Environ Earth Sci
DOI 10.1007/s12665-013-2482-0

ORIGINAL ARTICLE

The effect of desertification on carbon and nitrogen status in the northeastern margin of the Qinghai-Tibetan Plateau

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Received: 28 August 2012 / Accepted: 6 April 2013

Abstract Environmental degradation resulting from desertification often accelerates biodiversity loss and alters carbon (C) and nitrogen (N) stocks within grassland ecosystem. In order to evaluate the effect of desertification on plant diversity and carbon (C) and nitrogen (N) stocks, species compositions and C and N contents in plants and soil were investigated along five regions with different degrees of desertification in the northeastern margin of the Qinghai-Tibetan Plateau (control, light, moderate, severe and very severe stages). The study showed: (1) species composition and richness changed significantly with the development of grassland desertification; (2) the aboveground biomass C and N contents in the control were 101.60 and 4.03 g m^{-2}, respectively. Compared to the control, the aboveground tissue C and N contents significantly decreased from light, moderate, severe to very severe stages. (3) The root C and N contents in the control in 0–40 cm depth are 1,372.83 and 31.49 g m^{-2}, respectively, while the root C and N contents in 0–40 cm were also declining from the control, light, moderate, severe to very severe stages. (4) Compared to the plant, the soil made a greater contribution for C and N distribution, in which the soil organic C and total N contents in 0–40 cm depth in the control are 20,386.70 and 3,587.89 g m^{-2}, respectively. At the same time, soil organic C and N contents also decreased significantly from the control to very severe stages. These results suggest that grassland desertification not only alters species compositions and leads to the loss of plant diversity, but also results in greater loss of organic C and N in alpine meadow, in which there is a negative effect on reducing greenhouse gas emission.

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Keywords Desertification · Alpine meadow · Carbon · Nitrogen

Introduction

With the global warming and intensive human disturbances, more and more grasslands are facing severe desertification, which is becoming one of the most important environmental problems worldwide in the future (Schlesinger et al. 1990; Wilcox and Thurow 2006; Dong et al. 2010). Desertification not only results in soil degradation and severe decreases in land potential productivity (Gad and Abdel 2000; Li et al. 2006), but also can promote atmospheric emission of soil carbon (C) and nitrogen (N) as greenhouse gases (Zhao et al. 2009). Desertification has a significant impact on alteration of soil C and N storage by profoundly altering the biota, land cover, and biogeochemical cycles. Many studies on loss of C and N in worldwide grasslands are confined to overgrazing and lack of scientific management (Elmore and Asner 2006; Piñeiro et al. 2006; Maia et al. 2009). However, the effect of desertification on C and N storage in alpine meadow ecosystem is largely unknown, especially in the Tibetan Plateau, China.

The Tibetan Plateau, the largest geomorphological unit on the Eurasian continent, is an important part of the global terrestrial ecosystem. Alpine meadows, covering about 35 % of plateau area, comprise the representative vegetation and the major pastureland on the plateau (Cao et al. 2004). Alpine meadows ecosystem may be a major C sink because of its high productivity during the growing season and the low rate of decomposition resulting from low temperature (Cao et al. 2004). The amount of C stored in alpine meadows is 18.2 kg m^{-2} (Ni 2002), which is higher than savanna (5.4 kg m^{-2}) and temperate grassland (13.0 kg m^{-2}) (Adams et al. 1990). However, the plateau ecosystem is very fragile and sensitive to global climate changes and anthropogenic disturbances. At present, the grassland desertification is highly evident on the Tibetan Plateau resulting from overgrazing and climate changes (Yang et al. 2004; Liu et al. 2005). Alpine meadows ecosystem has been changed dramatically by grassland desertification. Ecosystem alterations cause changes in C and N cycling by altering plant production, rates of soil organic matter accumulation and decomposition, and the subsequent C content in soils (Lal et al. 1995). However, less information on the effect of desertification on plant diversity and carbon (C) and nitrogen (N) stocks is known in the Qinghai-Tibetan Plateau. Therefore, the five different degrees of desertification (control, light, moderate, severe and very severe stages) were selected in the northeastern margin of the Qinghai-Tibetan Plateau. The objectives of this study were (1) to examine changes in plant community characteristics, aboveground and underground biomass in the desertification process; (2) to examine changes in organic C and total N contents in aboveground plants tissues and root in the process of desertification; (3) to examine changes in soil texture, soil organic C and total N contents in the process of desertification.

Materials and methods

Study site

The study was conducted in the Maqu county which is located in the northeastern margin of the Qinghai-Tibetan Plateau (106°46′–102°29′E, 33°06′–34°23′N). The elevation is between 3,300 and 4,806 m, with mean annual precipitation of 598.5 mm (1970–2007), falling mainly from May to September (Fig. 1). The annual average temperature is 1.55 °C; the highest temperature is 11.13 °C in July and the lowest temperature is −9.20 °C in January (Fig. 1). Evaporation averages 1,353.4 mm yearly. Wind speed is greatest during winter and spring, with an average of 2.5 m s^{-1}.

The county was formerly strewn with streams and swamps and responsible for 45 % the Yellow River's discharge (Qian et al. 2002). The total area is 1.019×10^6 hm^2, of which 89.5 % is alpine meadow (Zhang and Ma 2001). The desertified grassland has been expanding at annual rate of 6.14 % since the early 1990s (Wang et al. 2006). Before desertification commenced, the soil was about 30–50 cm thick. The parent materials are chiefly slope deposits and residual deposits with coarse

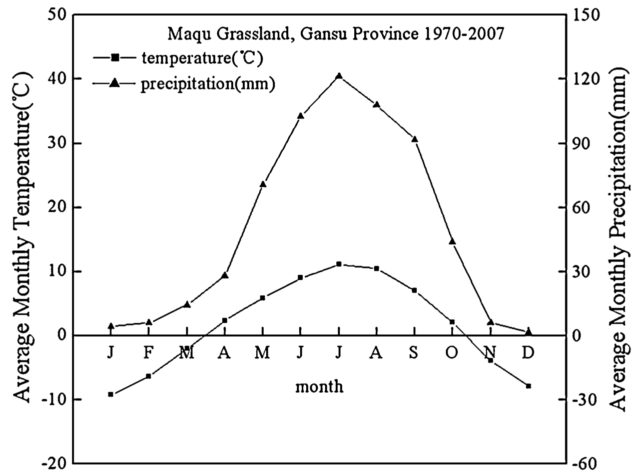

Fig. 1 Eco-climate of the Maqu grassland, Gansu Province

texture, consisting mostly of sand (Wang et al. 2003). Original vegetation was dominated by *Kobresia pygmaea* with the main associate plant species of *K. capillifolia*, *K. humilis*, *Blysmus sinocompressus*, and *Elymus nutans* (Guo et al. 2004).

Desertification grades

According to the classification of desertification types and degrees by Zhu and Chen (1994) and Li et al. (2006), grasslands of four types of desertification, namely, slight, moderate, severe, and very severe desertification stages, and a control site (original vegetation) were selected. Slight desertification grasslands (SLD) are characterized by stabilised sand. Mobile sand occupies 1–2 % of the total area, and vegetation cover is between 60 and 80 %. Moderate desertification grasslands (MD) are characterized by semi-fixed sand. Soil wind erosion can be found on windward slopes of semi-fixed sand dunes. Mobile sand ranges from 10 to 15 % of the total area, and vegetation cover is between 30 and 60 %. Severe desertification grasslands (SD) are characterized by semi-shifting sand dunes and plain sand areas, with intensified wind erosion on the soil surface. Mobile sand occupies 30–50 % of the total area, and vegetation cover ranges from 10 to 30 %. Very severe desertification grasslands (VSD) are characterized by evident sand-cover with mobile sand exceeding 50 % of the total area.

Vegetation survey

The 15 sites with the similar topographic conditions at five desertification stages were established in August 2010. Each site is about 10–20 hm^2 in size. At each site, 10 random quadrats (1×1 m^2) were placed to measure species abundance, height, percentage coverage, and total community coverage, respectively. In each quadrat, vegetation was clipped off flush with the ground. The harvested plants were separated into grasses, sedges, and forbs.

In each quadrat, root biomass was sampled in three soil cores (diameter 5 cm) at 0–20 and 20–40 cm. In the laboratory, root biomass was first carefully washed. No attempt was made to distinguish between live and dead roots. All vegetation material was dried at 80 °C to constant weight and weighed. Vegetation samples ground in an agate mortar were analyzed for organic C and total N concentration by dry combustion in a VarioEL® elemental analyzer.

Soil sampling

Three mixed soil samples were randomly taken in each site. Each mixed soil sample (0–20, 20–40 cm) was a mixture of 15 random soil cores using 3-cm-diameter soil auger in order to reduce soil heterogeneity in each community. In addition, soil bulk densities (0–20, 20–40 cm) in each site were measured by the core method. Soil samples were pretreated through a 2-mm screen to remove roots and other debris. Soil particle size was measured by the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (ISSCAS 1978). Soil samples ground in an agate mortar were analyzed for total organic carbon and nitrogen concentration by dry combustion in a VarioEL® elemental analyzer.

Calculation and statistics

Plant tissue C (or N) content (g m^{-2}) was calculated on an area and depth basis from biomass samples and plant C (or N) concentration analyses. The total amount of organic carbon and total N in each soil were calculated by the following equation (Duan et al. 2001):

Soil total organic C or total N storage in soil = (soil area) × (soil depth) × (soil average bulk density) × (average organic C or N content)

All data were analyzed using SPSS software, with multiple comparisons and analysis of variance (ANOVA) used to determine the differences among the different desertification stages. Results were checked by Duncan's test. Pearson correlation coefficients were used to evaluate relationships among soil sand, slit, clay content, soil organic C, and total N.

Results

Plant community characteristics

The type of plant community changed dramatically with the development of grassland desertification. The control was dominated by *K. pygmaea*, which was replaced by *E. nutans* and *Leontopodium leontopodiode* in the slight stage, by *E. nutans* and *Poa pratensis* in the moderate stage, by *P. pratensis* and *Carex praeclara* in the severe stage, and replaced by *C. praeclara* in the very severe stage. There were significant differences in vegetation coverage and species richness among the different desertification stages ($P < 0.01$), e.g., vegetation coverage decreased significantly from 86.90 % in the control to 7.74 % in the very severe stage, the species richness decreased from 44 species in the control to six species in the very severe stage (Table 1).

Aboveground biomass and C and N contents

The total aboveground biomass decreased from 260.0 g m^{-2} in the control to 20.0 g m^{-2} in the very severe stage (Table 2). At the early stage of desertification, sedges biomass decreased significantly, however, grasses and forbs biomass increased from control to slight stage, and then decreased gradually.

Carbon concentration for grasses, forbs, and sedges increased with development of desertification. However, N concentration for grasses, forbs, and sedges decreased with development of desertification (Table 3). The C and N contents for grasses, forbs, and sedges followed the same patterns as corresponding biomass in the process of desertification. The total aboveground biomass C and N contents decreased significantly in the process of desertification ($P < 0.05$) (Fig. 2). The aboveground biomass C and N contents in the control are 101.60 and 4.03 g m^{-2}, respectively. Compared to the control, the aboveground biomass C content in slight, moderate, severe, and very severe stages decreased 16.7, 29.8, 71.4, and 91.5 %, respectively, while aboveground biomass N content decreased 19.5, 35.4, 75.7, and 93.8 %, respectively.

Root biomass and root C and N

There are significant differences in root biomass in 0–20 and 20–40 cm among different desertification stages ($P < 0.05$). Root biomass in 0–20 cm decreased with the development of desertification (Table 4). However, root biomass in 20–40 cm increased at the early stage of desertification, and then decreased (Table 4).

The root C and N concentration increased, but root C:N ratio decreased with the development of desertification. The root C and N concentration in 0–20 cm was higher than 20–40 cm, but the root C:N ratio in 0–20 cm was lower than 20–40 cm.

The root C and N contents in 0–20 cm of control are 1,295.21 and 29.99 g m^{-2}, respectively. The root C and N content in 0–20 cm decreased significantly with the

Table 1 Changes in plant community characteristics in the process of grassland desertification

Stages of desertification	Dominant species	Species richness	Coverage (%)
Original vegetation	*Kobresia pygmaea*, *Potentilla fragarioides*, *Kobresia humilis*, *Stipa aliena*, *Leontopodium leontopodiode*	44 ± 3.54a	>80 (86.90 ± 8.46a)
Slight stage	*Elymus nutans*, *Leontopodium leontopodiode*, *Kobresia pygmaea*,*Poa pratensis*, *Potentilla bifurca*	30 ± 2.92b	60–80 (74.22 ± 7.51b)
Moderate stage	*Elymus nutans*, *Potentilla bifurca*, *Poa pratensis*, *Leontopodium leontopodiode*, *Thalictrum alpinum*, *Carex praeclara*	23 ± 1.87c	30–60 (46.20 ± 3.92c)
Severe stage	*Poa pratensis*, *Potentilla bifurca*, *Roegneria kokonorica*, *Carex praeclara*, *Leymus secalinus*	13 ± 1.58d	10–30 (25.97 ± 2.31d)
Very severe stage	*Carex praeclara*, *Leymus secalinus*, *Polygonum sibiricum*, *Potentilla bifurca*	6 ± 1.41e	<10 (7.74 ± 2.19e)

Values represent mean ± SE. The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.01$)

Table 2 Changes in grasses, sedges, and forbs biomass at different stages of desertification

Stages of desertification	Grasses (g m^{-2})	Sedges (g m^{-2})	Forbs (g m^{-2})	Total (g m^{-2})
Original vegetation	82.63 (7.03)b	100.67 (12.71)a	76.69 (11.44)a	260.0 (31.3)a
Slight stage	117.42 (9.53)a	16.02 (1.30)b	78.64 (6.38)a	212.1 (17.2)b
Moderate stage	92.57 (6.18)b	12.64 (0.84)b	68.07 (4.54)a	173.2 (11.6)c
Severe stage	31.63 (6.72)c	8.70 (1.85)b	28.73 (6.10)b	69.1 (14.7)d
Very severe stage	5.73 (0.78)d	12.85 (1.53)b	1.38 (0.16)c	20.0 (2.4)e

Values represent mean ± SE. The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.05$)

Table 3 Changes in C and N concentration and C:N ratio of grasses, forbs, and sedges at different stages of desertification

Stages of desertification	Grasses			Forbs			Sedges		
	C (%)	N (%)	C:N	C (%)	N (%)	C:N	C (%)	N (%)	C:N
Original vegetation	37.75 (0.95)c	1.56 (0.03)a	24.20 (0.56)d	40.35 (1.16)c	1.72 (0.12)a	23.47 (1.30)d	40.12 (1.28)b	1.41 (0.09)a	28.60 (2.57)b
Slight stage	39.24 (0.94)bc	1.48 (0.07)ab	26.53 (1.29)c	40.64 (0.75)c	1.64 (0.05)ab	24.79 (0.68)cd	40.35 (0.81)b	1.34 (0.07)ab	30.27 (2.07)b
Moderate stage	40.08 (0.63)b	1.45 (0.04)b	27.65 (1.14)c	42.57 (0.90)b	1.61 (0.04)bc	26.51 (0.53)bc	41.26 (1.17)ab	1.30 (0.10)ab	31.92 (2.13)ab
Severe stage	40.72 (0.96)b	1.34 (0.05)c	30.40 (0.46)b	43.52 (1.03)ab	1.55 (0.06)c	28.17 (1.02)ab	41.83 (0.75)ab	1.29 (0.08)ab	32.62 (2.41)ab
Very severe stage	42.96 (1.11)a	1.25 (0.07)c	34.40 (1.21)a	44.66 (1.12)a	1.48 (0.08)c	30.16 (1.35)a	43.06 (1.19)a	1.22 (0.07)b	35.26 (1.59)a

Values represent mean ± SE. The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.05$)

development of desertification ($P < 0.05$). Compared to the control, the root C content in 0–20 cm of the slight, moderate, severe, and very severe stages decreased 15.2, 64.4, 86.9, and 94.1 %, respectively, while the corresponding root N content in 0–20 cm decreased 13.9, 51.6, 82.2, and 92.3 %, respectively. The root C and N contents in 20–40 cm of the control are 77.62 and 1.51 g m^{-2}, respectively. Compared to the control, the root C content in 20–40 cm of the slight, moderate stages increased 143.4 and 81.0 %, respectively, but decreased 26.0 and 60.8 % in severe and very severe stages, respectively, while the root N content in 20–40 cm of the slight, moderate stages increased 153.0 and 140.7 %, respectively, but decreased 7.1 and 42.8 % in severe and very severe stages, respectively.

Soil organic C and total N contents

Soil organic C and total N concentrations in 0–20 and 20–40 cm decreased significantly with the development of desertification ($P < 0.05$) (Table 5). Soil organic C and total N concentrations in 0–20 cm of the control are higher than 20–40 cm, but soil organic C and total N concentrations in 0–20 cm of all desertification stages are lower than 20–40 cm.

The soil organic C and total N contents in 0–20 cm of the control are 11,473.73 and 2,026.29 g m^{-2}, respectively (Fig. 3). Compared to the control, the soil organic C content in 0–20 cm of the slight, moderate, severe, and very severe stages decreased 38.8, 66.6, 86.2, and 89.2 %, respectively.

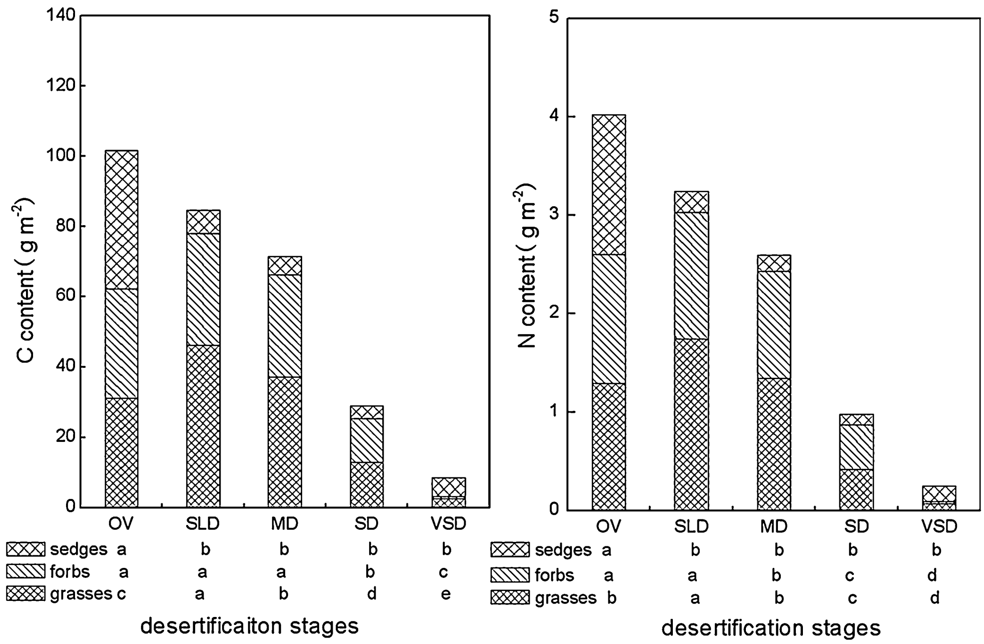

Fig. 2 Aboveground C and N content (g m^{-2}) in grasses, forbs, and sedges at different stages of desertification. The mean difference for a variable (grasses, forbs, or sedges) is significant at the 0.05 level ($P < 0.05$) if followed by the *different letter*. *OV* original vegetation; *SLD* slight desertification stage; *MD* moderate desertification stage; *SD* severe desertification stage; *VSD* very severe desertification stage

Table 4 Changes in root biomass and root tissue C and N at different stages of desertification

Stages of desertification	Depths	Root biomass (g m^{-2})	Root C concentration (%)	Root N concentration (%)	Root C:N	C content in roots (g m^{-2})	N content in roots (g m^{-2})
Original vegetation	0–20 cm	3,982.5 (579.9)a	32.99 (1.35)c	0.758(0.066)b	43.22 (2.70)a	1,295.21 (132.46)a	29.99 (2.62)a
	20–40 cm	242.2 (46.2)c	31.97 (0.96)c	0.627(0.061)c	51.39 (6.19)a	77.62 (16.25)c	1.51 (0.22)b
	Total	4,224.7 (541.0)a				1,372.83 (118.30)a	31.50 (2.41)a
Slight stage	0–20 cm	3,160.0 (299.9)b	34.54 (1.01)bc	0.820(0.082)b	42.61 (4.51)a	1,098.55 (136.09)b	25.83 (2.43)b
	20–40 cm	558.4 (53.6)a	33.82 (0.79)b	0.680(0.041)c	49.82 (2.46)a	188.94 (19.96)a	3.81 (0.59)a
	Total	3,718.4 (346.4)a				1,287.49 (150.34)a	29.64 (2.39)a
Moderate stage	0–20 cm	1,352.4 (107.0)c	34.86 (1.33)bc	1.071 (0.038)a	31.98 (2.30)b	461.62 (21.58)c	14.51 (1.66)c
	20–40 cm	414.1 (48.4)b	34.03 (1.27)b	0.873 (0.089)b	39.24 (4.15)b	140.51 (11.97)b	3.63 (0.65)a
	Total	1,766.5 (156.9)b				602.13 (15.76)b	18.14 (1.01)b
Severe stage	0–20 cm	481.5 (56.6)d	35.11 (0.89)b	1.113 (0.092)a	31.67 (2.25)b	169.13 (21.45)d	5.34 (0.57)d
	20–40 cm	165.2 (11.7)cd	34.77 (0.96)b	0.974 (0.062)ab	35.80 (2.71)b	57.42 (4.52)c	1.61 (0.21)b
	Total	646.6 (68.0)c				226.56 (25.60)c	6.95 (0.76)c
Very severe stage	0–20 cm	204.6 (9.5)d	37.27 (1.25)a	1.135 (0.068)a	32.88 (1.11)b	76.18 (1.28)d	2.32 (0.04)d
	20–40 cm	82.1 (7.7)d	37.09 (0.82)a	1.056 (0.082)a	35.23 (2.07)b	30.39 (2.13)d	0.86 (0.05)b
	Total	286.7 (46.4)c				106.57 (2.86)c	3.18 (0.09)d

Values represent mean ± SE. The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.05$)

Simultaneously, the soil total N content in 0–20 cm of the slight, moderate, severe, and very severe stages decreased 55.0, 78.1, 91.7, and 93.9 %, respectively. The soil organic C and total N contents in 20–40 cm are 8,912.97 and 1,561.60 g m^{-2}, respectively. Compared to the control, the soil organic C content in 20–40 cm of the slight, moderate, severe, and very severe stages decreased 13.7, 31.0, 74.6, and 85.6 %, respectively, while soil total N content in 20–40 cm of the slight, moderate, severe, and very severe stages decreased 33.6, 51.2, 84.0, and 91.7 %, respectively.

Discussion

Changes in vegetation in the process of desertification

The native alpine *Kobersia* meadow is characterized by the dominance of *Kobersia* plants that are perennial geophyta rhizomatosa (Zhou and Li 2001). The land surface covered by high coverage vegetation, and dense root distributed in surface soil are against wind erosion, but sandy sediments are poorly cemented in subsoil, therefore, it easily

Table 5 Changes in soil total organic C, N concentration at different stages of desertification

Stages of desertification	C %		N %		C:N	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Original vegetation	5.328 (0.193)a	3.482 (0.148)a	0.941 (0.049)a	0.610 (0.023)a	5.667 (0.153)c	5.715 (0.367)d
Slight stage	3.035 (0.119)b	3.076 (0.122)b	0.395 (0.021)b	0.415 (0.033)b	7.719 (0.716)b	7.448 (0.735)c
Moderate stage	1.325 (0.057)c	2.347 (0.150)c	0.154 (0.010)c	0.291 (0.009)c	8.671 (0.916)ab	8.084 (0.740)bc
Severe stage	0.512 (0.036)d	0.796 (0.068)d	0.054 (0.004)d	0.088 (0.005)d	9.539 (1.167)a	9.037 (0.439)ab
Very severe stage	0.375 (0.015)d	0.424 (0.023)e	0.038 (0.002)d	0.043 (0.002)e	10.010 (0.453)a	9.893 (0.929)a

Values represent mean ± SE. The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.05$)

undergoes wind erosion once the vegetation cover is destroyed. Human disturbances play a primary role that is responsible for aeolian desertification on the study area, such as overgrazing, the surface is exposed to wind because of decreased vegetation coverage and soil structure damaged by rodents resulting from overgrazing. The number of livestock increased rapidly in the past decades (Dong et al. 2010) that led to serious desertification in Maqu county. Climatic factors are also responsible for aeolian desertification, increasing temperature led to degradation of frozen soils which played an important role in maintaining the meadow vegetation in Qinghai-Tibetan Plateau. Furthermore, the plant community in severe and VSD stages was sensitive to precipitation fluctuation. Significant changes in plant community type, species composition, and vegetation cover were found in the process of desertification. The shift of dominant species indicates that communities composition followed the pattern of hygrophytes being gradually replaced by mesophyte, xerophyte, and some annual psammophilous plants (plants that grow in sand) in the process of *Kobersia* meadow desertification (Wang et al. 2007). Plant productivity is an important index to evaluate ecological functions of alpine meadow. In this study, the total aboveground biomass decreased significantly with the development of desertification. The C concentration increased and N concentration decreased for sedges, forbs, and grasses with the development of desertification. The main reason is that plant survival mainly depends on the C accumulation and N consumption in the process of desertification (Zhao et al. 2004).

Underground biomass in 0–20 cm decreased significantly with the development of desertification. However, underground biomasses in 20–40 cm of slight and moderate stages are higher than in control. The main reason is that the primary dominant plant is *E. nutans* in slight and moderate stages. The root of *E. nutans* distributed deeper than that of *K. pygmaea* which mainly distributes in 0–10 cm (Wang 2001). Our results showed that more biomass is allocated belowground than aboveground. Wang et al. (1995), Chen and Wang (2000), and Zhou

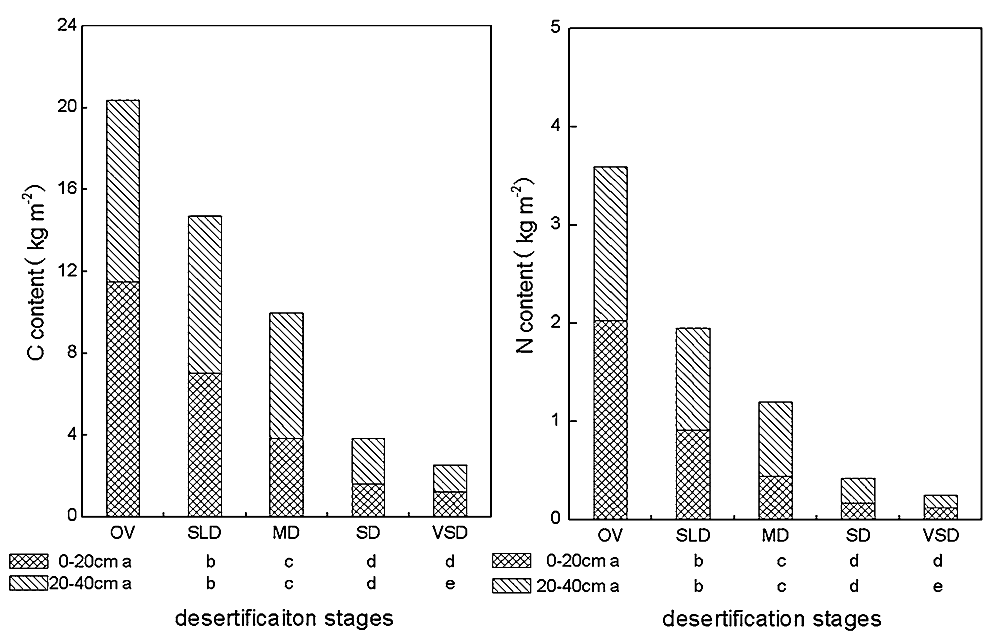

Fig. 3 Soil total organic C and total N contents in 0–20 and 20–40 cm at different stages of desertification. The mean difference is significant at the 0.05 level ($P < 0.05$) if followed by the *different letter*. *OV* original vegetation; *SLD* slight desertification stage; *MD* moderate desertification stage; *SD* severe desertification stage; *VSD* very severe desertification stage

(2001) found that underground biomass was higher in Tibetan alpine areas than in temperate areas of the Inner Mongolia in China. They reasoned that plants partition more energy reserves into roots in a low temperature environment. Low temperature not only reduces photosynthetic rate of plants, but also reduces respiratory losses (Gill and Jackson 2000) allowing the accumulation of biomass. High root mass raises soil temperature and improves the absorption of soil nutrients in a low temperature environment (Norbyr and Jackson 2000), an adaptation that aids plant survival.

All desertification stages exhibited a relatively greater quantity of higher quality root biomass (low C:N ratio) while the native *Kobersia* meadow contained larger quantity of lower quality (high C:N ratio) root biomass. The root N concentration in control is lower than all desertification stages. In the native *Kobersia* meadow with large root density and low biological nitrogen fixation, available N in the soil is mainly represented by NH_4^+–N (Cao and Zhang 2001), which is a poorly mobile ion in soil. So, this may be one reason for the low N concentration in the roots of the control (Wang et al. 2005). In addition, larger amount of dead roots with low C and N concentration were reserved in native *Kobersia* meadow (Li and Zhou, 1998). This is another reason for the low C and N concentrations in roots of the control than all desertification stages.

Fan et al. (2008) estimated that 56.4 % of the carbon stored in grassland vegetation in China is contained in the alpine grasslands of the Tibetan Plateau, of which 68.2 % is in alpine meadow. Desertification resulted in greater losses of C and N in plants in alpine meadow. In our study, both aboveground and underground (0–40 cm) C and N contents decreased significantly in the process of desertification. The main reason is that biomass decreased significantly because of soil nutrient loss due to severe wind erosion.

Changes of soil C and N storage

Organic carbon storage in the grassland soil on the Tibetan Plateau accounts for 2.5 percent of the global soil carbon pool. The soil C pool of the Tibetan Plateau is of great importance globally (Wang et al. 2002). However, grassland desertification has great influence on the soil organic carbon and total N storage of alpine meadow. Our results are consistent with several studies (Li et al. 2006; Zhao et al. 2009) suggesting that grassland desertification resulted in greater loss of soil organic C and total N contents. In this study, compared to the control, the organic C content in 0–40 cm of slight, moderate, severe, and VSD stages decreased 27.8, 51.0, 81.1, and 87.6 %, respectively, while the total N content in 0–40 cm decreased 45.6, 66.4, 88.4 and 92.9 %, respectively. This suggested that the loss of soil total N is more significant than soil organic C in the process of desertification. Our results also showed that the loss of soil organic C and total N in top soil is more significant than that in deeper soil in the process of desertification (Fig. 3).

Historically, Maqu grassland was natural alpine meadow with plenty of water. Desertification expanded from near zero during the 1950s to reach 84,804.8 hm^2 in 2005, which amounts to 8.96 % of Maqu's total land area (Lu 2010). Multiplying area figures by values for nutrient loss per unit area gives an idea of the total amounts of organic C and total N loss through desertification. Across all desertified area, 10.46×10^6 t of soil carbon was lost, and 2.13×10^6 t of nitrogen was lost (Table 6). Large losses of soil C and N represent substantial environmental degradation in the process of desertification. As C and N are lost from the soil, land productivity deteriorates, grassland desertification inevitably resulted in greenhouse gases released from soil to the atmosphere, which contributes to global climate change (Duan et al. 2001). The main factors responsible for loss of soil organic carbon and N are the significant decrease of vegetation coverage and productivity during the development of desertification. Wang et al. (2003) found organic matter and total N of alpine meadow decreased significantly when the vegetation coverage decreased from 90 to 30 %. The main reason is that soil texture becomes coarser as soil wind erosion becomes more severe when vegetation coverage decreased. Most of soil organic matters and total N are positively associated with clay and slit (Zhao et al. 2009). Our results showed soil sand contents increased significantly, and soil slit and clay contents decreased significantly with development of desertification (Table 7, $P < 0.01$). Regression analysis indicated soil organic C and total N are negatively correlated with soil sand content ($P < 0.01$), and positively correlated with soil clay content (Table 8, $P < 0.01$). This suggested that grassland desertification by wind erosion is

Table 6 Desertification area in 2005 and total amount of organic C and total N lost from 1950s to 2005 in Maqu County

Items	Light	Moderate	Severe	Very severe	Total
Desertified grassland (hm^2)	22,850.8	29,441.9	27,643.3	4,868.9	84,804.8
Lost organic C (10^6 t)	1.32	3.30	4.91	0.94	10.46
Lost total N (10^6 t)	0.38	0.71	0.88	0.16	2.13

Table 7 Changes in soil particle size distribution and bulk density at different stages of desertification

Stages of desertification	Sand (>0.05 mm)		Silt (0.05–0.002 mm)		Clay (<0.002 mm)		BD (g cm^{-3})	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Original vegetation	38.78 (2.98)d	54.34 (2.65)d	55.51 (2.91)a	41.34 (1.73)a	5.71 (0.27)a	4.32 (0.29)a	1.08 (0.04)d	1.28 (0.03)c
Slight stage	76.13 (1.60)c	70.43 (2.03)c	20.57 (1.59)b	26.40 (1.40)b	3.30 (0.19)b	3.17 (0.17)b	1.16 (0.04)d	1.25 (0.04)c
Moderate stage	82.96 (2.21)b	74.99 (2.43)c	14.05 (1.22)c	23.07 (1.50)b	2.99 (0.14)b	1.94 (0.11)c	1.45 (0.03)c	1.31 (0.04)c
Severe stage	90.68 (1.40)a	88.31 (1.85)b	7.65 (1.28)d	10.04 (0.96)c	1.67 (0.11)c	1.65 (0.16)c	1.55 (0.04)b	1.42 (0.05)b
Very severe stage	94.71 (1.36)a	95.26 (1.50)a	4.13 (0.34)d	4.16 (0.45)d	1.16 (0.20)d	0.58 (0.06)d	1.65 (0.06)a	1.51 (0.03)a

The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.05$)

Table 8 Relationship between soil organic C, total N, and particle proportion

Particle size (mm)	Depths (cm)	Linearity regression equation	*P*	R^2	*N*
C					
>0.05	0–20	$C = -0.091X_1 + 9.041$	0.000	0.931	15
	20–40	$C = -0.081X_1 + 8.226$	0.000	0.911	15
0.05–0.002	0–20	$C = 0.098X_2 + 0.091$	0.000	0.933	15
	20–40	$C = 0.089X_2 + 0.157$	0.000	0.910	15
<0.002	0–20	$C = 1.138X_3 - 1.278$	0.000	0.925	15
	20–40	$C = 0.864X_3 + 0.010$	0.000	0.846	15
N					
>0.05	0–20	$N = -0.017X_1 + 1.586$	0.000	0.964	15
	20–40	$N = -0.014X_1 + 1.385$	0.000	0.957	15
0.05–0.002	0–20	$N = 0.018X_2 - 0.053$	0.000	0.973	15
	20–40	$N = 0.016X_2 - 0.043$	0.000	0.972	15
<0.002	0–20	$N = 0.203X_3 - 0.286$	0.000	0.919	15
	20–40	$N = 0.156X_3 - 0.074$	0.000	0.927	15

mediated through a loss of soil fine particles, with a resultant decrease in soil organic C and total N. C:N ratio in both 0–20 cm and 20–40 cm increased in the process of desertification. Further increase of C:N ratio in the process of desertification is unfavorable to N fixation in the grassland.

Conclusion

Significant changes in species composition, plant community structure, and C and N stocks in plant and soil were found in the process of desertification. Species richness and vegetation cover declined from the control to very severe stage. Organic C and total N contents in plant and soil decreased significantly in the process of desertification. The loss of total N is more significant than the loss of C in plant and soil system in the process of desertification. Organic C and total N contents are ranked in the order of soil > underground biomass > aboveground biomass among different desertification stages. These indicated that the process of desertification had a great negative influence on ecosystem structure and function in the alpine meadow.

Acknowledgments We gratefully acknowledge the funding received from Foundation for Excellent Youth Scholars of CAREERI, CAS (Y251981001), and the Natural Science Foundation of China (41130533, 40901003, 31100306).

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