m, and decreases gradually from west to east. Aeolian sandy soil dominates this area, while other soil types include meadow, alkaline, and marsh. Three dune types alternate between fixed dune, semi-fixed dune, and shifting dune. Spring maize is the dominant crop in this area. Cropland and grassland are dominant land cover types in this area, accounting for 78.53% of the total area. The area of bareland is around half that of cropland, accounting for 14.47%. The area of other types, including wetland, water, forest, and impervious surface, is finite, accounting for merely 6.88% in total (Table 1).

2.2. Data set

Land cover data were collected from FROM-GLC10 (http://data.ess.tsinghua.edu.cn), which was based on 10-m Sentinel-2 data acquired in 2017 (Fig. 1). Several land cover types, including cropland, forest, grassland, shrubland, wetland, water, impervious surface and bare land were classified, and the overall accuracy was 72.76% (Gong et al., 2019). ASTER GDEM V002 was chosen to calculate a topography index, which is freely available at the spatial resolution of 30 m. Seven Landsat8 Operational Land Imager (OLI) images (L1T) from the 2017 summer were collected to calculate the vegetation index. These data were acquired from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) (http://earthexplorer.usgs.gov/). The cloudiness of Landsat8 OLI images on the left part of the study area was high, which were inappropriate for this study. HJ-1 CCD images, therefore, with higher time resolution were selected. Additional 3 HJ-1 CCD images were downloaded from the China Center for Resource Satellite Data and Applications (CRESDA). HJ-1 satellite constellation comprises HJ-1A, HJ-1B, and HJ-1C. HJ-1A and HJ-1B are optical satellites and equipped with two CCD cameras. The temporal resolution can reach 2-days. The CCD data include four multispectral bands at 30 m spatial resolution (blue: 430–520 nm, green: 520–660 nm, red: 630–690 nm, near-infrared: 760–900 nm) (CCFRSDA, 2014). A total of ten images were chosen for this study, and are summarized in Table 2. A quadrot survey was conducted in Horqin zuoyihou Banner in July 2016 and July 2017. The topography is characterized by sand dunes alternating with undulating lowland areas in this Banner. Three dune types alternate between fixed dune, semi-fixed dune, and shifting dune. Sand plants, including herbaceous species and shrub species, were also distributed extensively. Five 1 × 1 m quadrats were selected randomly at five different slope positions to investigate the species, coverage, and height of herbaceous plants. For shrubs, three 5 × 5 m quadrats were correspondingly chosen. A handheld global positioning system (GPS) was used to record geographical locations and elevations of quadrats.

2.3. Methods

2.3.1. Image preprocessing

The preprocessing of images included radiometric calibration, atmospheric correction, mosaic, geometric registration, and GRNDVI calculation. Radiometric calibration was applied to convert the digital number (DN) to the TOA according to the Eq. (1):

$$ L = DN / g + L_0 $$

where $L$ represents the top of atmosphere radiance, $DN$ is the digital number, and $g$ and $L_0$ represent the gains and offsets, respectively.

Gains and offsets were provided in the metadata files of images. Spectral response functions for HJ-1 CCD sensors, downloaded from the China Center for Resource Satellite Data and Applications (CRESDA), were used to generate Spectral respond curves. The FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercube) module (Cooley et al., 2002) was employed to convert the top of atmosphere radiance into surface reflectance. Landsat images were mosaicked by the Seamless Mosaic tool in ENVI 5.3. For HJ-1 CCD images, automatic registration was utilized to reduce the error between adjacent images due to satellite scan time difference, with root mean square error (RMSE) controlled within 1 pixel. After automatic registration, three HJ-1 CCD images were mosaicked. Landsat 8-OLI (L1T) products have been ortho-rectified utilizing ground control points (GCP) and a digital elevation
Therefore, mosaicked Landsat 8 images were used as base images to warp the mosaicked HJ-1 CCD images, while the RMSE was less than 1 pixel. Considering the band differences of Landsat 8 and HJ-1 CCD images, we calculated corresponding GRNDVI separately firstly, a vegetation index, based on these 2 types of images. Then, the result of GRNDVI originating from different satellite images was mosaicked. GRNDVI of Horqin Sandy Land was extracted by subset with vector boundary (Fig. 2).

2.3.2. Topography index (TI)

The focal statistics tool in ArcGIS was utilized to calculate the topography index based on the DEM, which was developed to reflect the relative topography in the study area. The mathematical expression of the topography index can be defined as:

\[ TI = \frac{E - E_{\text{mean}}}{\text{mean elevation difference}} \]

where TI is the Topography index (m), E is the elevation of a pixel (m), and \( E_{\text{mean}} \) is the mean elevation difference.
and $E_{\text{mean}}$ is the average elevation of the pixels in the neighborhood (m). In the field surveys, the distances between topography positions (from the bottom of the slope to the top of the slope) of multiple dunes were observed to select an appropriate threshold. A rectangle with a width and height of 20 pixels (600 m × 600 m) was selected as the neighborhood type. When TI less than 0, it means the elevation of the pixel is lower than the surrounding pixels and vice versa.

### 2.3.3. GRNDVI

GRNDVI, the vegetation index used in this study, was developed and improved based on NDVI. The formula of NDVI can be transformed into Eq. (3), which indicates NDVI is related to $\rho_{\text{NIR}}/\rho_{\text{RED}}$. In fact, $\rho_{\text{NIR}}/\rho_{\text{RED}}$ was simple ratio vegetation index (SR). Baret and Guyot (1991) analyzed the relationship between SR, NDVI, and LAI in detail. When the LAI is small, $\rho_{\text{NIR}}$ is higher and $\rho_{\text{RED}}$ lower, and a small change in $\rho_{\text{NIR}}$ has a greater effect on NDVI than SR. In contrast, under higher LAI, $\rho_{\text{NIR}}$ is higher and $\rho_{\text{RED}}$ lower, and a small change in $\rho_{\text{NIR}}$ produces a larger effect on SR than NDVI. To balance the change between SR and NDVI and increase their correlation with LAI, NDVI*SR was proposed by Gong et al. (2003) (Eq. (4)). The formula of NDVI*SR, however, enhanced the effect on NDVI rather than SR. To improve this change, Zhao et al. (2011) squared the NDVI*SR and added 1 to NDVI to ensure results were positive. Thus, GRNDVI was generated and performed better than NDVI in both low and high vegetation cover. The formula was shown in Eq. (5).

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}}$$

$$\text{NDVI} \times \text{SR} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \times \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} + 1$$

$$\text{GRNDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{RED}}} \times \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} + 1$$

where GRNDVI is the growth root normalized difference vegetation index; SR is simple ratio vegetation index; and $\rho_{\text{NIR}}$ and $\rho_{\text{RED}}$ are the reflectance in the electromagnetic spectrum at near-infrared band and red band, respectively.

### 2.3.4. Tasseled cap wetness

To understand plant growth patterns in spectral space, which belongs to the orthogonal transformation, the tasseled cap transformation (TCT) was proposed by Kauth and Thomas (1976). Three components were generated from the TCT: Brightness, Greenness, and Wetness. The Brightness component is related to bare or partially covered soil, natural and man-made features, and varies in topography. The Greenness component measures the contrast between the visible bands and near-infrared band, which is the axis perpendicular to Brightness. The Wetness component is orthogonal to the Brightness and Greenness component and is related to soil moisture, water, and other moisture features (Crist and Cicone, 1984; Crist and Kauth, 1986; Liu and Liu, 2009). Among the three components, Tasseled Cap Wetness has been used to assess changes in vegetation and soil (Skakun et al., 2003; Schultz et al., 2016; Mostafiz and Chang, 2018; Han et al., 2019). For the Landsat 8-OLI image, the Wetness component can be calculated as the following (Baig et al., 2014):

$$\text{Wetness} = 0.1511 \times b_2 + 0.1973 \times b_3 + 0.3283 \times b_4 + 0.3407 \times b_5 + 0.7117 \times b_6 - 0.4559 \times b_7$$

where $b_2$ to $b_7$ are the corresponding bands of the Landsat 8 image.

### 3. Results

#### 3.1. Spatial distribution of GRNDVI

Vegetation index measures can indicate the regional vegetation growth spatially. GRNDVI of cropland and grassland was calculated and Fig. 3a shows clearly the spatial distribution of GRNDVI of cropland in Horqin Sandy Land in the summer of 2017. GRNDVI in the east was higher than in the west, especially in the southeast, including Horqin district, Kailu County, Horqin Zuoyizhong Banner, east of Horqin zuoyihuou Banner, and north of Naiman Banner. Cropland with higher GRNDVI values was also distributed in a strip rather than a sheet shape. Crop growth was relatively poor in the Hure, Aohan, Ongniudr, Bairin you, Bairin zuo, and west of Ar Horqin Banners where GRNDVI values were less than 2.42.

The spatial distribution of GRNDVI of grassland in the summer of 2017 is shown in Fig. 3b. Grassland growth in the north was better than other areas, especially in Jarud, Ar horqin, horqin youyizhong, and Bairin zuo Banners where the GRNDVI values were more than 2.72.
Meanwhile, GRNDVI values of the south were less than 1.96 mainly, including Aohan, Bairin you, Ongniud, and Hure Banners.

3.2. Topography index distribution

The spatial distribution of the Topography Index (TI) is shown in Fig. 4. Five groups were classified by using the natural breaks classification method, which aimed to reduce each class average deviation from the class mean and maximize every class deviation from the means of the other groups (Jenks, 1967; Aretano et al., 2015). TIs were mainly distributed at \([-3.59, 2.68)\) m over 47% of the total area, followed by \([2.68, 14.33)\) m over 24.37%, \([-11.65, -3.59)\) m, and 20.65% respectively. TIs that less than \(-11.65\) m and greater than 14.33 m were limited, accounting for 4.35% and 3.63% respectively.

TI spatial distribution was fragmented, values less than \(-11.65\) m and greater than 14.33 m were concentrated in the northwest and southwest, while those in the range of \([-11.65, -3.59), [-3.59, 2.68), and [2.68, 14.33)\) m were distributed extensively, especially in the central and eastern areas. Six TI samples were extracted to show more spatial detail. Samples, including a, b, and c (Fig. 4(a)-(c)), were extracted from the west and south of the study area, and contained 5 particular TI groups spatially distributed in strips. Meanwhile, samples including d, e, and f (Fig. 4(d)-(f)) extracted from the east of the study area, generally contained TIs in the range of \([-11.65, -3.59), [-3.59, 2.68), and [2.68, 14.33)\) m, predominantly distributed in a patch shape.

3.3. GRNDVI changes with topography index

The overlay analysis tool in ArcGIS was employed to understand the relationship between GRNDVI and the Topography index. Fig. 5 illustrates cropland GRNDVI changes with increasing TI. Cropland GRNDVI increased a little initially and then decreased continuously. When TI was \(-124.53\) to \(-11.65\) m, GRNDVI of cropland was 2.97 but when TI increased to \(-11.65\) to \(-3.59\) m, corresponding GRNDVI increased to 2.98. GRNDVI of cropland decreased to 2.96, however, when TI was distributed at \(-3.59\) to 2.68 m. Next, GRNDVI of cropland continued to decrease to 2.94 and 2.74 with TI increasing further. Therefore, cropland growth was highest when TI was distributed at \(-11.65\) to \(-3.59\) m and lowest at 14.33 to 103.91 m.

Grassland GRNDVI initially decreased and then increased. When TI was \(-124.53\) to \(-11.65\) m, GRNDVI of grassland was 2.22, but when TI was \([-11.65, -3.59)\) and \([-3.59, 2.68)\) m, corresponding GRNDVI were 2.07 and 1.97, respectively. However, grassland GRNDVI increased to 1.99, when TI was 2.68 to 14.33 m, and increased further to 2.03 when TI was 14.33 to 103.91 m. Therefore, grassland growth was highest when TI was distributed at \(-124.53\) to \(-11.65\) m and lowest at \(-3.59\) to 2.68 m.
4. Discussion

4.1. Spatial distribution of cropland and grassland GRNDVI

Horqin sandy land is a typical agro-pastoral transition zone, with a semi-arid climate typified by limited and highly variable annual precipitation. Water availability has a critical effect on cropland, which tends to have better growth when water is readily available. Fig. 7 shows the spatial distribution of DEM and rivers in Horqin Sandy Land, which reflects declining altitude from west to east. The topography of the east was lower and flatter than the west, which is more convenient for the development of agriculture, which is why the east has more cropland than the west. There are several rivers flowing from the west to east, including the Liao, Jiaolai, Xinkai, and Hong rivers, which provide convenient irrigation water for agriculture. Therefore, cropland adjacent to rivers has higher GRNDVI than away from rivers, and is the main reason for the distinct spatial distribution of cropland GRNDVI.

For grassland, precipitation and temperature may have more effect. Firstly, annual precipitation decreases gradually from the southeast to northwest owing to the monsoon. The topography of west, however, is mountains with high altitude. Thus, more precipitation is generated on windward slopes where water vapor is hindered by mountains. Therefore, annual precipitation initially decreases and then increases from southeast to northwest (Fig. 8). Precipitation in the north is higher than in the central area, and is also a basic source of supply for rivers in the north. Therefore, water resources are readily available for grassland in the north. Second, the altitude range of this area is 2019 m which reflects a temperature difference of about 12°C, since temperature decreases by 0.6°C per 100 m rise in altitude. Therefore, temperature in the north is lower than in the south. Thus, the north is certainly more humid than the south and provides good natural conditions for grass growth, which may explain why the grasslands in the north have higher GRNDVI.

4.2. Cropland growth variation with topography index

Tasseled cap wetness was calculated to analyze soil moisture distribution in different TIs. HJ-1 CCD, on the left side of the study area, couldn’t calculate the wetness with 4 bands. Landsat 8-OLI images, therefore, were employed to calculate wetness, which accounted for 71.82% of the total area after removing areas heavily affected by cloud (Fig. 9). Fig. 10 shows cropland mean wetness changes in different TIs. Cropland mean wetness initially increased slightly and then decreased continuously. When TI was $-124.53$ to $-11.65$ m, cropland mean wetness was $-0.0163$, but when TI increased to $-11.65$ to $-3.59$ m, it increased to $-0.0136$. Cropland mean wetness declined to $-0.0142$,
however, when TI was $-3.59$ to $2.68$ m. Finally, cropland mean wetness continued to decrease to $-0.0164$ and $-0.0294$ when TI increased further.

Tasseled cap wetness changes indicated variable soil moisture content along TIs to some extent. Soil moisture increased initially and then decreased with increasing TIs, indicating that it was affected by topography. Soil moisture was highest when TIs was between $-11.65$ and $-3.59$ m, followed by $[-3.59, 2.68]$, $[2.68, 14.33]$, and $[-124.53, -11.65]$ m, while the lowest when TIs were $14.33$ to $103.91$ m. For the Horqin Sandy Land, the dominant sandy soil, with a coarse texture and loose structure, has a poor water-holding capacity. It is challenging to generate surface runoff when it rains due to rapid leakage. Soil tends to be wet in low-lying areas with a readily accessible underground water table while drier in higher terrain with limit water supply. Soil water content decreases with increasing topography, which is consistent with Wei et al. (2019). Furthermore, water will be redistributed by changes in topography (Qiu et al., 2001; Schoorl et al., 2002). As a result, croplands on different topographies have distinctly different available water supplies, and therefore crop growth is different, resulting in differences in GRDNVI distribution. However, places where the terrain is too low can be waterlogged, and those that are too high may suffer water shortages and drought.

### 4.3. Grassland growth variation with topography index

Fig. 11 illustrates the grassland mean wetness changes in different TIs. Mean grassland wetness decreased continuously with increasing TI, which is distinct from the cropland mean wetness changes. When TI was $-124.53$ to $-11.65$ m, grassland mean wetness was $-0.064$, but when TI was between $-11.65$ and $-3.59$ m, it decreased to $-0.073$. Mean wetness of grassland was $-0.079$, $-0.084$ and $-0.097$ when TIs were $[-3.59, 2.68]$, $[2.68, 14.33]$, and $[14.33, 103.91]$ m.

Grassland mean wetness changes indicate that grassland soil moisture decreased with increasing TIs. Changes in vegetation types, indicate this declining trend. According to the field survey, the main herbaceous species include *Juncus effusus*, *Eriochloa villosa*, *Thalictrum*, *Suaeda*, *miscanthus sacchariflorus*, and *Artemisia halodendron*. The Main shrub species include *Caragana microphylla*, *Lespedeza juncea*, and *Gueldensstaedtia stenophylla*. There are differences in the distribution of herbaceous and shrub species according to slope position (Fig. 12). Mean coverage of herbaceous species decreased gradually from flat to

### Table 3

Mean coverage and mean height of herb and shrub species at different slope positions.

<table>
<thead>
<tr>
<th>Slope position</th>
<th>Herbaceous species</th>
<th>Shrub species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage (%)</td>
<td>Height(cm)</td>
<td>Coverage (%)</td>
</tr>
<tr>
<td>Hilltop</td>
<td>31.24</td>
<td>18.60</td>
</tr>
<tr>
<td>Upper slope</td>
<td>59.52</td>
<td>23.51</td>
</tr>
<tr>
<td>Mid slope</td>
<td>70.46</td>
<td>26.50</td>
</tr>
<tr>
<td>Lower slope</td>
<td>61.83</td>
<td>30.62</td>
</tr>
<tr>
<td>Flat</td>
<td>94.52</td>
<td>23.65</td>
</tr>
</tbody>
</table>

Fig. 12. Photographs of herb and shrub species at different slope positions.
hilltop (Table 3), and mean height increased slightly at first and then declined. Mean coverage of shrub species was lower than herbaceous species overall, however, mean coverage and height of shrub species, increased slowly from flat to hilltop. This pattern indicates that her-
aceous species are the dominant species while shrub species are sub-
ordinate. Herbaceous species are more common at low TIs, while shrub species tended to be more distributed at higher TIs. Soil water declined with increasing TIs, however, shrub species, including *Caragana microphylla*, are more drought tolerant than herbaceous plants due to their strong root systems that could access water even in deeper soil (Zhou et al., 2013; Xu et al., 1998) and therefore, could also survive in windy and sandy environments (Cao et al., 2008). Shrub growth was also in-
directly affected by topographic position. Shrubs growing at higher topographic positions had higher photosynthetic activity, longer shoots, bigger leaves, and more biomass, with richer soil phosphorus avail-
ability and lower herbaceous aboveground biomass (Zhao et al., 2011).

The development of shrubs could also improve soil physical and chem-
ical properties significantly and facilitate the enrichment of herbac-
eous species with the “islands of fertility” (Yang et al., 2011; Zhao et al.,
2007). GRNDVI of grassland declined initially and then increased, in
agreement with Zhou et al. (2019). However, GRNDVI changes were
also influenced by the distributional differences of plants whose posi-
tions were not only determined by soil water availability.

4.4. Land use suggestions

The terrain in Horqin Sandy Land is obviously highly variable. Therefore, it’s important to optimize land utilization based on the
natural condition at different topographic positions to promote sus-
tainable development. The schematic diagram in Fig. 13 shows 4 to-
pographic positions/classes. Class a is located in the lowest dunes, with
optimal moisture conditions, and those also likely to have water ac-
cumulation. This situation is more suitable for a wetland rather than
cropland, which could provide good habitat for some aquatic organisms and also protect biodiversity. Class b has relatively flat terrain and good
moisture conditions, which is most appropriate for agricultural food
production. Farmland infrastructures should be constructed and pro-
tected effectively here. Class c has inferior moisture conditions and
terrain, which is not convenient for agricultural management but could
be developed into grassland. Firstly, it would be suitable for growing
the main herbaceous plants to improve the ecological environment, and
secondly, it could be used to grow appropriate sandy pastures for local
livestock. For class d, where soil moisture was poor and terrain is
higher, crops would struggle, especially in the absence of ample pre-
cipitation. These sites should be planted with drought-tolerant shrub
species and well protected to prevent land degradation.

5. Conclusion

This paper evaluated the effect of topography on cropland and
grassland growth in Horqin Sandy Land. GRNDVI of vegetation and
topography index were calculated, and spatial distribution of GRNDVI
along a topography index was analyzed. GRNDVI was clearly influ-
enced by topography, cropland growth initially increased and then
decreased with increasing topography index, which was caused mainly
by soil moisture difference on different terrains. Soil moisture initially
increased and then decreased with a decreasing supply of underground
water. Grassland growth decreased initially and then increased with
increasing topography index and was caused by differences in soil
moisture and plant species. Soil moisture decreased continuously with
increasing topography index. Coverage and growth of herbaceous spe-
cies were better in lower terrains while shrub species was better in high
terrains. Different optimal land uses were proposed based on water
availability and topographic conditions. In the lowest areas, wetlands
could be developed to promote natural habitat for aquatic plants and
animals. In low areas, water facilities could be constructed and crops
planted to supply food. In the middle area, grassland should be utilized
to provide some pastures. In the upper and highest areas, drought toler-
ant shrubs should be planted to stabilize slopes and enhance native
biodiversity and ecological integrity. The findings of this paper could be
used to optimize functional land utilization and promote sustainable
development. We used wetness to represent the soil moisture distribu-
tion trend, but more field surveys may further refine the soil moisture
gradient.

CRediT authorship contribution statement

Jiaqi Fan: Formal analysis, Software, Data curation, Writing - original
draft, Writing - review & editing. Yan Xu: Conceptualization, Project
administration, Funding acquisition, Writing - original draft, Writing - review & editing. Haoyuan Ge: Supervision, Validation, Visualization. Wei Yang: Investigation, Methodology, Resources.

Declaration of Competing Interest

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

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