Land Cover Change and its Environmental Impact in the Upper Reaches of the Yellow River, Northeast Qinghai-Tibetan Plateau

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Many studies have focused on desertification processes in northern China in an attempt to understand desertification-related ecological problems. Desertification on the Qinghai-Tibetan Plateau has received little attention, even though desertification resulting from overgrazing is a widespread phenomenon there. This study focuses on the Gonghe Basin in the upper reaches of the Yellow River, located on the northeast Qinghai-Tibetan Plateau, to shed light on desertification processes and associated environmental impacts during a 10-year period from 1987 to 1996. We first used 2 thematic mapper images to classify land cover for 2 summers (1987 and 1996) into 9 land cover types related to desertification. To assess the severity of desertification and to calculate the total soil carbon emission caused by desertification, we first defined severity by comparing land cover differences between 1987 and 1996 and then determined the differences in organic carbon content of the soil in grasslands during different stages of desertification between 1987 and 1996. The results showed that about 240 km^2 of grasslands was lost to agricultural encroachment and about 190 km^2 became sand-covered area between 1987 and 1996. During the same period, desertification affected 569.6 km^2 of grasslands, with desertification assessed as very severe for 41.8%, severe for 15.1%, and moderate for 43.1% of the area. The results also show that carbon emissions from grassland deterioration caused by desertification amounted to 2.06 $\times$ 10^6 tC during the 10-year period, the average annual emission rate being 0.206 $\times$ 10^6 tC.

Introduction

Land degradation is a widespread phenomenon, with both ecological and economic impacts that threaten sustainable development throughout the world (Dregne 1990, 1995, 2002; Schlesinger et al 1990; Dregne and Chou 1992; Zhu and Cheng 1994; Daily 1995; Dregne et al 1996; Darkoh 1998; Shen et al 2001; Le Houerou 2002). As a specific expression of land degradation, desertification in arid and semiarid areas directly affects nearly a quarter of the total land area of the world (ie, about 3.6 billion hectares) and threatens the very existence of about one sixth of the world's population (UNEP 1992). Desertification also degrades vulnerable ecosystems by altering regional hydrological cycles; this has an impact not only on socioeconomic development but also contributes to large-scale climate change (IGU 1998). Desertification has thus become a global concern not only in terms of ecological restoration, but also in terms of understanding the role it plays in global change (IGU 1998).

China is an extreme example, with severe land degradation resulting from a long history of inappropriate land management and increasing population pressure (Zhu and Liu 1981; Zhu and Cheng 1994; Li et al 2001; Shen et al 2001). Because of economic expansion and population increases in arid and semiarid China, desertification-related ecological degradation has been both so intensive and so extensive as to constitute a severe threat to regional sustainable development (Wang et al 1999b). Many studies have focused on desertification processes in northern China to understand desertification-related ecological problems (Zhu and Liu 1981; Zhu and Cheng 1994; Ci 1997; Wang et al 1998, 1999a,b). Desertification in the Qinghai-Tibetan Plateau has received little attention, even though desertification resulting from overgrazing there is widespread (Cheng 1998; Dong et al 1998; Niu 1999; Li et al 2001). The importance of understanding desertification in the Qinghai-Tibetan Plateau cannot be overemphasized, given the significance of the plateau in global climatic systems (Cheng et al 1997; Feng et al 1998; Zheng et al 2002). Equally important are the economic implications of desertification on the plateau: decreases in primary productivity resulting from desertification directly threaten the husbandry-based economy. Hence, there is a pressing need to monitor desertification processes on the plateau to assess environmental impacts and to provide a basis for sustainable economic planning.

The upper reaches of the Yellow River, located on the northeast Qinghai-Tibetan Plateau, consist of extensive grasslands of intrinsic ecological value that have long suffered from grassland degradation and desertification resulting from overgrazing (Cheng 1998; Dong et al 1998; Li et al 2000; Wang and Cheng 2000; Wang et al 2000, Zhang et al 2000). Although both intensive and extensive grassland degradation and desertification have been documented in the upper reaches of the Yellow River, few studies have focused on spatial and temporal variations in land cover and associated desertification.

The aim of this study is to detect changes in land cover and to assess its impacts on the environment in the Gonghe Basin, 1 of the main basins in the upper

FIGURE 1, A–C Population, livestock, and farmland statistics for the Gonghe Basin, 1985 through 1996. Farmland includes dry and irrigated farmland. (Source: SBHQ 1996)
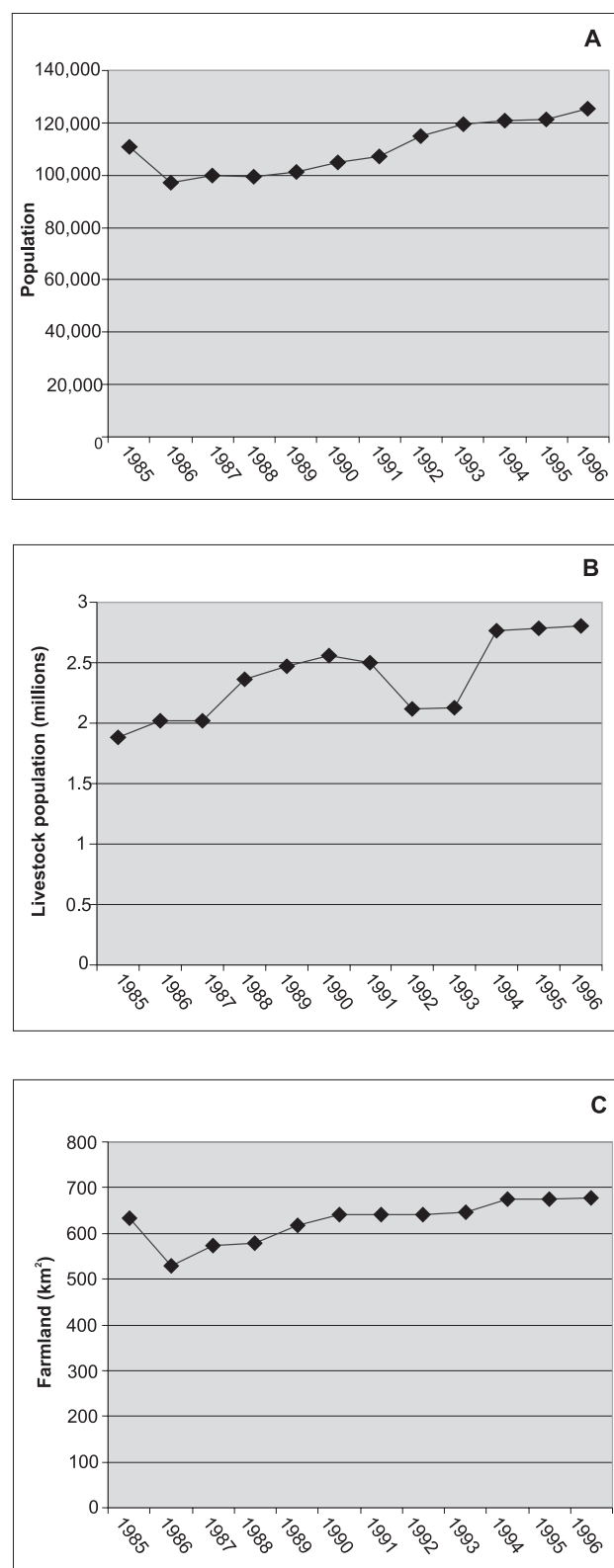
reaches of the Yellow River, where grasslands became severely degraded from the 1950s to the 1980s (Dong et al 1993). It attempts to document land cover changes since 1985 using 2 sets of multispectral thematic mapper (TM) images (1987 and 1996) to detect trends in desertification in the late 1980s and early 1990s, when the climate entered a dry period (Cheng et al 1997; Ye et al 1997; Shang et al 2001) and the Chinese economy entered a new mode (privatization oriented). This study is specifically concerned with the analysis of the processes leading to land cover change and the assessment of related environmental impacts and socioeconomic consequences. Land cover change was the result of physical and anthropogenic factors. To depict land cover change since 1985, 2 sets of multispectral TM images seemed sufficient because the climate mode was generally the same (Cheng et al 1997; Ye et al 1997; Shang et al 2001), and the variables indicating the effects of human activities show nearly linear increasing trends during this period. Although there are some fluctuations in these variables, human and livestock populations and farmland acreage have generally increased since 1985 (Figure 1A–C).

The study area (Figure 2), Gonghe Basin (35°27′–36°20′N, 100°–101°20′E), has a total area of about 11,500 km², with elevations ranging from 2400 to 3500 m. A desert-steppe landscape dominates low areas of the basin, whereas steppe landscape is found at high altitudes. The mean summer temperature is about 16°C, and the mean winter temperature is about –12°C. The mean annual precipitation varies from 311 mm in the northern (lower) part to 402 mm in the southern (higher) part of the basin (Dong et al 1993). The dominant sandy soil is low in inherent fertility, field water capacity, and organic matter content.

Methodology

Land cover categories
To detect changes in land cover during a 10-year period (1987–1996) using remote-sensing data, a new set of land cover categories was developed by modifying the National (China) Land Survey and Provincial (Qinghai) Land Survey standards applicable to the study area, taking full account of our field investigations. These categories are presented in hierarchical form. Three ecosystems are identified, first according to major land uses and then further divided into 9 land cover types that can be identified relatively quickly from remote-sensing data and linked to the severity of desertification (Table 1).

Data and processing
Two sets of cloud-free TM data were obtained, one in July 1987 and the other in July 1996, to capture the most

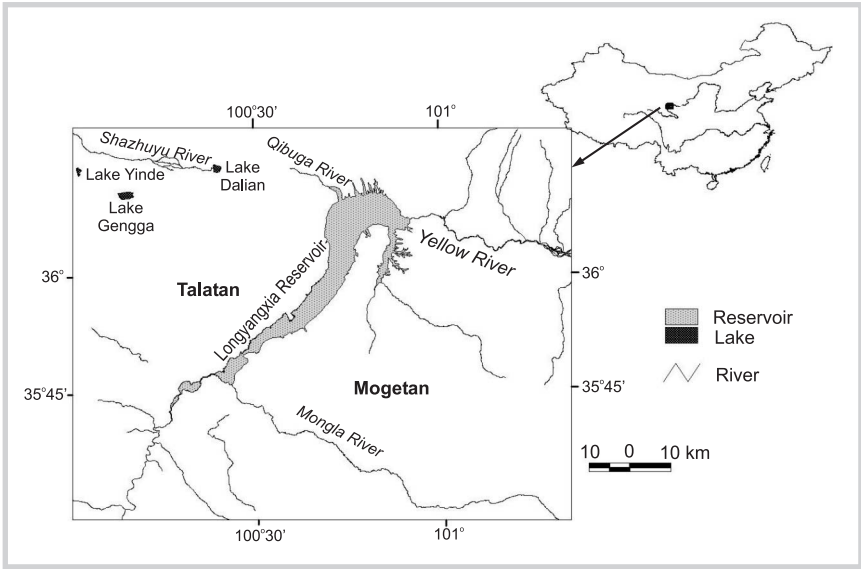FIGURE 2 Map of the study area. (Map by Zeng Yongnian)


TABLE 1 Hierarchical land cover classification.

Ecosystem	Land-cover type	Description of land-cover type
Bare ecosystem	Water	Salt lake, freshwater lake, reservoir, river
	Sand-covered area	All types of active sand dunes without grass cover
	Bare rock	Dry, denuded, rocky mountain terrain
Grassy ecosystem	Sparsely covered grassland	Vegetation coverage: 10–30%
	Moderately covered grassland	Vegetation coverage: 30–70%
	Densely covered grassland	Vegetation coverage: >70%
	Marshland	Wetlands in lowlands near foothills
Man-made ecosystem	Dry farmland	Farmland with rainfed agriculture
	Irrigated land	Irrigated farmland

informative and representative land cover signatures in a year because July is the warmest and wettest season of the year. Because the climate in 1987 and 1996 was nearly the same, the 2 sets of TM data are representative of changes that occurred during this period. Ancillary data, either to facilitate TM data classification or to assess desertification processes (including environmental and socioeconomic factors), were acquired from the provincial census bureau and meteorological bureau.

The TM images were geometrically corrected, first by identifying ground control points on the original images and on the reference topographical maps and then by applying quadratic polynomial transformation equations. Subsequently, images were resampled by applying a nearest neighbor algorithm, and the root mean square error of <0.3 pixel (9 m) was obtained to ensure accuracy. The original TM bands 3, 4, and 5

were selected as classification bands, and supervised classification was executed using the maximum likelihood classification algorithm. Because the supervised maximum likelihood classification is based solely on spectral properties, the accuracy of classification results was not sufficient to meet our needs in detecting temporal variations in land cover. A postclassification technique, therefore, was used to improve accuracy. Specifically, thematic information (eg, on water, sand-covered area, and irrigated lands) was first extracted from TM data with the assistance of a TM-based vegetation index and DEM-based geomorphic analyses.

The thematically mapped land cover categories were then overlaid with the land cover categories classified using the maximum likelihood classification (ie, preclassification) to correct previously misclassified land cover categories. This process substantially

FIGURE 3, A AND B Land-cover patterns in Gonghe Basin, 1987 and 1996. (Based on TM data)
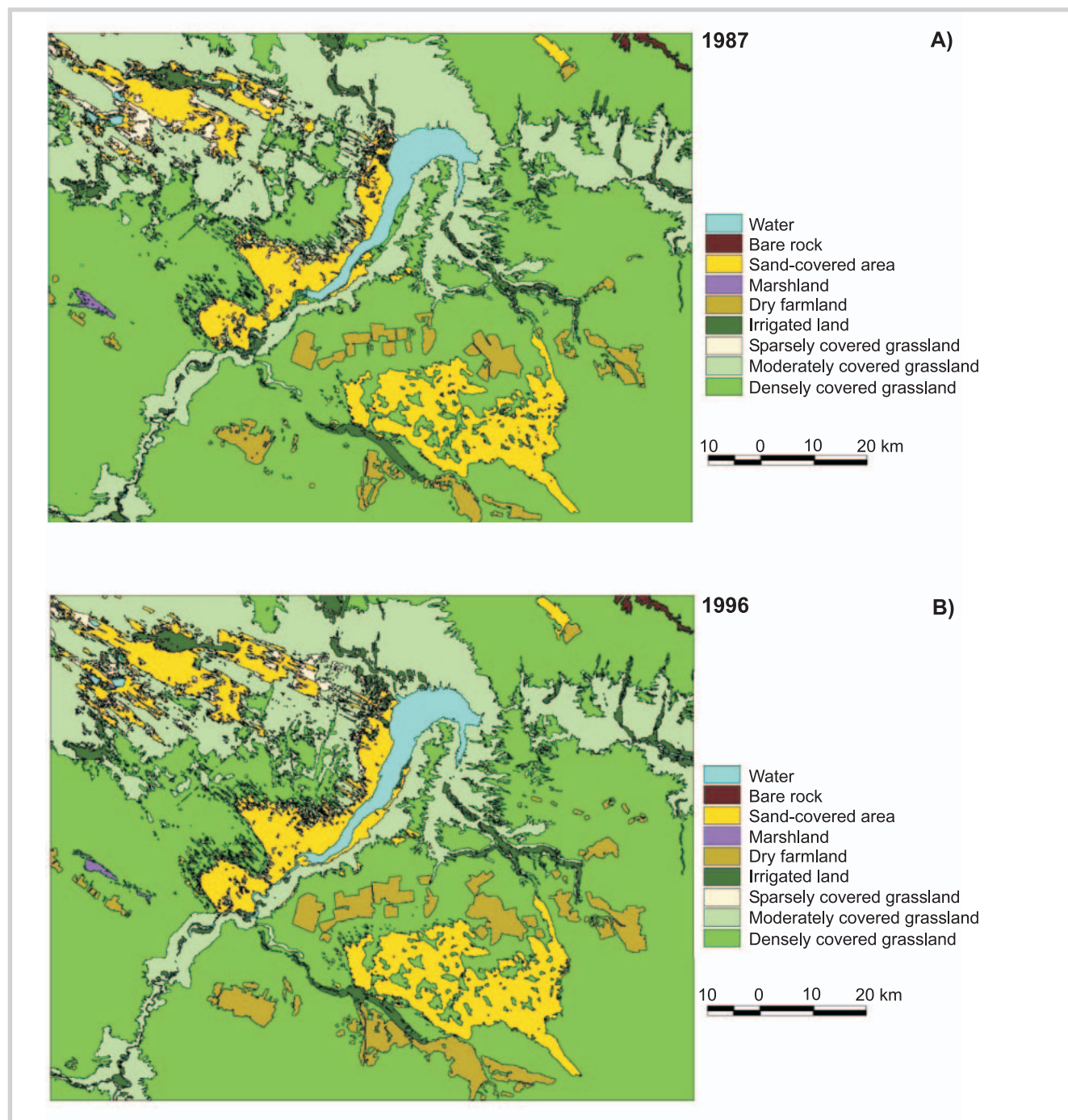
improved the results of preclassification. To ensure acceptance based on accuracy, we took sample points from the classified images in 1987 and 1996. Subsequently, direct comparison of land cover types was carried out on the basis of geographical location, with available primary data such as grassland maps in 1986 and 1997, land use maps in 1995, and our own field data. We then used a Kappa coefficient to evaluate accuracy. The Kappa coefficient was 91% for 1987 and

92.3% for 1996, ensuring our confidence in the accuracy of the classification.

Results and discussion

Changes in land cover

Our classification results show that 3 land cover categories changed significantly in the study area during the 10-year period: grassland, dry farmland, and sand-

TABLE 2 Land cover changes from 1987 to 1996.

Type of land cover	Area in 1987 (km^2)	Area in 1996 (km^2)	Difference (km^2)	Rate of change (%)
Water	207.4	227.9	20.5	9.9
Bare rock	19.1	19.1	0	0
Sand-covered area	1058.5	1247.4	188.9	17.8
Marshland	12.7	15.5	2.8	22
Dry farmland	362.1	549.7	187.6	51.8
Irrigated land	193.4	245.9	52.5	27.1
Sparsely covered grassland	181.3	152.1	−29.2	16.1
Moderately covered grassland	2673.4	2590.2	−83.2	3.1
Densely covered grassland	6787.7	6447.8	−339.9	5.0
Total area	11,495.6	11,495.6		

covered area. Specifically, the total area of dry farmlands increased from 362.1 km^2 in 1987 to 549.7 km^2 in 1996, and sand-covered areas increased from 1058.5 km^2 in 1987 to 1247.4 km^2 in 1996. The largest net change in terms of acreage (452.3 km^2) was of grasslands, which decreased from 9642.4 km^2 in 1987 to 9190.1 km^2 in 1996. Among the 452.3 km^2 of grasslands lost, densely covered grasslands were affected most (339.9 km^2), whereas moderately covered grasslands

(83.2 km^2) and sparsely covered grasslands (29.2 km^2) suffered much less (Figure 3A,B; Table 2).

To determine trends in land cover change and converted acreage from 1 category to another during the 10-year period in relation to desertification, we overlaid a 1987 land cover map with a 1996 land cover map. The results show that the sparsely covered grasslands were reduced by 71.3 km^2, all of which was transformed into sand-covered areas (Table 3).

TABLE 3 Matrix of land cover conversions from 1987 to 1996 (km^2).

Land-cover type	Water	Bare rock	Sand-covered area	Marshland	Dry farmland	Irrigated land	Sparsely covered grassland	Moderately covered grassland	Densely covered grassland	Total area (1996)
Water	196.4	0	7.5	0	0	0	0.3	10.8	12.9	227.9
Bare rock	0	19.1	0	0	0	0	0	0	0	19.1
Sand-covered area	3.4	0	1005.7	0	0	1.4	71.3	83.9	81.7	1247.4
Marshland	0.6	0	0	8.2	0	0	1	0.2	5.5	15.5
Dry farmland	0	0	0	0	331.7	0	0	1.9	216.1	549.7
Irrigated land	0.6	0	0	0	0	163.6	1.6	45.4	34.7	245.9
Sparsely covered grassland	0	0	12.3	0	0	0.4	53.6	81.2	4.6	152.1
Moderately covered grassland	5.1	0	12.3	0	0.7	11.2	50.9	2276.6	233.4	2590.2
Densely covered grassland	1.3	0	20.7	4.5	29.7	16.8	2.6	173.4	6198.8	6447.8
Total area (1987)	207.4	19.1	1058.5	12.7	362.1	193.4	180.3	2673.4	6787.7	1495.6

Moderately covered grasslands were reduced by 210.5 km², 83.9 km² of which was transformed into sand-covered areas, 45.4 km² into irrigated lands, and 81.2 km² into sparsely covered grasslands. Densely covered grasslands were reduced by 565.9 km², 81.7 km² of which was transformed into sand-covered areas, 216.1 km² into dry farmlands, 34.7 km² into irrigated lands, and 233.4 km² into moderately covered grassland. These data demonstrate that 299.7 km² of grasslands were lost and 556.1 km² were degraded to different degrees.

Overgrazing has been widely blamed for grassland deterioration in the study area (SBHQ 1996; OIT 1997). To further confirm the responsibility of overgrazing for grassland deterioration from 1987 to 1996, we looked at the Talatan area of the Gonghe Basin. The total livestock population far exceeded reasonable livestock density in terms of carrying capacity by about 23.5% in the Talatan area (OIT 1997) and by as much as 116% in some hot spots within the area (OIT 1997).

The second land cover/use category of environmental concern is dry farmlands, which increased by 187.6 km² during the period from 1987 to 1996, primarily as a result of cultivation of densely covered grasslands (Tables 2, 3). Cultivation of grassland has destroyed soil structure, increased soil erosion, and triggered desertification and sandstorm activity (Dong et al 1993; Li et al 2001). The increase in sand-covered areas is the ultimate consequence of land degradation. Our analysis shows that sand-covered area increased by 188.9 km² from 1987 to 1996, primarily as a result of overgrazing and cultivation. The increase in sand-covered area during the 10-year period indicates that overexploitation of natural resources in the study area has not been slowed when compared with the trend between the 1950s and the 1980s (Dong et al 1993).

Impacts on the environment

Compared with ecosystems in other climatic regimes, ecosystems in arid and semiarid regions are disproportionately prone to ecological damage from inappropriate forms of land use. According to our field investigations and data analysis, different types of land cover change, from better ecological conditions to worse ones, corresponded to different degrees of desertification severity in the study area.

For example, change from any kind of land cover to sand-covered area is considered very severe desertification. Change of densely covered or moderately covered grassland to sparsely covered grassland is categorized as severe desertification. Change from densely covered grassland to moderately covered grassland is classified as moderate desertification. Change from densely covered grassland (ie, >80% coverage) to identifiably deteriorated, densely covered grassland (ie, <80% coverage) constitutes mild desertification.

Comparison of land cover between 1987 and 1996 shows that the total area of desertified lands increased by 569.6 km². Very severely desertified land increased at a mean annual rate of 23.8 km² during the 10-year period, severely desertified land at a rate of 8.6 km², and moderately desertified land at a rate of 24.5 km². The desertified acreage and the rate of desertification easily qualify the study area as 1 of the most desertified regions in the Qinghai-Tibetan Plateau, according to overall statistics on desertification in the entire plateau (Li et al 2001).

Terrestrial carbon and its sequestration have become issues of worldwide concern (Post et al 1982, 1990; Wisniewski and Sampson 1993; Fang et al 1996; Cao and Woodward 1998; Wang and Zhon 1999; Lal 2000; Follett 2001; Swift 2001). Land use change and land degradation have been shown to be significant in modulating atmospheric CO_2 levels by emitting or sequestrating soil organic carbon (Heimann 1997). Recent studies have shown that in the past 30 years approximately 3.02 Pg C has been emitted from grassland soils on the Qinghai-Tibetan Plateau because of land-use change and grassland degradation (Wang et al 2002).

To assess the trends in soil organic carbon emission resulting from desertification during the 10-year period in the study area, we used the most common and simplest method based on land cover (Wang et al 1999). Organic carbon storage in the soil under a particular land cover in the specified area is a product of the mean soil organic carbon content per unit area and the total area of that particular land cover. The total organic carbon storage is then obtained by adding the organic carbon content of all soils under different forms of land cover in a specific area. Our study used relationships between land cover and associated soil organic carbon content established by field investigations (Shao et al 1988; Shen et al 1992). The soil organic carbon content was directly obtained from the soil organic matter content by multiplication, using the van Bemmelen conversion coefficient (0.58 g Cg^{-1}). The mean soil organic carbon per unit area was estimated by

$$C_i = 0.58 \ O_i W_i H_i \qquad (1)$$

where *C* is mean soil organic carbon per unit area, *i* the type of desertified land, 0.58 the van Bemmelen Index, *O* the mean organic matter content in the soil under a specific land cover, *W* the mean soil bulk density, and *H* the mean soil analytical thickness. Because the soils in the plateau are generally thin (Dong et al 1993), 0.7 m of the soil analytical thickness (*H*) was proposed by Wang et al (2002) and adopted in this study.

TABLE 4 Soil carbon content by category of desertified land.

Type of desertified land	Soil organic matter content (%)	Mean soil bulk density (g/cm^3)	Soil organic carbon content per unit area (kg/m^2)
Identifiably deteriorated densely covered grassland (mildly desertified)	1.189	1.48	7.144
Moderately covered grasslands (moderately desertified)	0.337	1.54	2.107
Sparsely covered grasslands (severely desertified)	0.148	1.55	0.931
Sand-covered area (very severely desertified)	0.094	1.56	0.595

TABLE 5 Desertification and associated carbon emission.

Degree of desertification	Land cover conversion	Converted area (km^2)	Change of soil organic carbon content per unit area (10^2 tC)	Carbon emission (10^2 tC)
Very severe desertification	Sparsely covered grasslands → very severely desertified land	71.3	3.36	239.57
	Moderately covered grasslands → very severely desertified land	83.9	15.12	1268.57
	Identifiably deteriorated, densely covered grassland → Very severely desertified land	83.1	65.49	5442.22
Severe desertification	Moderately covered grasslands → severely desertified land	81.2	11.76	954.91
	Identifiably deteriorated, densely covered grassland → severely desertified land	5.0	62.13	310.65
Moderate desertification	Identifiably deteriorated, densely covered grassland → moderately desertified land	245.1	50.37	12,345.69
Total		569.6		20,561.61

Soil organic matter content and bulk densities under different degrees of desertification related to land cover change are listed in Table 4 (Shao et al 1988; Shen et al 1992), and soil carbon content per unit area is then calculated using Equation 1. To calculate total soil carbon emission, we first defined the degree of desertification by comparing the land cover differences between 1987 and 1996. We then found the differences in the soil organic carbon content of grassland with different degrees of desertification between 1987 and 1996 (Table 5). The estimated total carbon emission caused by desertification was 2.06×10^6 tC during the 10-year period, and the mean annual soil carbon emission flux was 0.206×10^6 tC, suggesting that desertification in the upper reaches of the Yellow River is partly responsible for significant emission of CO_2 into the atmosphere from the Qinghai-Tibetan Plateau.

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