Desertification and carbon emission in the headwater area of the Yellow River using remote sensing

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Abstract This study deals with desertification and its impacts on the environment in the headwater area of the Yellow River, China. Our objectives were to quantitatively detect desertification processes from 1990 to 2000 using remote sensing, and to evaluate its impacts on carbon emission. The results indicate that the study area is one of the most desertified regions in the Tibetan Plateau and the desertification qualifies the region as a vital source of carbon emission. The desertification might have contributed a disproportionate share to overall CO\(_2\) emission from the grasslands of the Tibetan Plateau, implying that there is great potential to resequestrate carbon through controlling overgrazing and restoring the ecosystem.

Key words carbon emission; desertification; the headwater area of the Yellow River; remote sensing

INTRODUCTION

Many studies have shown that severe environment issues have been occurring in the Yellow River basin since the 1970s. Among the environmental issues, land degradation-related water shortage and soil erosion are the major ones that have a direct impact on socioeconomic sustainable development, not only in the headwater area of the Yellow River, but also in the entire Yellow River basin. These issues have recently caught the attention of the Chinese government and relevant scientific communities. Considering the special climatic and ecologic significance and the important role in global climatic systems of the Tibetan Plateau, studies of land degradation and its impacts on the environment have important scientific and practical implications in assessing the response of the plateau to global changes and its feedback effect. Although high rates of grassland degradation in the headwater area of the Yellow River have been documented, there have been few studies that focus on relevant desertification processes over time, although such information is essential to plan ecological restoration and to assess carbon exchange of terrestrial ecosystems in the Tibetan Plateau.

This study specifically deals with desertification and its impacts on the environment in the headwater area of the Yellow River. The objectives were to quantitatively detect desertification processes from 1990 to 2000 using remote sensing and to
evaluate the impacts on the carbon cycle in the context of global terrestrial ecosystems. It is also hoped that this evaluation can help to realize soil carbon storage potential through desertification control and ecological restoration.

STUDY AREA

The headwater area of the Yellow River, located in the northeastern Tibetan Plateau, is extensive grassland. It is a typical area in the Tibetan Plateau where grassland degradation has been a widespread phenomenon. The study area (33°42'-35°20'N, 95°52'-99°29'E) is about 37 000 km² (Fig. 1) and ecologically lies in the transitional zone between alpine meadow and alpine grassland, including alpine meadow, marshy meadow, alpine steppe, and alpine cushion vegetation. The climate is characterized by low, highly variable temperature and rainfall, high speed winds and frequency, and high evaporation losses. The mean summer temperature is below -4°C and the mean annual precipitation is about 312 mm. The dominant soils, textured sandy soils, are generally low in inherent fertility status with poor water holding capacity.

METHODOLOGIES

The employed methodology is separated in four distinct processing steps: Geometric and radiometric pre-processing of remotely sensed data ensures the necessary accuracy
for detecting desertification in a quantitative way. Data analysis by means of desertification index opens the pathway to derive desertification severities. Time series analysis is employed to derive spatio-temporal patterns of desertification changes. Finally, soil carbon emission is quantified throughout the study area by applying the field-measured soil organic data into remote sensing-obtained severities of desertification.

Pre-processing

In this study, the Landsat Thematic Mapper (TM) data for July 1990 and Landsat Enhanced Thematic Mapper Plus (ETM+) data for July 2000 under good atmospheric conditions were obtained. The radiometric correction and atmospheric correction were applied to visible and near-infrared channels by using PCI image processing software that is based on “a fast atmospheric correction algorithm” (Richter, 1990). After the correction the original radiance images were transformed into the reflectance images. All images were registered on a referenced map of the area through second order transformation and nearest neighbour re-sampling method. After the pre-processing of images, the widely used spectral indices—such as Normalized Difference Vegetation Index (NDVI)—is calculated as NDVI = \( (p_3 - p_4)/(p_3 + p_4) \), where \( p_3 \) and \( p_4 \) represent the Landsat TM/ETM+ band 3 and 4 surface reflectivities, respectively. Finally, the land surface albedo, ratio of land surface upwelling radiation flux to the solar radiation downward flux, was computed using an algorithm developed by Liang (2000).

Desertification indexing

The usefulness of integrating biological and physical variables derived from satellite data, such as Normalized Difference Vegetation Index (NDVI) and land surface temperature \( (T_s) \), for studying ecological systems was discussed in several studies. Lambin & Ehrlich (1995, 1996, 1997) used Advanced Very High Resolution Radiometer (AVHRR) data and combined the derived \( T_s \) and NDVI data into a unique variable for differentiating biomes and analysing land cover changes on a continental scale (Lambin & Ehrlich, 1995, 1996, 1997). Through repeated experiments we found that albedo-NDVI space can be more easily constructed and has the same biophysical properties as \( T_s \)-NDVI space. Thus, we combined the land surface albedo and vegetation index (NDVI) data to form an albedo-NDVI space or variable as an index for identifying severity of desertification. Based on our experiment, the desertification index \( (DDI) \) is defined as follows:

\[
DDI = 1.3437 \text{NDVI} - \text{albedo}
\]

The value of desertification index \( (DDI) \) can be used to indicate desertification severity. In order to identify the desertification severities using \( DDI \), we firstly defined four different categories of desertification severity: very severe, severe, moderate and mild. We then applied remote sensing derived vegetation index (NDVI) and land surface albedo data to equation (1), and calculated the desertification index \( (DDI) \) of the study area on a pixel scale. Thirdly, based on field investigation, we established a
corresponding relationship between severities of desertification and the desertification index (DDI): (a) low values desertification index (23–33) suggesting that desertification is very severe; (b) middle values of desertification index (34–42) indicating that desertification is severe; (c) high values of desertification index (43–50) implying that desertification is moderate; and (d) very high values of desertification index (51–63) indicating that desertification is mild. Finally, we identified severities of desertification and detected changes over time in the headwater area of the Yellow River using remote sensing derived desertification index (DDI).

Calculation of soil carbon emission

The soil carbon emission of different types of desertified lands can be calculated by the following formula:

\[ C_i = 0.58O_i W_i H_i S_i \]  

where \( i \) is the type of desertified land, \( C \) the soil carbon emission of the desertified land, 0.58 Bemmlen Index, \( O \) mean organic matter content in the soil under the specified desertified land, \( W \) the soil bulk density, \( H \) the mean soil analytical thickness, and \( S \) change in the area of the specified desertified land. Here we use 0.2 m as topsoil thickness.

Through fieldwork and analysis of soil samples, we obtained the data of organic matter contents, and bulk density of soils in different desertified lands (Table 1). With these data, remote sensing-detected results of desertification changes in study area, and the calculations based on equation (2), carbon emission in the topsoil (0.2 m thick) was calculated.

RESULTS AND DISCUSSION

Spatial distribution of desertification

The spatial distribution of desertified land is showed in Figs 2, 3. The desertified lands are mainly distributed in the river valley and around the lakes. The area of total desertified lands is 3519.97 km\(^2\), accounting for 9.4% of the total study area. To define the severity of desertification, we classified desertified lands into four different categories: very severely desertified; severely desertified; moderately desertified; and mildly desertified. The very severely desertified lands refer to the lands where the desertification

<table>
<thead>
<tr>
<th>Desertified land</th>
<th>Organic matter of content (%)</th>
<th>Mean bulk density (g cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No desertified</td>
<td>5.24</td>
<td>1.294</td>
</tr>
<tr>
<td>Mild</td>
<td>4.98</td>
<td>1.275</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.97</td>
<td>1.447</td>
</tr>
<tr>
<td>Severe</td>
<td>0.65</td>
<td>1.497</td>
</tr>
<tr>
<td>Very severe</td>
<td>0.23</td>
<td>1.485</td>
</tr>
</tbody>
</table>
reaches its climax stage. The severely desertified lands are the land where the desertification is approaching its climax stage. The rapidly-deteriorating grasslands are
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defined as the moderately desertified lands that can be easily detected by satellite remote sensing technology. The mildly desertified lands are in the early stage of desertification. Our results show that very severely, severely, moderately, and mildly desertified lands account for 14.2%, 13.8%, 26.2% and 45.8% of total desertified lands, respectively (Table 2).

Changes in desertification

The desertification changes during the period 1990–2000 are shown in Table 2, where change is the differences of desertified lands between 2000 and 1990, rate of expanding the ratio of change and desertified land in 1990 at a given desertification severity, and annual rate the ratio of rate of expanding and time interval from 1990 to 2000.

In one decade, 1990–2000, the desertified area has increased by about 755.36 km² at an annual rate of 2.7% (Table 2). Since the 1990s, the regional desertification has been intensifying in the study area, although desertification has reversed locally in certain areas. Comparing with the published data for the entire Tibetan Plateau, the headwater area of the Yellow River is apparently one of the most desertified regions in the Tibetan Plateau.

Soil carbon emission

Using soil organic data and remote sensing-detected results of desertification in the study area, carbon emission was spatially quantified throughout the study area. The

<table>
<thead>
<tr>
<th>Severity of desertification</th>
<th>1990</th>
<th>2000</th>
<th>Change</th>
<th>Rate of expanding (%)</th>
<th>Annual rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very severe</td>
<td>429.11</td>
<td>499.10</td>
<td>69.99</td>
<td>16.31</td>
<td>1.63</td>
</tr>
<tr>
<td>Severe</td>
<td>360.00</td>
<td>486.10</td>
<td>126.10</td>
<td>35.03</td>
<td>3.50</td>
</tr>
<tr>
<td>Moderate</td>
<td>633.61</td>
<td>922.07</td>
<td>288.46</td>
<td>45.53</td>
<td>4.55</td>
</tr>
<tr>
<td>Mild</td>
<td>1341.89</td>
<td>1612.70</td>
<td>270.81</td>
<td>20.18</td>
<td>2.02</td>
</tr>
<tr>
<td>Total</td>
<td>2764.61</td>
<td>3519.97</td>
<td>755.36</td>
<td>27.32</td>
<td>2.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expanding of desertification</th>
<th>Area of Change (km²)</th>
<th>Carbon emission(10⁶ t C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe→very severe desertified land</td>
<td>90.4381</td>
<td>0.066291</td>
</tr>
<tr>
<td>Moderate→very severe desertified land</td>
<td>52.6203</td>
<td>0.153178</td>
</tr>
<tr>
<td>Mild→very severe desertified land</td>
<td>26.2854</td>
<td>0.183183</td>
</tr>
<tr>
<td>No desertified→very severe desertified land</td>
<td>14.4054</td>
<td>0.107594</td>
</tr>
<tr>
<td>Moderate→severe desertified land</td>
<td>156.8925</td>
<td>0.341712</td>
</tr>
<tr>
<td>Mild→severe desertified land</td>
<td>106.8696</td>
<td>0.666439</td>
</tr>
<tr>
<td>No desertified→severe desertified land</td>
<td>18.0729</td>
<td>0.121739</td>
</tr>
<tr>
<td>Mild→moderate desertified land</td>
<td>400.2201</td>
<td>1.624093</td>
</tr>
<tr>
<td>No desertified→moderate desertified land</td>
<td>118.4544</td>
<td>0.539915</td>
</tr>
<tr>
<td>No desertified→mild desertified land</td>
<td>621.4356</td>
<td>0.310718</td>
</tr>
<tr>
<td>Total</td>
<td>4.114862</td>
<td></td>
</tr>
</tbody>
</table>
carbon emission from topsoil as a result of desertification was estimated to be 4 110 000 t C (ton carbon) during the period from 1990 to 2000 (Table 3), the mean annual soil carbon emission flux being about 411 000 t C. According to these results, the desertification in the source region of the Yellow River might have contributed a disproportionate share to the overall CO₂ emission from grasslands of the Tibetan Plateau.

CONCLUSION

Nearly 10% of the study area was desertified from 1990 to 2000, 14.2% was very severely desertified, 13.8% was severely desertified, 26.2% was moderately desertified, and 45.8% was mildly desertified.

The total desertification-resulted carbon emission from the topsoil was estimated to be 4 110 000 t C from 1990 to 2000 and the desertification in the headwater area of the Yellow River might have contributed a disproportionate share to the overall CO₂ emission from grasslands of the Tibetan Plateau.

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REFERENCES


